MINERvA Constraints on the NuMI Beam Flux

Neutrino Beams and Instrumentation 2014

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Northwestern University

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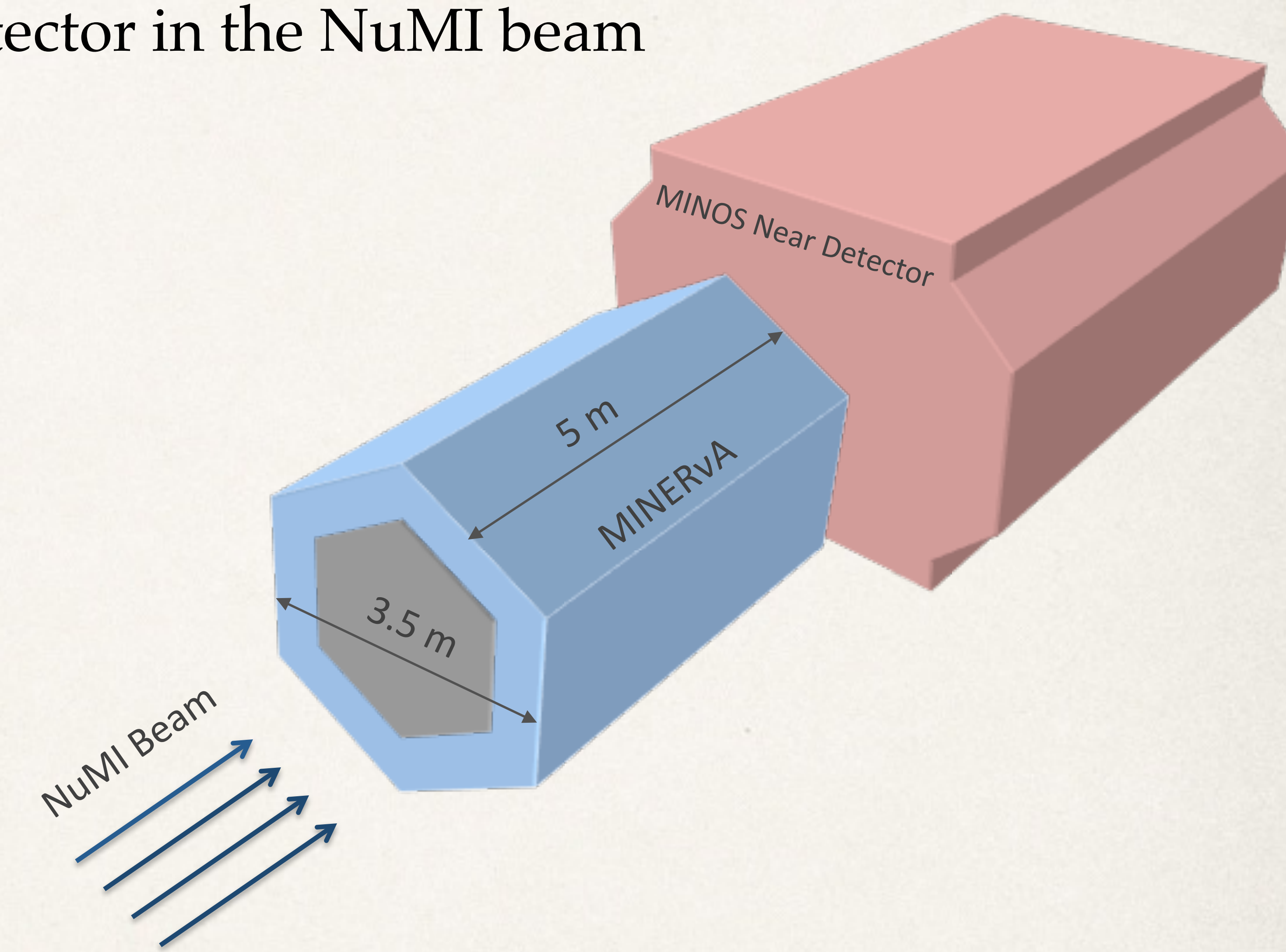
Outline

- The MINERvA Experiment
- MINERvA's Flux Estimate
  - Basic Simulation
  - External Data Constraints
  - ν-e Scattering Constraint
  - Future Plans: Low-ν and Special Runs
- Conclusion

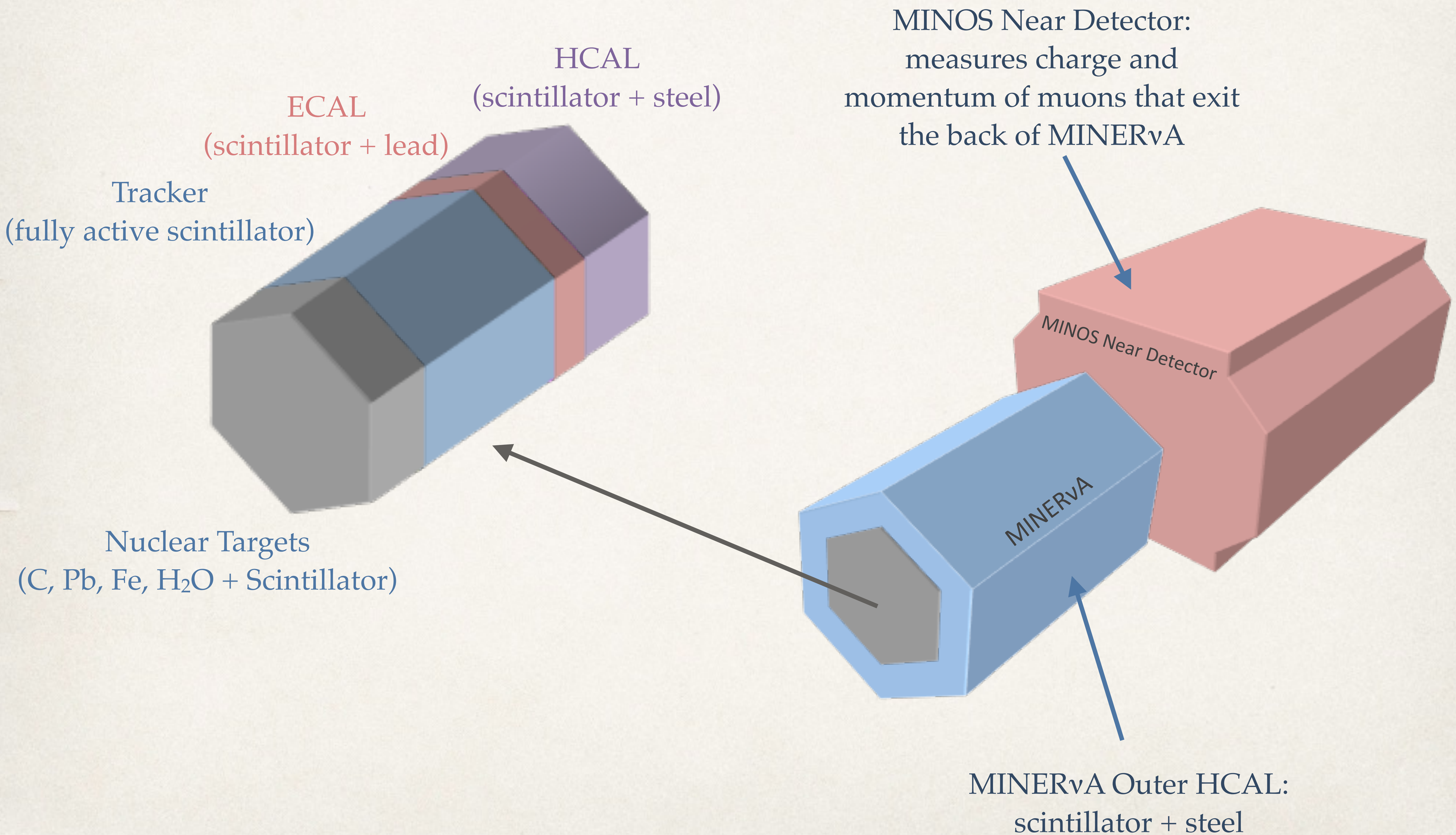
MINERνA Overview: Detectors

- MINERνA is a scintillator-based neutrino detector that sits just upstream of the MINOS near detector in the NuMI beam

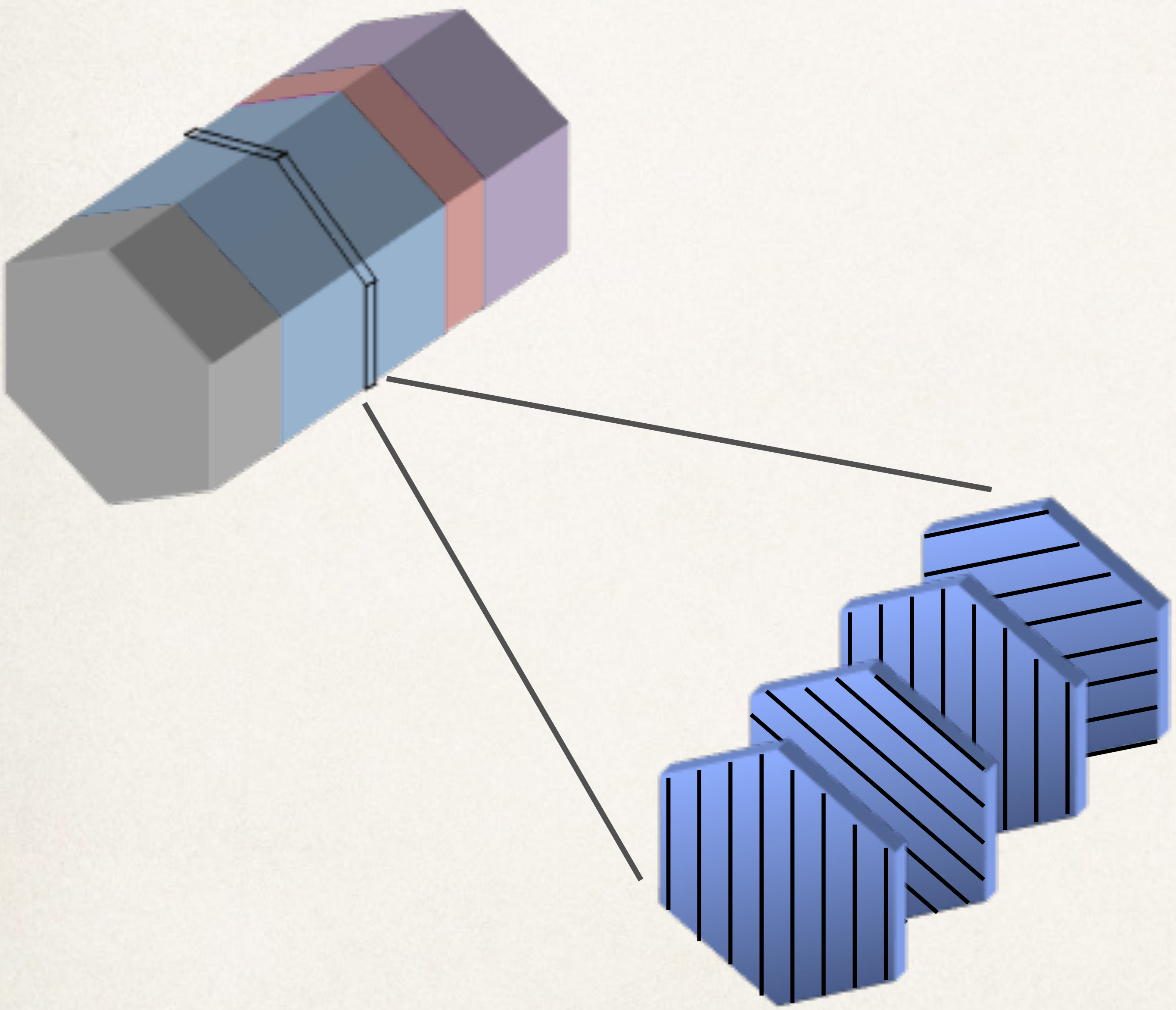


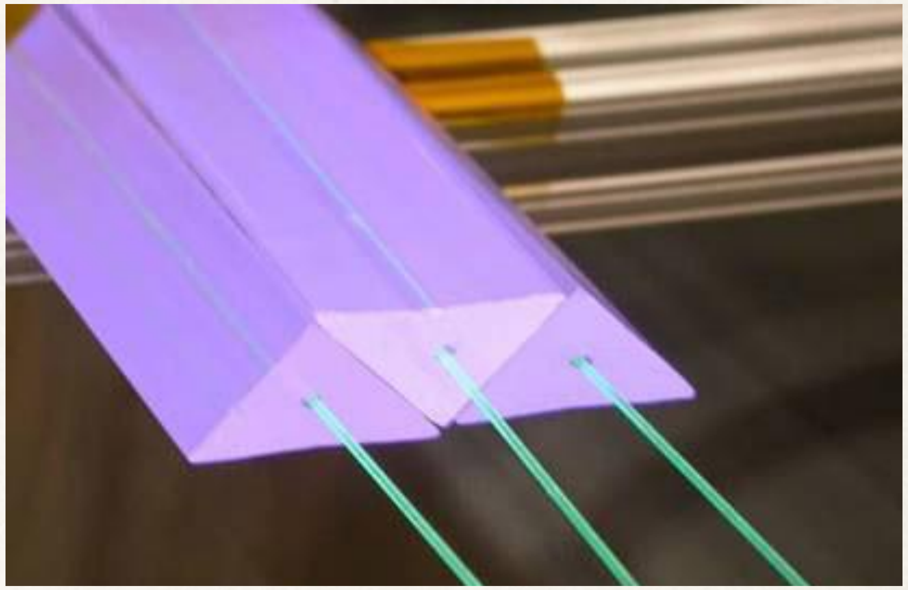
- MINERνA was designed to make high precision measurements of neutrino interaction cross sections for $E_\nu \sim$ 1 - 20 GeV

MINERνA Overview: Detectors



MINERνA Overview: Detectors



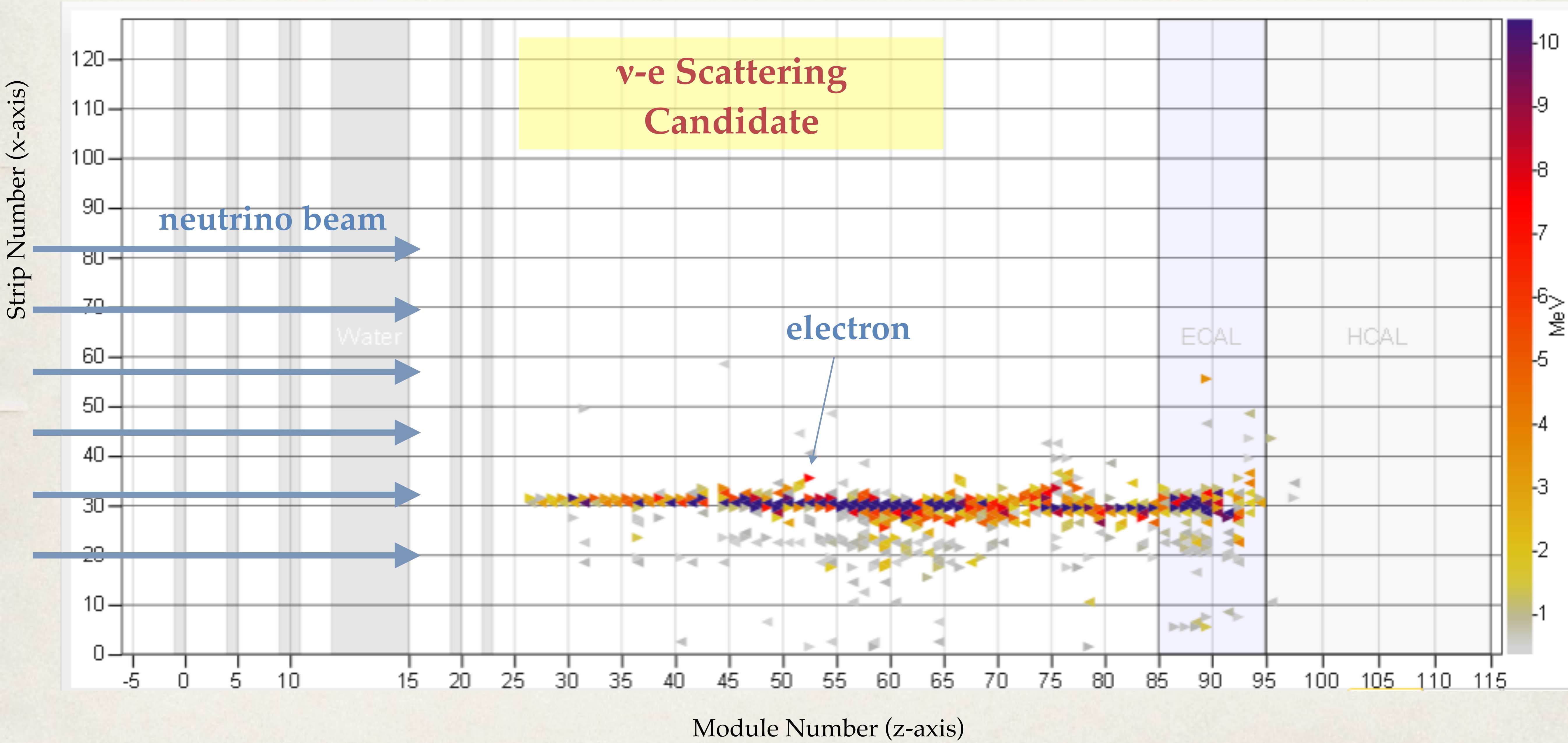


- Scintillator is divided into ~200 vertical planes, each formed from 127 triangular plastic strips (3.3 x 1.7 cm) arrayed in one of three orientations for 3-dimensional reconstruction

MINERνA Overview: Detectors

- What a neutrino interaction looks like in MINERνA:

MINERνA Data — View From Above Detector



MINERνA Overview: Goals

- A central goal of MINERνA is measurement of absolute neutrino interaction cross sections:

Number of observed interactions

$$\sigma = \frac{N}{\epsilon A \Phi}$$

Efficiency

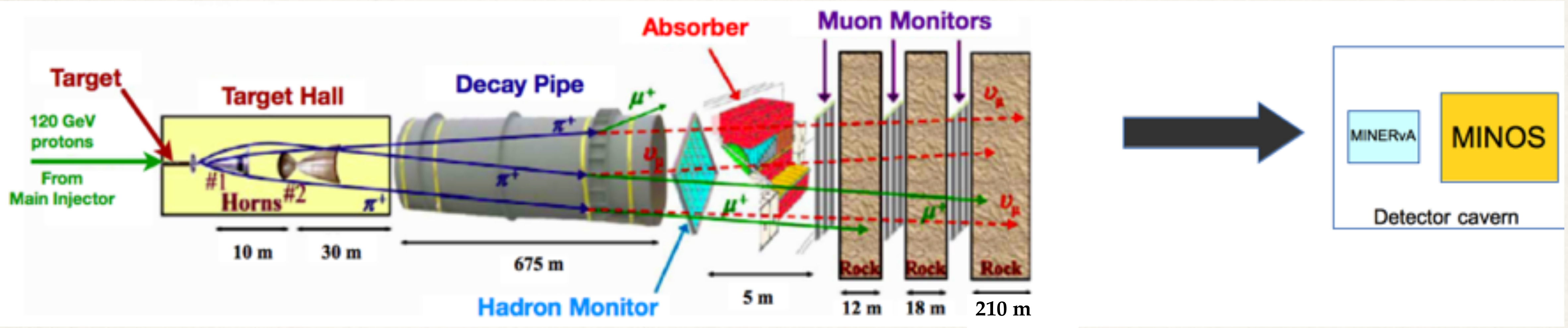
Neutrino Flux

Number of scattering targets

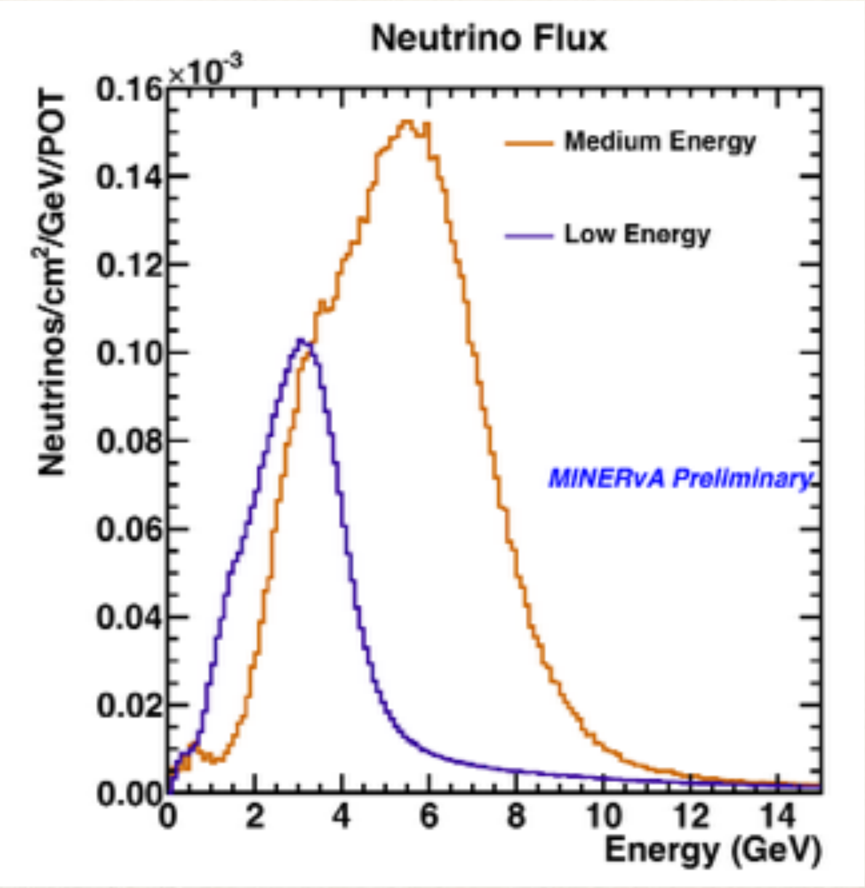
- An estimate of the neutrino flux is in the denominator of all absolute cross sections. Uncertainties on the flux become uncertainties on our cross section measurements

