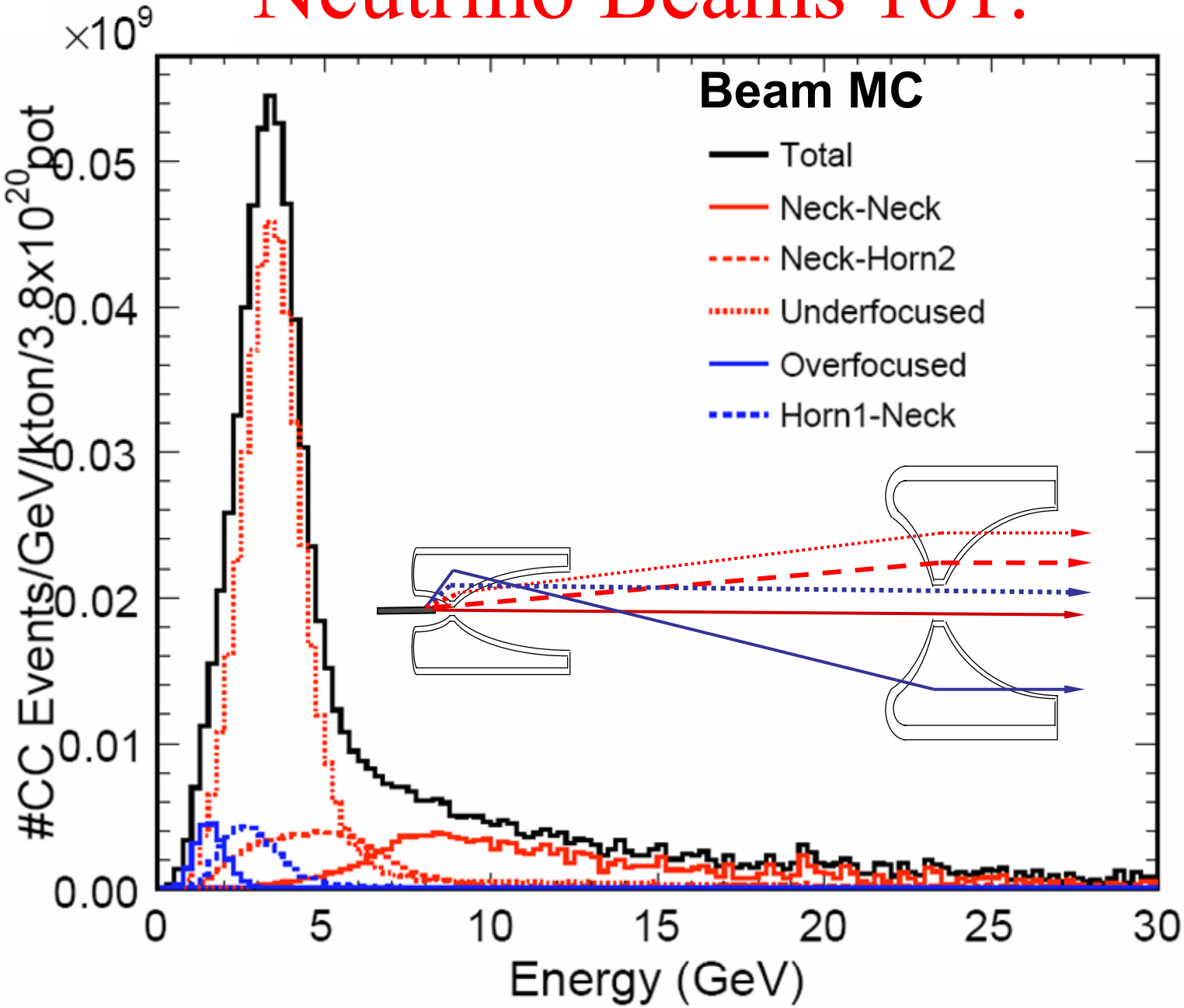
Proposed Blessed Beam Plots

Encapsulated postscript files of the plots in this ppt file are available at the following link off the Beam Systematics Group's web page:

http://www.hep.utexas.edu/numi/beamMC/blessed-plots/

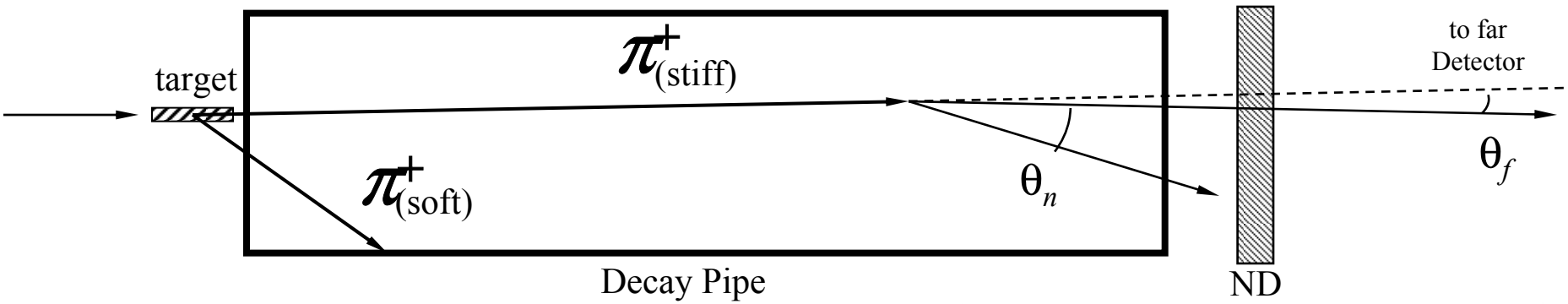
Neutrino Beams 101:



Caption to previous page

- There are 5 general trajectories of mesons that pass through the horns.
- Diagram shows the 5 categories, plot shows in the ND what those categories contribute to the spectrum.
- There is an inverse correlation between pion momentum and angle as it leaves the target. Thus, the wide-angle pions produce the softest neutrinos, as can be seen upon inspection of the plot.

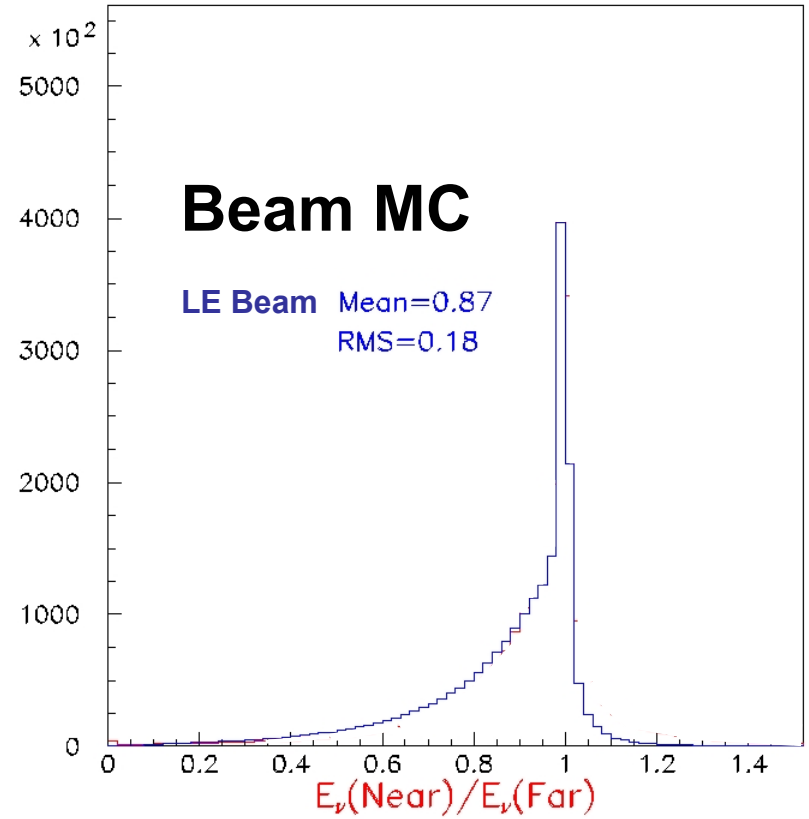
Neutrino Beams 102:



- ND and FD spectra similar, but not identical

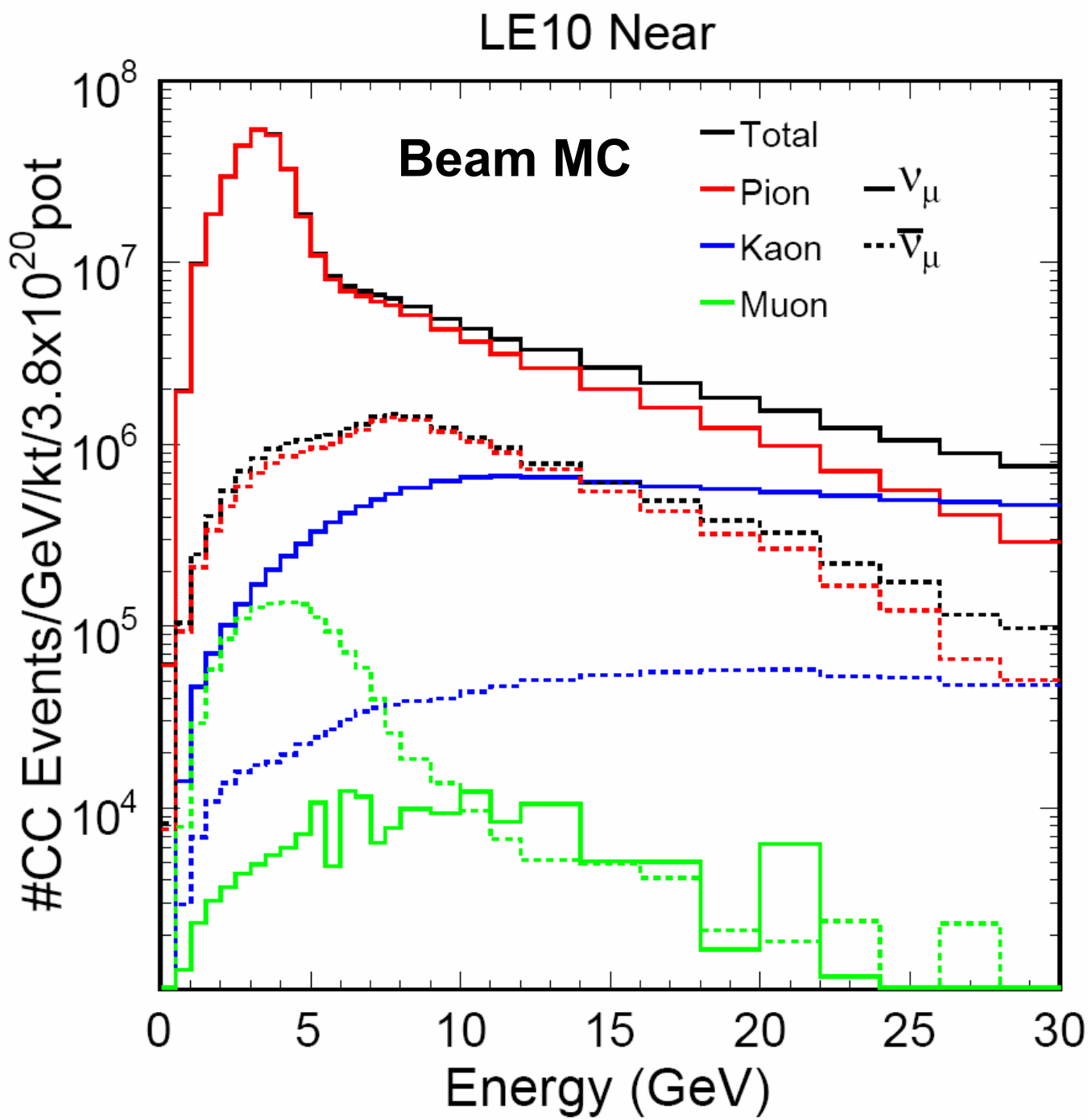
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$



Caption to the previous page

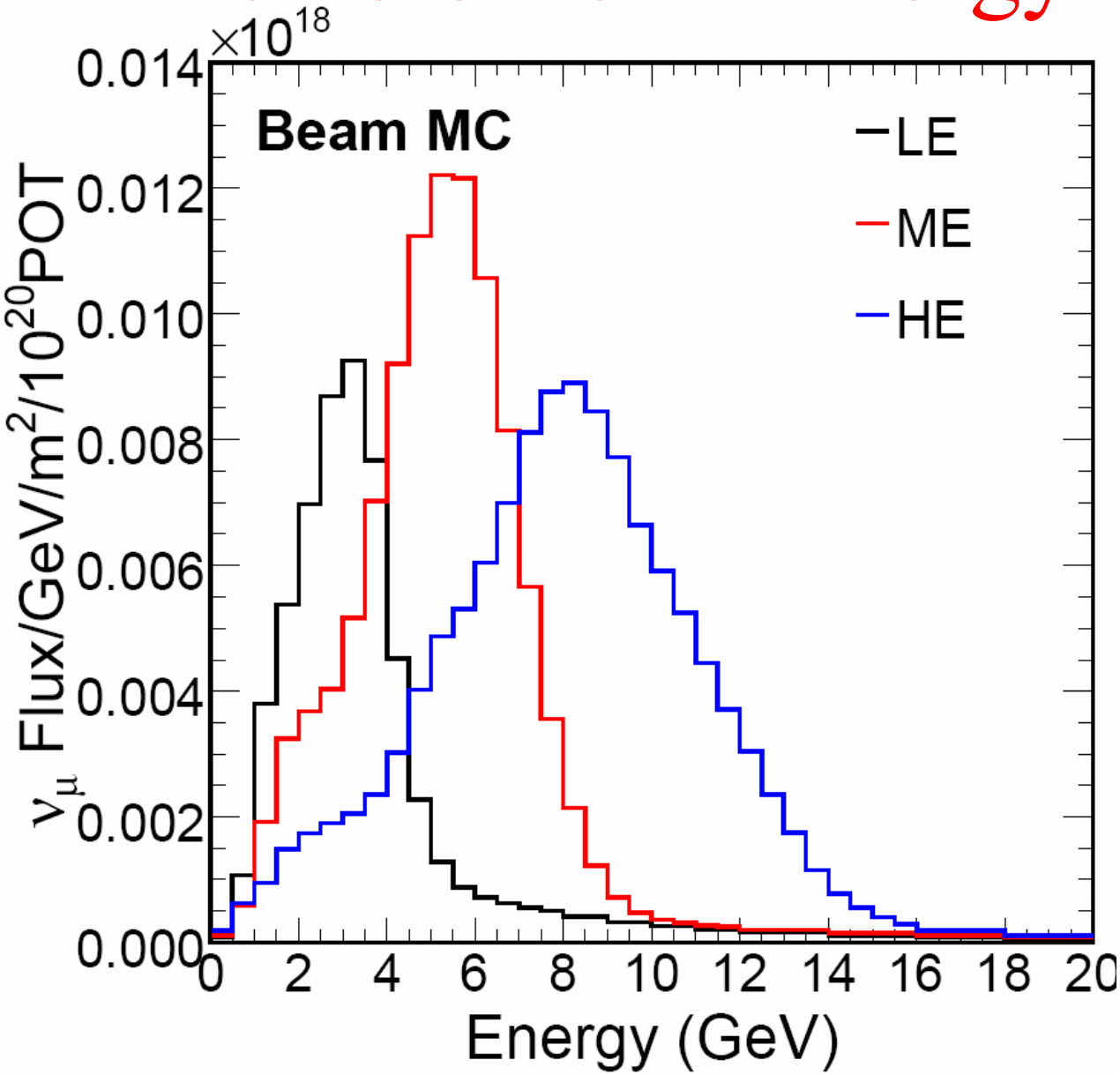
- Every pion decaying in the decay pipe can, in principle, send its neutrino to the ND or FD.
- The ND has a much larger solid angle acceptance than the FD, so wider-angle pion decays can still give neutrinos in the ND
- The correlation between pion decay angle and neutrino energy (see eq'n) means that the ND energy spectrum can be quite different than the FD spectrum.
- The ND-FD difference is exacerbated by the fact that fast pions decay "right in front" of the ND, exaggerating their solid angle contribution.
- The lower plot shows the ratio of nu energy that would arise from a given pion decay if that nu hit the ND vs if it hit the FD. There is one entry per pion in the beam MC, weighted with unit weight (NB: the probability of hitting the ND and FD are quite different, so this is just a measure of energy difference for that pion decay).


