MINERvA Adventures in Flux Determination

NuInt 2018

DEEPIKA JENA
FERMILAB

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Introduction

- *NuMI Beamline*
- *Why Flux is important for MINERvA ?*
- *Low Energy Flux Predictions for MINERvA*
- *Low-nu Flux Measurements*
- *Flux constraint using ν-e scattering Measurements*
- *Medium Energy Flux Predictions for MINERvA*
- *Conclusions*

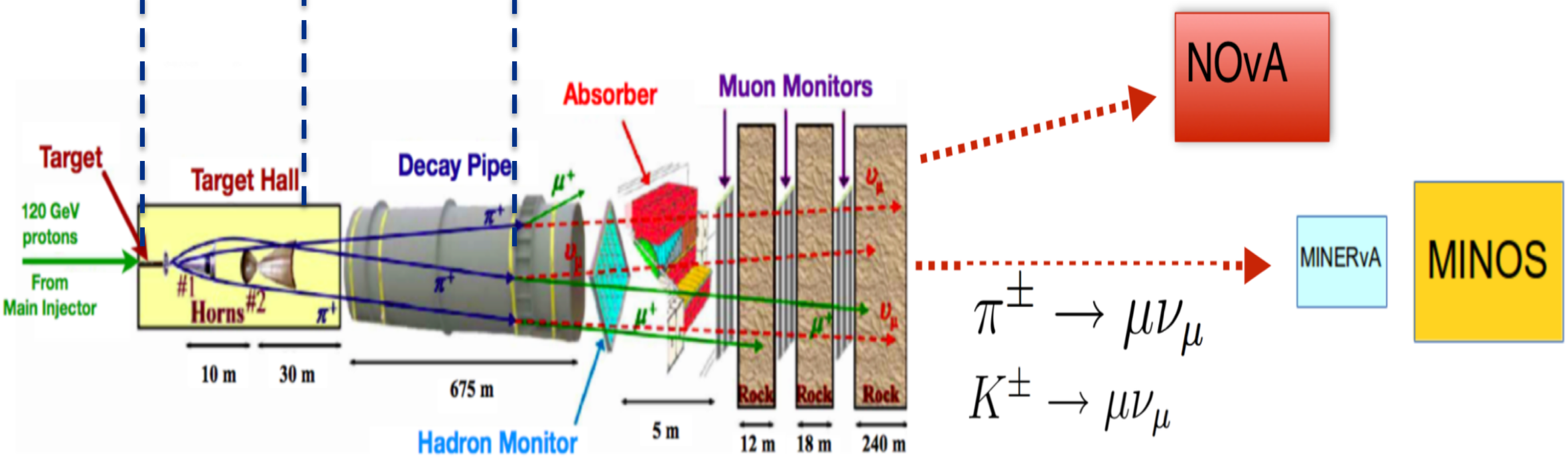
NuMI (Neutrinos at the Main Injector)