→ **an accurate neutrino flux estimate is crucial to MINERνA!**

Flux Estimate: GEANT Simulation



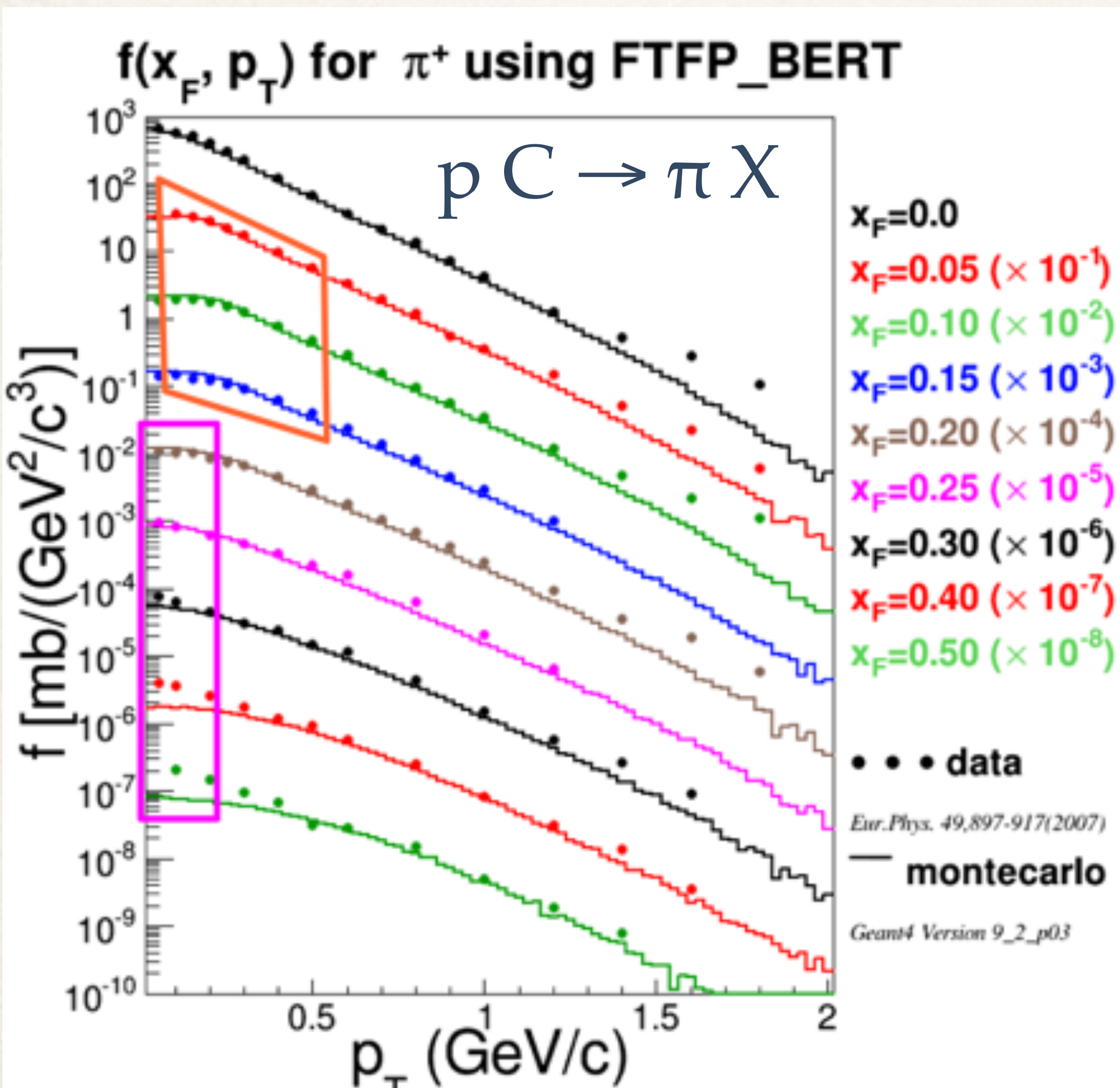
- Flux simulation starts with a GEANT4 simulation of the NuMI beam line (G4NuMI)
  - Uses same geometry as other NuMI experiments, but differs in that we simulate protons on the target with GEANT4, not Fluka
  - We currently use GEANT version 4.9.2p03 with the FTFP_BERT hadronic physics list



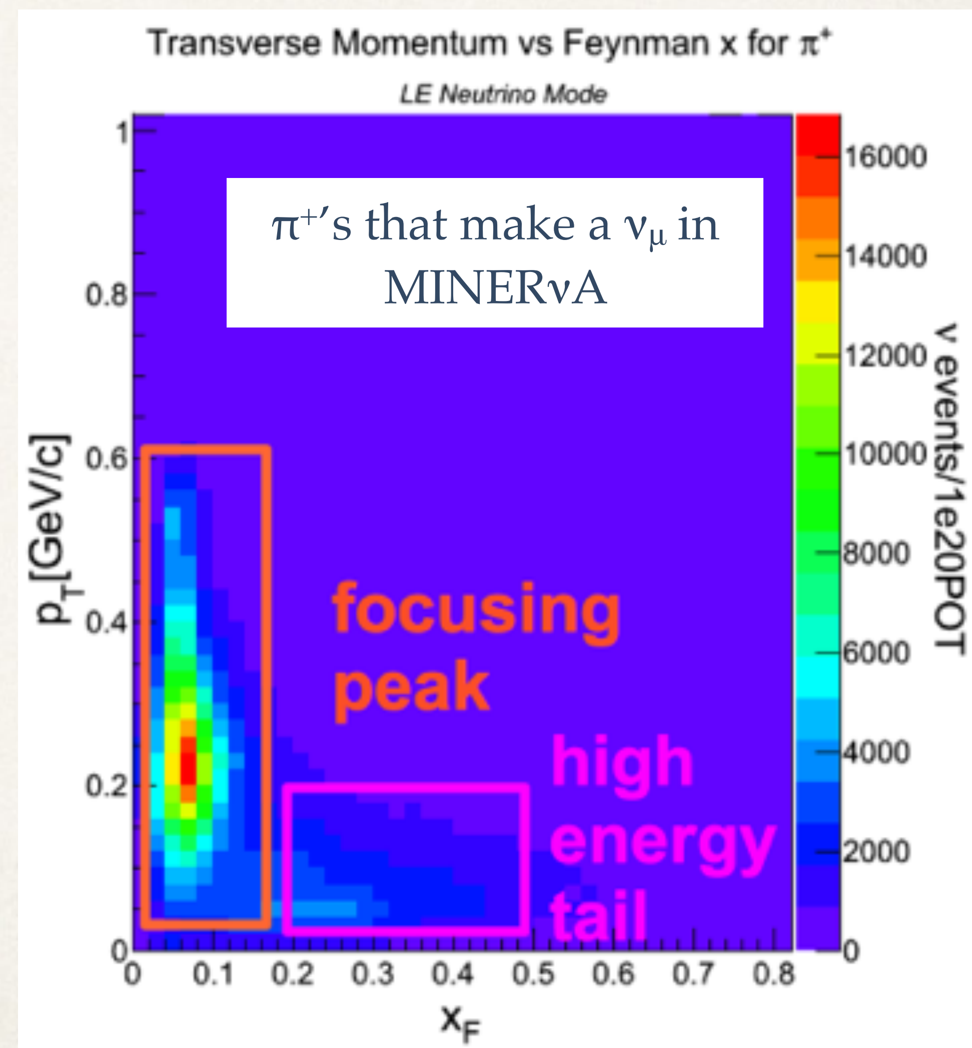
Flux Estimate: Adding External Data

- We correct the GEANT-based simulation using several external datasets; most of the constraints are from the NA49 experiment:

$f(x_F, p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section



$$x_F = 2\frac{P_L}{E_{cm}}$$



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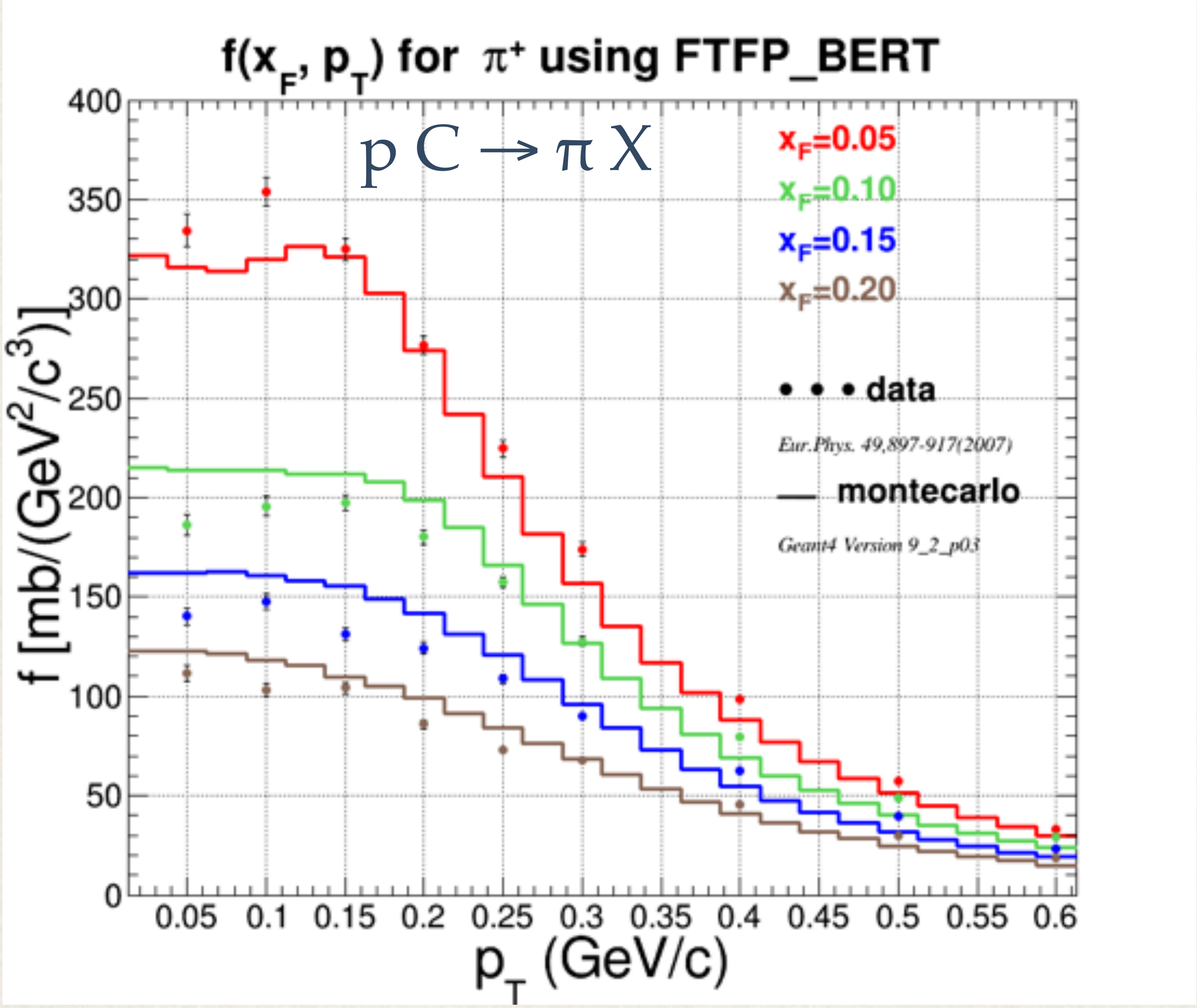
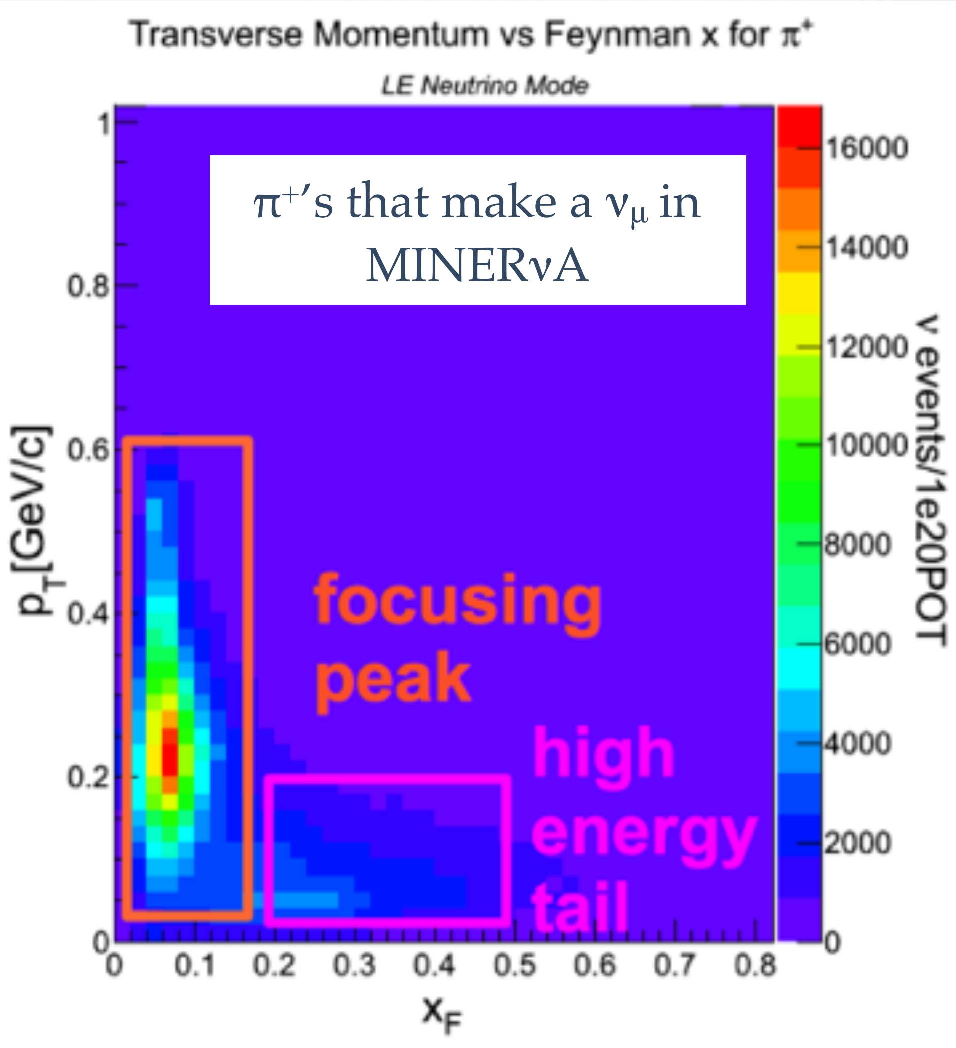




Flux Estimate: Adding External Data

- How the external data constraint works in practice:
  - Complete information about cascades leading to a neutrino is recorded for each proton on target and stored in the flux tuples
    - Including interaction materials and ancestor kinematics
  - In MINERvA analyses, neutrino events are weighted by:

$$w_{\mathrm{HP}} = \frac{f_{\mathrm{Data}}\left(x_F, p_T, E\right)}{f_{\mathrm{MC}}\left(x_f, p_T, E\right)} \qquad f = E\frac{d^3\sigma}{dp^3}$$

  - Weights are applied for incident protons 12 < E_p < 120 GeV/c, scaled by Fluka and checked by comparing to NA61 pC @ 31 GeV [Phys. Rev. C84 (2011)034604]

Flux Estimate: Adding External Data

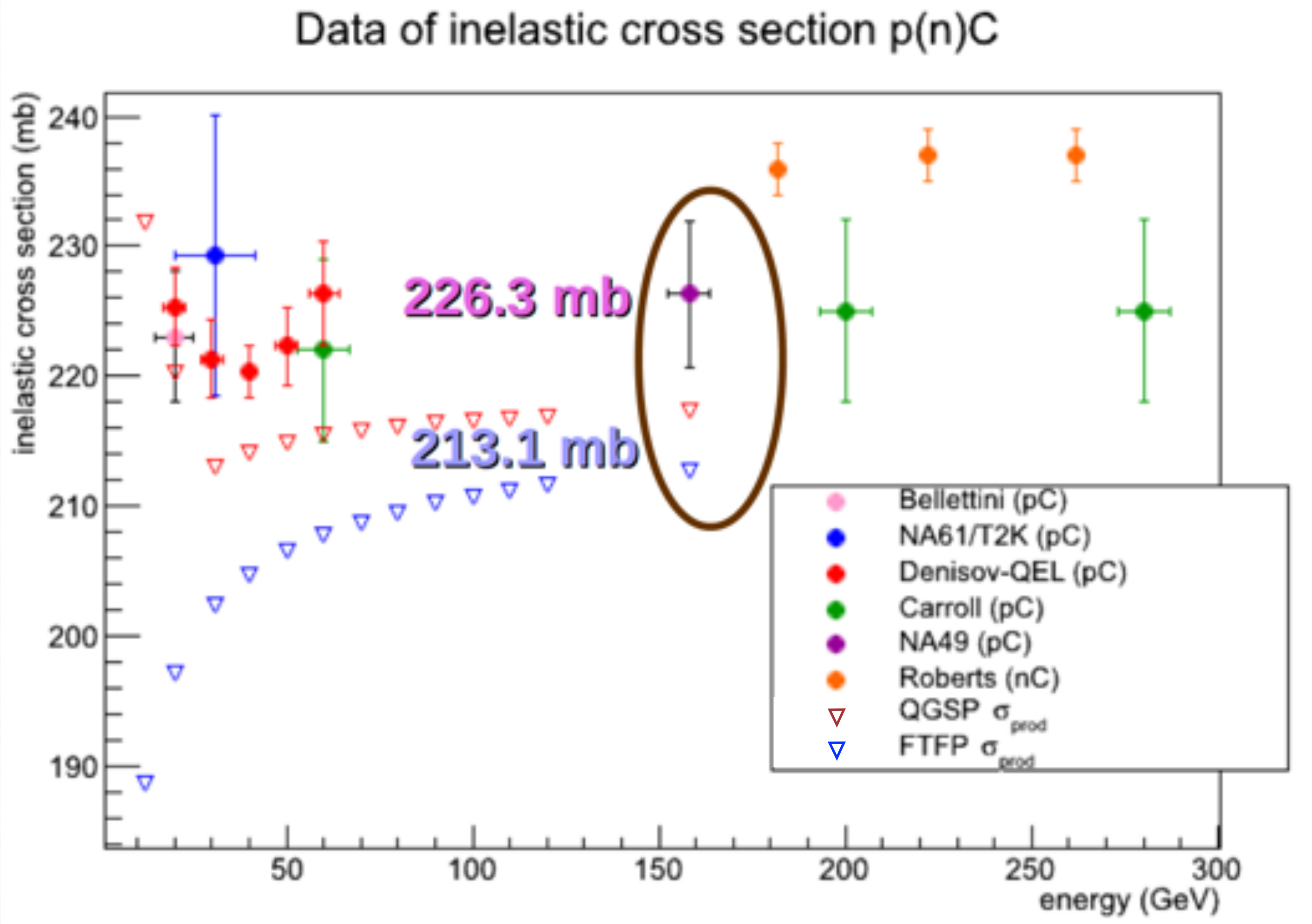
- Datasets that we currently use:
  - NA49 pC @ 158 GeV (w/ P_T dependence)
    - $\pi^{\pm}$ production for $X_F < 0.5$ [Eur.Phys.J. C49 (2007) 897]
    - $K^{\pm}$ production for $X_F < 0.2$ [G. Tinti Ph.D. Thesis]
    - p production for $X_F < 0.95$ [Eur.Phys.J. C73 (2013) 2364]
  - Barton pC @ 100 GeV ($0.3 < P_T < 0.5$ GeV/c)
    - $\pi^{\pm}$ production for $X_F > 0.5$ [Phys.Rev.D27 (1983) 2580]
  - MIPP pC @ 120 GeV
    - K/π + NA49 extend kaon coverage to $X_F < 0.5$ [A. Lebedev Ph.D. Thesis]

Currently using ONLY K/π ratio from MIPP; more on MIPP later in the talk

Flux Estimate: Adding External Data

- We also correct for beam attenuation due to mismodeling of total inelastic cross section:
  - A second weight is applied to neutrino interactions assuming exponential decay of beam:

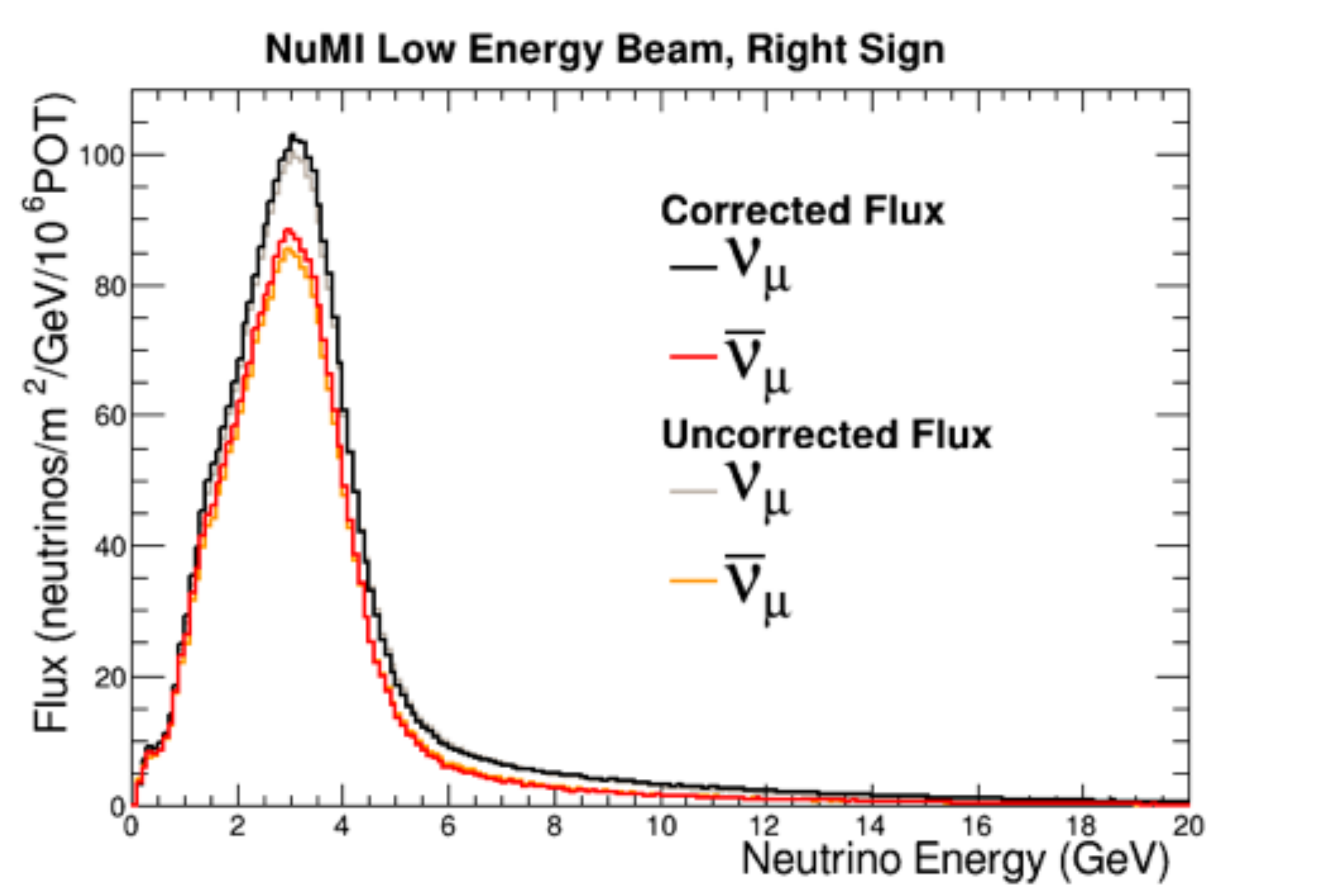
$$w_{\mathrm{att}} = e^{-L\rho(\sigma_{\mathrm{data}} - \sigma_{\mathrm{MC}})}$$