LE10 Near
Beam MC
Total
Pion
Kaon
Muon
ν_μ
$\bar{\nu}_\mu$
#CC Events/GeV/kt/3.8x10^{20}pot
Energy (GeV)
10^8
10^7
10^6
10^5
10^4
0
5
10
15
20
25
30

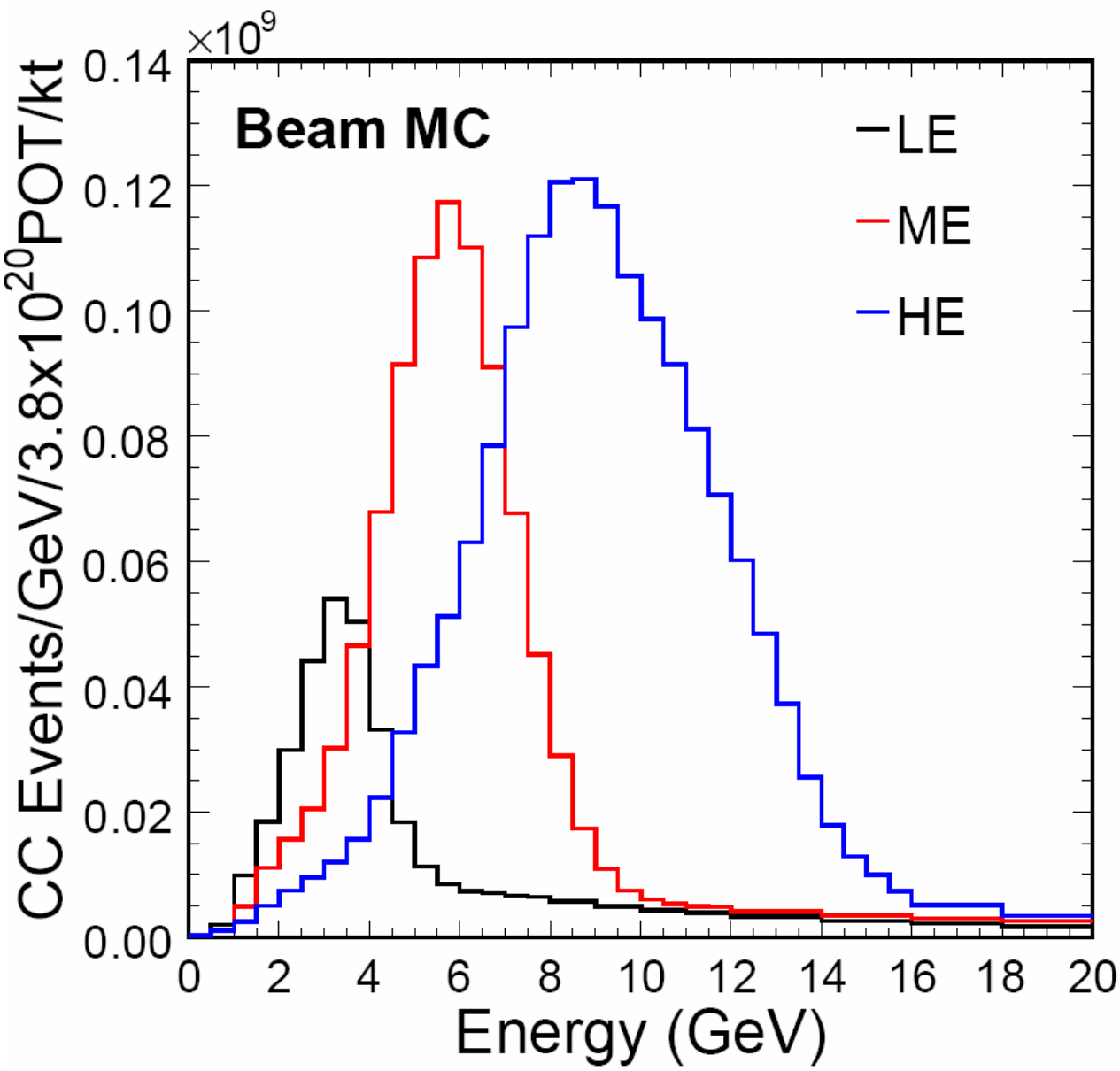
Caption to previous page

- This is the decomposition of the nu and numubar flux coming from pion and kaon and muon decays.
- This plot produced with GNuMI v.18

Flexible Beam Energy



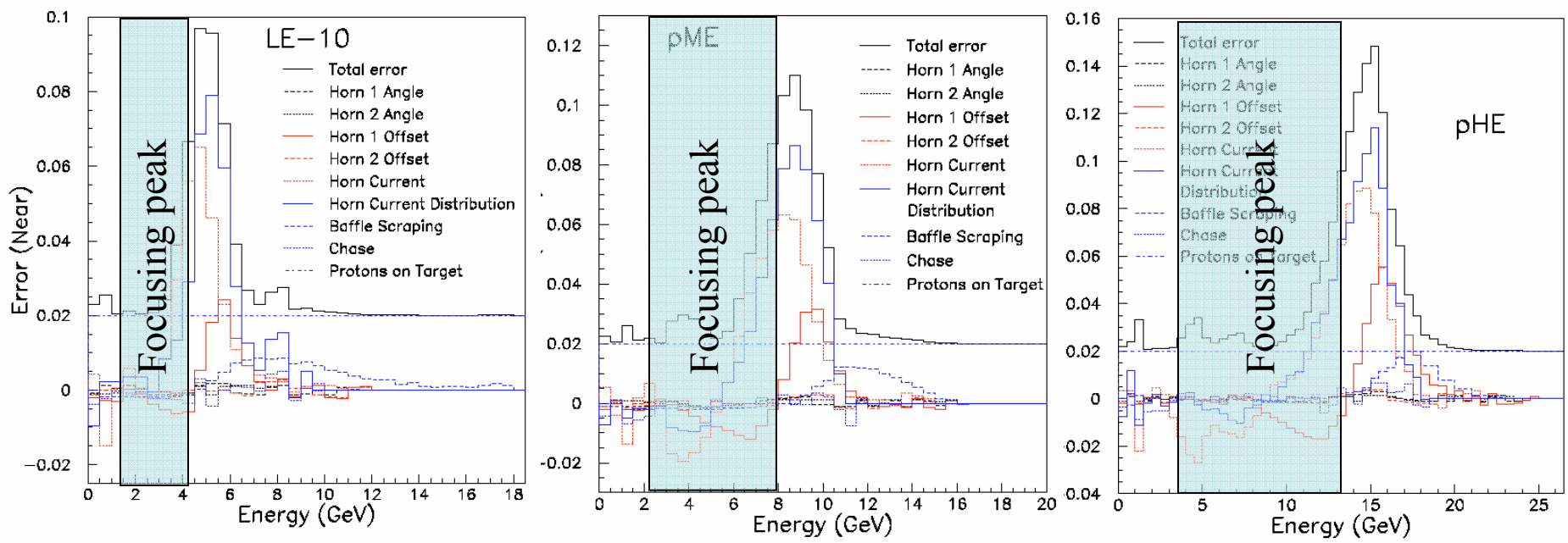
Flexible Beam Energy



Caption to the previous 2 pages

- These are the energy spectra for 3 standard beam configurations, each of which has run for at least 1.5E18 POT
- Note there is one page for flux (neutrinos/square-meter) and one for CCevts
- LE – target 10cm upstream from ‘full insertion’ into the horns and horns at 185kA
- ME – target 100cm upstream of full insertion and horns at 200 kA
- HE – target 250cm upstream of full insertion and horns at 200 kA
- Note these are the “semi-beams” and not the ful ME and HE beams from old TDR days, so we discourage showing those old plots or talking about re-positioning the horns to get the beam spectra – only the target is moved here.
- Spectra produced with GNuMI-v.18.

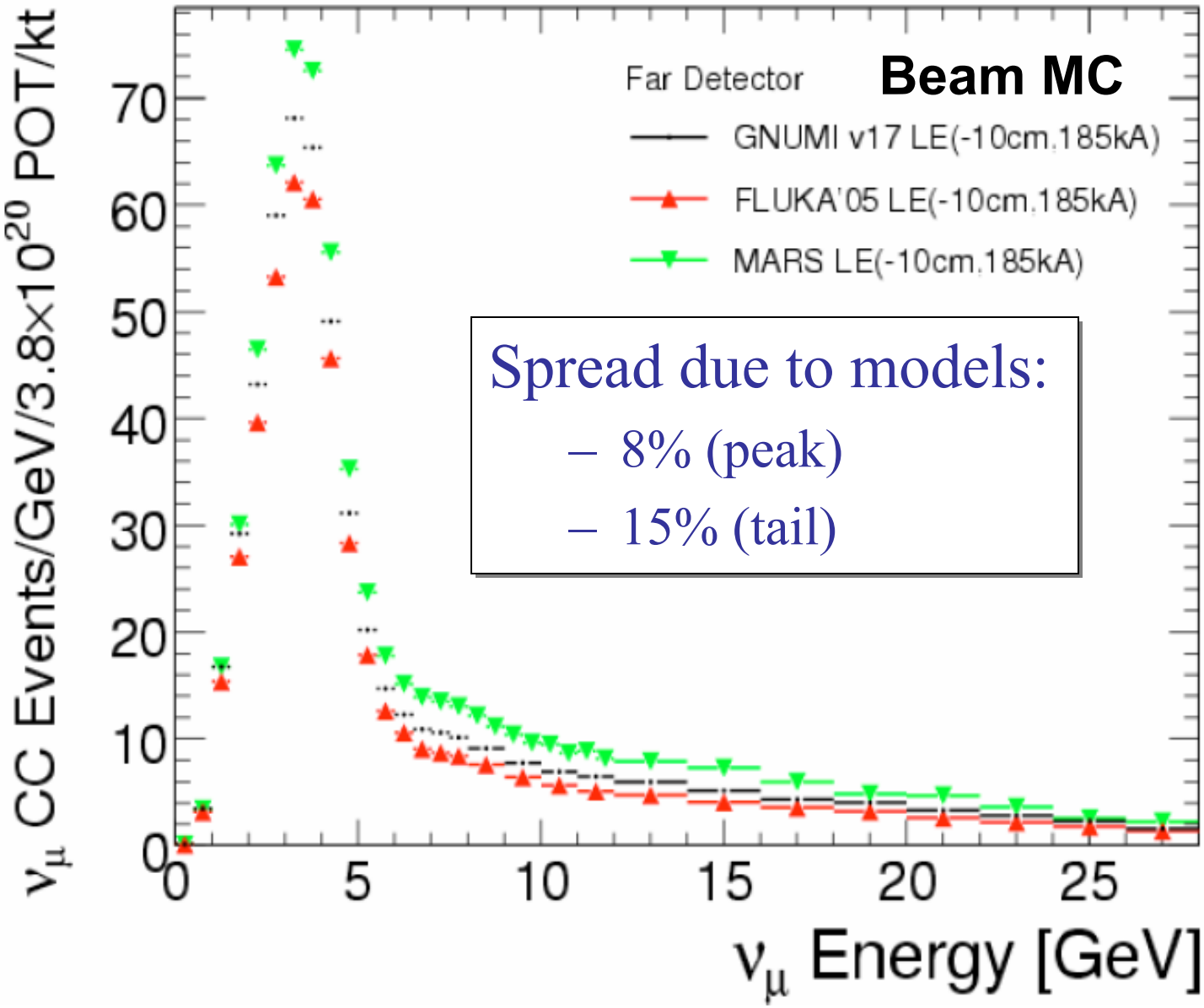
ND Flux Uncertainty



- These are relative errors in the ND flux as a function of true neutrino energy. All effects not including hadron production uncertainties. Plots documented in minos-doc-1283.

- In most cases these errors backed up by actual beam instrumentation measurements.

Hadron Production Uncertainty



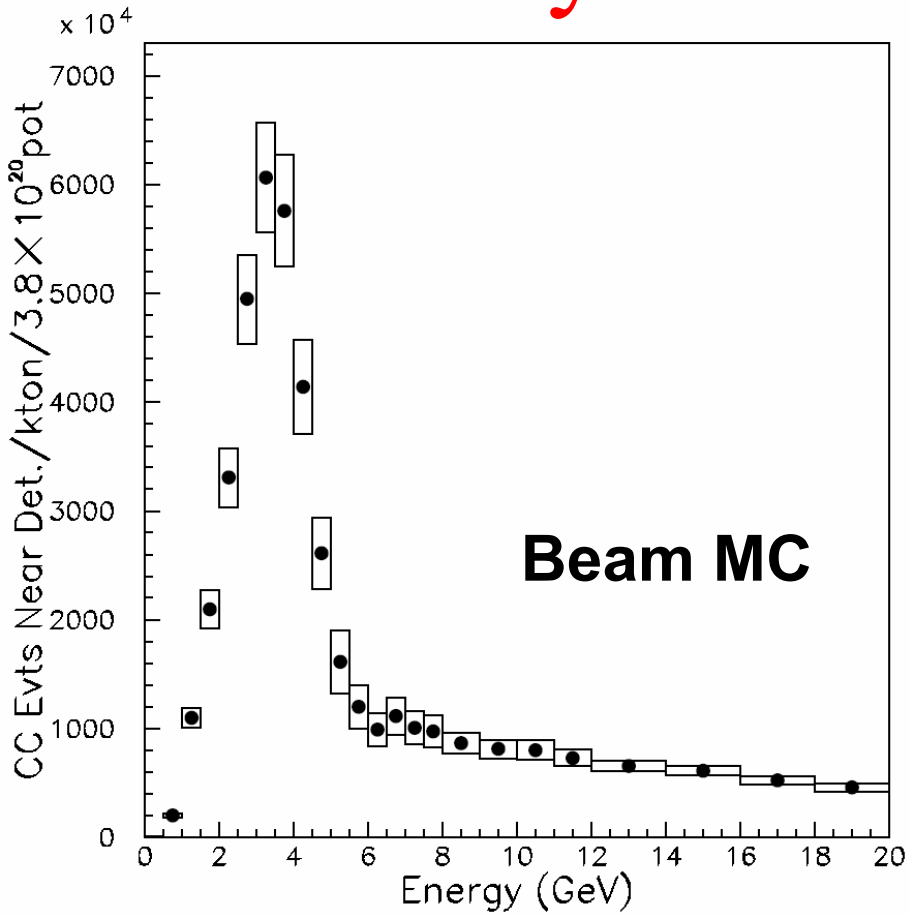
Spread due to models:

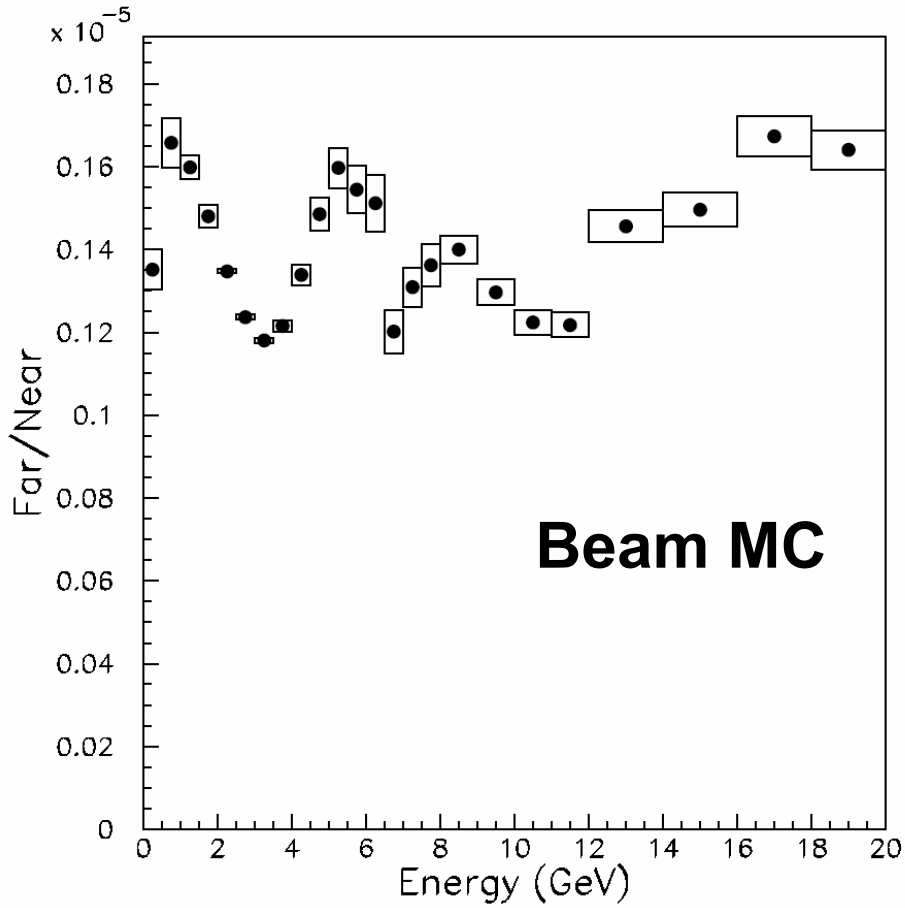
- 8% (peak)
- 15% (tail)