Need to understand each step from the primary proton to the final neutrino

120 GeV protons strike a graphite target and hadronic cascade is created

Pions and kaons are focused by 2 magnetic horns

Pions and kaons decay



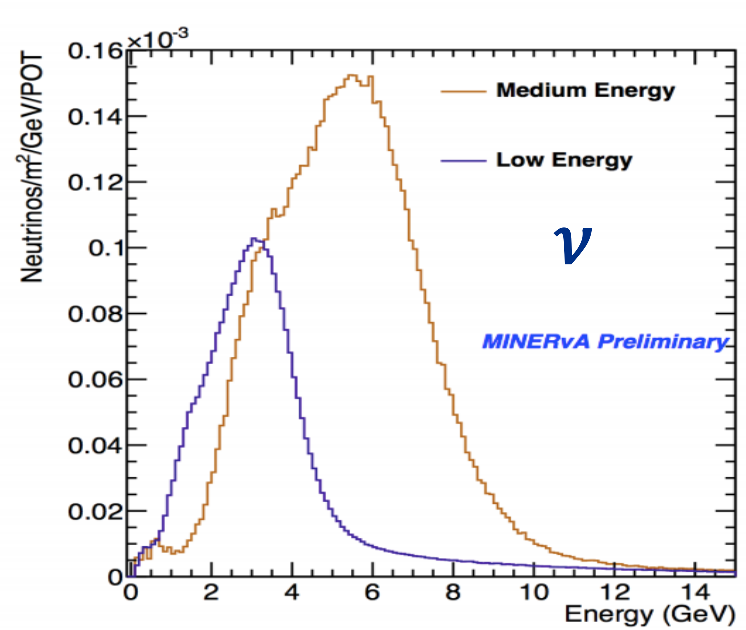
$$\pi^{\pm} \rightarrow \mu\nu_{\mu}$$

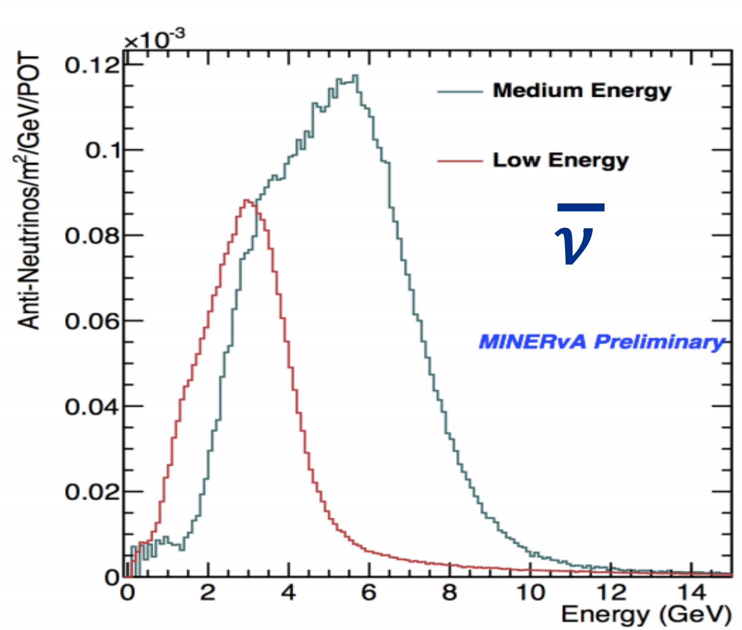
$$K^{\pm} \rightarrow \mu\nu_{\mu}$$

NuMI

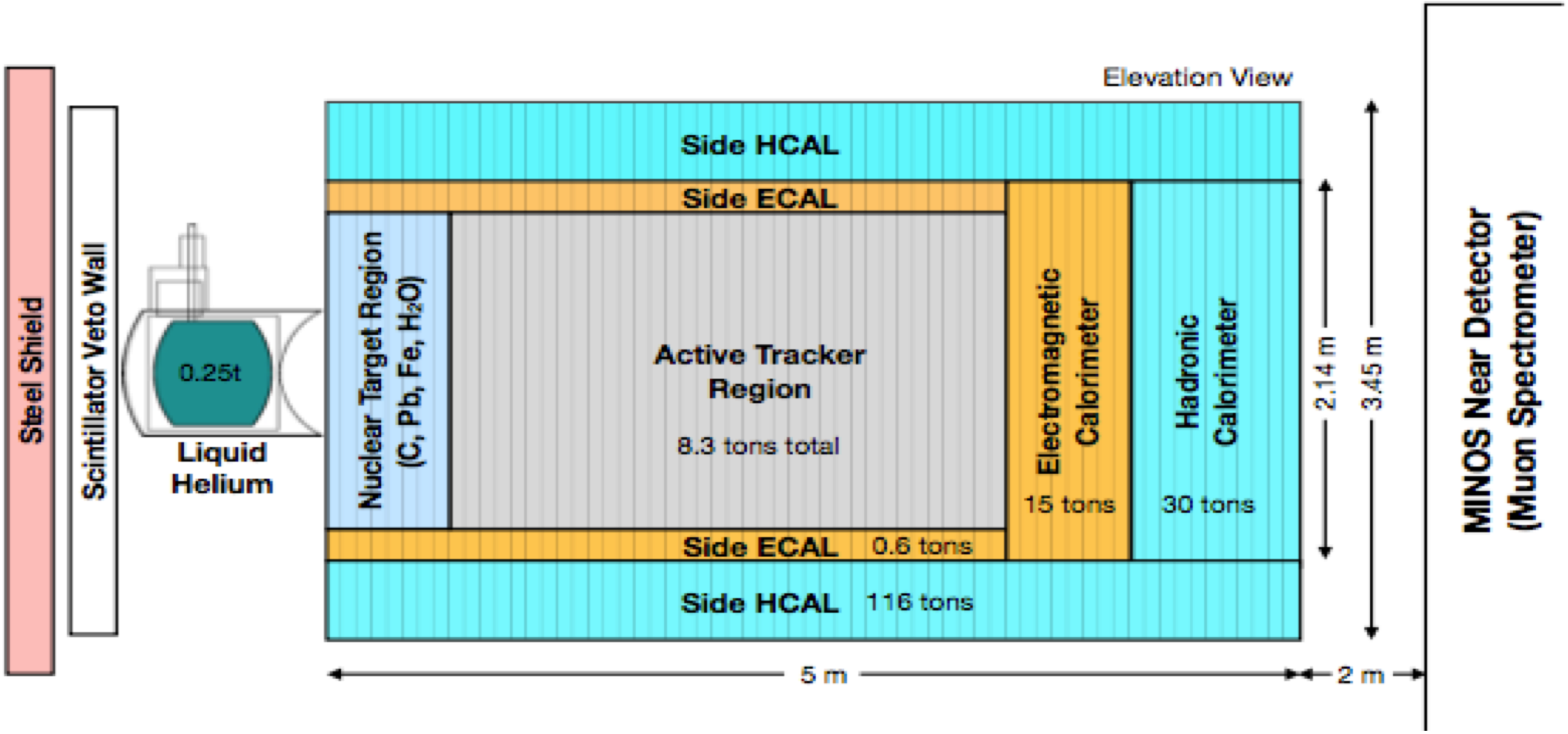
Mode	Period	POT (Neutrinos)	POT (AntiNeutrinos)
Low Energy (LE)	2009 - 2012	3.4e^{20}	2e^{20}
Medium Energy (ME)	2013 - present	12e^{20}	9.2e^{20} (still counting !)