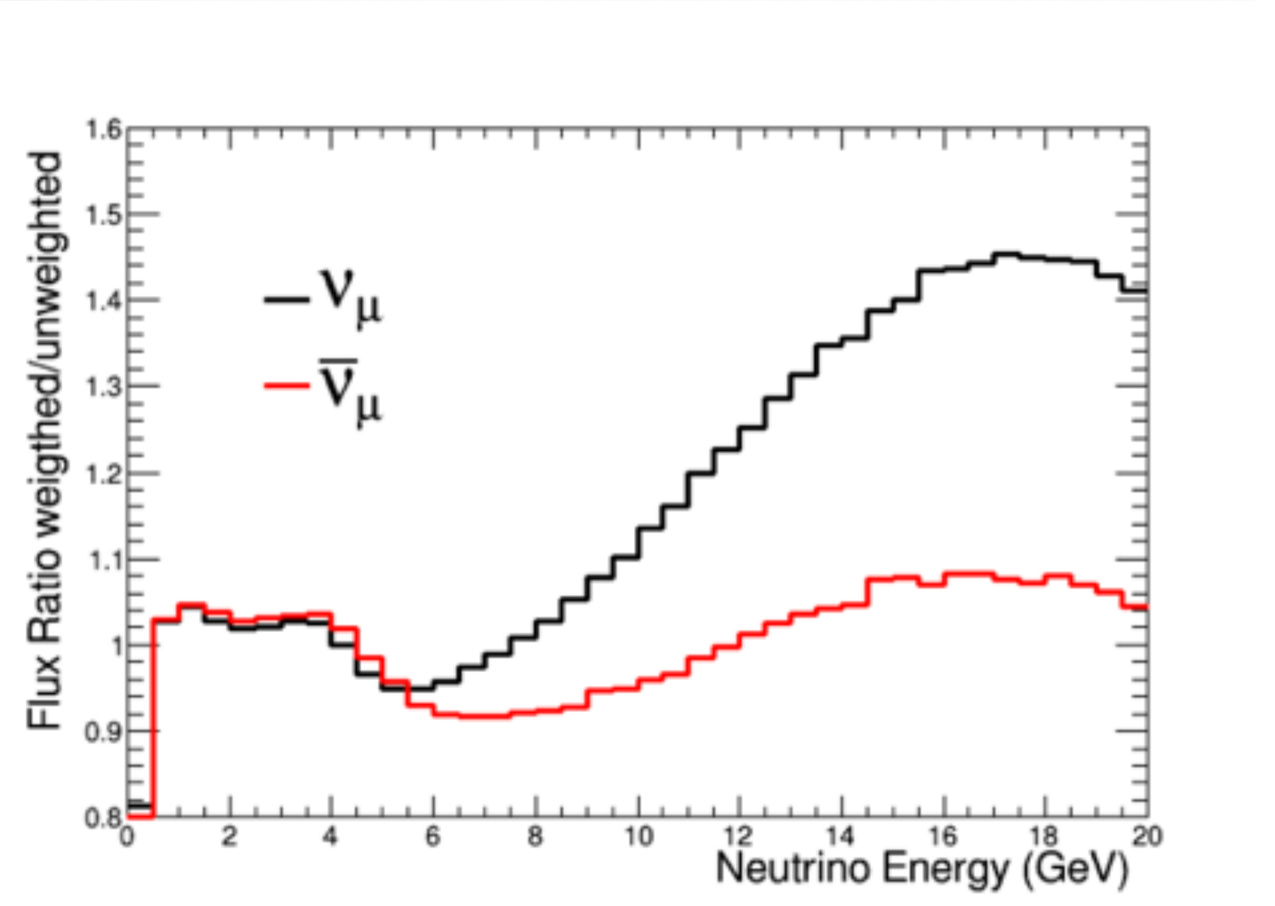


  - Currently applied to primary protons only
  - ~5% effect, flat in energy

Flux Estimate: Adding External Data

- Result of all of the corrections:



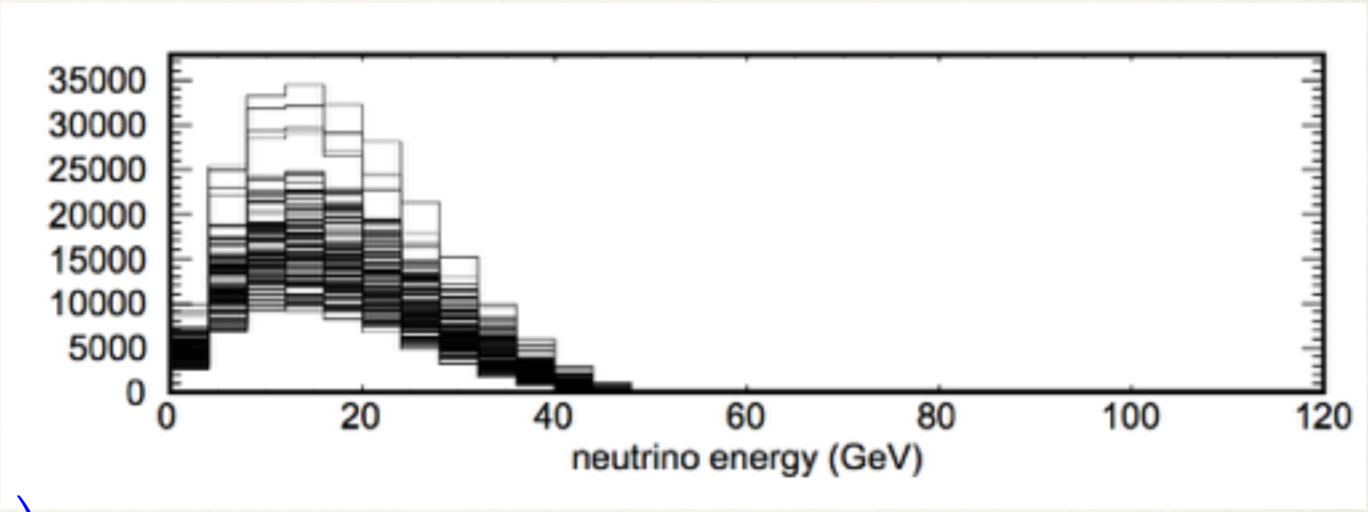


- Correction is modest in focusing peak; substantial at moderate and high energies

Flux Estimate: Uncertainties

- Uncertainties on the external data constraints are propagated to uncertainties on our flux and other simulated distributions using a "Many-Universes" method:

  - For each event, in addition to the central value weights we have discussed:

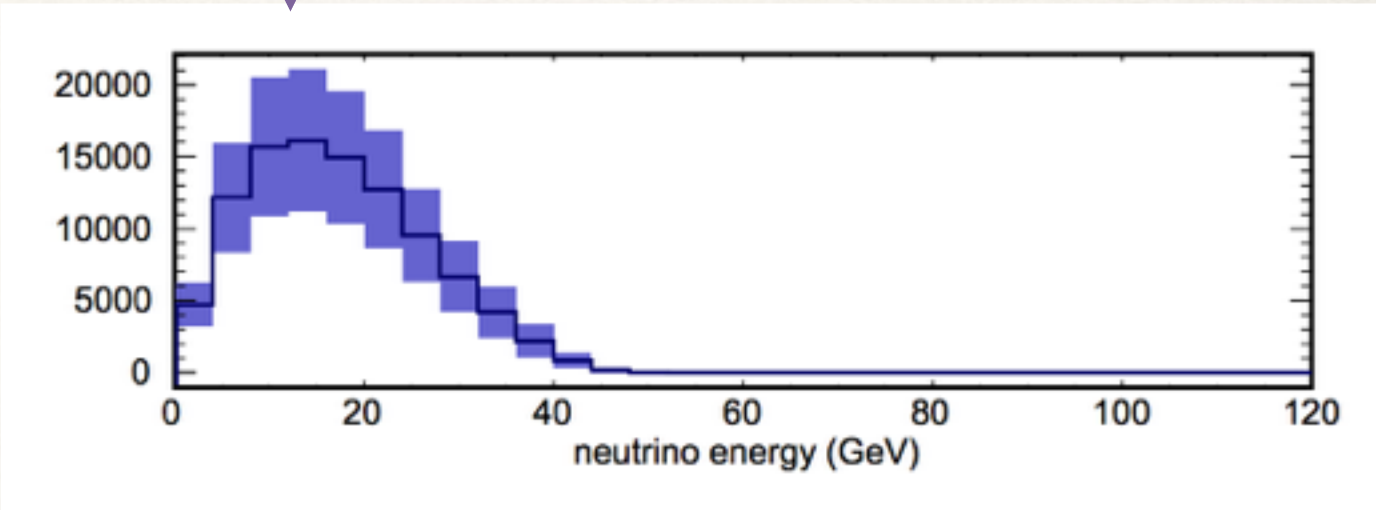


M. Kordosky

$$w = e^{-L\rho(\sigma_{\rm Data}-\sigma_{\rm MC})}\left(\prod_{\substack{\rm reweightable \\ \rm interactions}} \frac{f_{\rm Data}\left(x_F, p_T, E\right)}{f_{\rm MC}\left(x_f, p_T, E\right)}\right)$$

RMS of resulting weighted distributions gives uncertainty on those distributions

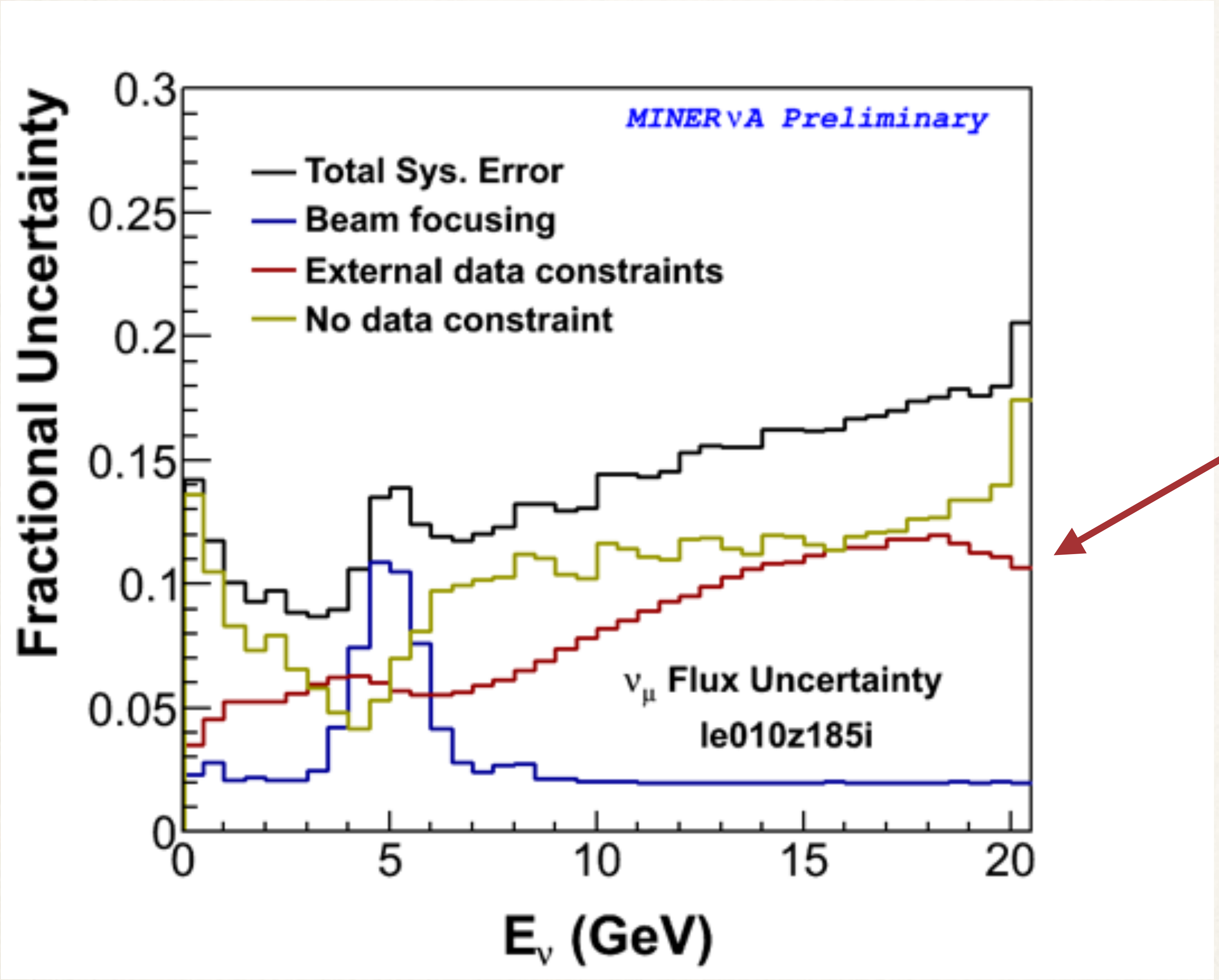
We also store many (~1000) weights constructed from data cross sections varied according to their uncertainties (taking into account correlations)



This is technique sometimes referred to as "multisim"

Flux Estimate: Uncertainties

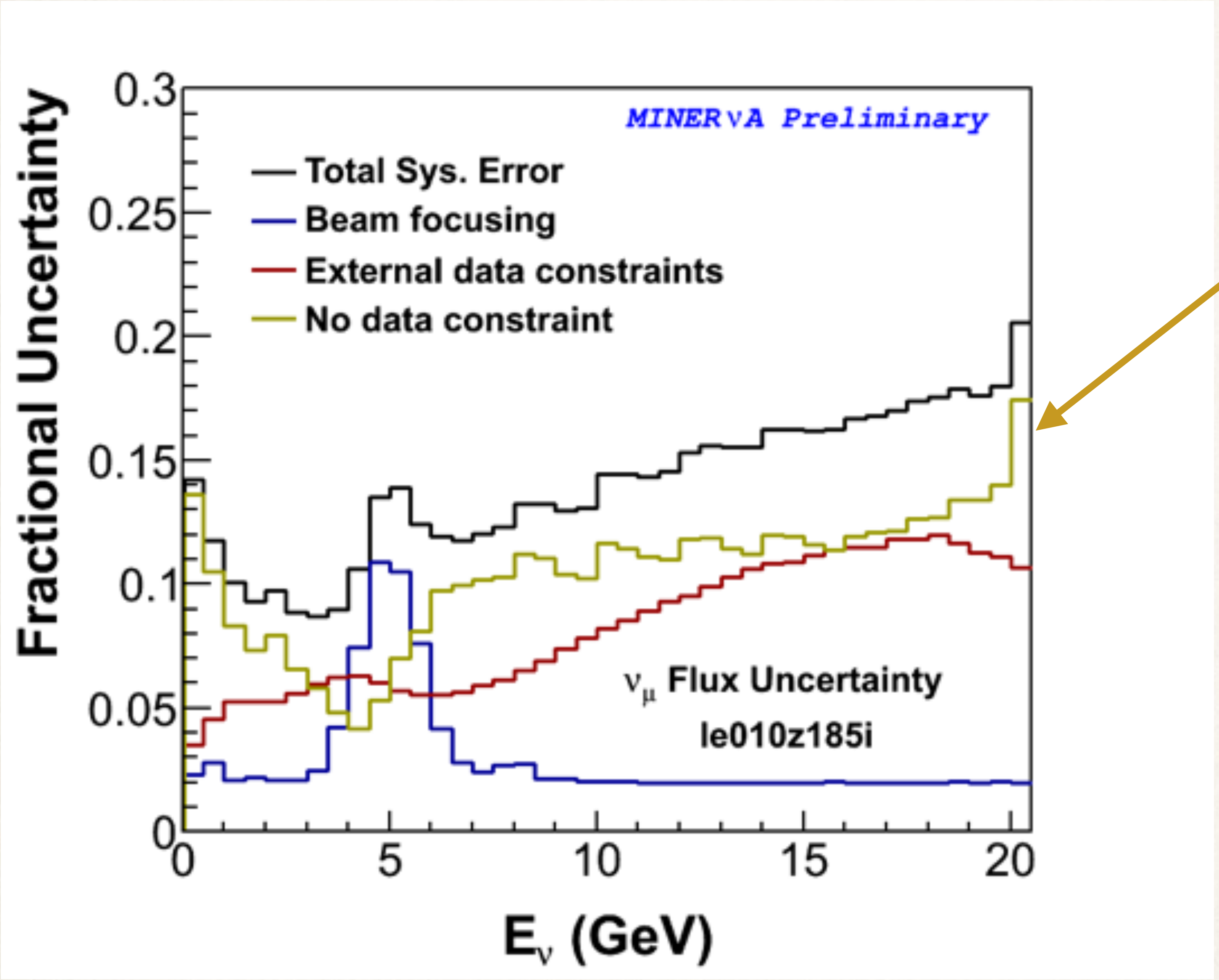
- Flux uncertainties on GEANT simulation with external data constraints:



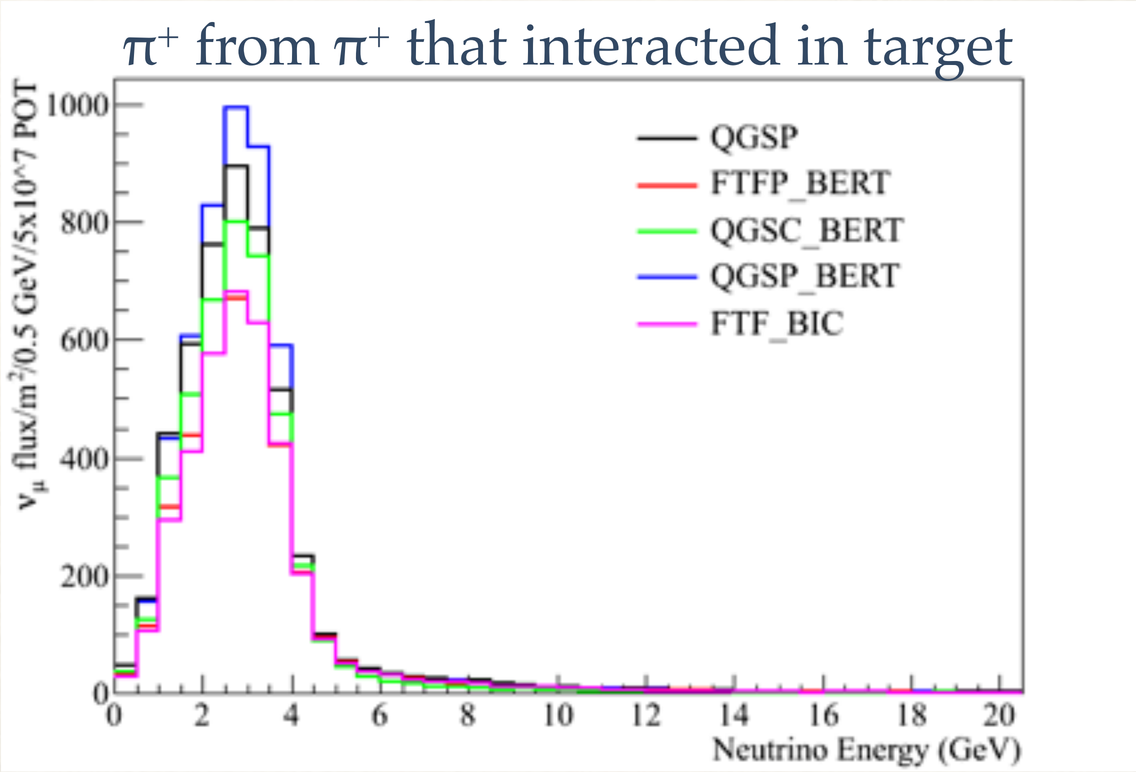
Errors on the total FHC ν_μ flux due to errors on hadroproduction data — primarily NA49, whose errors are ~7.5% systematic, 2-10% statistical

Flux Estimate: Uncertainties

- Flux uncertainties on GEANT simulation with external data constraints:

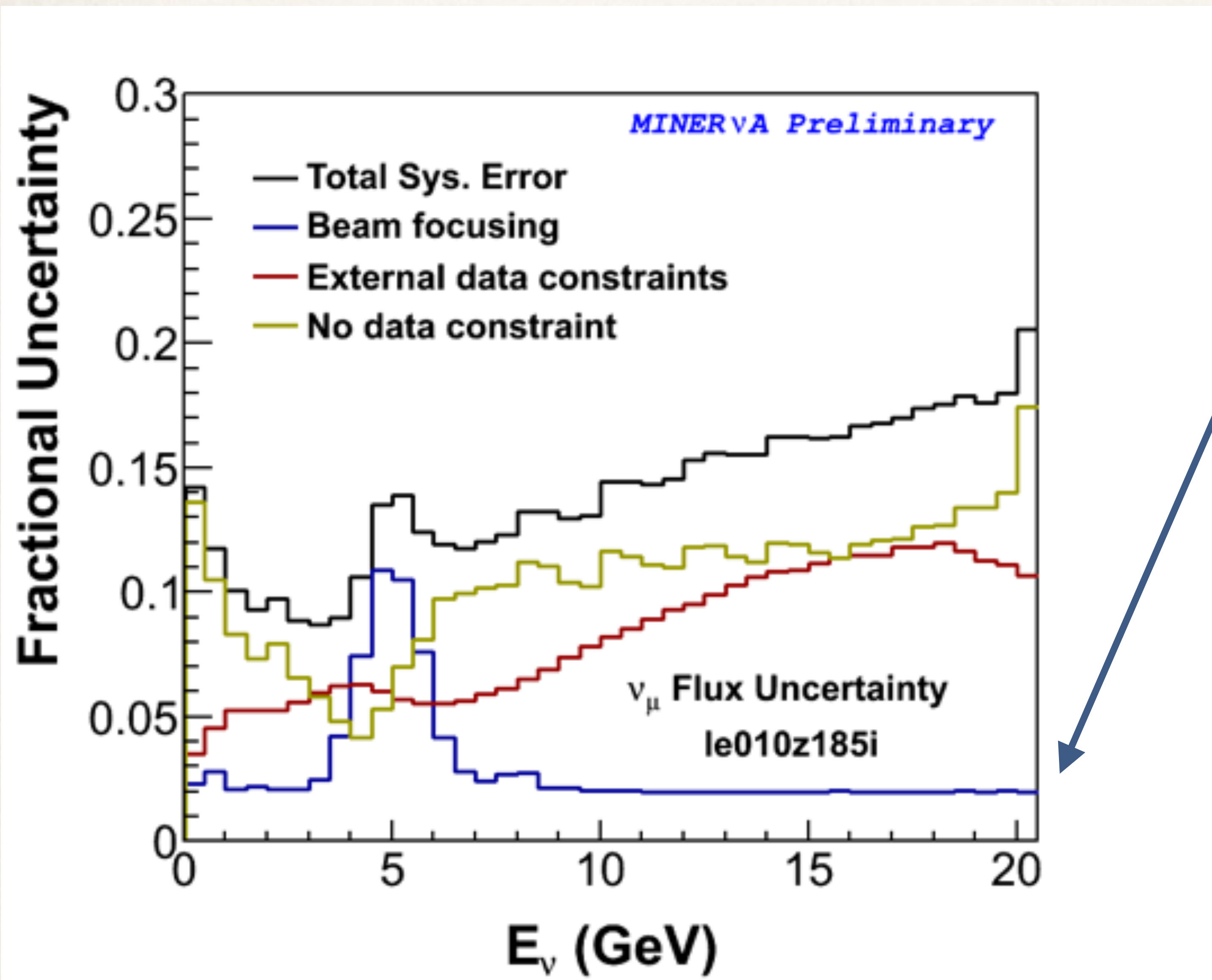


Errors on unconstrained interactions in GEANT4 are estimated using model spread and also propagated using a many universes method