Caption to previous page

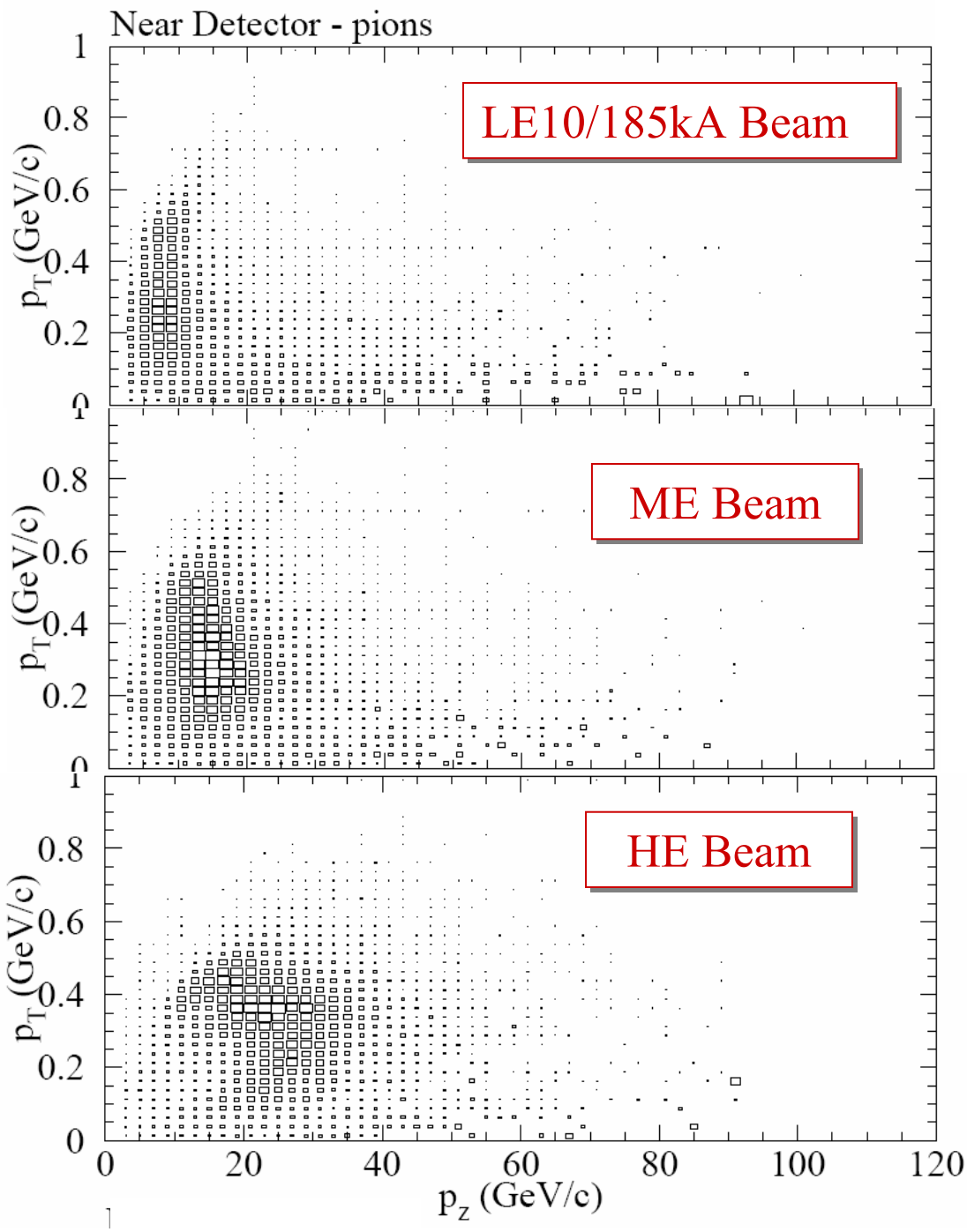
- GNuMI-v.18 is a two-step MC:
  - Step 1: a proton beam is impinged on a model of the target and the yield of particles of various momenta and angles are counted as they come off the target. This is performed in either Fluka2005 or MARS-v.15
  - Step 2: The particles from the target are tracked through the horns and decay pipe. Decays to neutrinos are calculated in a weighted manner to the ND and FD for each pion
- The particle yields from step 1 (differences between MARS and Fluka) amount to the larges source of uncertainty in the MC simulation.

Total Systematic Uncertainties





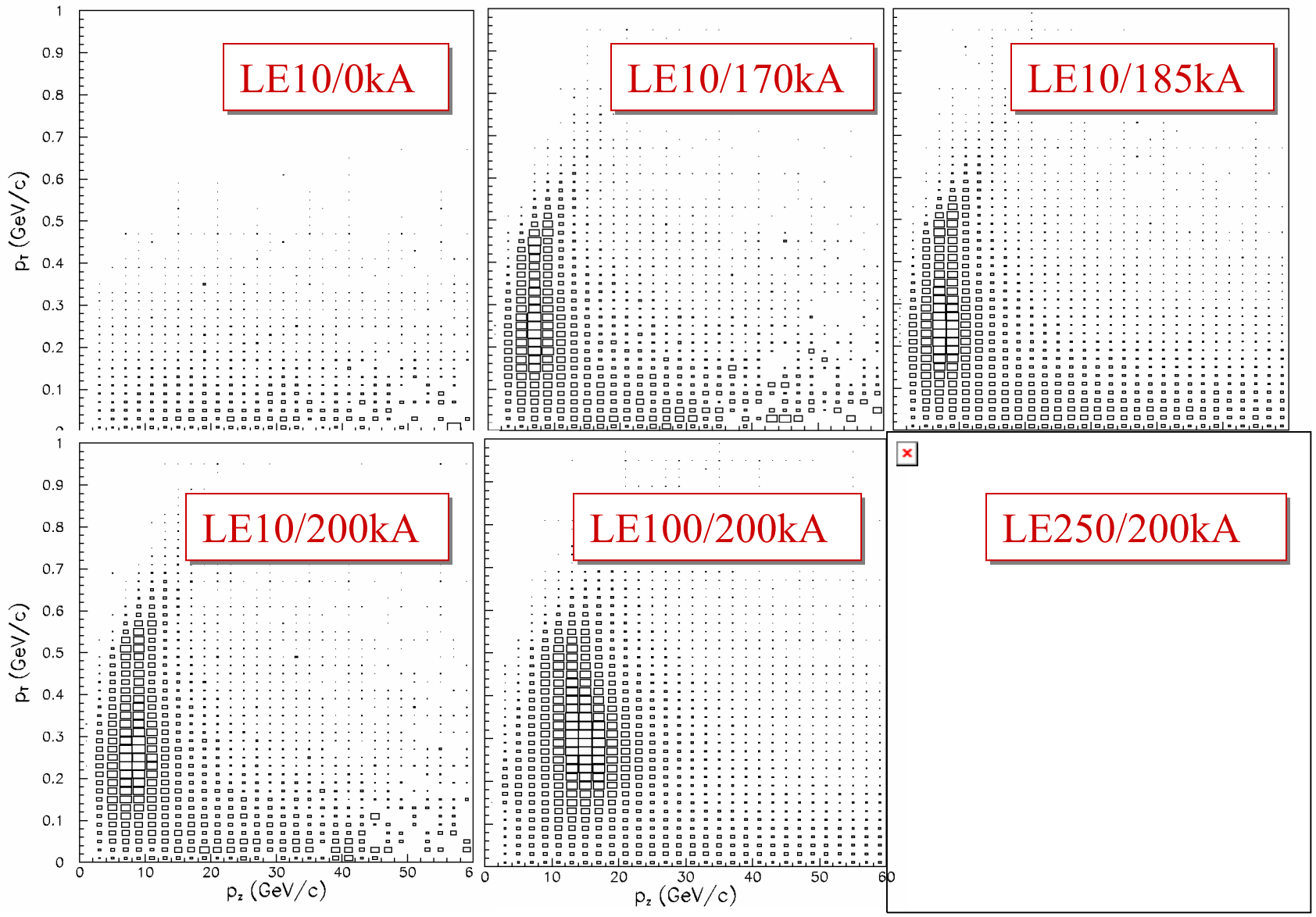
- This is GNuMI-v.18 (Fluka 2005 for hadron production) for the spectrum and F/N ratio
- The uncertainties are the full uncertainty (from all effects, including hadron production) provided by the beam systematics group. These are documented in minos-doc-1283.
- Note that these are uncertainties to be used before hadron reweighting



Horn Focusing

- This plot shows the p_z and p_T of pions that lead to neutrinos in the LE, ME, HE beams. Size of box is proportional to the neutrino flux in the ND.
- The NuMI horns focus particular ranges of x_F and p_T for particles emanating from the target.
- Variation of the target configuration (and also horn current) allows us to test our understanding of hadron production from the target across a wide range of x_F and p_T .

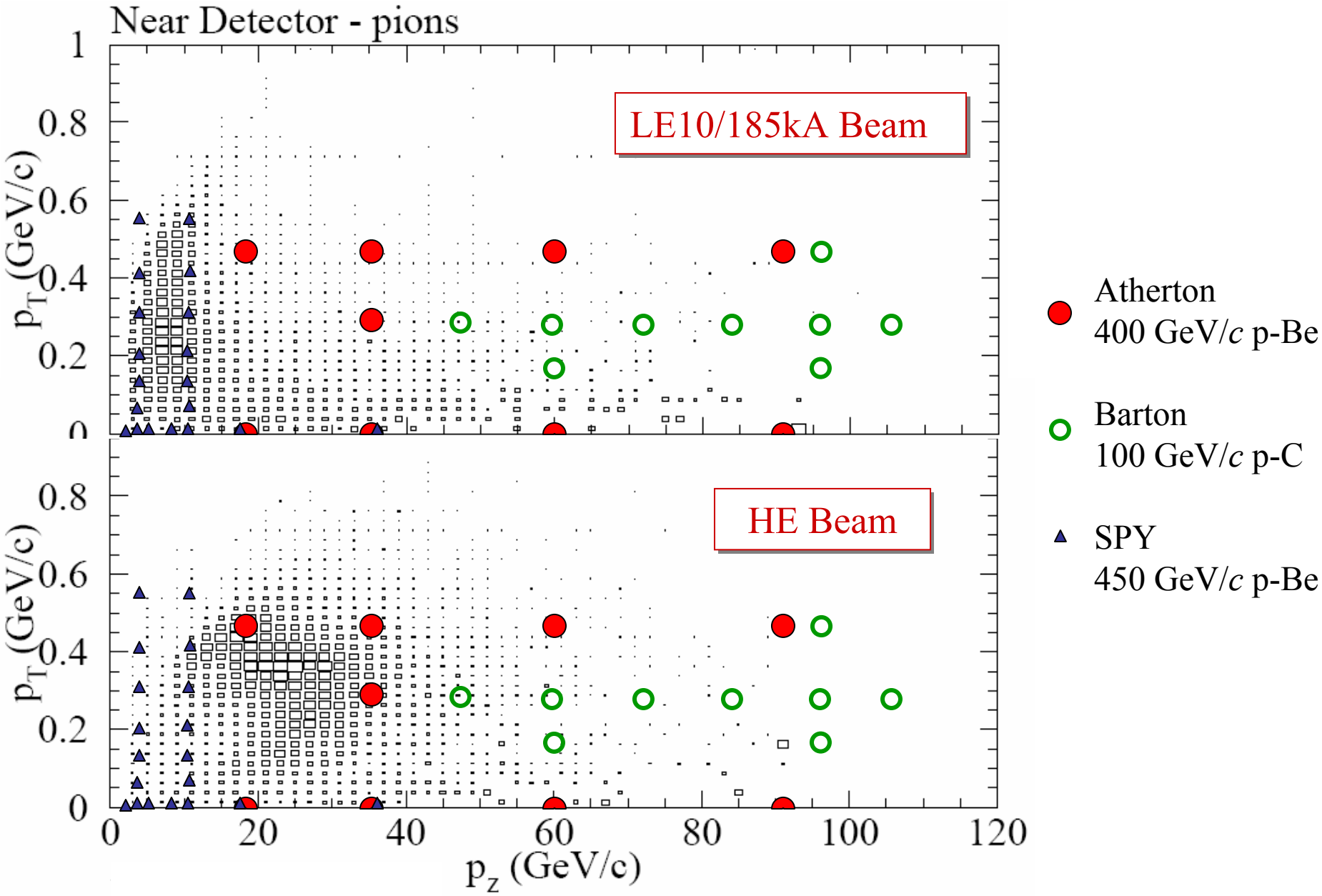
Horn Focusing



Caption to Previous Page

- These plots show the p_z and p_T of pions that lead to neutrinos in the LE, ME, HE beams. Size of box is proportional to the neutrino flux in the ND.
- The NuMI horns focus particular ranges of x_F and p_T for particles emanating from the target.
- Variation of the target configuration (and also horn current) allows us to test our understanding of hadron production from the target across a wide range of x_F and p_T .
- This set of 6 plots has 3 which are identical to the previous page, but I wanted to give folks the option of showing all the beams if they wish. The 170kA/200kA runs in the LE10 setting sample slightly different p_T at the same x_F, so were a helpful constraint. We haven't used the horn off data yet, but it agrees very well with the fit from the other 5 beams.

Previous Hadron Production Data



Caption to previous page

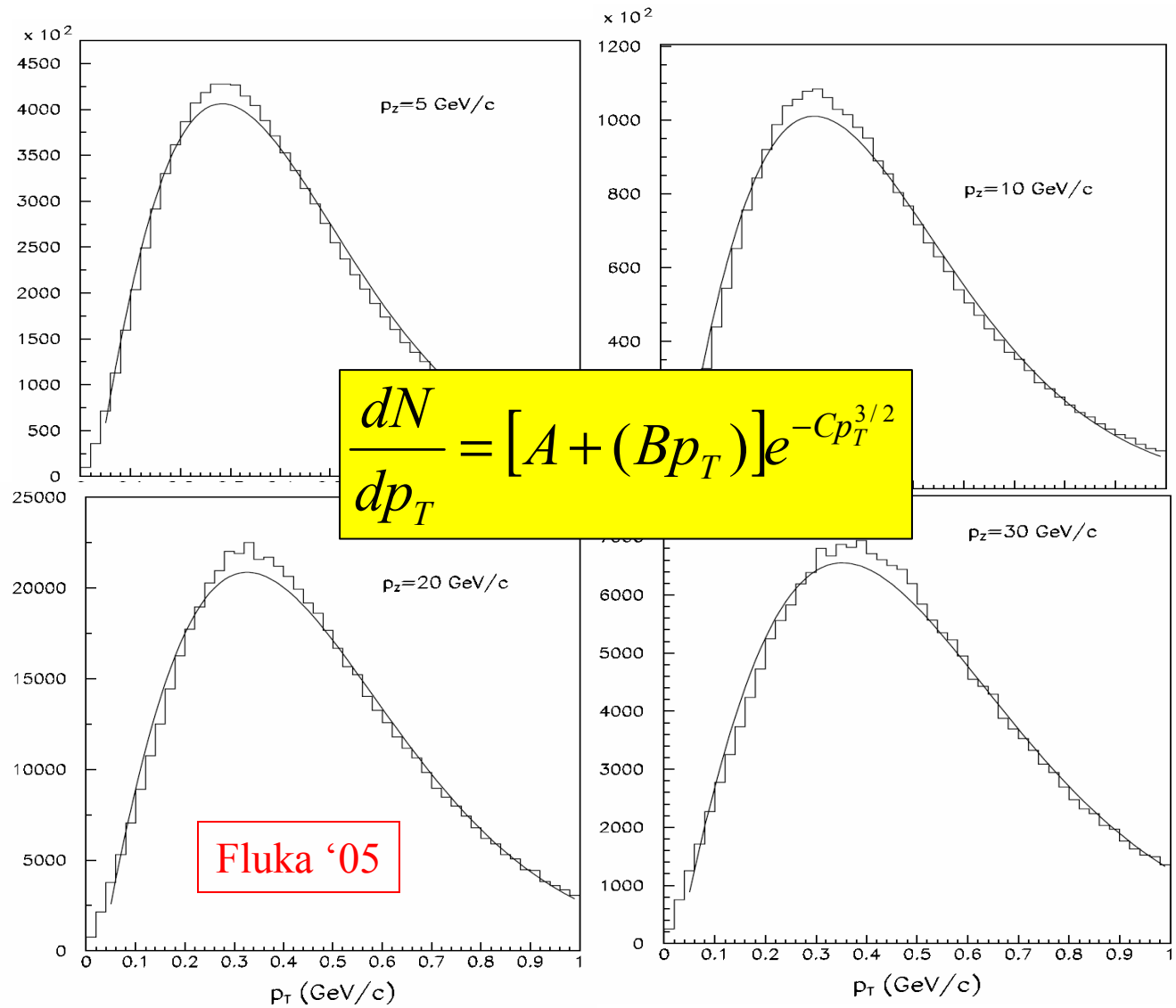
- The p_z and p_T of particles off of targets has never been measured for a thick target of Carbon. I compare here the distributions for the LE and HE beams to previous hadron production experiments.
- The best data of relevance to us is SPY, also of relevance is Atherton's & Barton's exp'ts.
- Note how little data is available to constrain the HE beam.
- Note also how little data there is to constrain the high-energy tail of the LE beam.
- Where there is little data to constrain the models, it is easy to imagine that the model uncertainty is greatest.