ME mode is produced by moving the target position upstream and moving the horn to downstream.



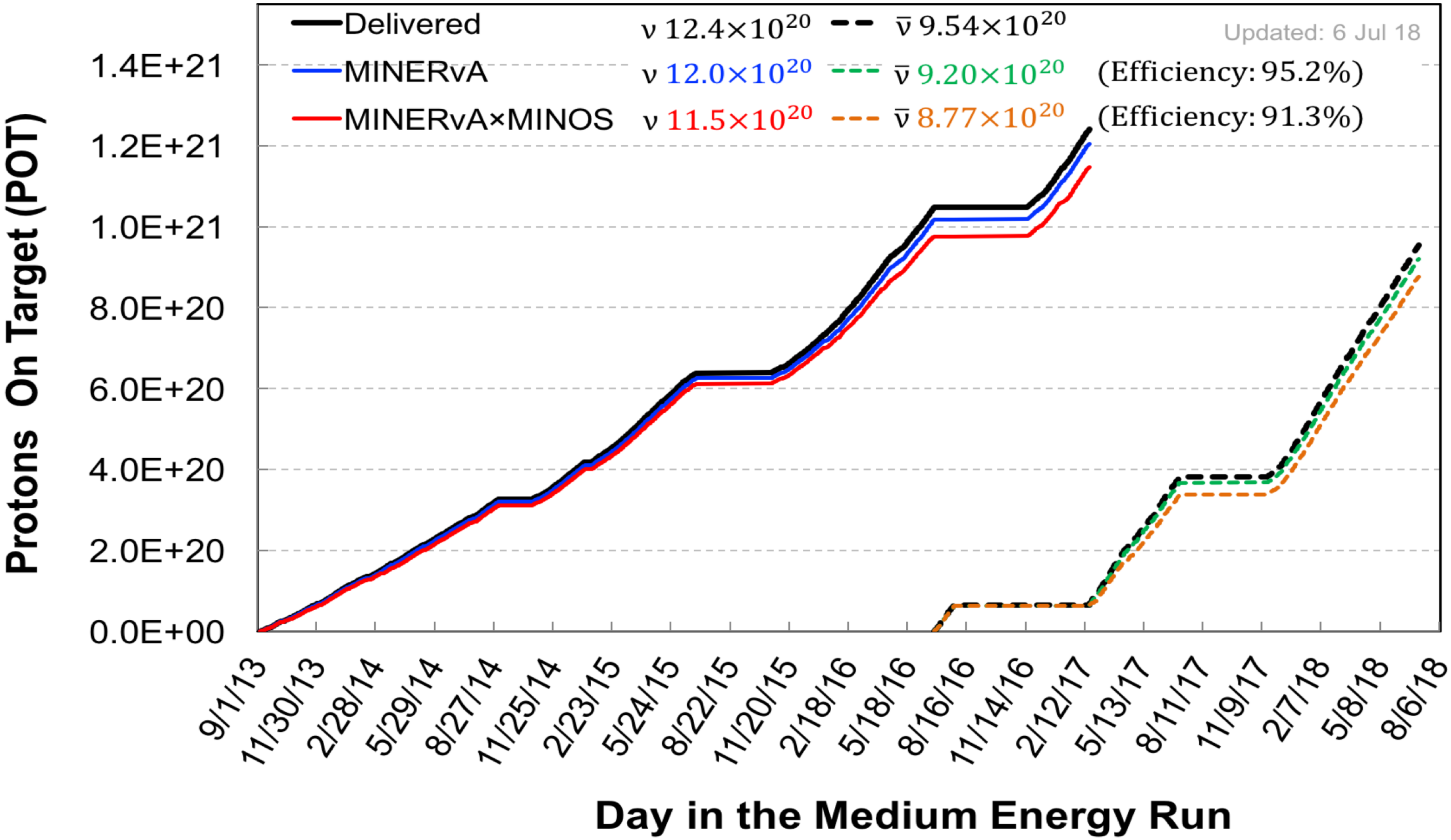


MINERvA (Main INjector ExpeRiment for ν- A)