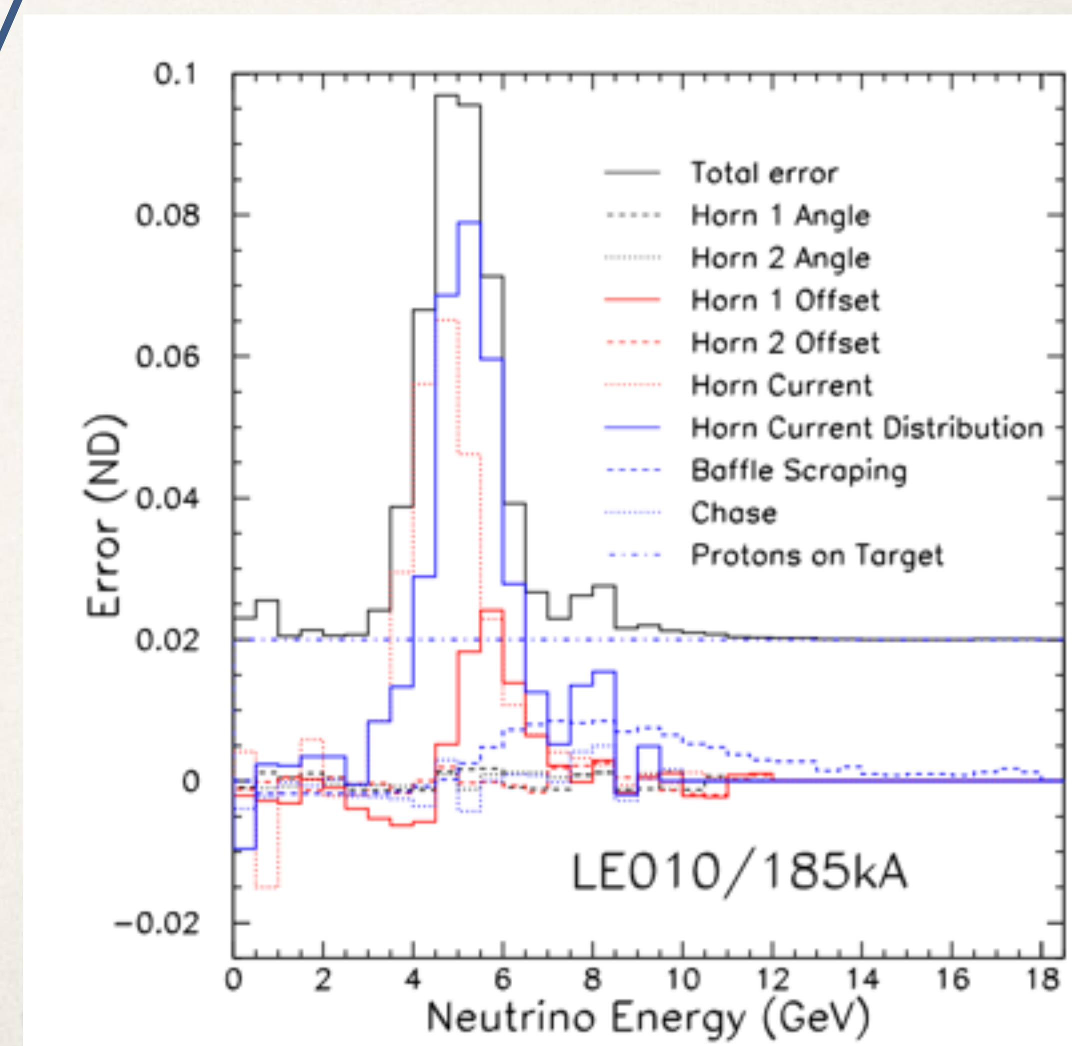


Flux Estimate: Uncertainties

- Flux uncertainties on GEANT simulation with external data constraints:



Errors due to beam focusing are taken from a MINOS study



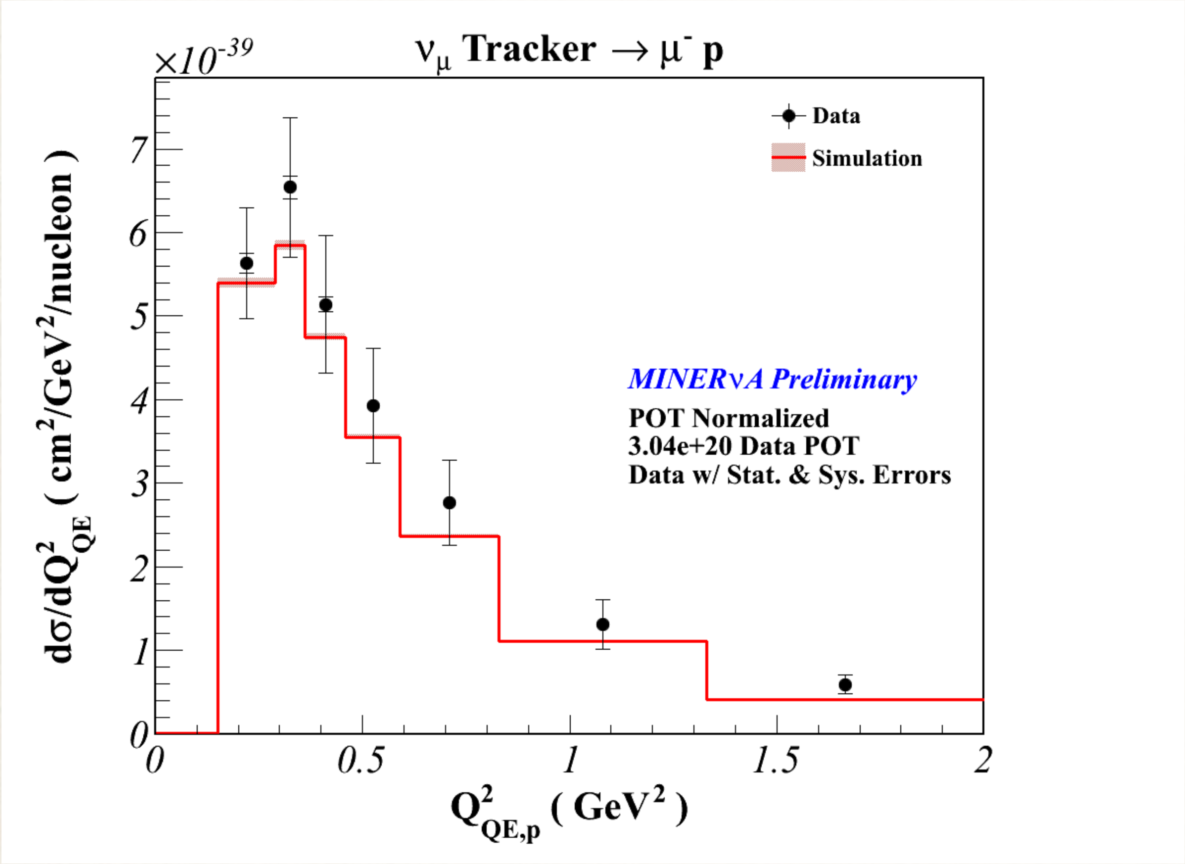
Z. Pavlovic Thesis UT Austin 2008

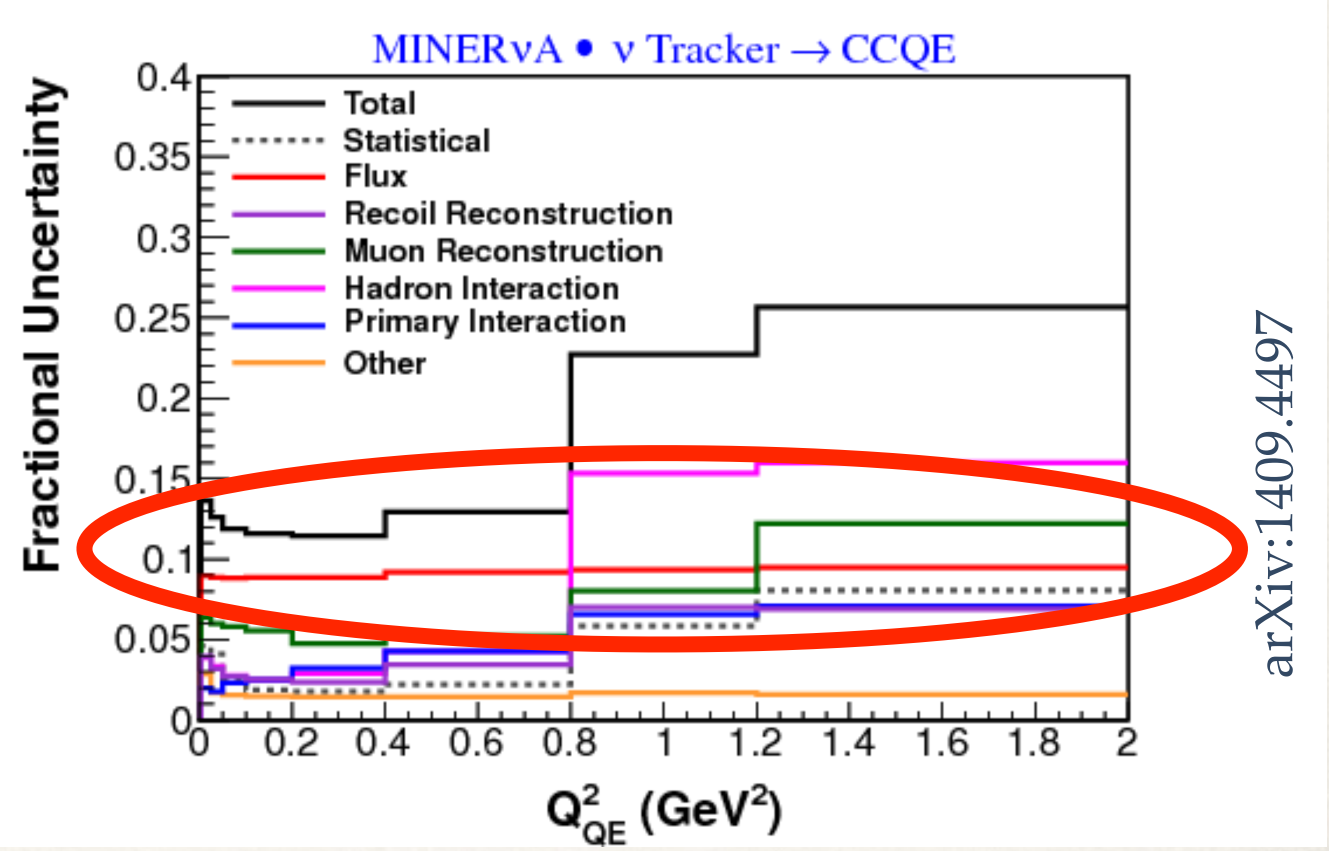
MINERvA is currently conducting a cross check of focusing uncertainties.

Flux Estimate: Uncertainties

- The flux estimate + constraints that I just described are used in all MINERvA papers so far:

An Example: Quasi-elastic Scattering:





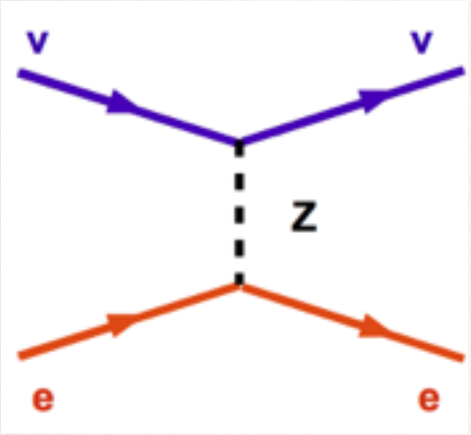
arXiv:1409.4497

Flux uncertainty dominates

- But analyses are starting to incorporate a new flux constraint…

Flux Estimate: ν-e Scattering Constraint

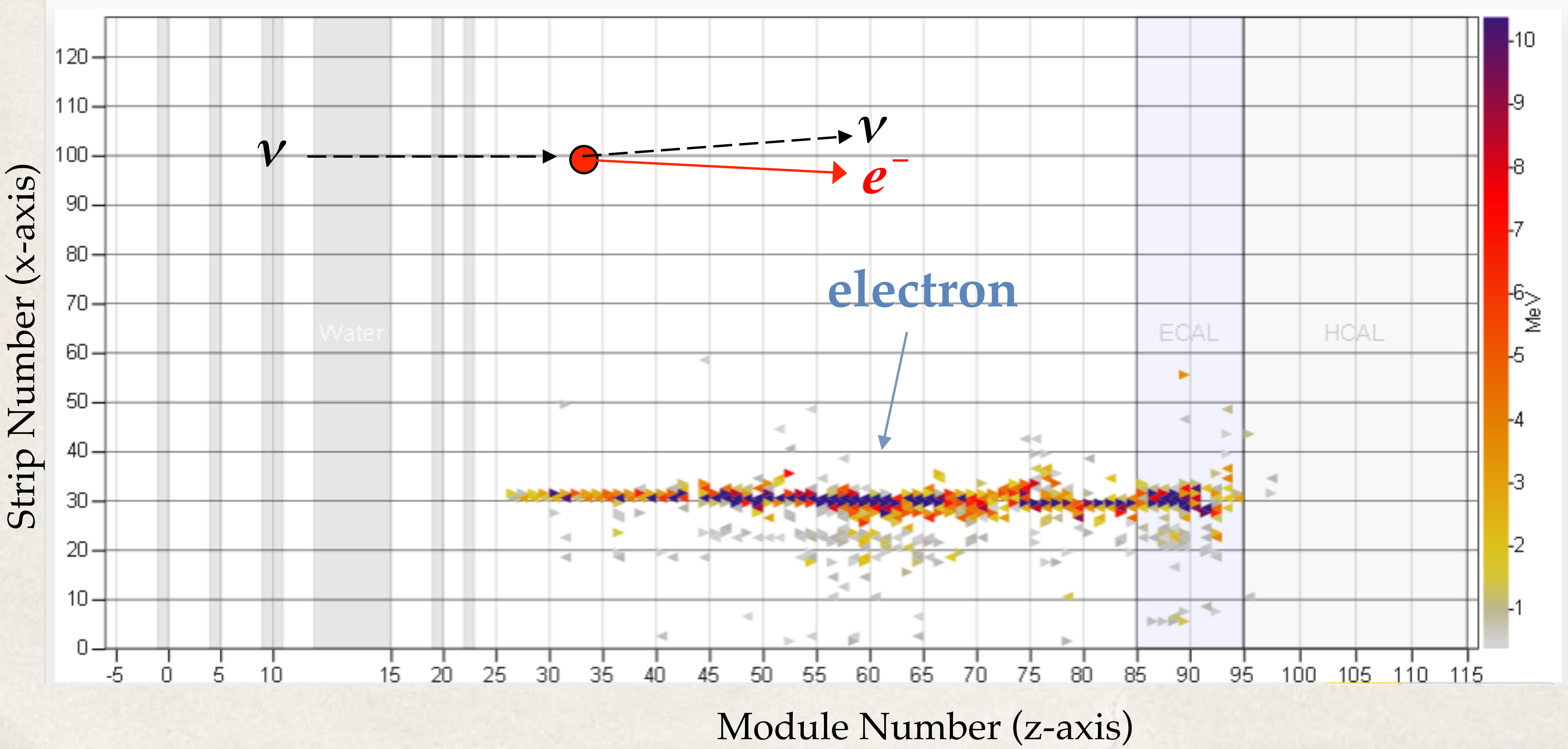
- Neutrino elastic scattering on electrons is a standard candle that can be used to constrain flux:



- Standard electroweak theory predicts it precisely
- Experimental signature is a very forward single electron in the final state
- Good angular resolution is important to isolate signal

$$\Phi = \frac{N}{\epsilon A \sigma}$$

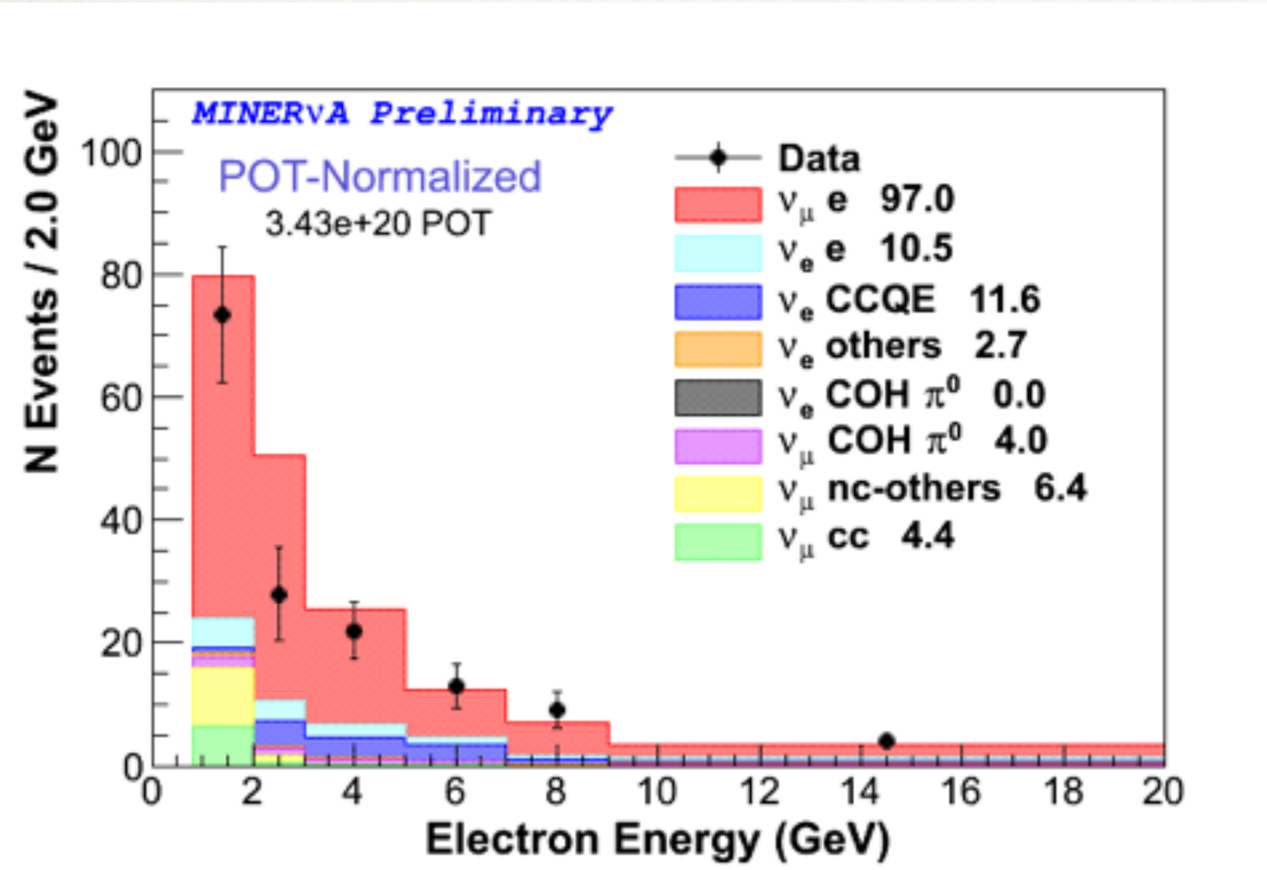
MINERνA Data



- Drawback: very small cross section (~1/2000 times the neutrino-nucleus cross section) limits statistics

Flux Estimate: ν-e Scattering Constraint

- MINERvA's analysis of ν-e scattering in the low energy beam is now complete:



Predicted number of signal events, given Geant4 simulation constrained with external data:
149.3 ± 0.7 ± 18.6

Observed in Data:
123.8 ± 17.0 ± 9.1

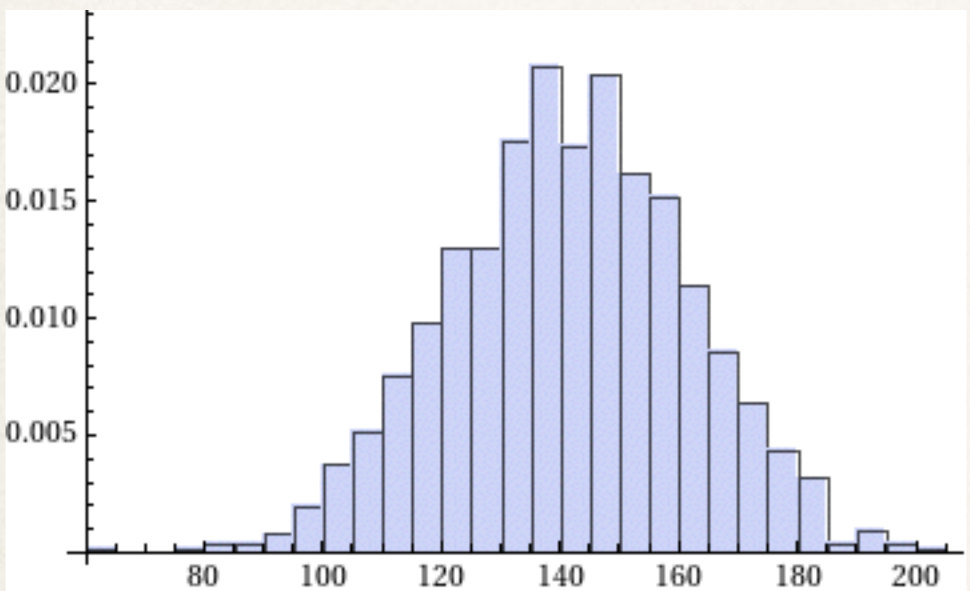
Net effect on flux FHC ν_μ flux between 0 and 8 GeV:
Lowers prediction by 5%
Lowers fractional uncertainty from 8.7 to 6.1 %
Adding spectrum information decreases error to 5.8%