Caption to the next two pages

- The largest uncertainty in the neutrino beam MC is the yield of pions and kaons (as a function of momentum and angle) off the target. We attempted to "fit" our ND data to tell us this yield using the fact that we have taken data in 5 very distinct beam configurations, allowing some measure of the target particles' yields in different kinematic regimes.
- We tried to come up with a parameterization of the target pions which we could "warp" in such a way as to better agree with the ND data.
- The first slide shows fits to Fluka2005 (used in the beam MC to get the yield of pions and kaons from the target) to a functional form of particles as a function of pion momentum and transverse momentum. We will later warp that functional form.
- The second slide shows the components of the parameterization that fits Fluka2005 (SKZP functions) which we will warp as necessary to fit the ND.

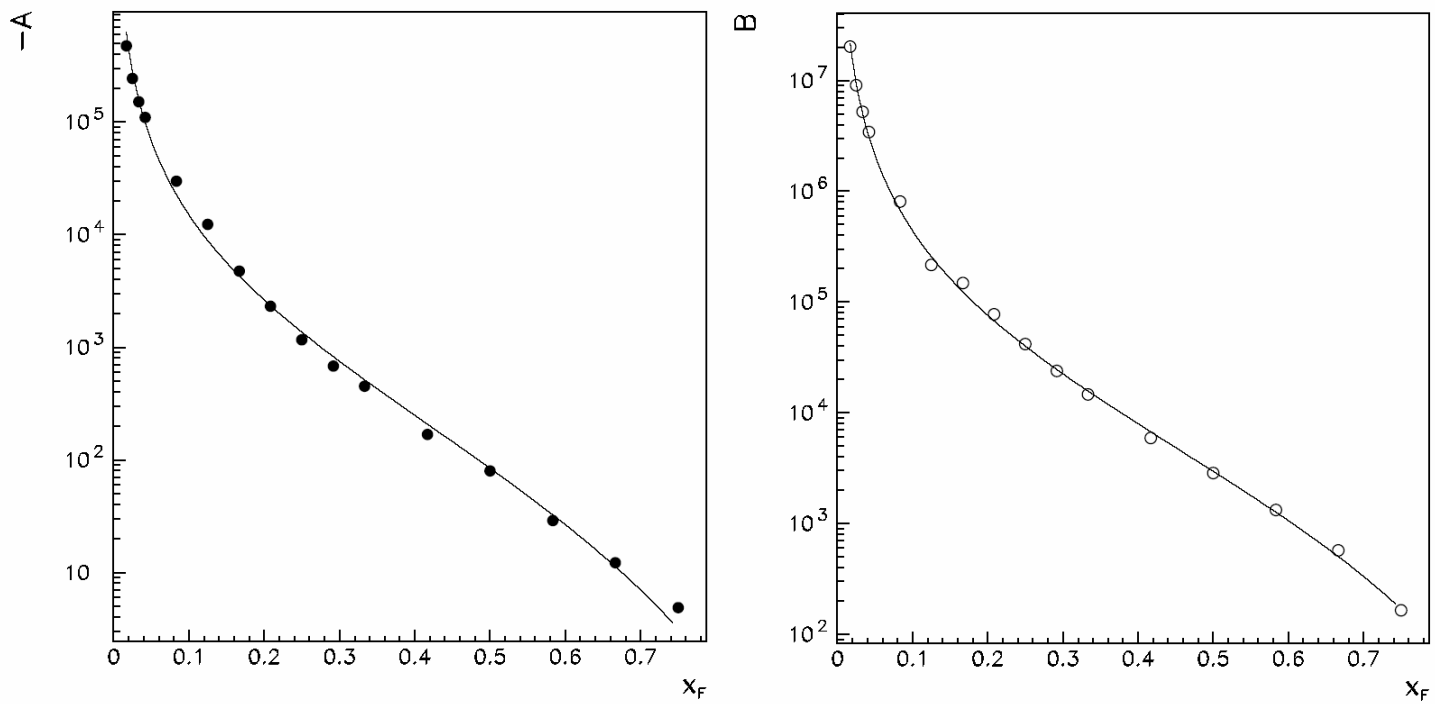
Parameterizing Hadron Production

- We tried to parameterize the Fluka'05 (x_F, p_T) distributions with an empirical formula.
- In this fit,
  - $A = A(x_F)$
  - $B = B(x_F)$
  - $C = C(x_F)$
- This form is quite similar to BMPT
- The $(p_T)^{3/2}$ fits the data rather well.



$$\frac{dN}{dp_T} = \left[A + (Bp_T)\right]e^{-Cp_T^{3/2}}$$

Fitting for Hadron Production (*cont'd*)

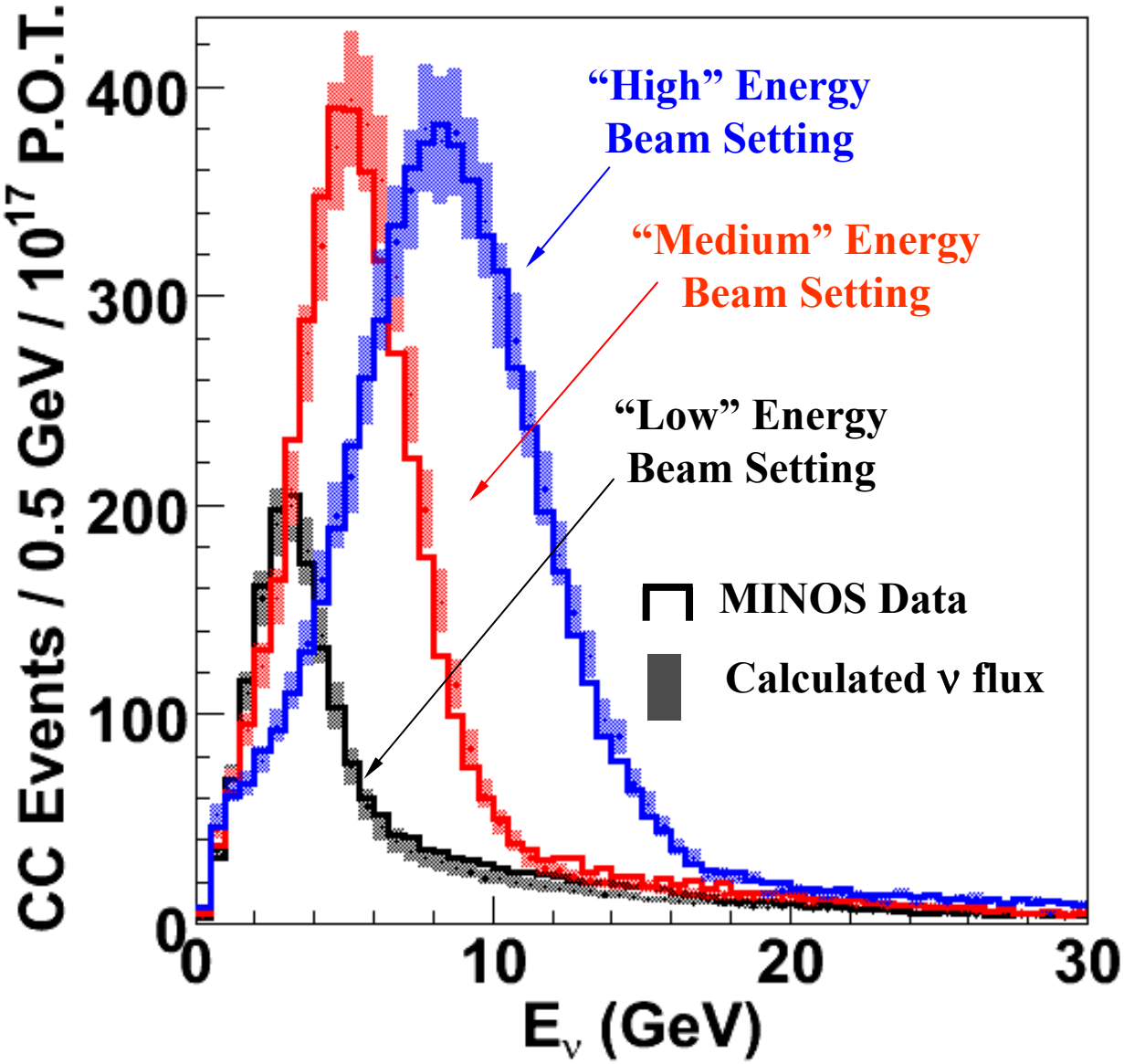


- Both $A(x_F)$ and $B(x_F)$ fit reasonably well to following shape

$$(1-x_F)^{\alpha}(1+bx_F)x_F^{-\beta}$$

- The values of the exponents are different from BMPT's paper, but this is a thick target parameterization, and they quoted invariant cross section.
- Variations of these parameters were attempted to characterize allowed variations in hadron production.

ND Spectra Before Reweighting

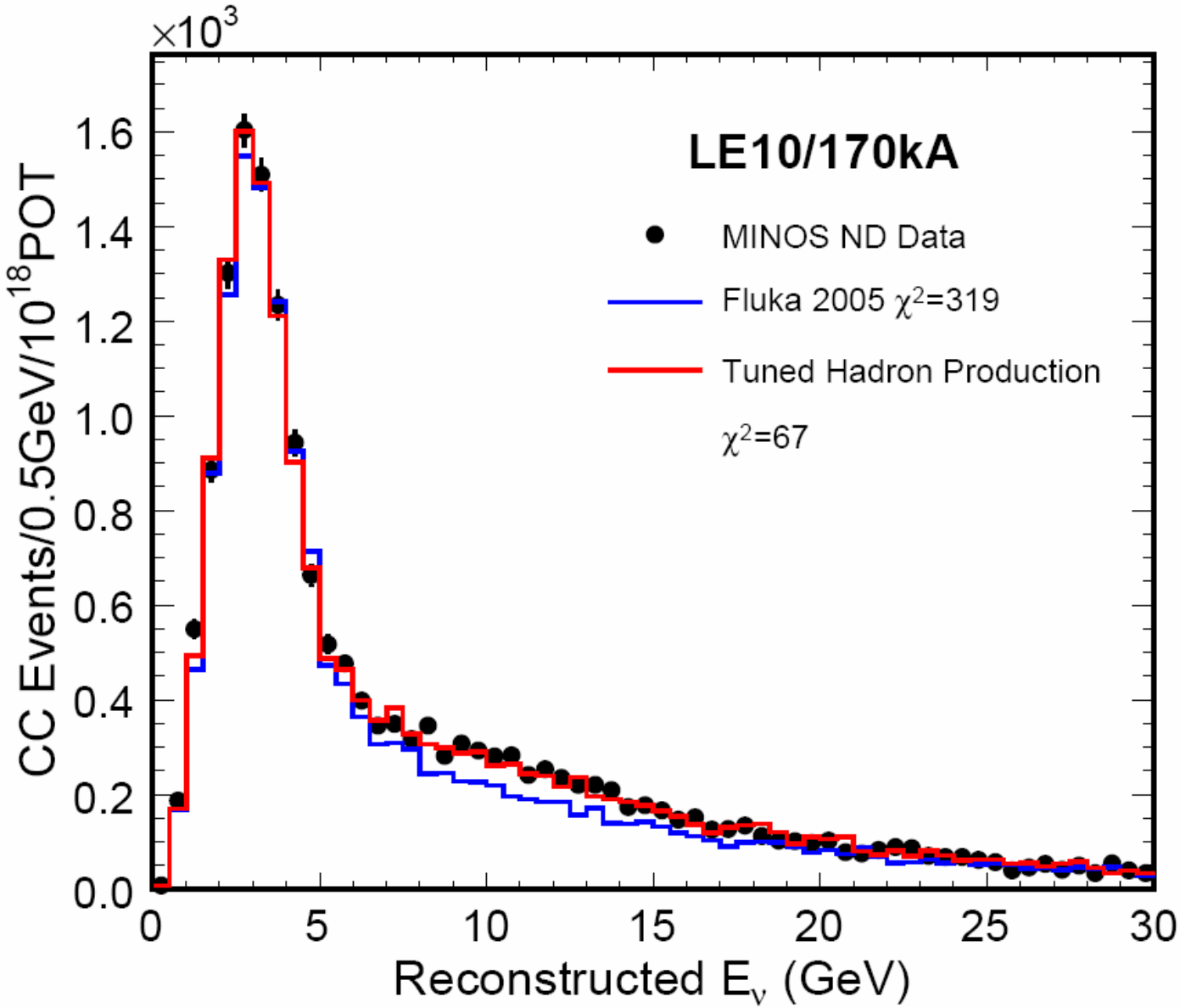


- These plots show the beam spectrum before any tuning.
- Error bars are from the beam
- CC events selected using cuts based analysis (Trish)
- The MC is the nominal R1.18.2 (GNuMI-v.18 with Fluka particles).
- Error bars are from the beam systematic errors (dominated by hadron production uncertainty, but all effects are included).

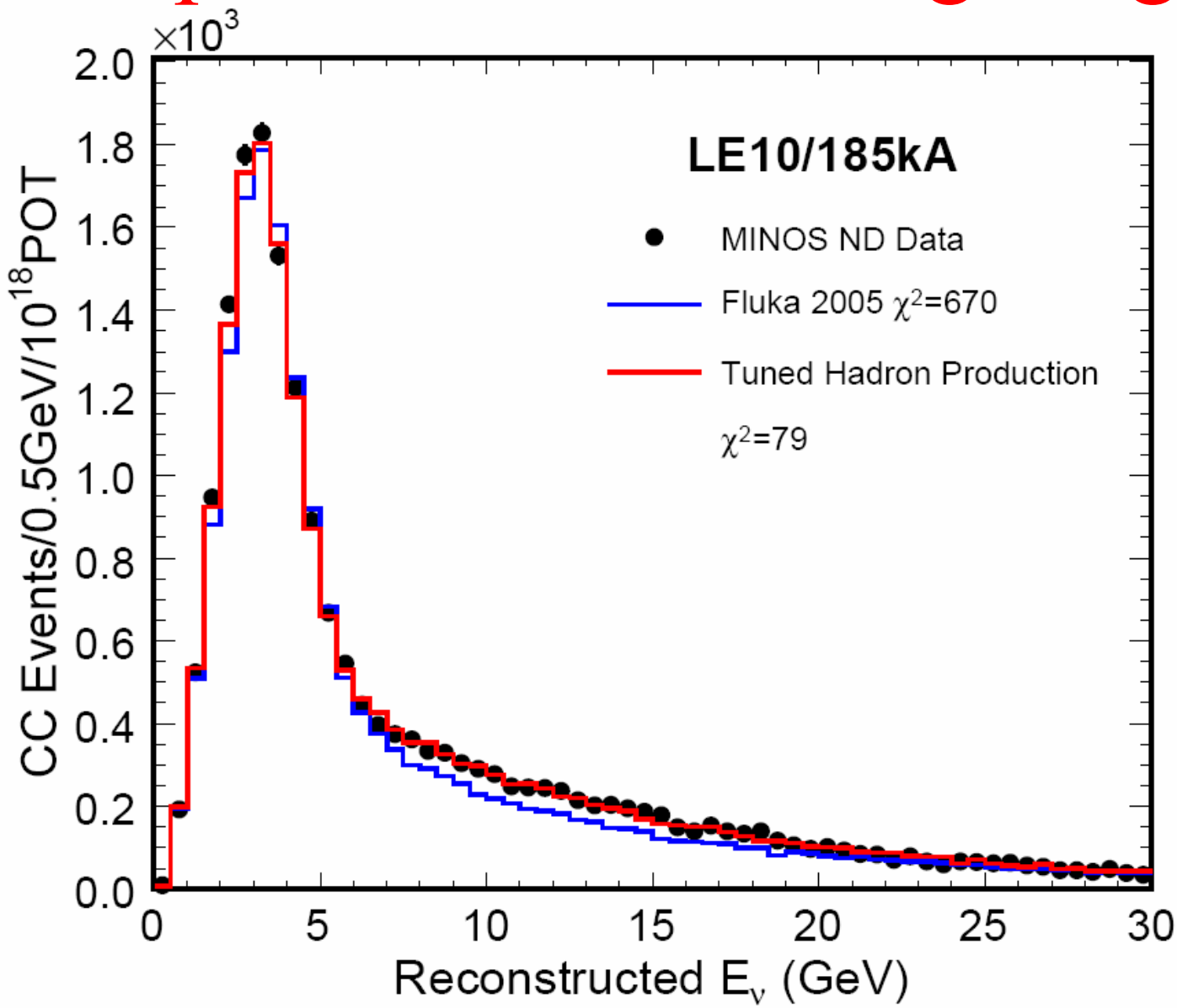
Caption to next 5 slides

- The next 5 slides show the results of the re-fitting of the beam MC from Fluka2005 hadron production to a warped (x_F,p_T) distribution – the SKZP2 model.
- The hadron production model has 7 input parameters, which were fit using MINUIT to give the best chi**2 to the 5 beam spectra simultaneously.
- At the same time as the hadron production was fitted, we fit for the best horn current, skin depth, *etc*. Most other beam effects came out with little or zero pull – the largest was the skin depth effect which came out pulled by 0.9σ. This is actually reasonable since we were concerned we put the wrong current distribution in the GNuMI MC in the first place.
- The chi**2 shown have 60 *dof* per plot (total 300), and we've used up just 15 parameters in the fit.
- Each beam configuration was selected to be ~1.5E18 POT so that no one would pull the fit more than others.
- The data selection to get to these plots makes a difference in the extracted beam parameters, though not so much to the actual ND spectra.
- We found that we are not very sensitive to the hadron production parameters – both the TV and SKZPs fit the ND data well, but the two models actually give different mean p_T of pions.