Flux Estimate: ν-e Scattering Constraint

- How this calculation works:

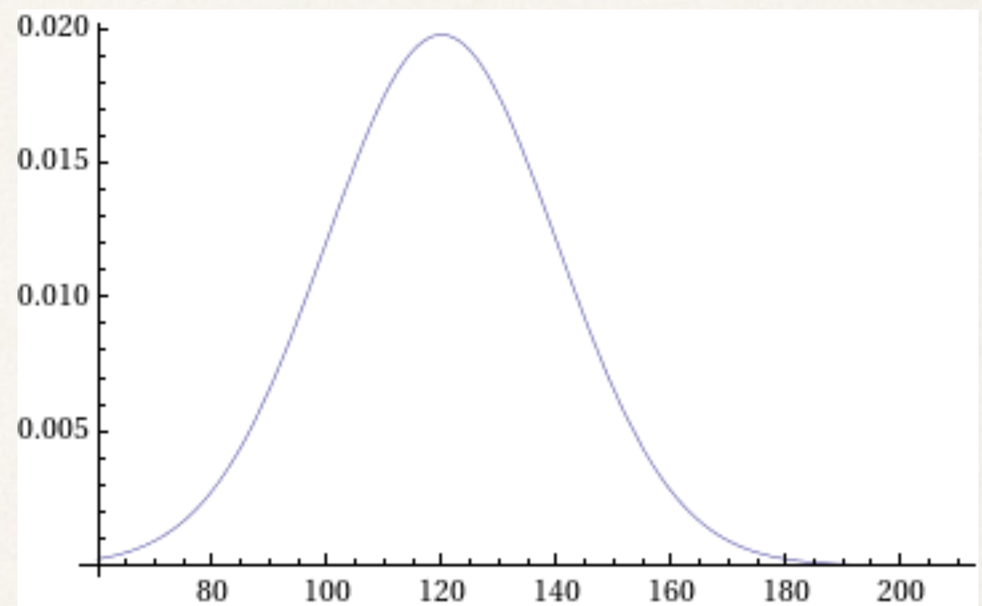
Distribution of some quantity in multi-universes before constraint

K. McFarland



X

Probability of the ν-e scattering data given the prediction in a simulated universe



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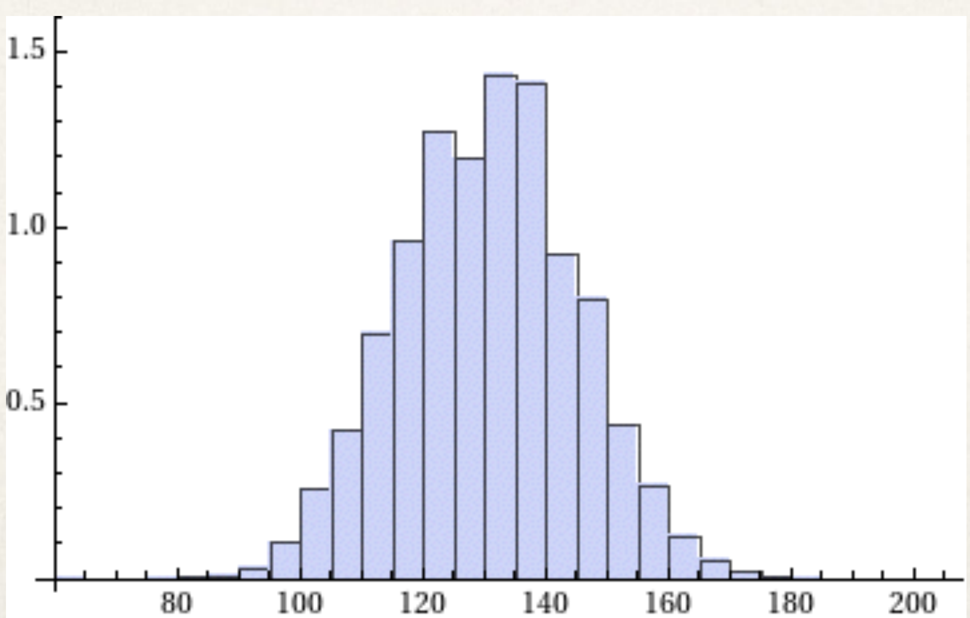
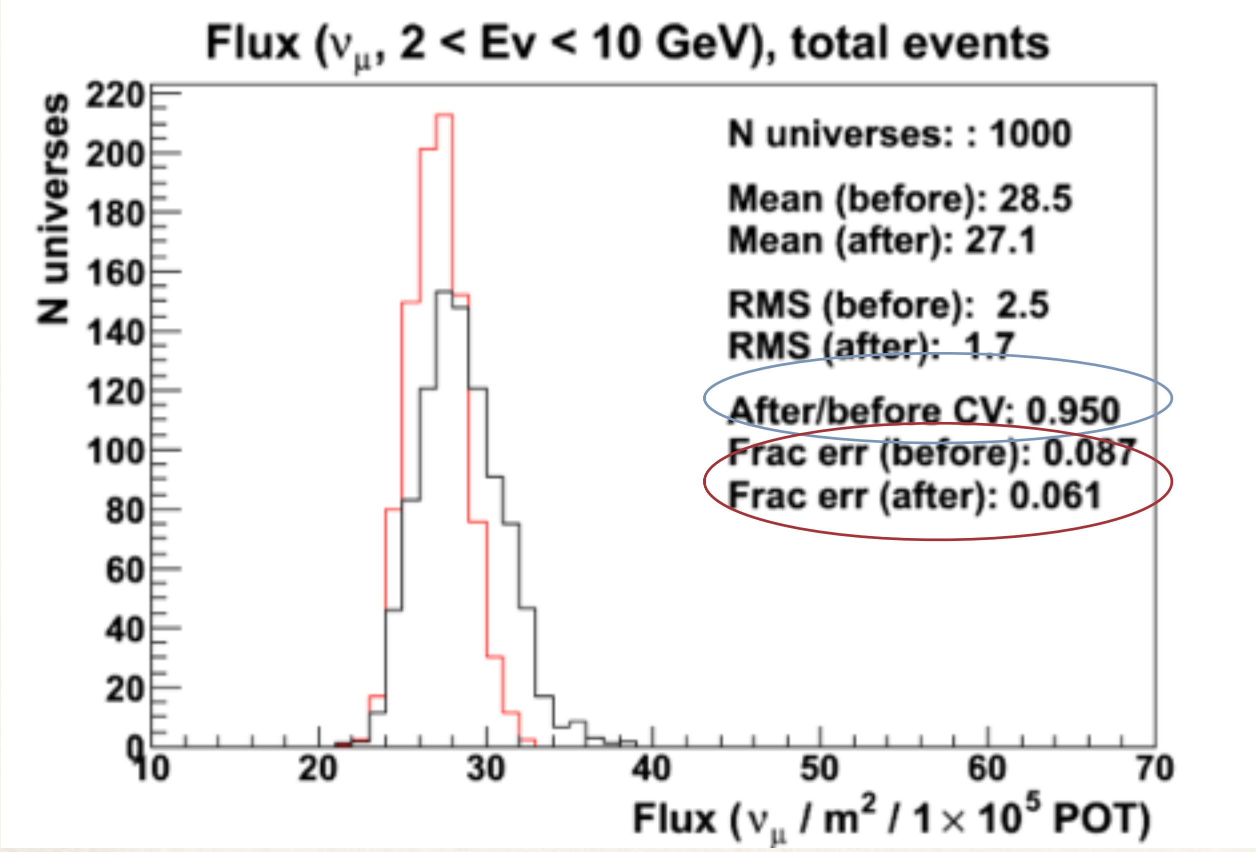


New distribution of multi-universes; mean and width of this distribution give the new value/uncertainty of the quantity in question

Flux Estimate: ν-e Scattering Constraint

- Distributions of total FHC ν_μ flux before and after ν-e constraint:

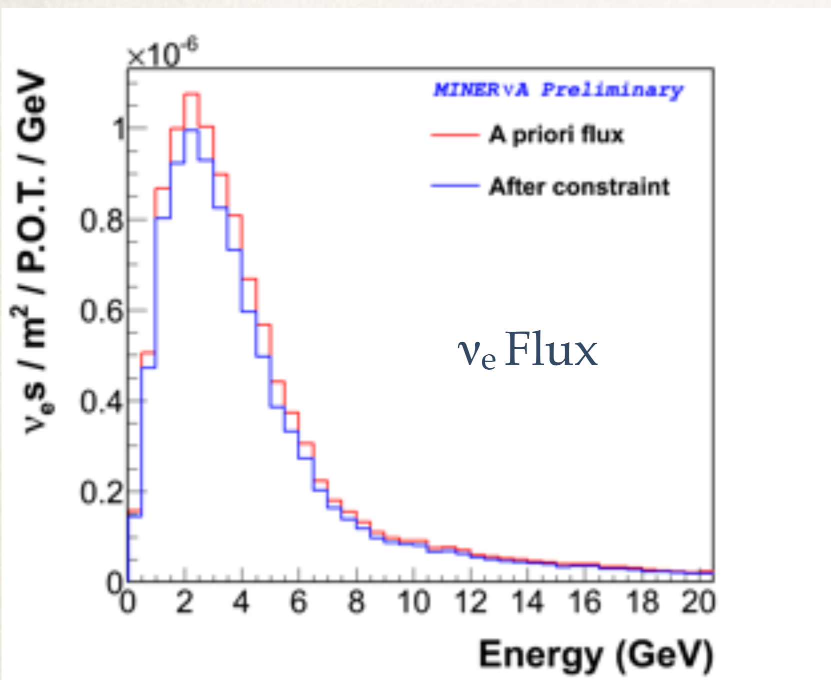


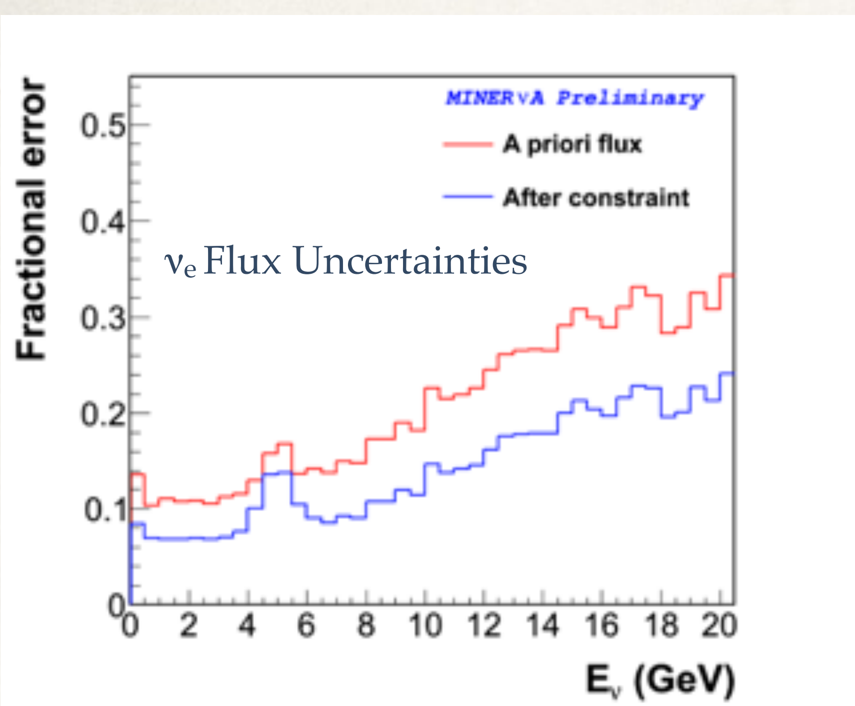
Here, the shift in mean (5%) is the amount the constraint shifts the total FHC ν_μ flux between 2 and 10 GeV

And the change in RMS gives the reduction in uncertainty — from 8.7% to 6.1%

Flux Estimate: ν-e Scattering Constraint

- The first analysis to use this constraint is a ν_e CCQE measurement:



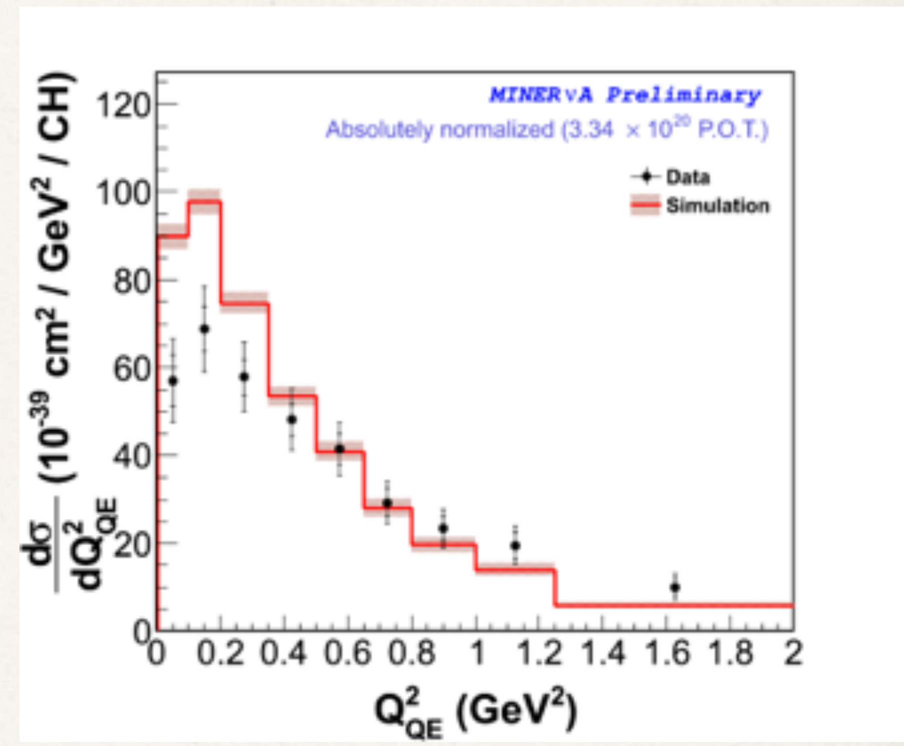


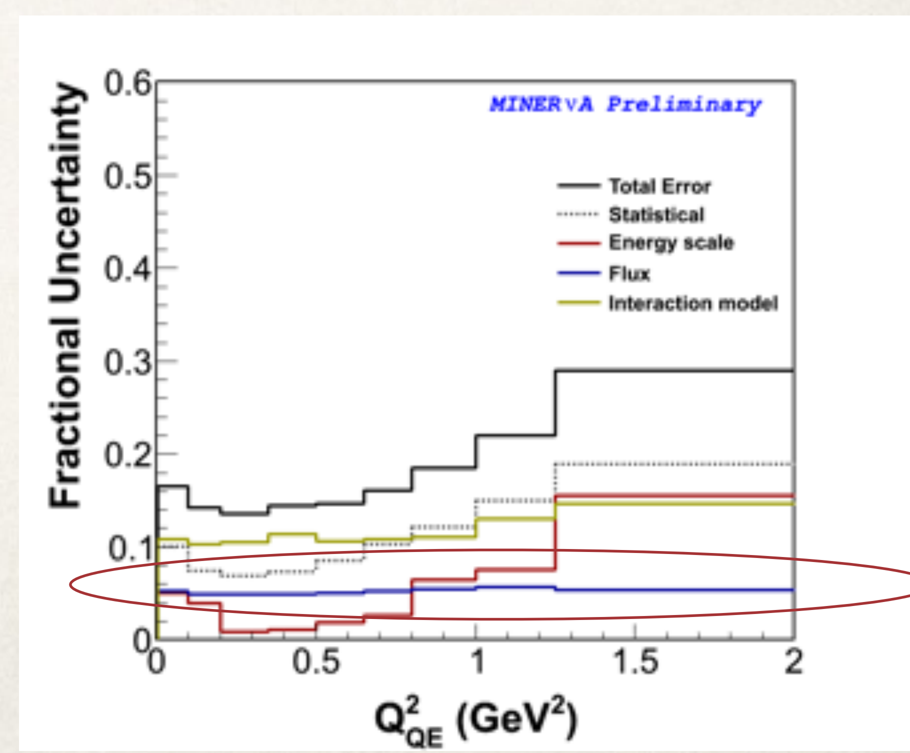
Uncertainties are lowered by 3-10%

Flux is not the dominant systematic

Will be applied to other MINERvA analyses soon

Could also be used by other NuMI experiments





J. Wolcott NuFact 2014

Future Plans: More External Data

- We currently constrain ~70% of the interactions that happen in our simulation:

neutrino energy	average # interactions / event	% interactions reweighted
3-4 GeV	1.362	75.18%
15-16 GeV	1.303	71.93%
30-31 GeV	1.30	64.0%
0-30 GeV	1.463	69.62%

- It's possible to constrain a few more:

Proton Interactions — Avg # interations/event

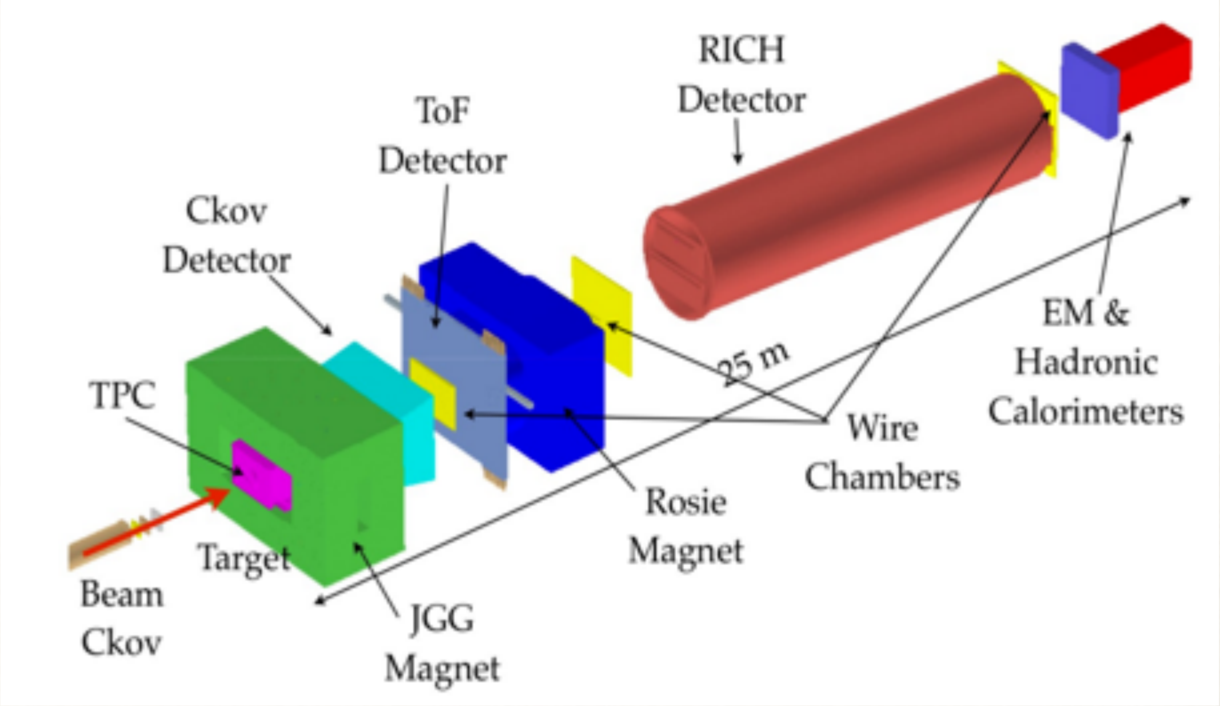
produced particle	unconstrained	all
p	0.108	0.236
$\pi\pm$	0.015	0.877
K±	0.002	0.031
Ks KL	0.028	0.028
n	0.049	0.049

Other Interactions — Avg # interations/event

incident particle	interactions/event
$\pi\pm$	0.134
n	0.057
K±, Ks KL	0.018
all others	0.013

Future Plans: More External Data

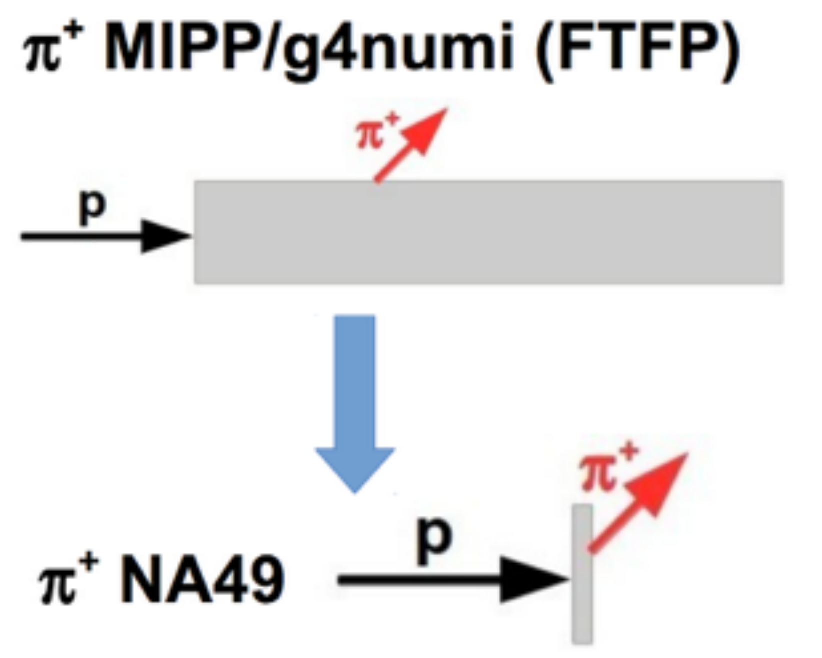
- An important next step in the external data constraint program is incorporation of measurements of pion yields off the NuMI target by the MIPP experiment
  - Currently only use the MIPP thin target k/π ratio measurement to extend phase space of kaon production constraint
  - We plan to use MIPP data to constrain particles created in the target and covered by MIPP, and to use thin target data elsewhere

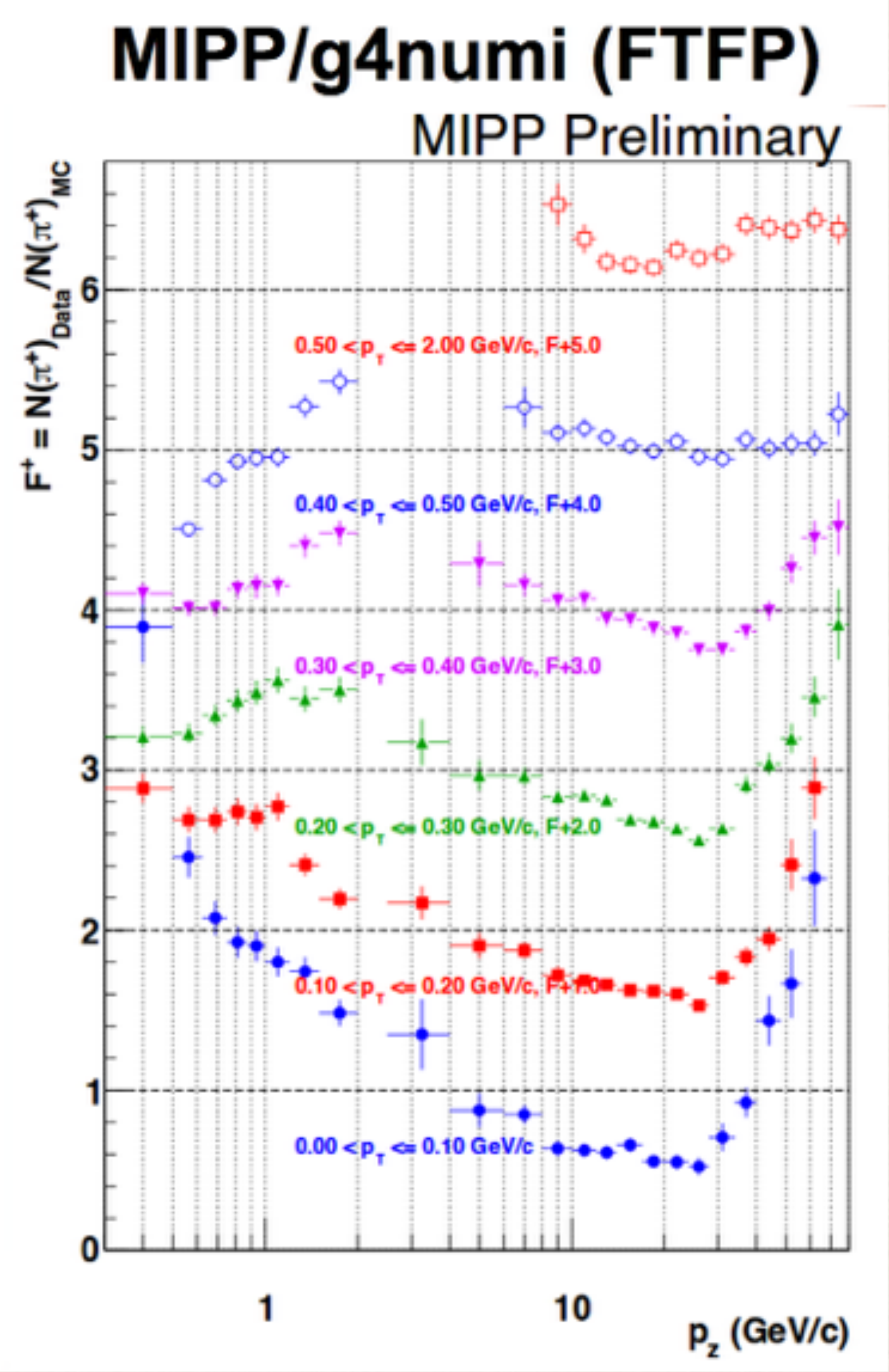


Using MIPP will reduce uncertainties on the currently unconstrained portion of the flux → expect a significant reduction in final hadron production uncertainties.

Future Plans: More External Data

- We are currently working to understand differences between the MIPP and thin target data
- Discrepancies between the two datasets are likely due to secondary interactions in the target



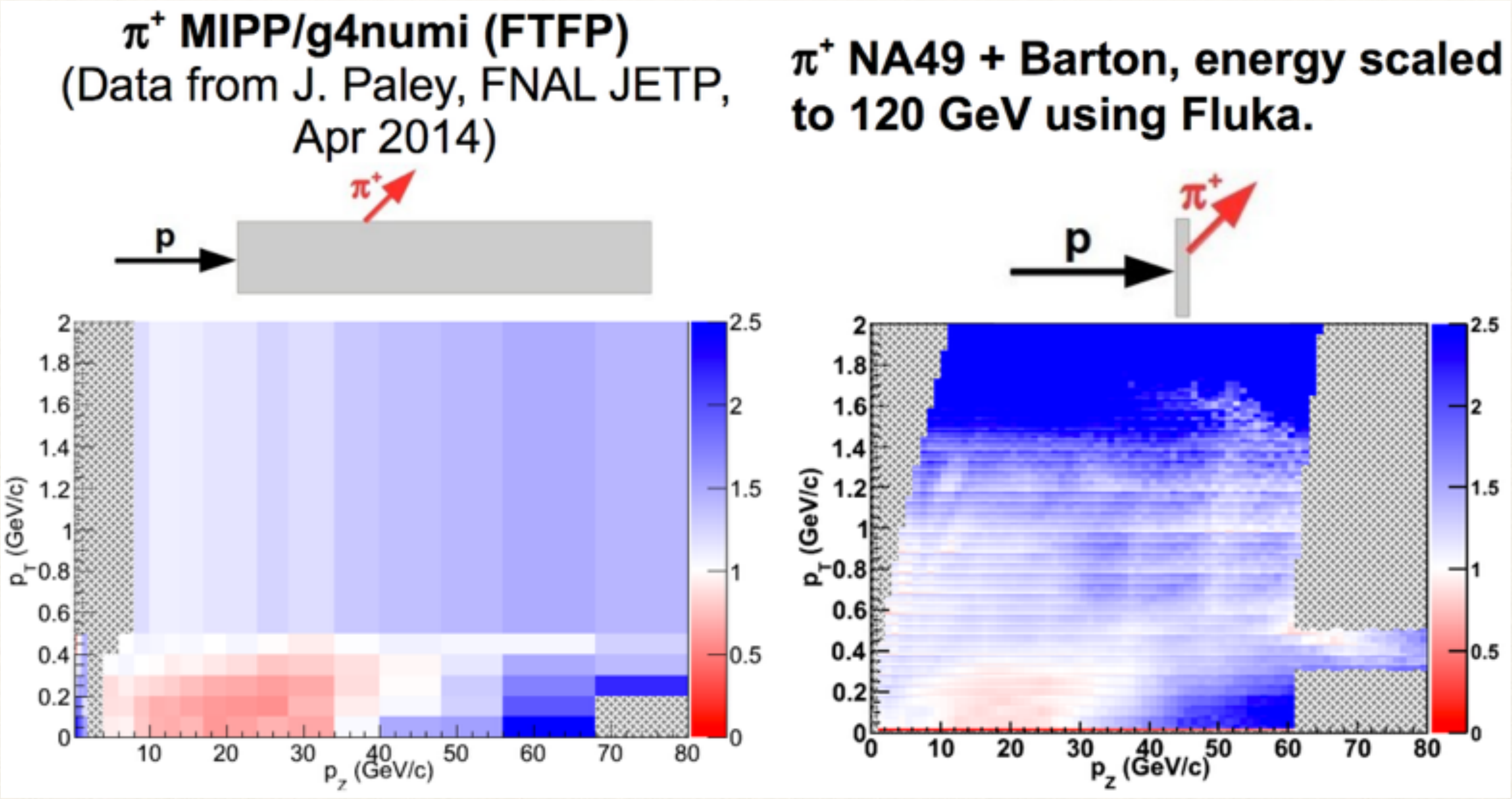


J. Paley and L. Aliaga

Future Plans: More External Data

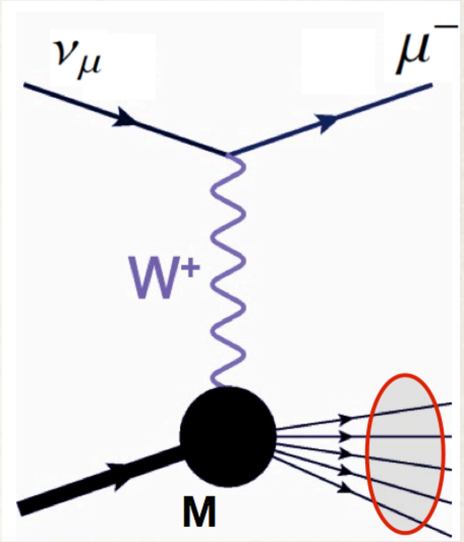
- A quick look at MIPP vs thin target weights:

L. Aliaga



- More comparisons of MIPP and thin-target constraints coming soon

Future Plans: Low-ν Constraint



- Charged-current ν_μ scattering with low hadronic recoil energy (ν) is another standard candle:
  - Differential cross section can be approximated by:

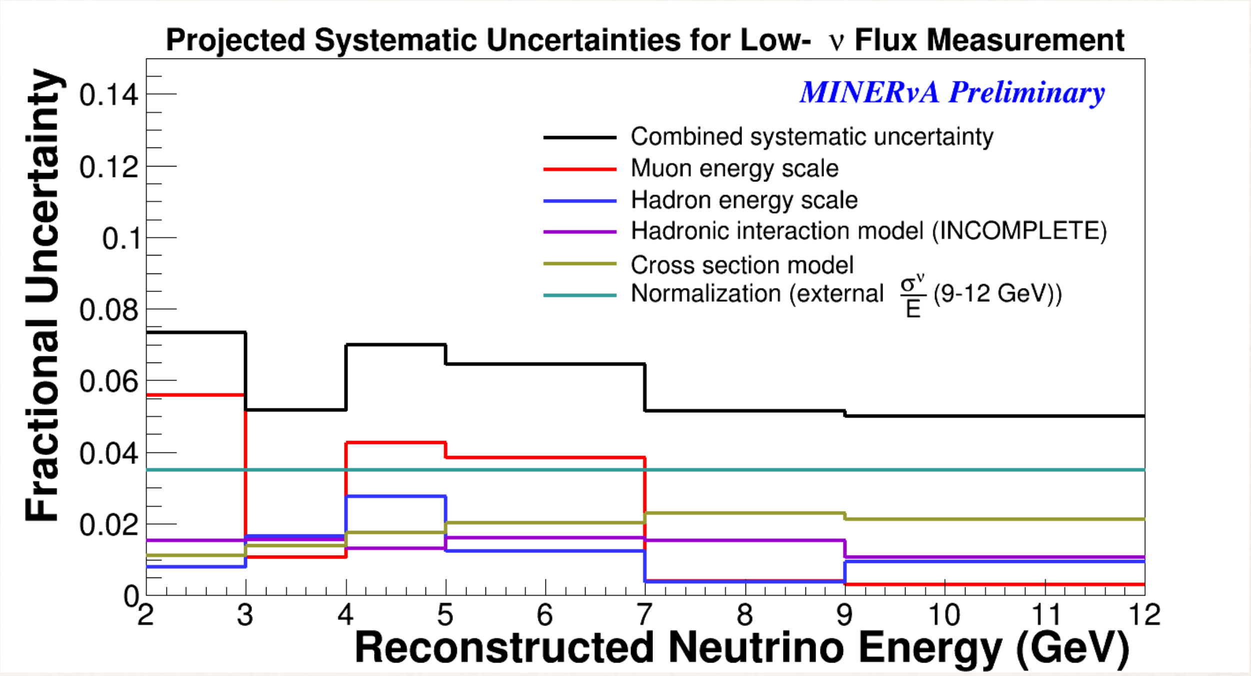
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{E^2}\right)$$

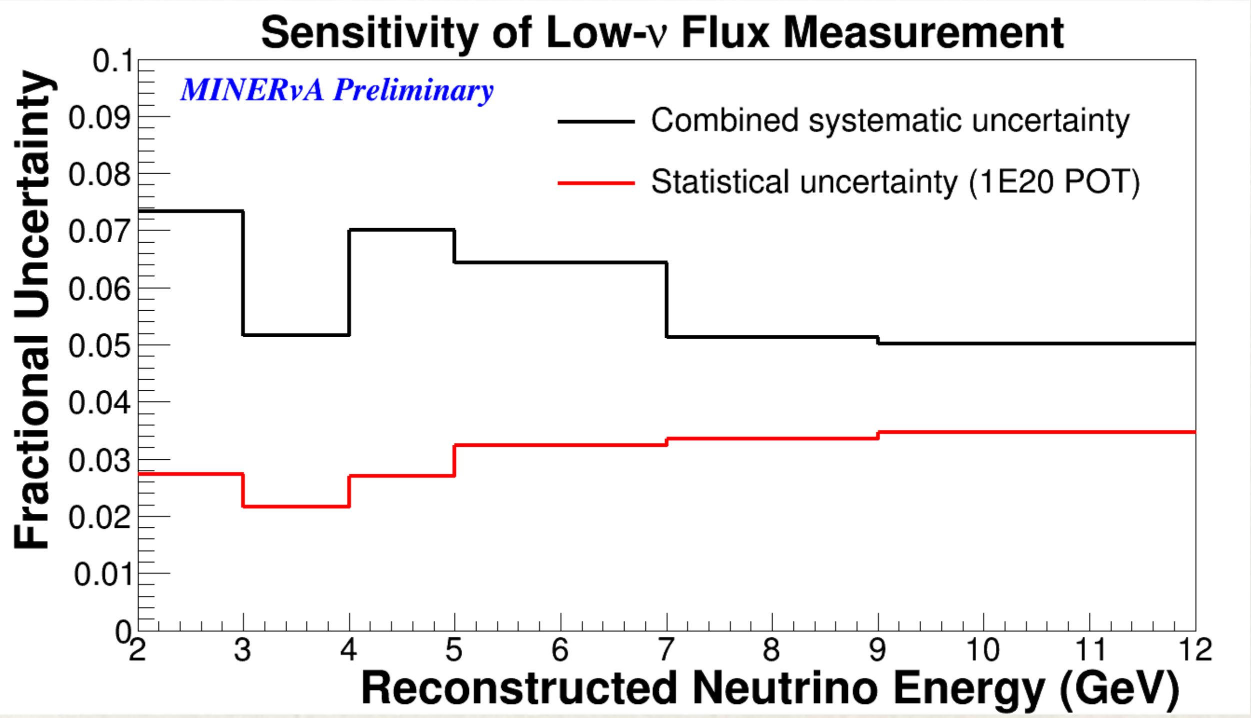
ν: energy transfer to the hadronic system.
E: neutrino energy.
A,B, C: integral over structure functions.

  - For small values of ν/E, cross-section is constant with energy and can be used to extract the energy-dependent shape of the flux
  - Normalization is fixed at high energies using high precision cross section measurements (from e.g. NOMAD)
  - Challenge lies in correctly measuring the hadronic energy of the system
    - Multi-nucleon interactions may also complicate this measurement

Future Plans: Low ν

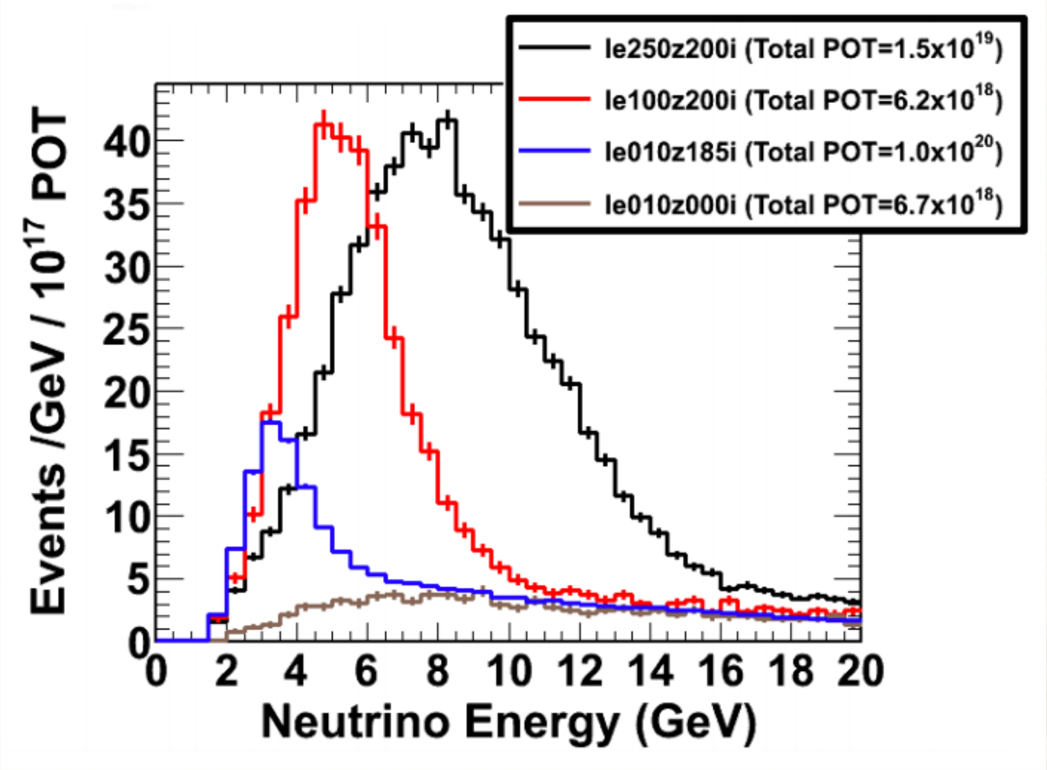
- No results yet, but preliminary estimates of systematic uncertainties are promising



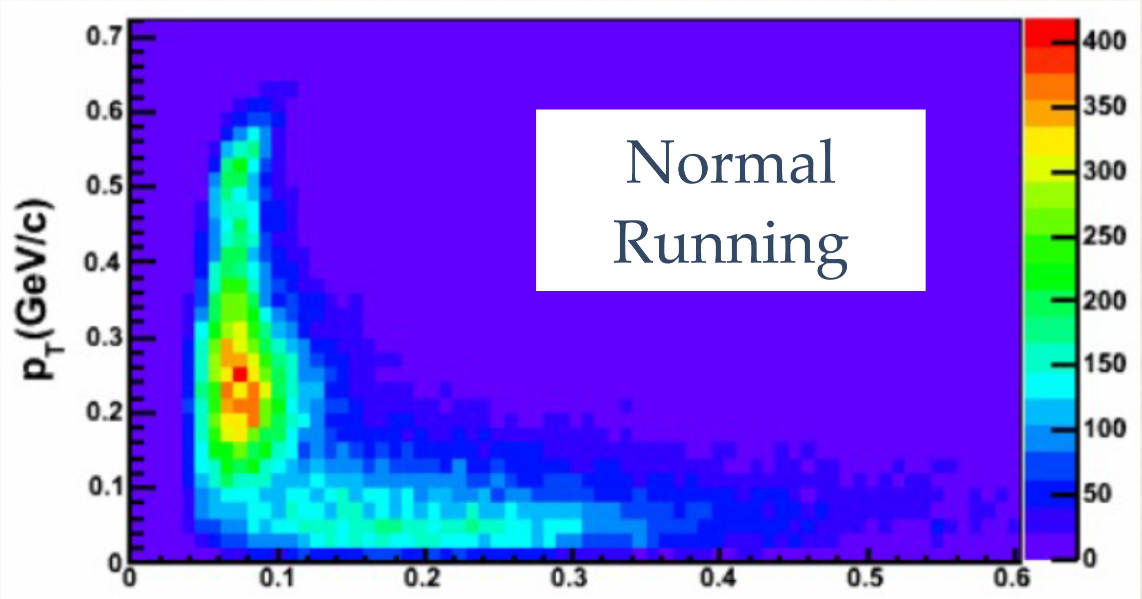


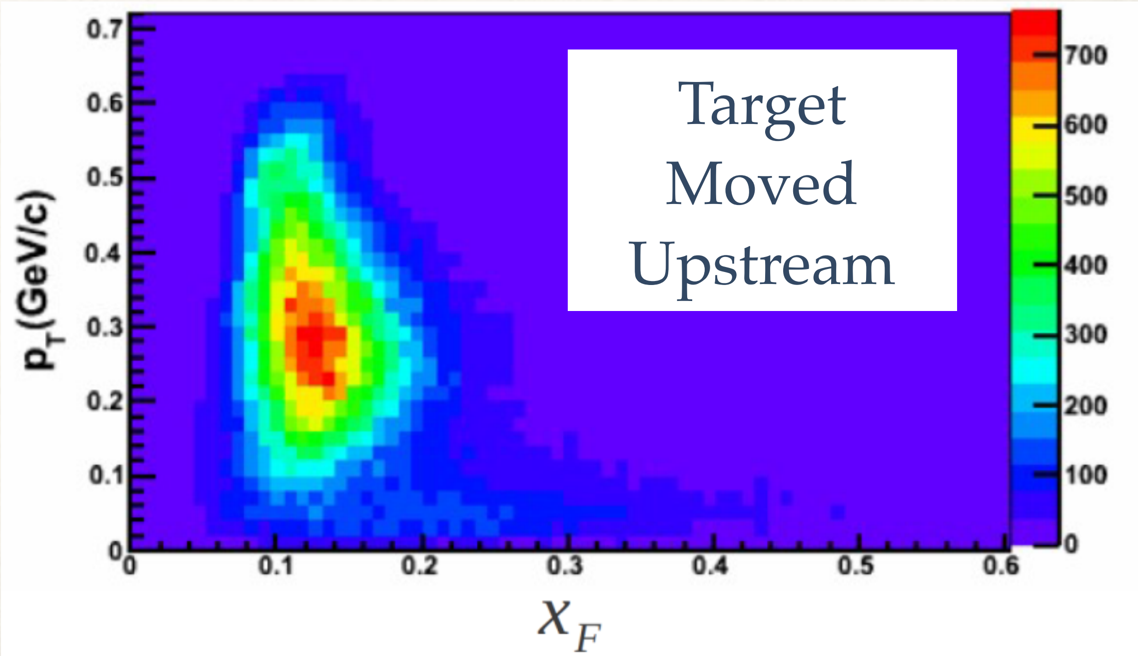
Future Plans: Special Runs

- Can also utilize "special runs" data taken with various target positions and horn currents
- Disentangles focusing uncertainties from hadron production uncertainties
- An important cross-check of other constraints