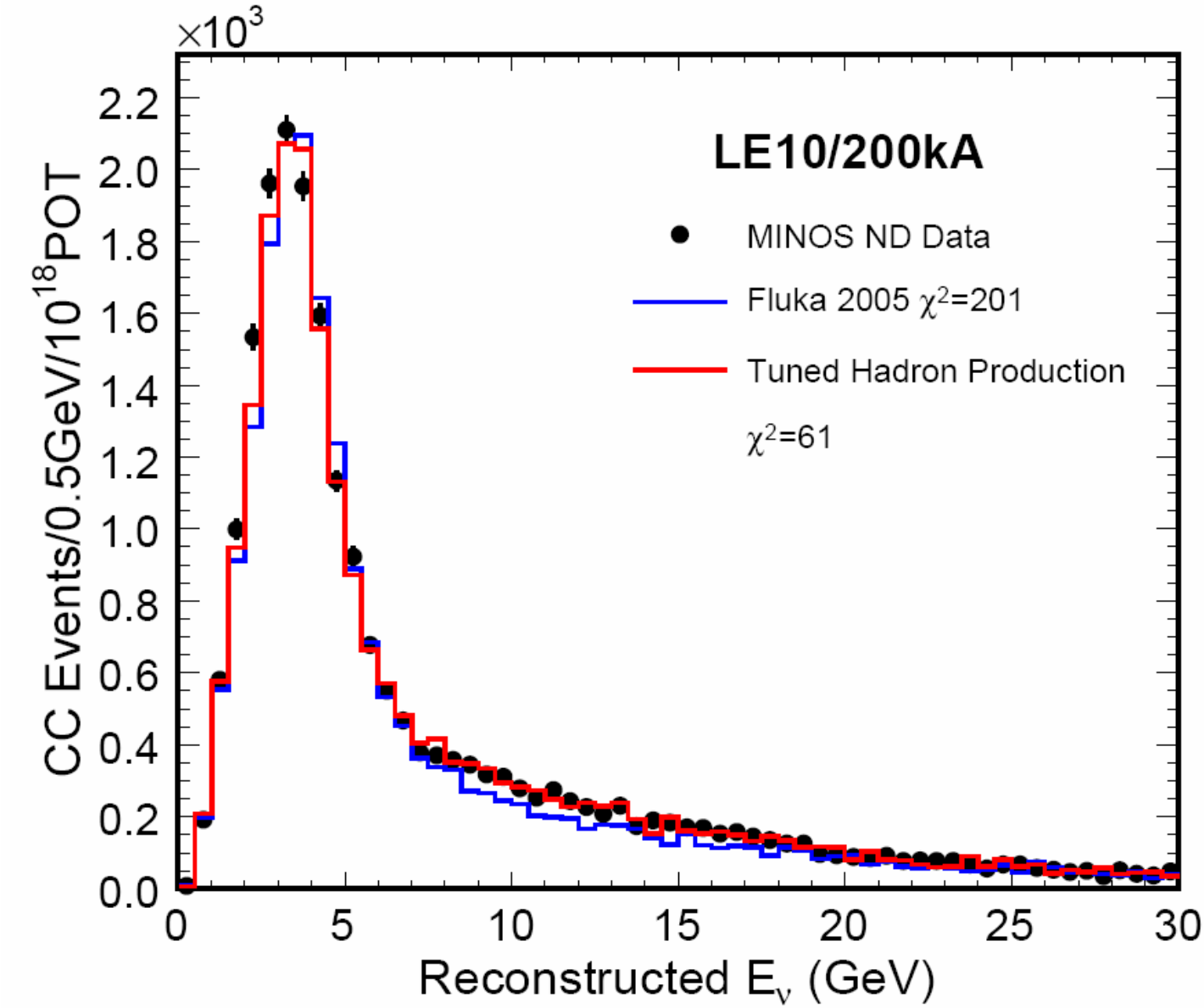
ND Spectra After Reweighting (I)



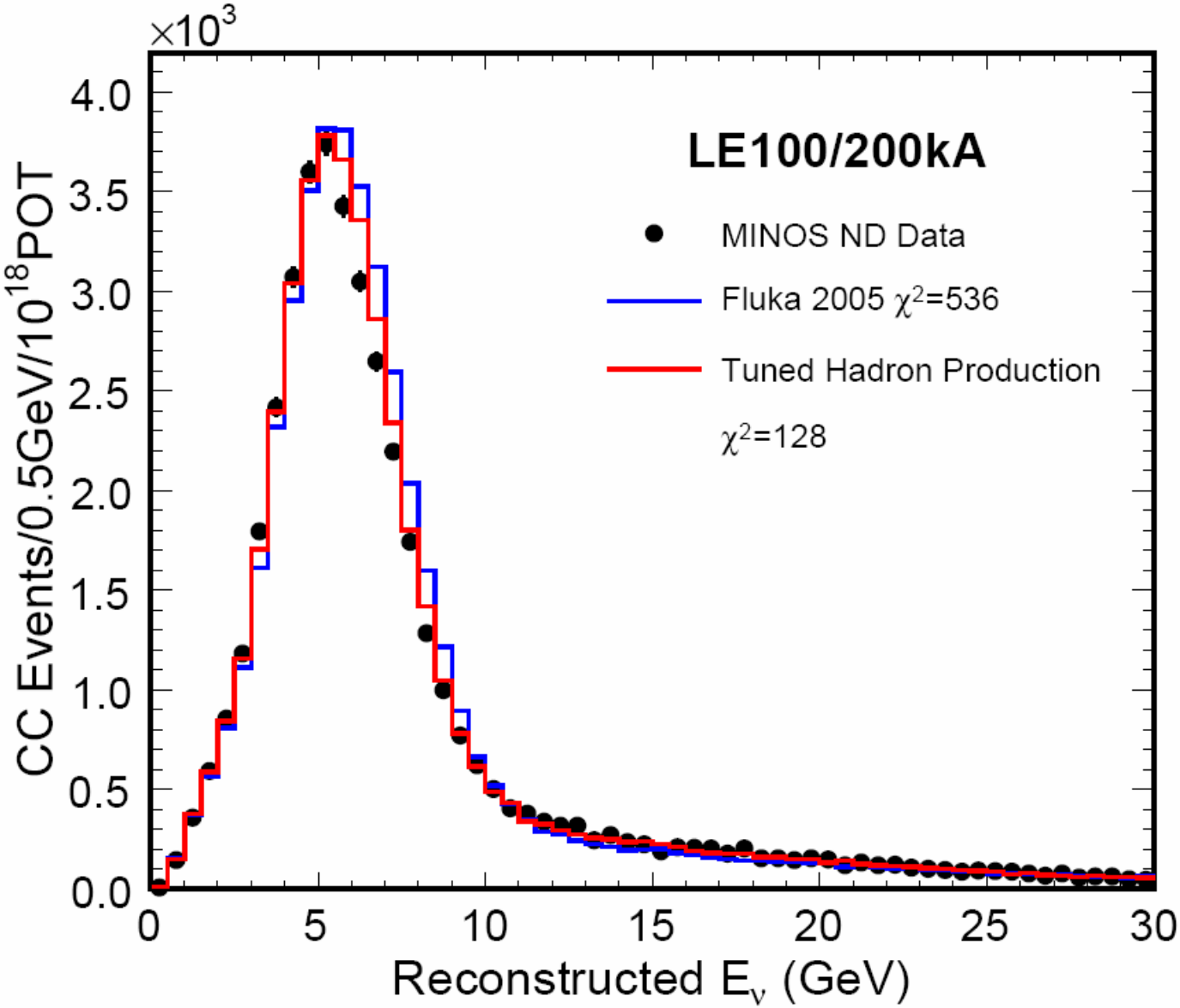
ND Spectra After Reweighting (II)



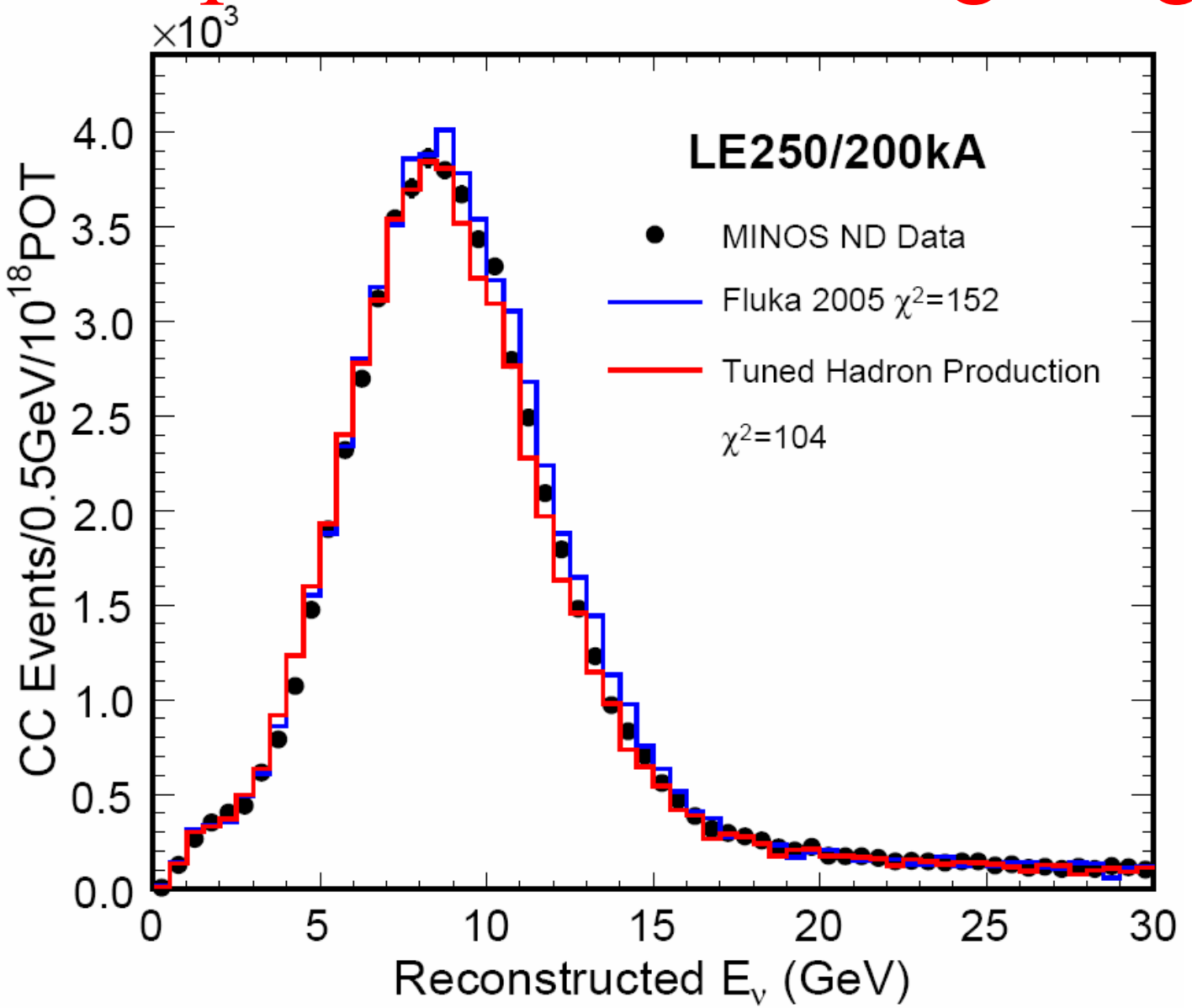
ND Spectra After Reweighting (III)



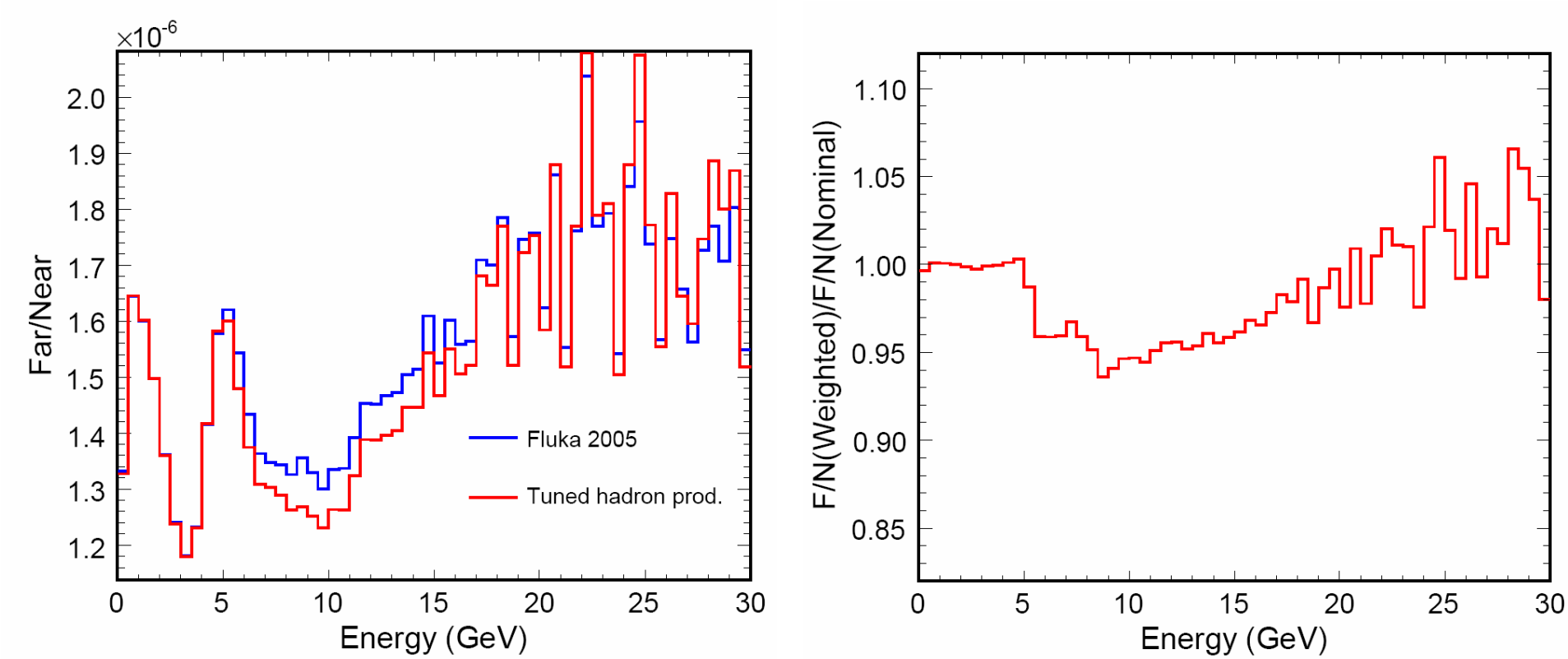
ND Spectra After Reweighting (IV)



ND Spectra After Reweighting (V)