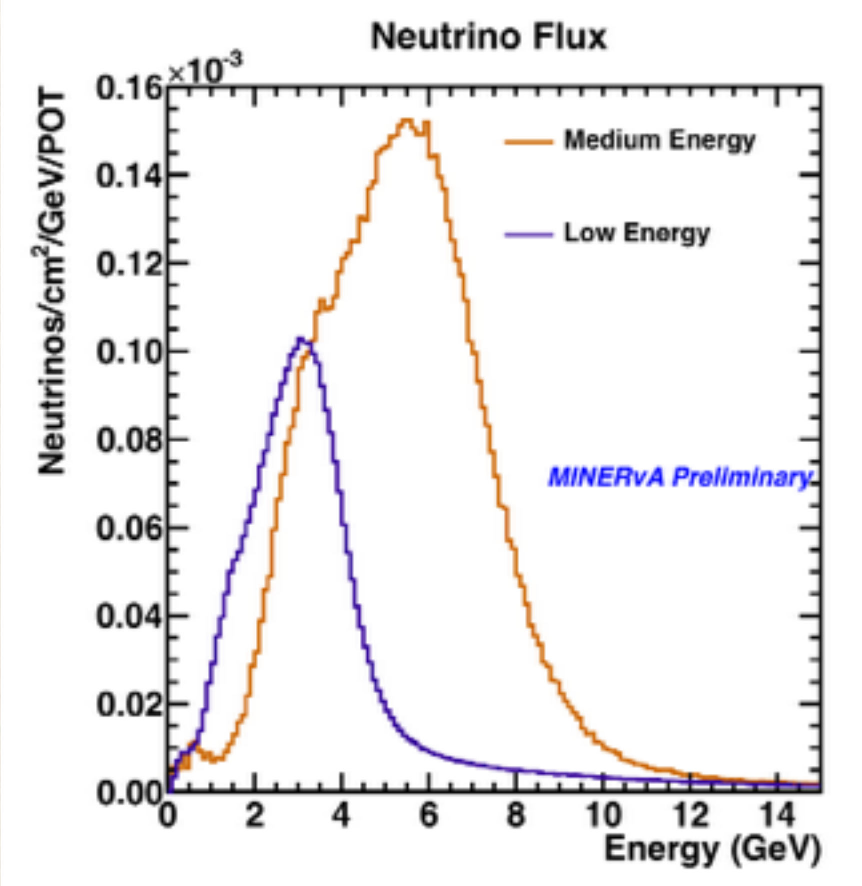
Pions that produce neutrinos in MINERvA





Future Plans: Medium Energy Flux

- MINERvA is also actively working on several measurements of absolute cross sections using the "Medium Energy" data that we began taking last year:



- Thin target constraint machinery can be applied to ME flux simulation with very little additional effort

- ν - e scattering cross section measurement will have much improved statistics (expect ~2% statistical uncertainties, 5% systematic)

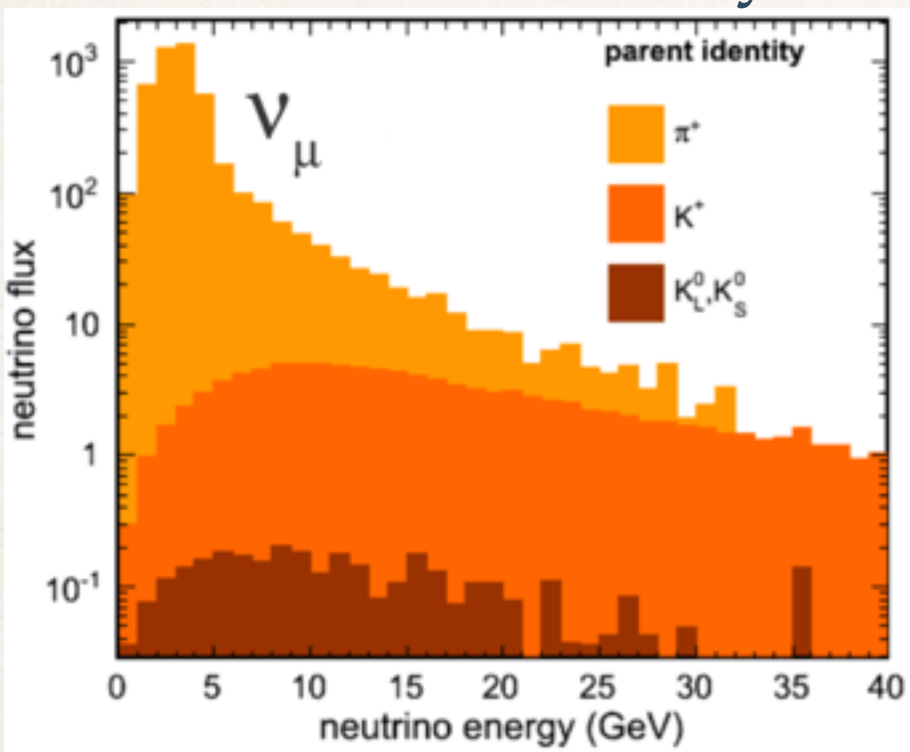
Conclusions

- MINERvA takes a multi-pronged approach to estimating our neutrino flux
- Current analyses use a GEANT4-based simulation constrained with external data, which achieves ~10% flux uncertainties on absolute cross section measurements
- The ν -E scattering analysis in the LE beam is complete and will be used to further reduce flux uncertainties on future analyses
- Ongoing work includes: incorporation of MIPP data, a constraint using the low-ν technique and cross-checks using special beam configurations
- **We look forward to working with NuMI experiments and the neutrino community to share these constraint techniques**

The End

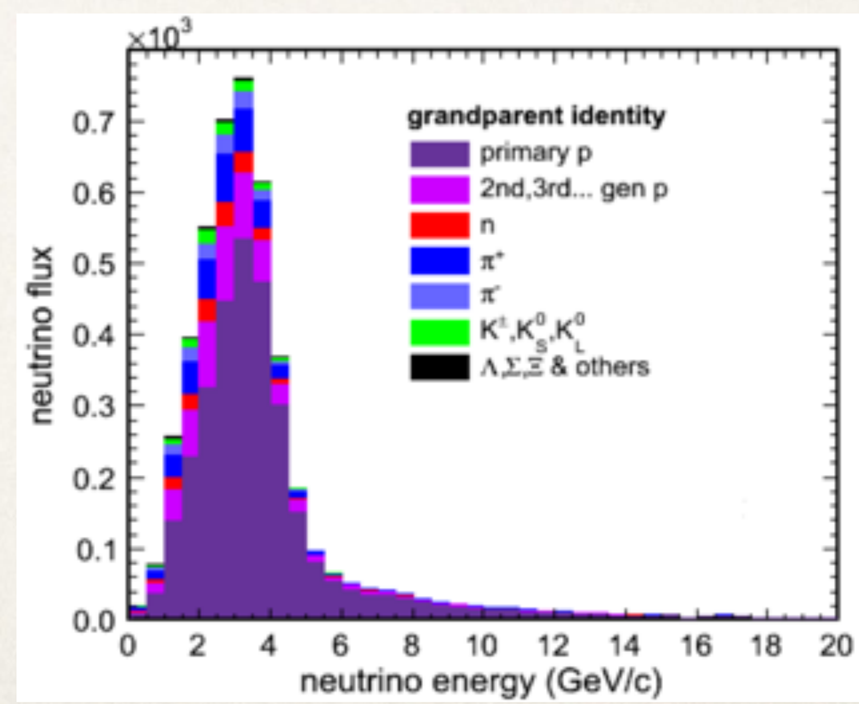
Neutrino Flux Parentage

Parent Identity



Parent Origin

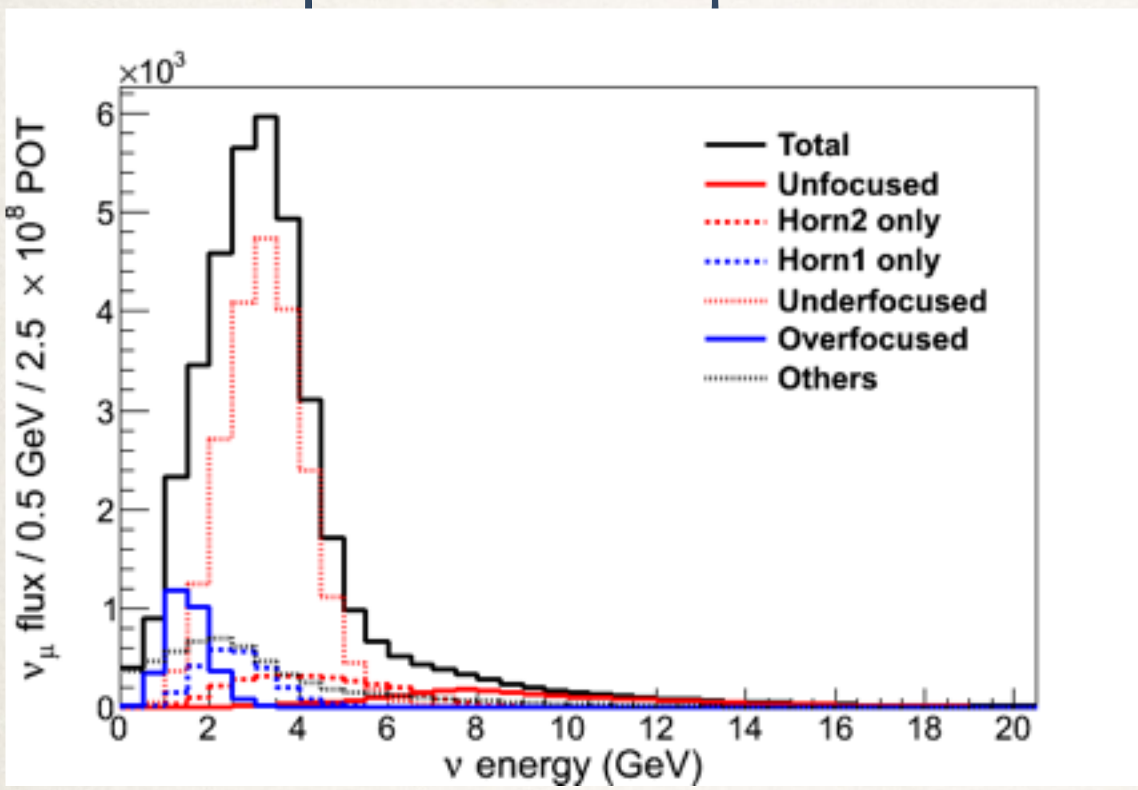
Target Fins (84.4%) & "Budal Monitor (4.6%) [C]"	**89.0%**
Decay Pipe Walls [Fe]	**2.6%**
Target Hall Chase [air]	**2.2%**
Decay Pipe [He]	**1.8%**
Horn 1 Inner Conductor [Al]	**1.5%**
All other summed	**2.9%**



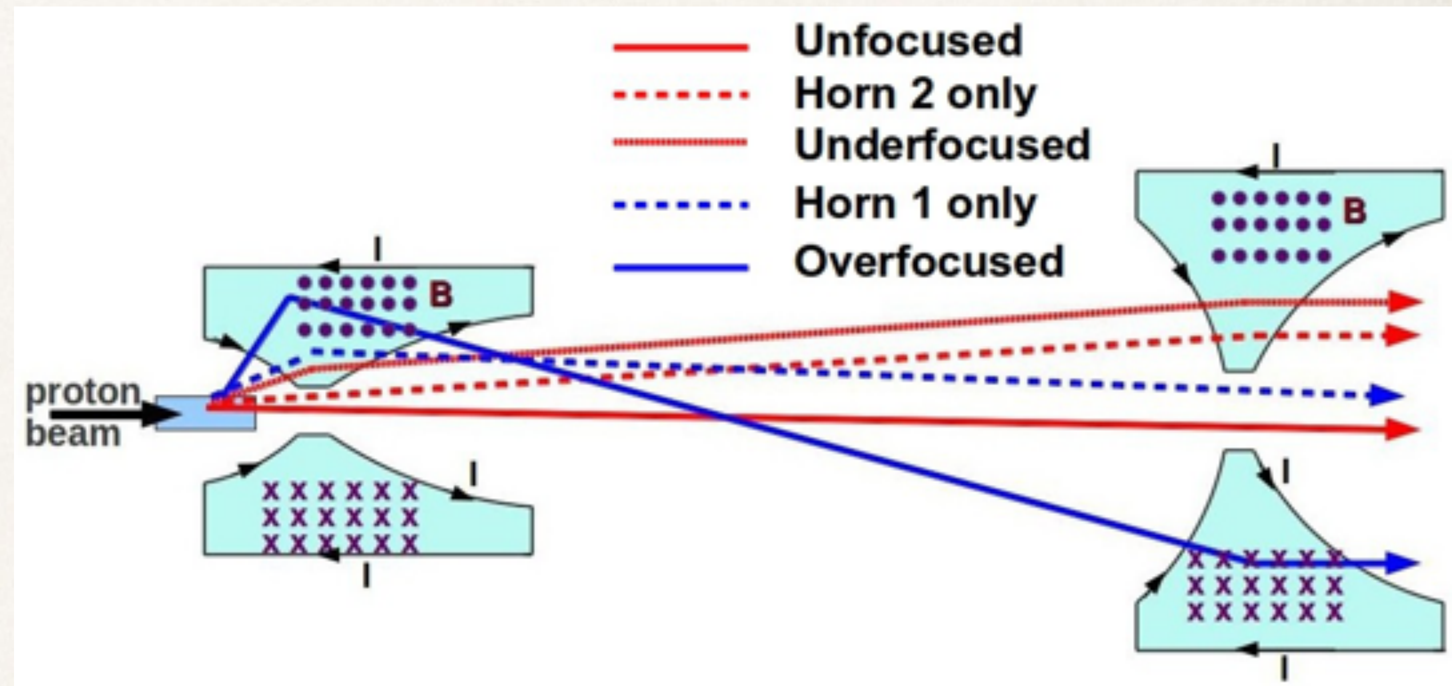
- Pion parents dominate below 20 GeV; Kaons dominate above 20 GeV

Focusing Components

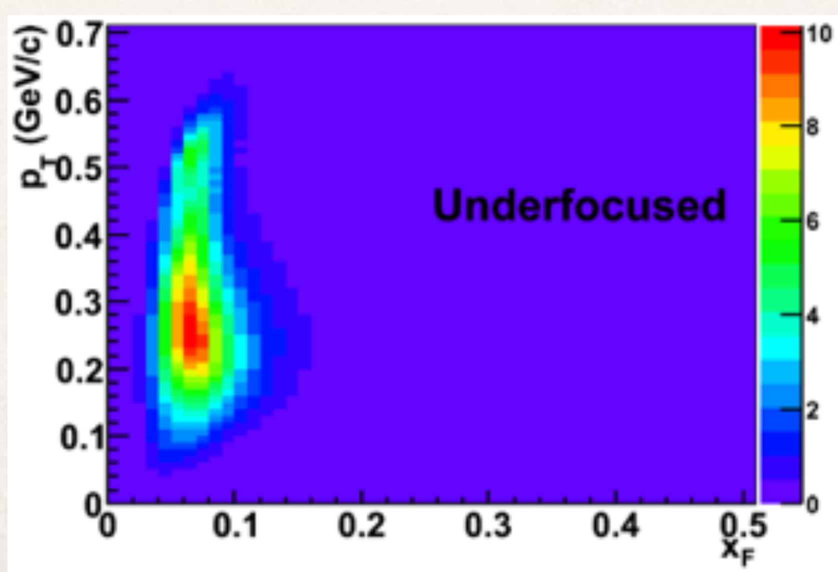
pions from protons

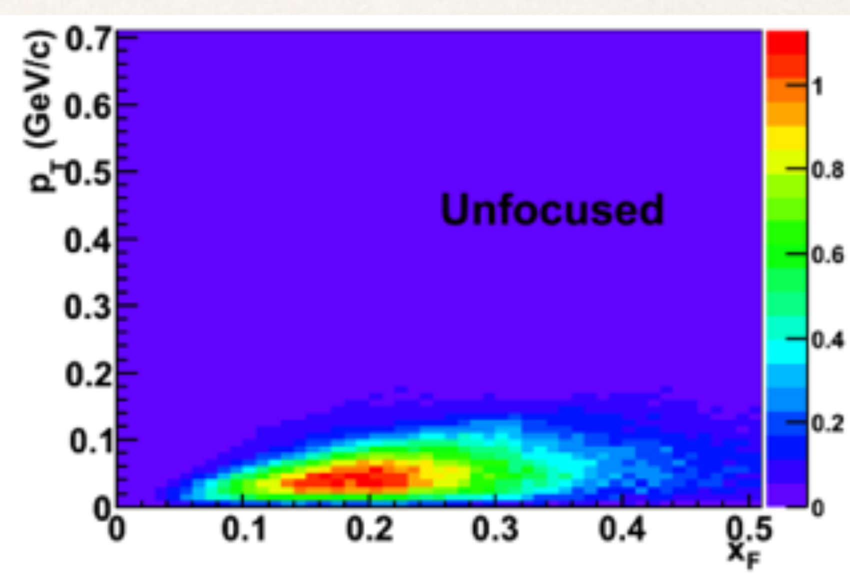


Parent Origin

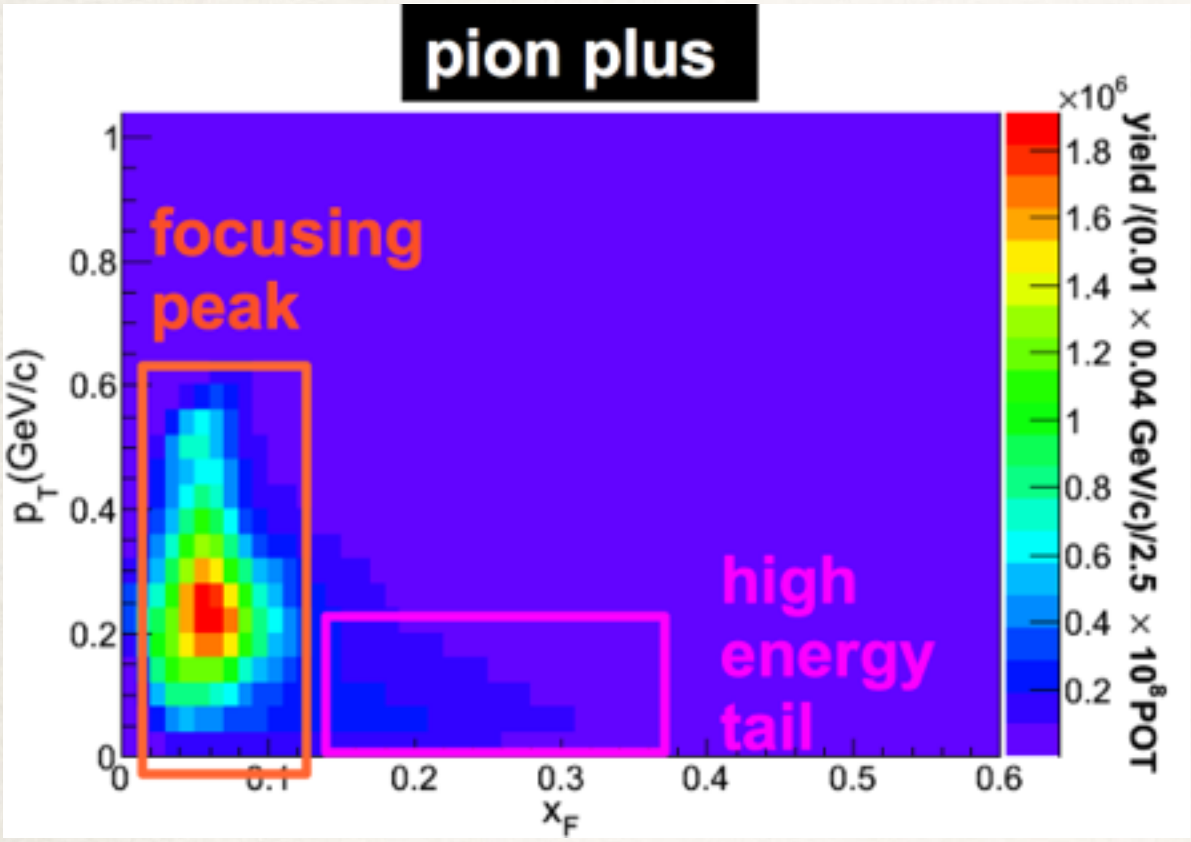


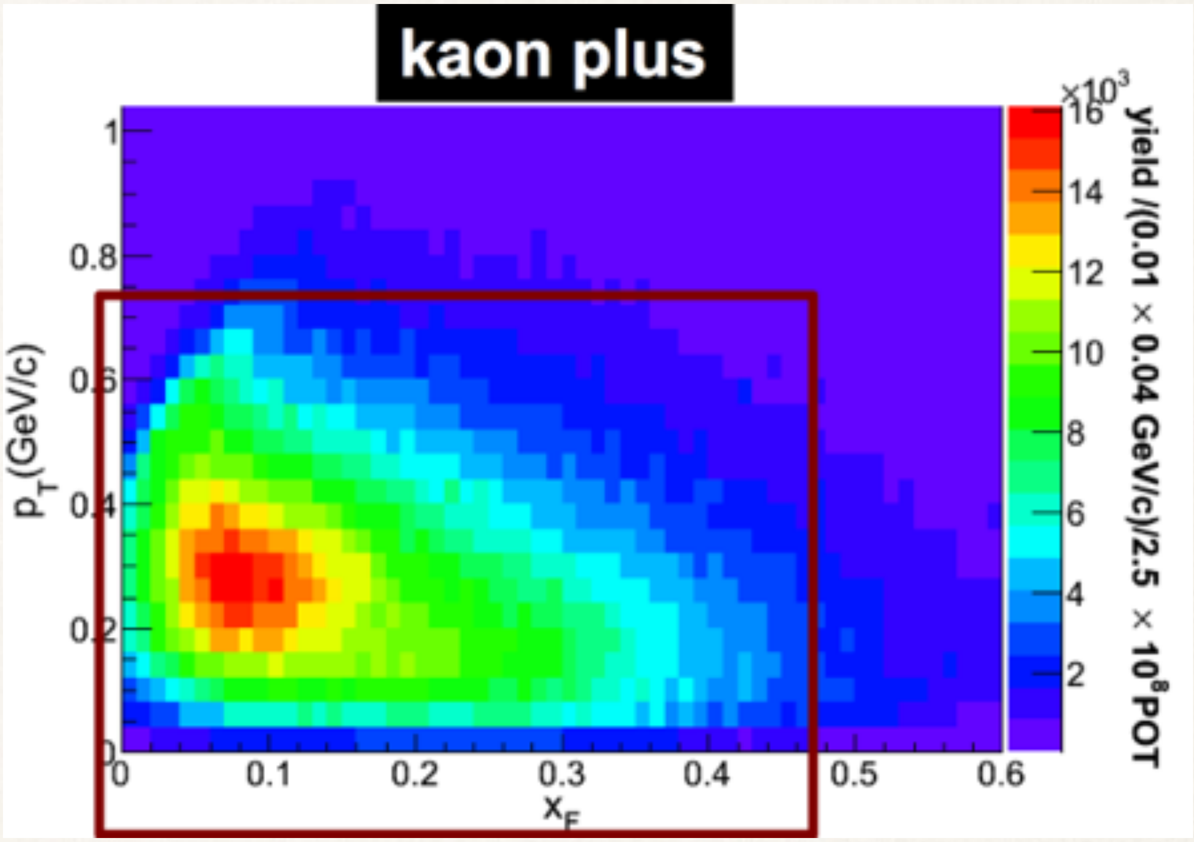
- Underfocused pions dominate focusing peak; unfocused dominates high energy tail

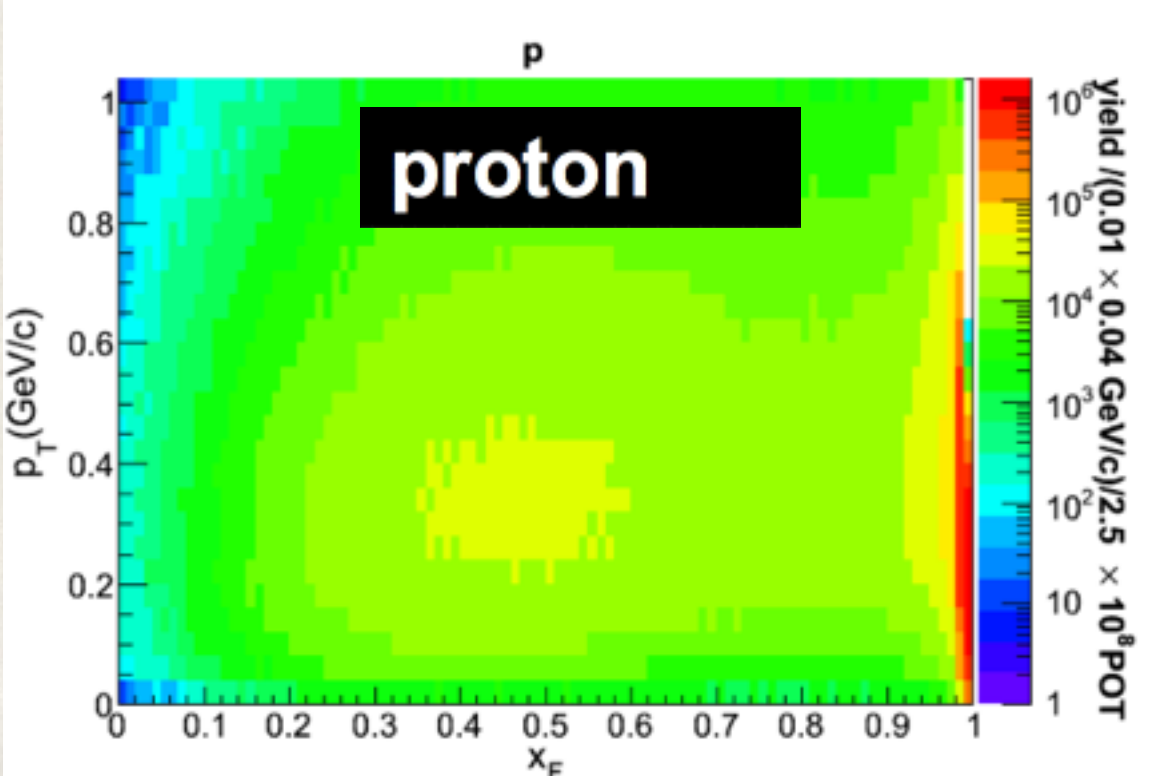




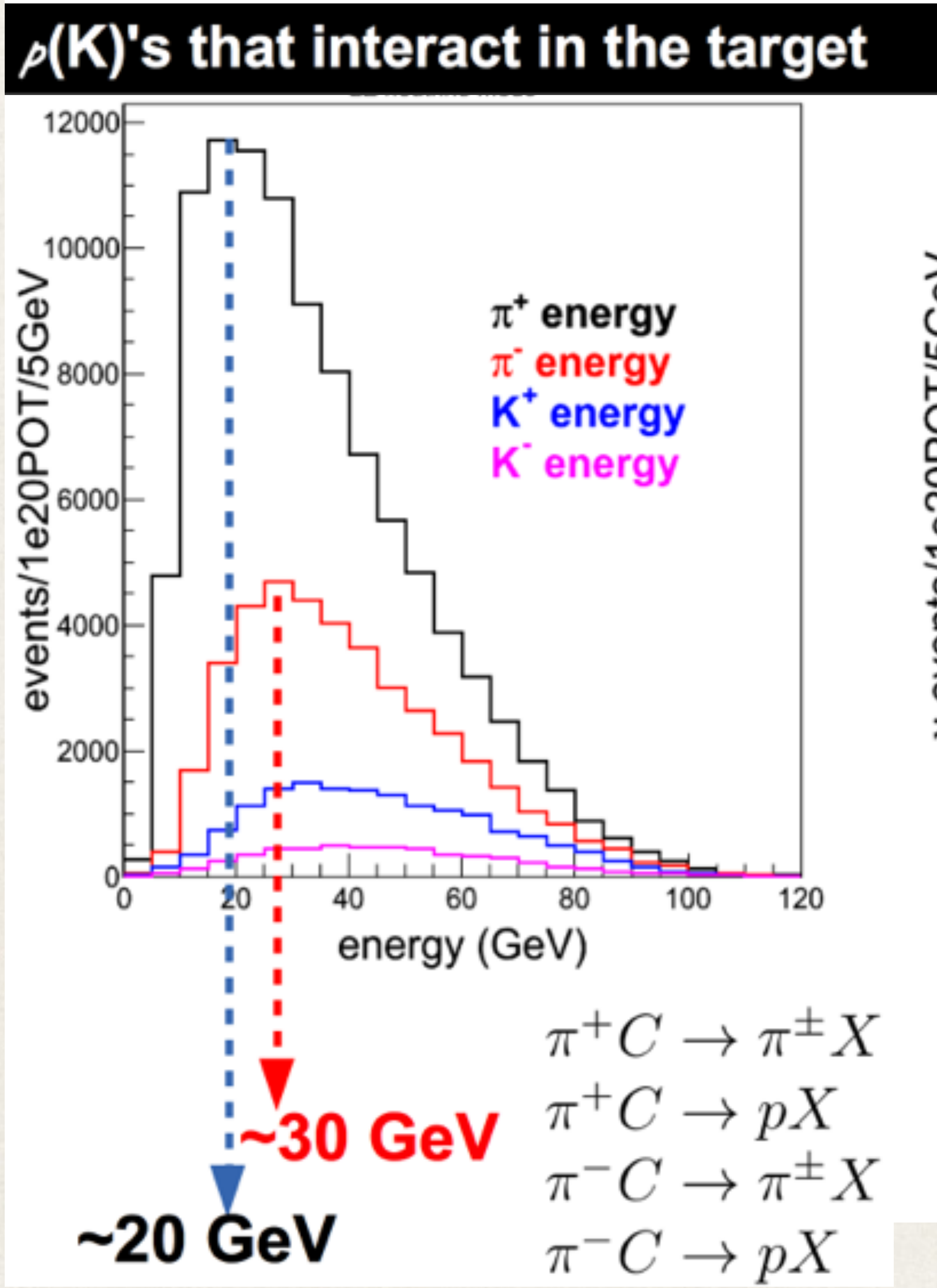
Hadron Production







Interaction in the Target

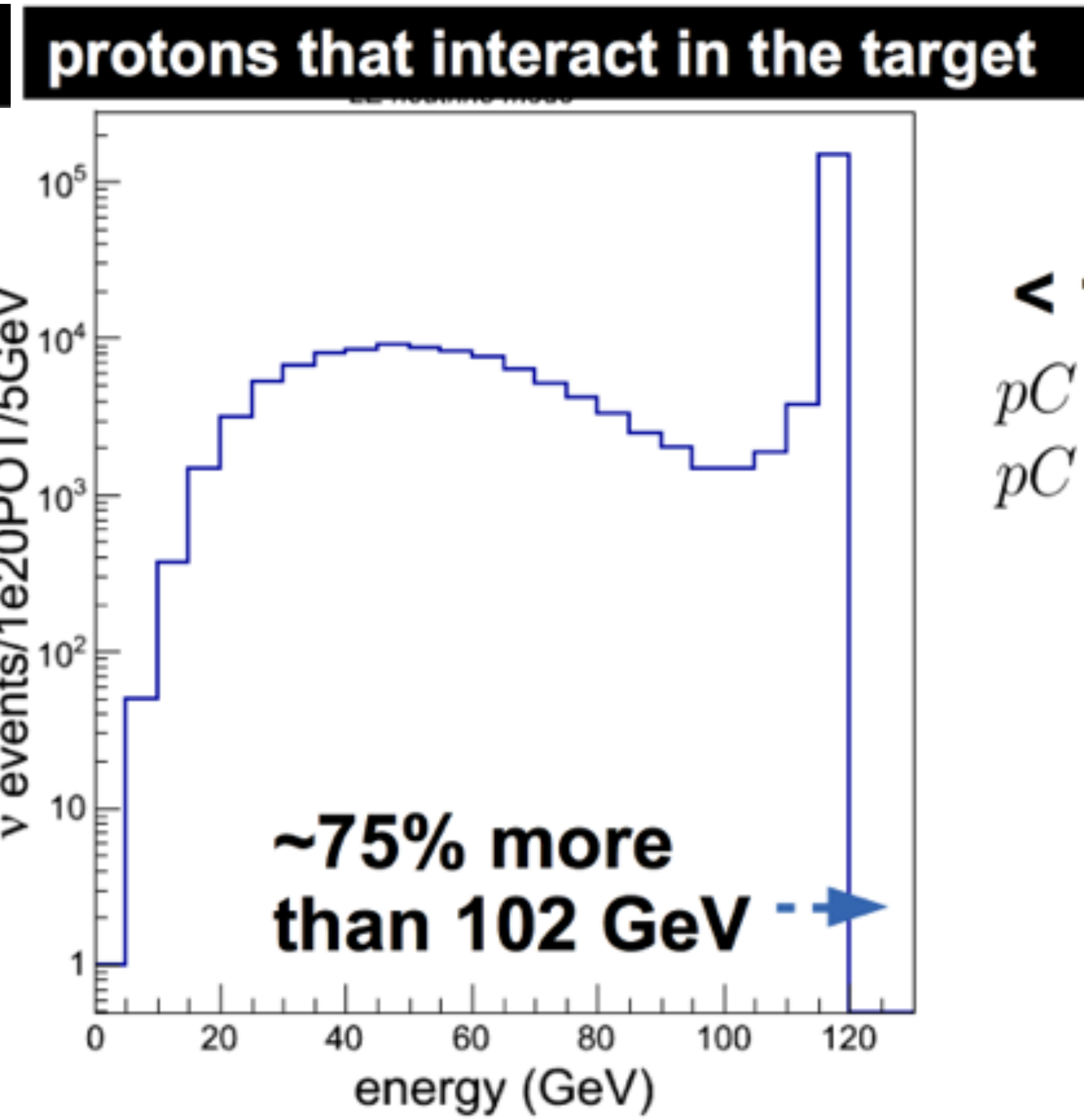


$\pi^+ C \rightarrow \pi^\pm X$

$\pi^+ C \rightarrow pX$

$\pi^- C \rightarrow \pi^\pm X$

$\pi^- C \rightarrow pX$



< 120 GeV

$pC \rightarrow pX$

$pC \rightarrow pN'n$

@ 120 GeV

$pC \rightarrow pX$

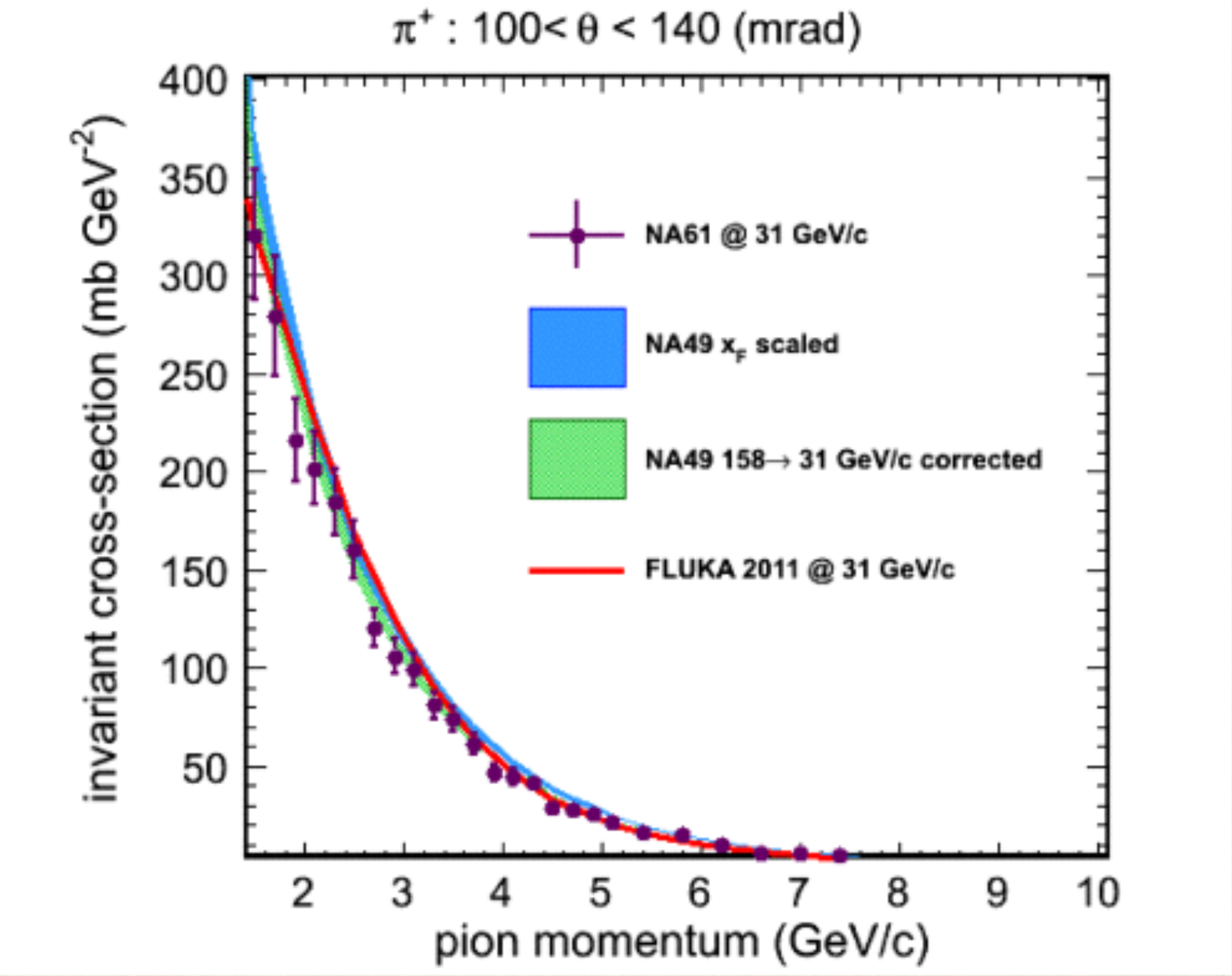
$pC \rightarrow pN'n$

Flux Estimate: Adding External Data

- More detail on the scaling correction:

- Scaling correction are applied to shift NA49 measurements at 158 GeV to the 120 GeV energy of the NuMI beam

- We test the procedure and include a systematic by scaling NA49 @ 158 to 31 GeV and comparing with NA61 data taken at 31 GeV

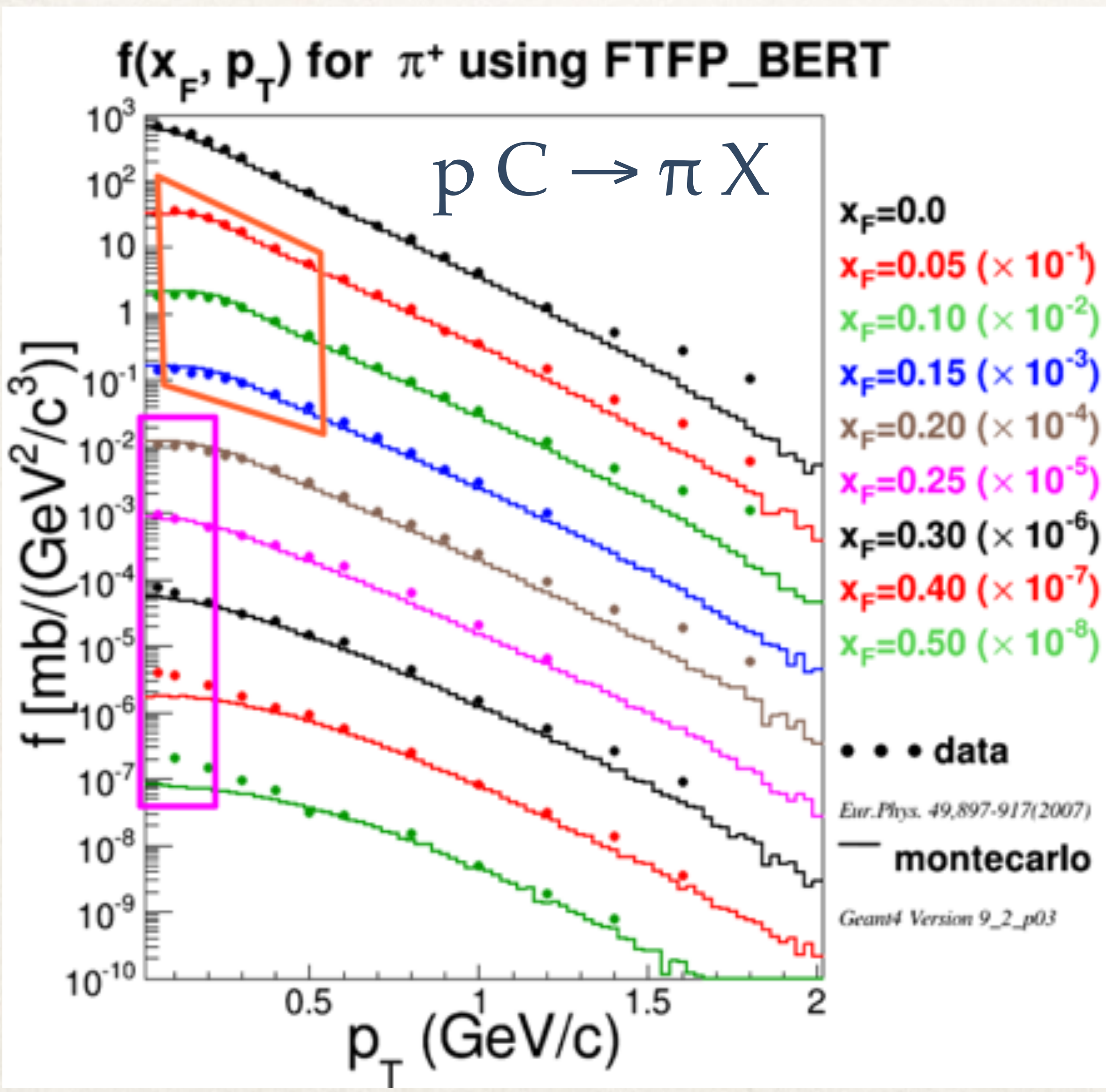


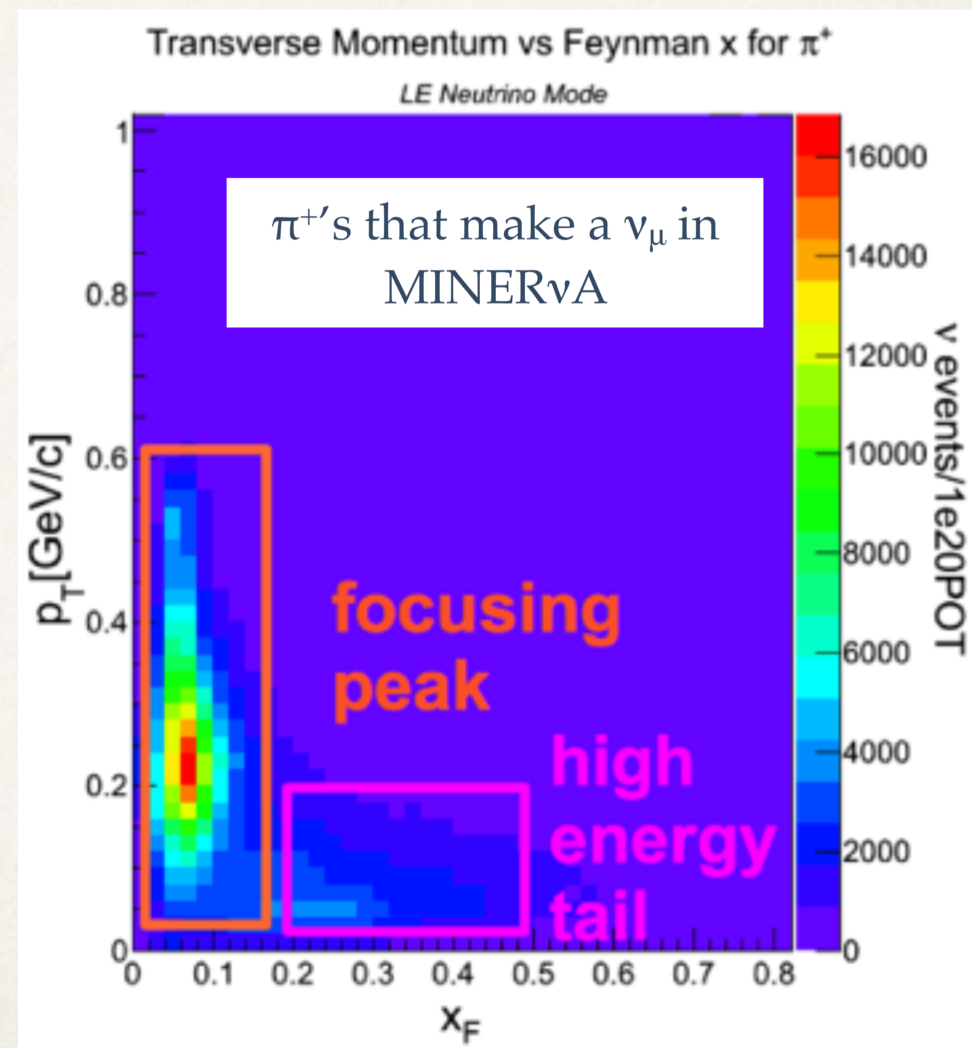
Flux Estimate: Adding External Data

- We correct the GEANT-based simulation using several external datasets; most of the constraints are from the NA49 experiment:

$f(x_F, p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section

$$x_F = 2\frac{P_L}{E_{cm}}$$





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