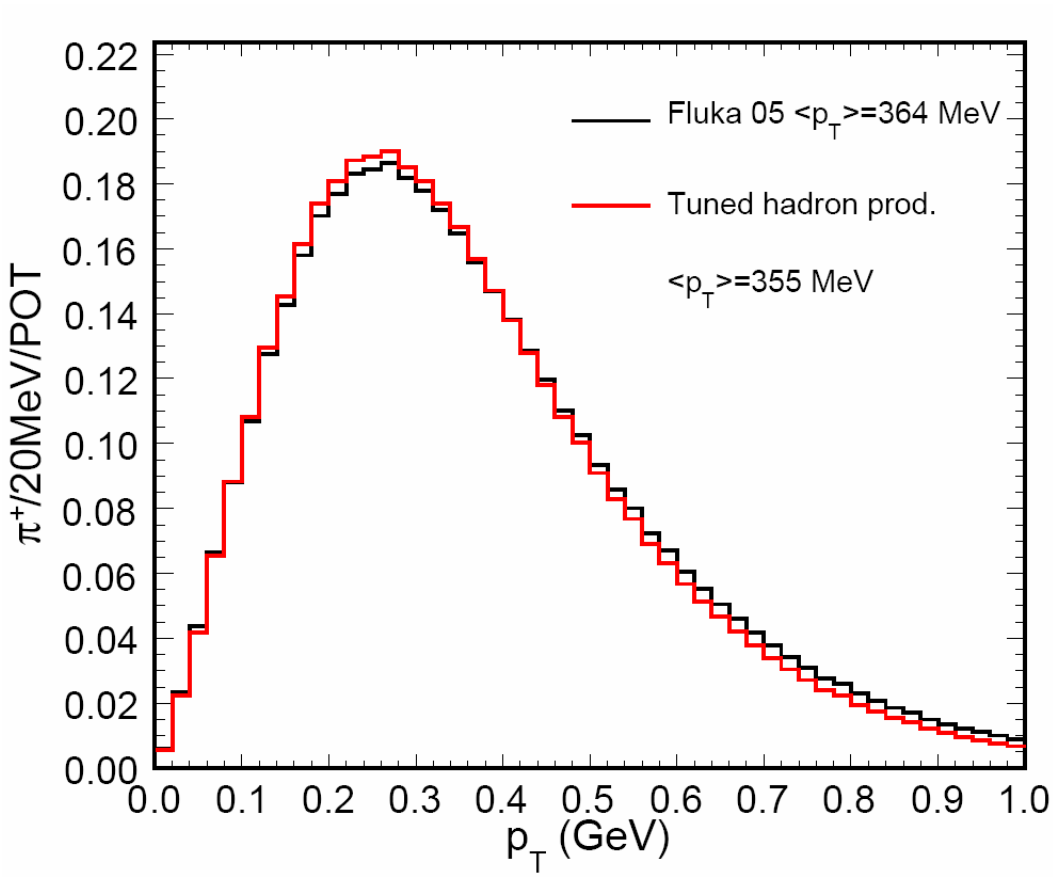
F/N Ratio After Reweighting



Caption to previous slide

- Shown are nominal F/N with GnuMI-v.18 and also the hadron weighting's effect on F/N.
- The post-hadron reweighting is SKZP2, 15 parameter fit.
- The reweighting appears to cause <5% distortions in F/N. It could have been worse or better than this, but this sets the scale for how much the procedure affects the FD spectrum.
- As might be expected, the largest effects are seen just off the focusing peaks for the various beams.

Is this fitted x_F and p_T reasonable?

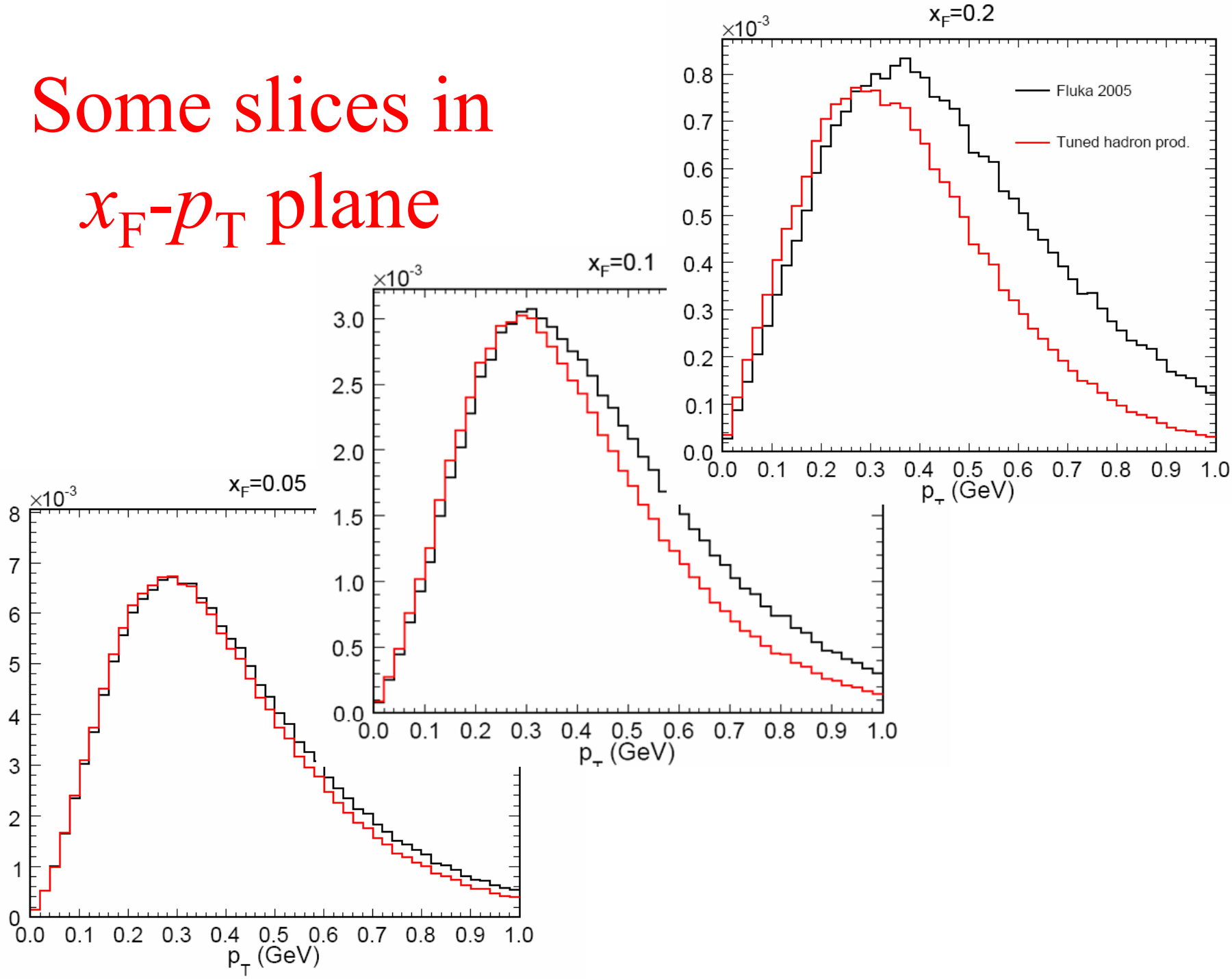


Model	$\langle p_T \rangle$ (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.36
Our Fluka2005 (reweighted to ND)	0.36

Caption to Previous Slide

- The fit we did which warps the hadron production spectrum to fit the data was done one of two ways
  - Allow all (x_F, p_T) of particles to move as needed according to the new warped distribution
  - Apply a penalty term if the new warped function shifts the $\langle p_T \rangle$ of all pions moves by 15 MeV. This attempts to preserve one of the global variables used to characterized hadron production models.
- Both constrained and unconstrained fits were performed. They both give a good fit to the ND data, and both distort the F/N ratio in about the same way (they disagree with one another in F/N only by 2% at 10GeV).
- We advertised the constrained fit as the default. It's mean p_T is shown along with some standard hadron production models in the table.
- The plot shows that p_T of all pions that come from our distorted Fluka after the ND fit. What's happening is that large p_T is being pushed downward. When we did the unconstrained fit, this was more noticeable: the low- p_T stuff was about the same, but the large p_T was pushed further down. It points out an important thing: we aren't very sensitive to large pT parts of the spectrum, since both constrained and unconstrained fits gave about the same chi**2.
- Another thing we'd point out is that the change in p_T is quite small even compared to two versions of Fluka which came out 4 years apart and which are allegedly tuned to the same data! We are no less justified using our fit as the standard MC than Fluka (one can ask which Fluka? The old one would fit our ND better. We just happened to have updated before we looked at our ND data – unlucky?)

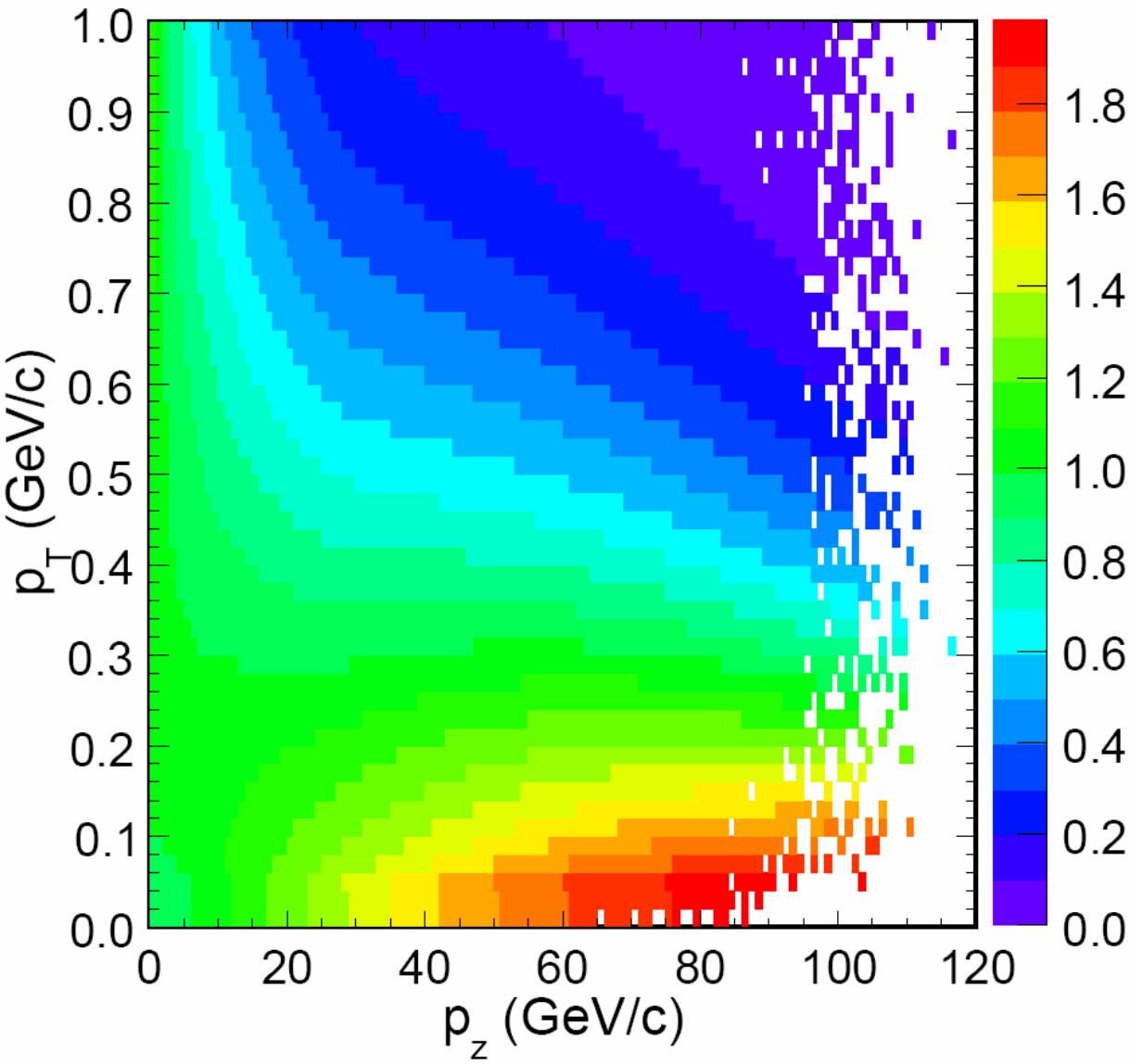
Some slices in x_F-p_T plane



Caption to previous slide

- This slide shows a breakdown of what we have done to the p_T distribution at several values of x_F. As can be seen, it is at the largest x_F where the fit particularly tries to 'narrow' the p_T distribution.
- This is not surprising, because the low p_T particles are responsible for the high energy tail of the low energy beam, and the fit needed to bring that higher in rate.

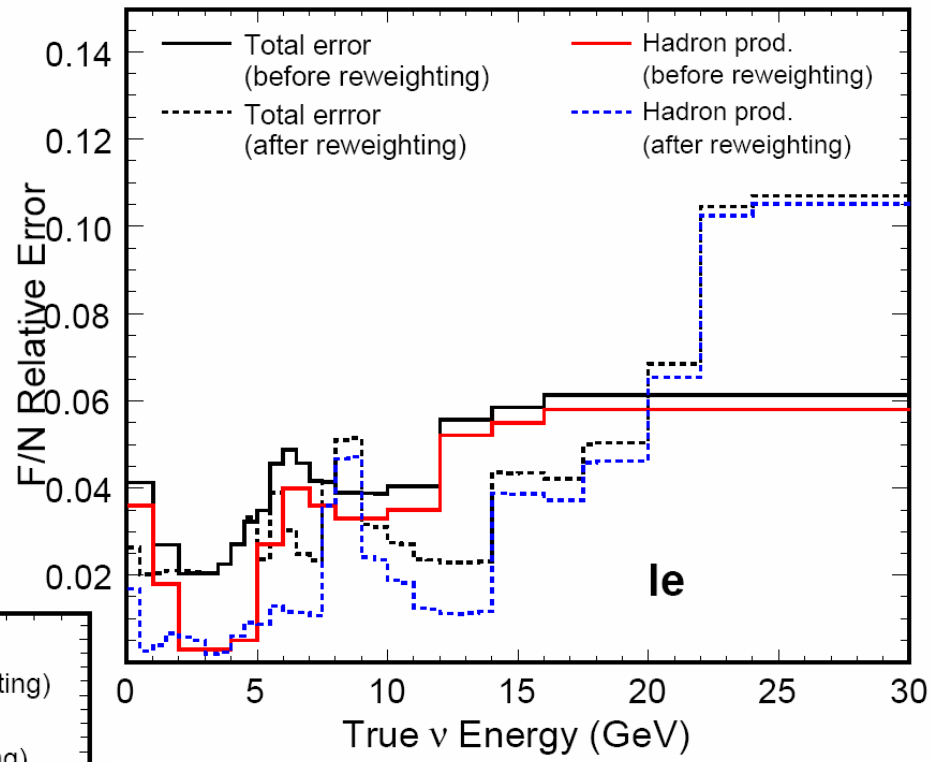
Demonstration of weights

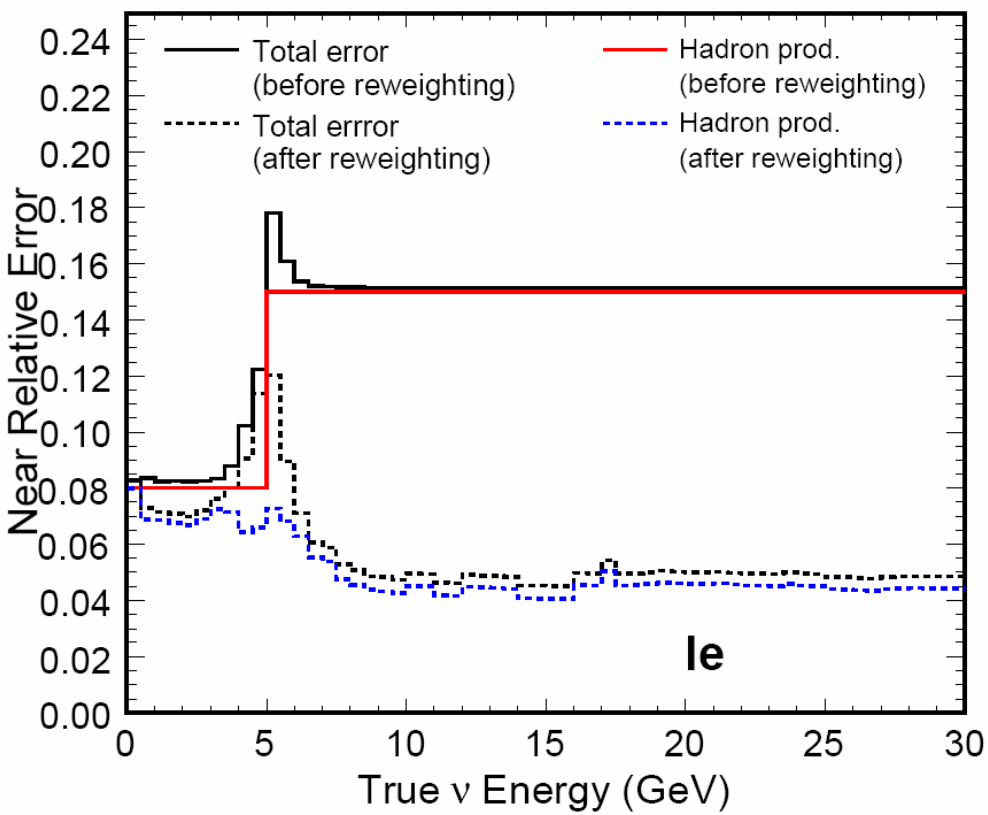


- This plot shows the weights we applied to the various parts of the (x_F, p_T) spectrum. It is a smooth function and is accentuating the low- p_T region.
- This plot develops some other large-weight regions if we do a fit to only hadron production or a fit which floats only beam parameters. The plot at left is for the combined det+beam fit.

Remaining Hadron Production Uncertainty

- Previously quoted uncertainty of 8% (peak), 15% (tail) in ND spectrum of LE beam.
- Beam tuning procedure reduces uncertainty (esp in ND spectrum) – no longer "dead reckoning" the flux.

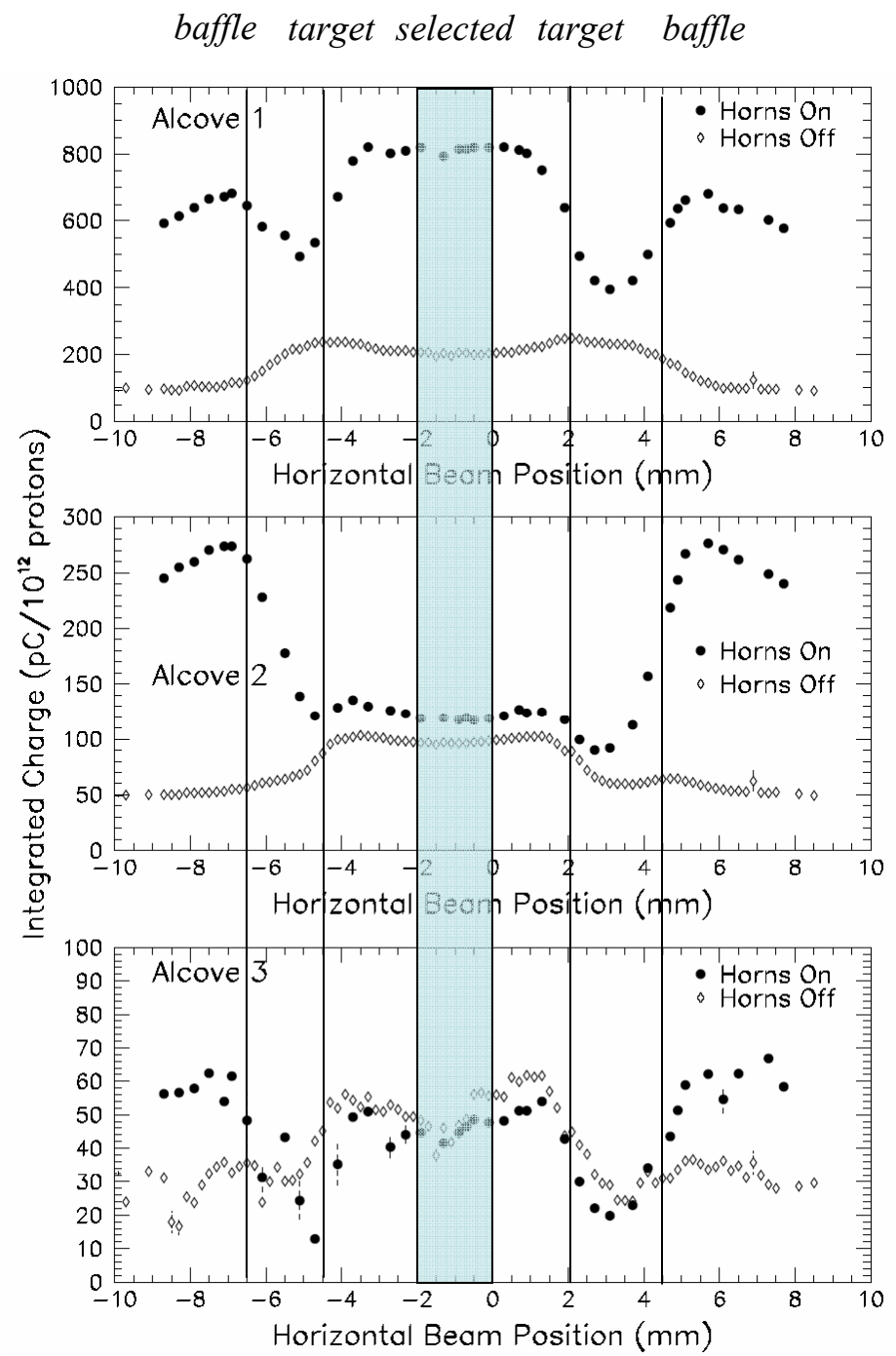


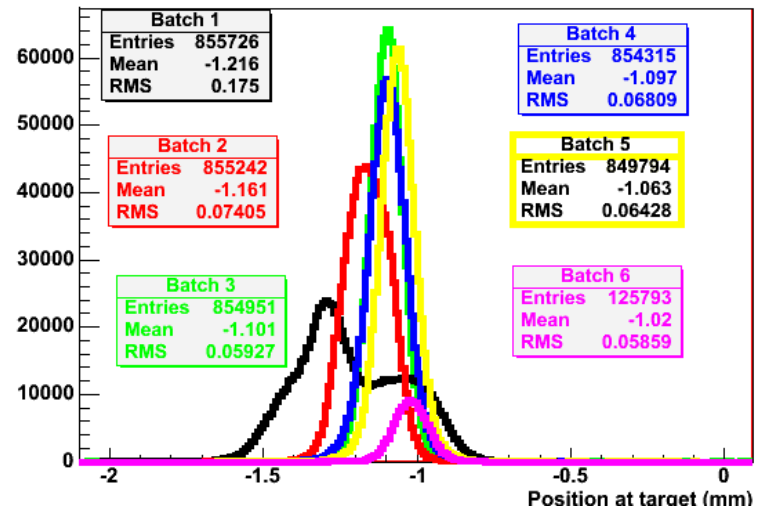


- Remaining uncertainty from
  - Imperfect knowledge of parameterization
  - Statistical uncertainties of fit parameters
  - Observed remaining data/MC disagreement.
- Reweighting reduces uncertainty on ND more than on F/N ratio.

Beam Performance Plots

Proton Beam Stability





- Proton beam position controlled by active feedback.
- Variation ~0.25mm over course of the run.

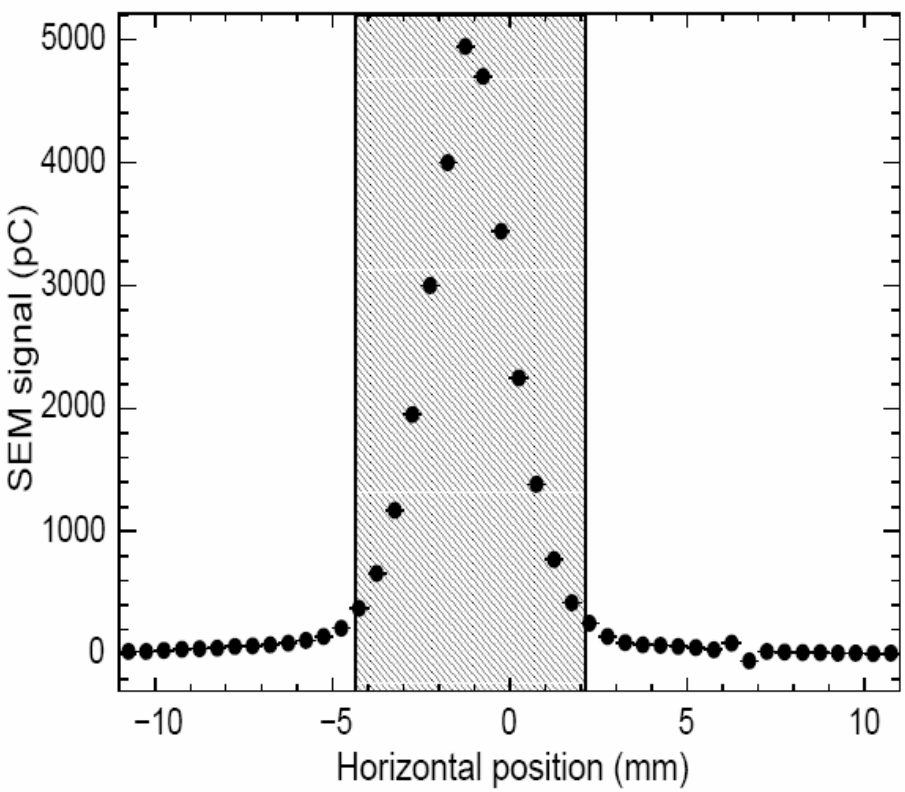
Caption to previous slide

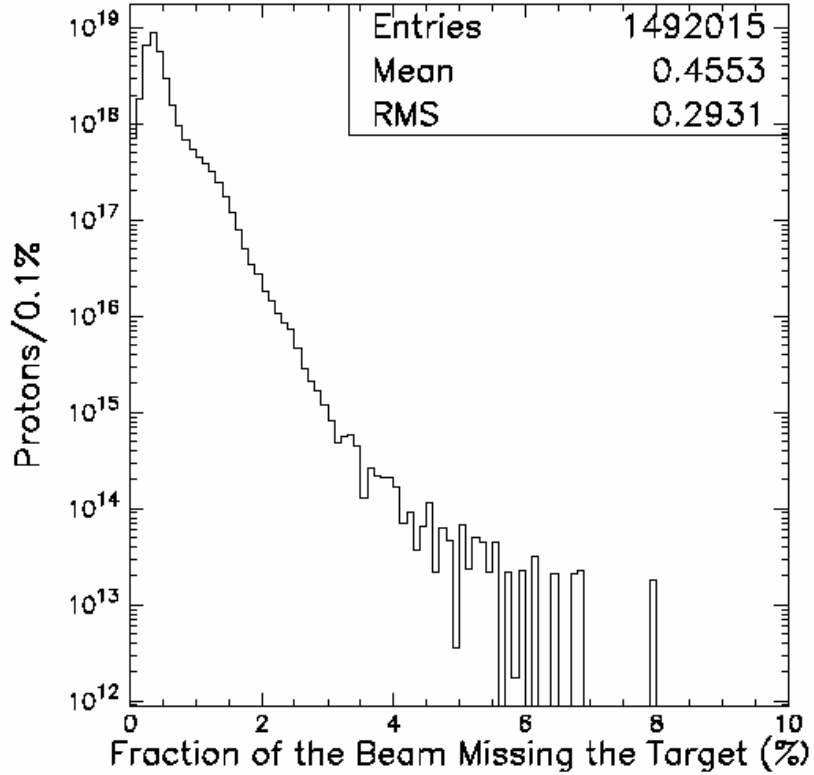
- This is data meant to show (a) how stable the proton beam is on target, and (b) how sensitive is the neutrino beam to such variation.

- (a) the far right plot is a histogram of 850K spills to the NuMI target. The horizontal beam position monitor (BPM) upstream of the target is read out separately for each of the 6 batches delivered in one spill (we take 5-6 depending upon running conditions). One sees that the first batch is oscillating between two values, corresponding to NuMI-only (6batch) and combined pbar/NuMI (5batch to NuMI) running. If pbar is running then their extraction kicker affects our first batch of protons' orbit in the Main Injector. Even so, this level of position stability is exceptionally good.

- (b) the plots at left show the outcome of a scan of the proton beam across the target. We watched the muon yield in each of the muon alcoves and could see the edges of the target and inner edges of the upstream collimating baffle. The blue band indicates the Beam Group's suggested cut of $-2.0<x_{beam}<0.0$mm, where the muon rate is constant to within ~2%.

Beam Missing the Target

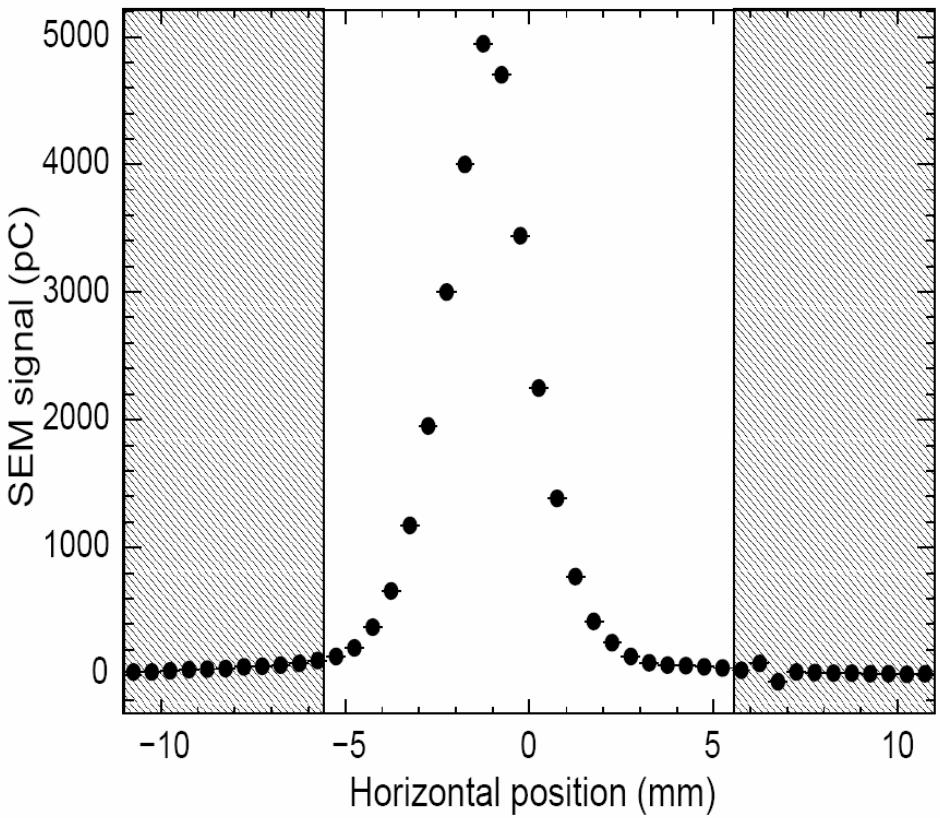


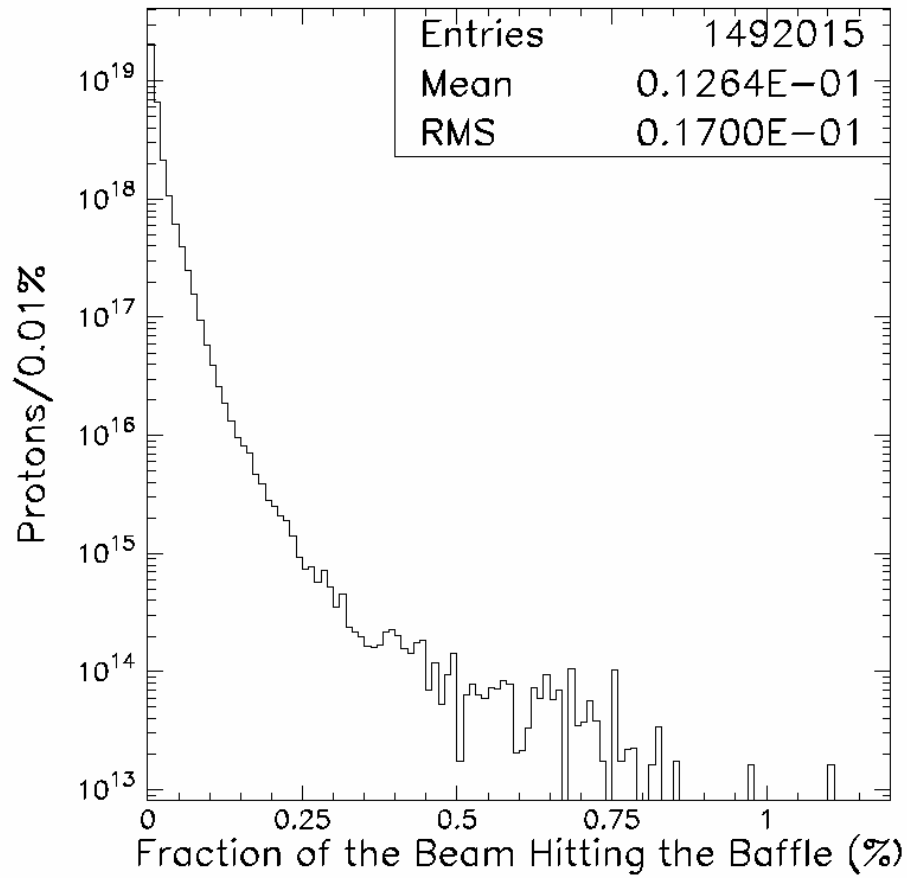


- This plot is the horizontal profile of our proton beam immediately upstream of the NuMI target. The profile typically has sigma=1.1mm, and this number can grow as the beam intensity increases due to a number of accelerator effects.
- The beam profile is measured by a thin foil Secondary Emission Monitor (SEM) which is segmented into 0.5mm strips, each of which gives a charge proportional to beam intensity through that strip (hence the pC shown above).
- The location of the 6.4mm wide target is indicated by the shaded box. It is actually offset by ~1.2mm. This offset was measured directly using the beam, and that analysis is documented in Bob Zwaska's thesis.

- This plot shows the fraction of the proton beam in each spill that misses the target. The plot has 1.5M spills from May-June, and on average 0.5% of the protons in a spill fall off the side of the target, yielding no neutrino interactions.
- The target is only 6.4mm wide, and the finite horizontal size of the beam means that the tails fall to the left or right of the target. Since the target is 15mm tall, there is less of a problem in the vertical direction. Those protons that fall of the sides mostly travel down the gap between the target and baffle, and are transported directly to the beam dump (this is confirmed by the hadron monitor).
- This observation corrects the actual number of protons on target.
- The measurements above come from the foil SEM.

Beam Scraping the Baffle

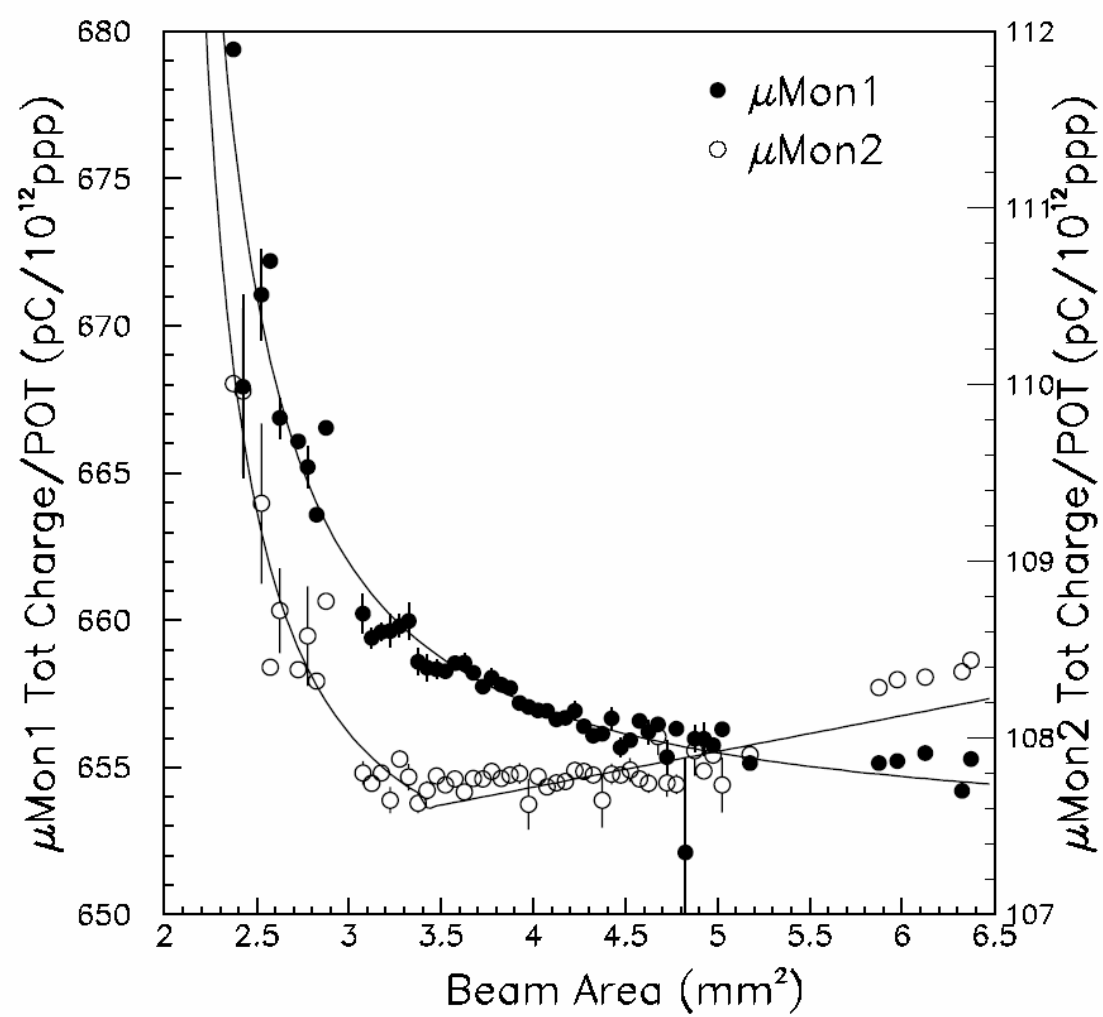




- This plot is the horizontal profile of our proton beam immediately upstream of the NuMI target. The profile typically has sigma=1.1mm, and this number can grow as the beam intensity increases due to a number of accelerator effects.
- The beam profile is measured by a thin foil Secondary Emission Monitor (SEM) which is segmented into 0.5mm strips, each of which gives a charge proportional to beam intensity through that strip (hence the pC shown above).
- The location of the 11mm diameter aperture collimating baffle is also shown. The baffle protects critical, delicate features of the target from direct strike from the proton beam, and also protects the horn (which has 18mm inner diameter).

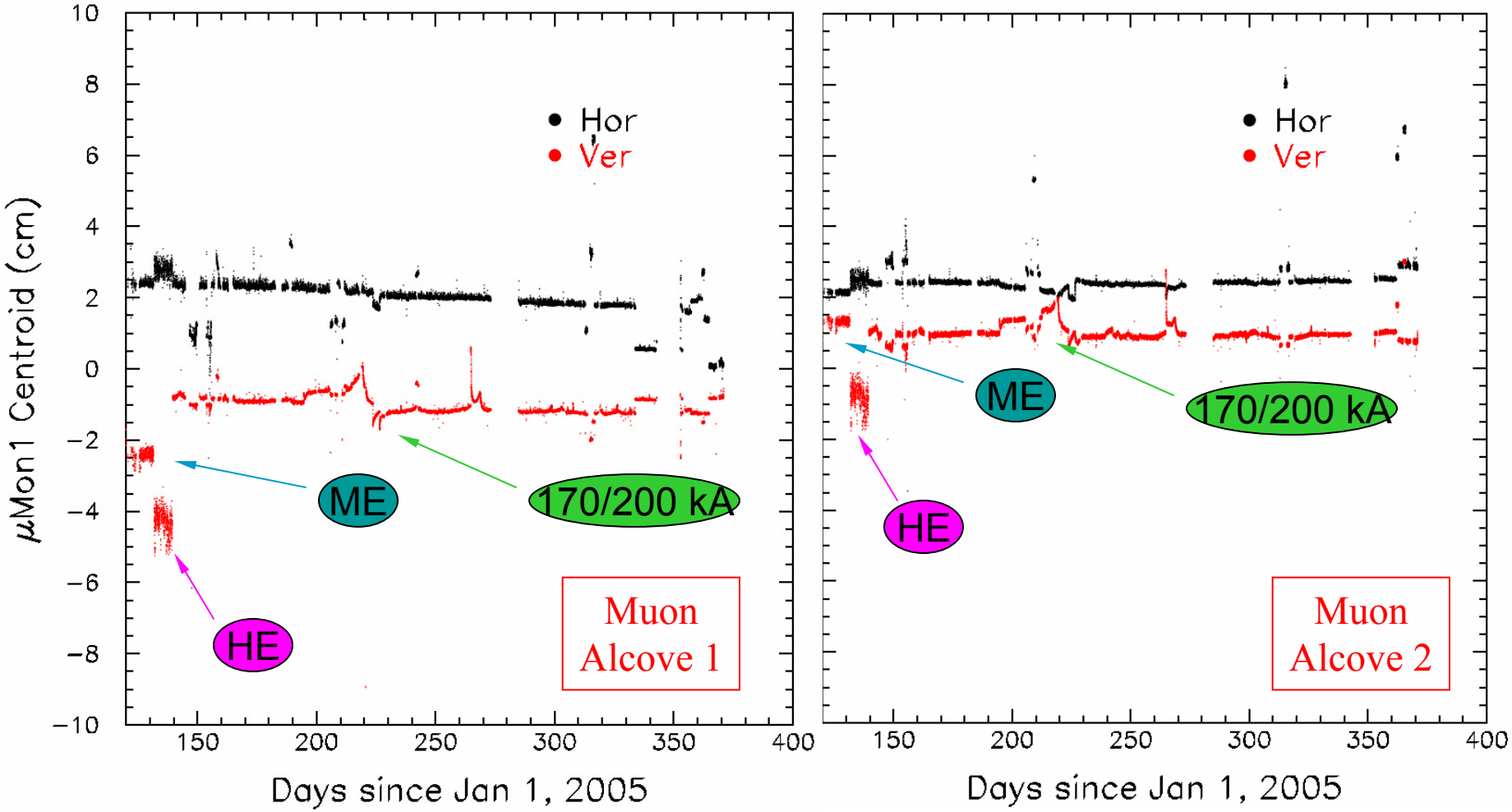
- This plot shows the fraction of the proton beam in each spill that misses the target amd furthermore strikes the upstream baffle. The plot has 1.5M spills from May-June, and on average 0.13% of the protons in a spill hit the baffle.
- The baffle is also made of graphite and acts like a target. The fact that it is further upstream than our target means that it produces pions going through the horns which have higher energy on average. Thus we worry about a "high energy beam" contamination to our low energy setting.
- The muon monitors show an effect where the high energy muon yield goes up if the proton beam spot size increases, corroborating this effect.

Beam Spot Size Effects



- This plot corroborates the previous two pages.
- It shows the total intensity of the muon beam reaching alcove 1 (equivalent to Enu>3.8 GeV) or alcove 2 (Enu>8 GeV), plotted as a function of the proton beam spot size at the target.
- The muon monitors are arrays of ionization chambers in 3 alcoves downstream of the beam dump.
- As the proton beam spot size increases, some beam misses the target, hence the drop at the left of the plot.
- As the proton beam spot size increases further, some beam scrapes the baffle out at 5.5mm radius, producing a higher-energy neutrino beam. This is manifested by the alcove 2 rate going up even as the overall muon rate (alcove 1 at lower threshold) goes down.

Muon Beam Direction

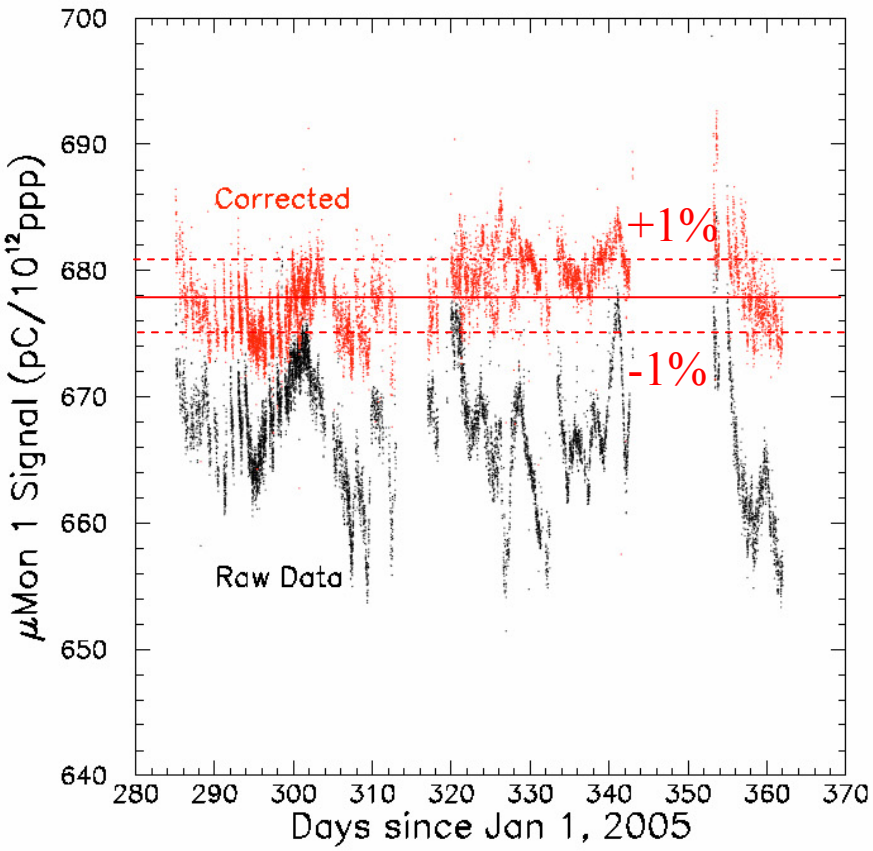


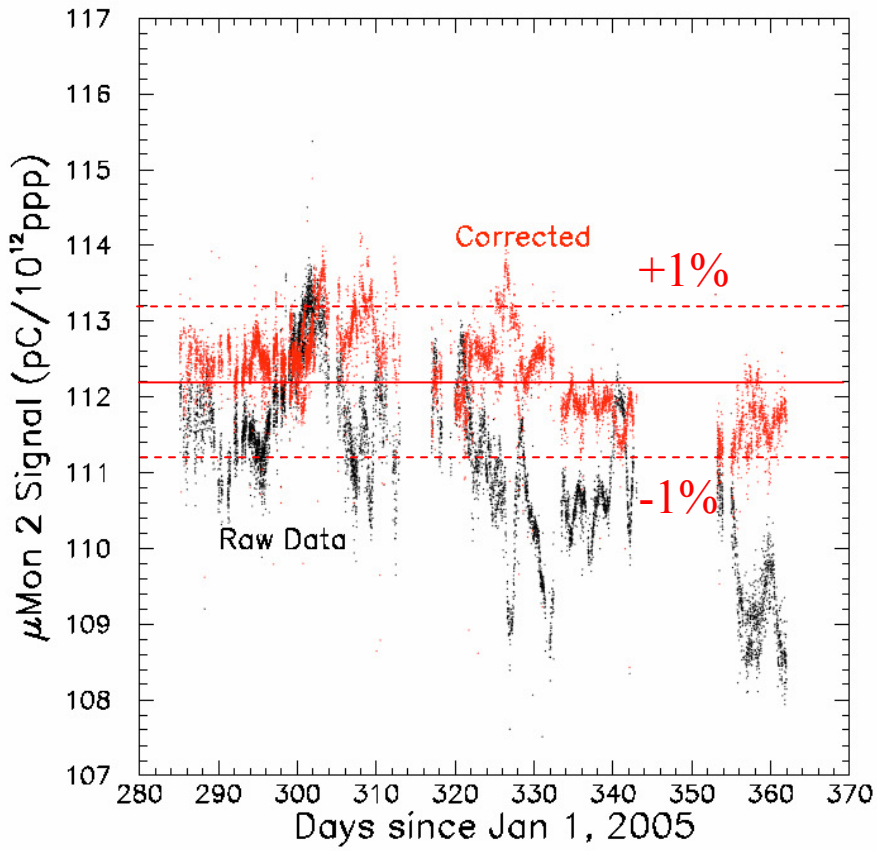
- To keep distortions in the FD spectrum <1%, we require <100μrad mis-steering of the ν beam from FNAL
- At the muon monitors, a 10 cm shift in the muon beam centroid corresponds to a 130μrad angular deviation.

Caption to previous page

- Each muon monitor alcove has a 2D array of ion chambers, so can measure the muon beam profile in horizontal and vertical directions.
- Studies by Wes Smart indicate that distortions in the neutrino spectrum at the FD become appreciable (~1%) when the beam is 100 microradians off-center.
- A 100 microradian mis-steering of the neutrino beam would translate to a 7cm shift of the muon beam direction. While there is clearly motion of the muon beam over the course of this run (particularly when shifting between LE/ME/HE), we are well-within our tolerance.

Muon Rates





- The muon rate per proton on target is a good measure of the stability of the neutrino beam. If the horns were changing, or if a piece of the target failed, then we would expect the neutrinos per proton (hence the muons per proton) to change.
- The muon rate has been stable within 1% over the time the muon monitors have measured this quantity. We had two periods where the muon rate was not stable because of incorrect gas bottles being hooked up to the system. Thus, we plot this only for the latter period of the run.
- The muon monitors are ionization chambers, requiring calibration for gas pressure & temperature. The raw and corrected data are shown for alcoves 1 and 2 (alcove 3 has very little signal in the LE beam).