- MINERvA: a dedicated on-axis neutrino-nucleus scattering experiment running at Fermilab in the NuMI (Neutrinos at the Main Injector) beamline.
- Consists of a core of scintillator strips surrounded by ECAL and HCAL.
- Several nuclear targets (C, Fe, Pb, water and He) in the same beam line to take simultaneous measurements.

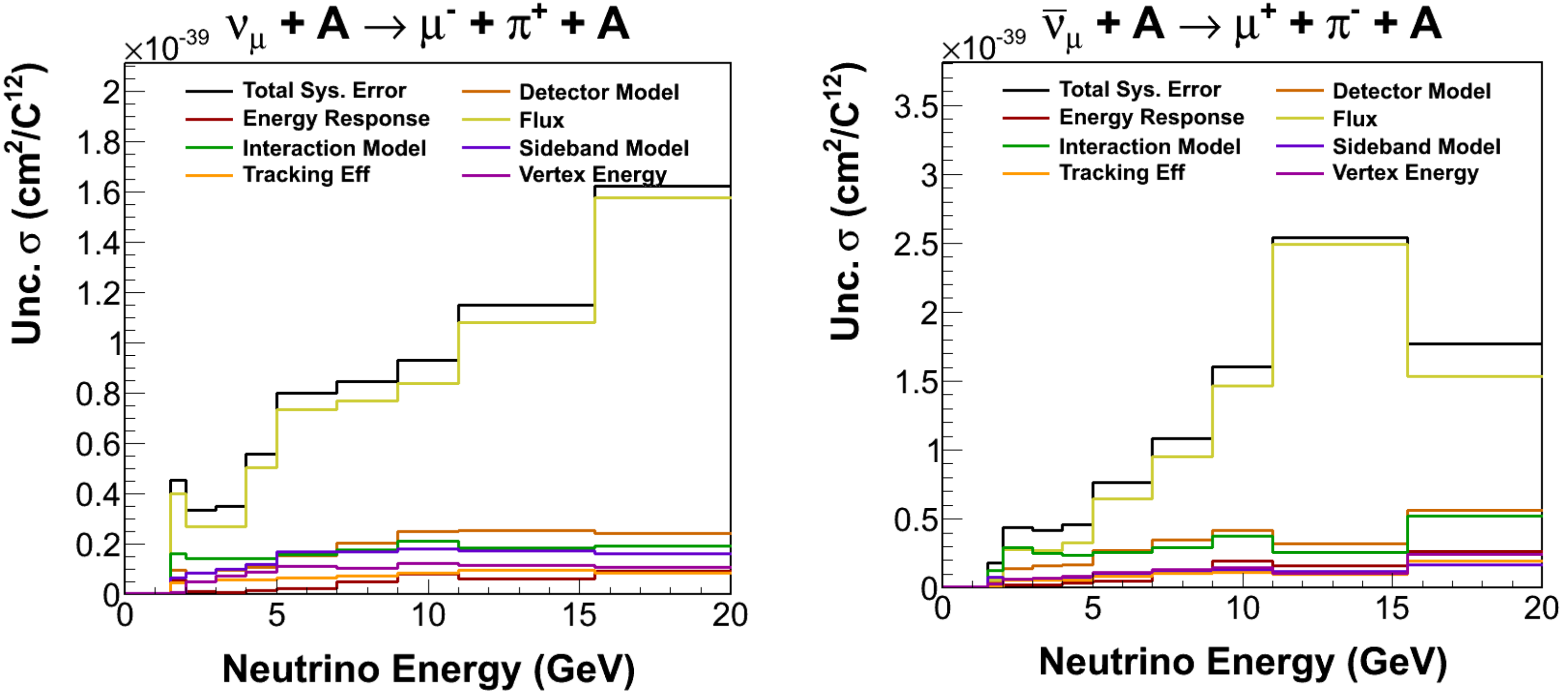
Low Energy Era ➡ Medium Energy Era



- “Protons on target” is a proxy for number of neutrinos
- Higher energy -> More events per POT

Why is the flux important for cross-section?

Example: MINERvA **Coherent charged pion production** using the low energy data set in Neutrino and Anti-neutrino mode configuration.



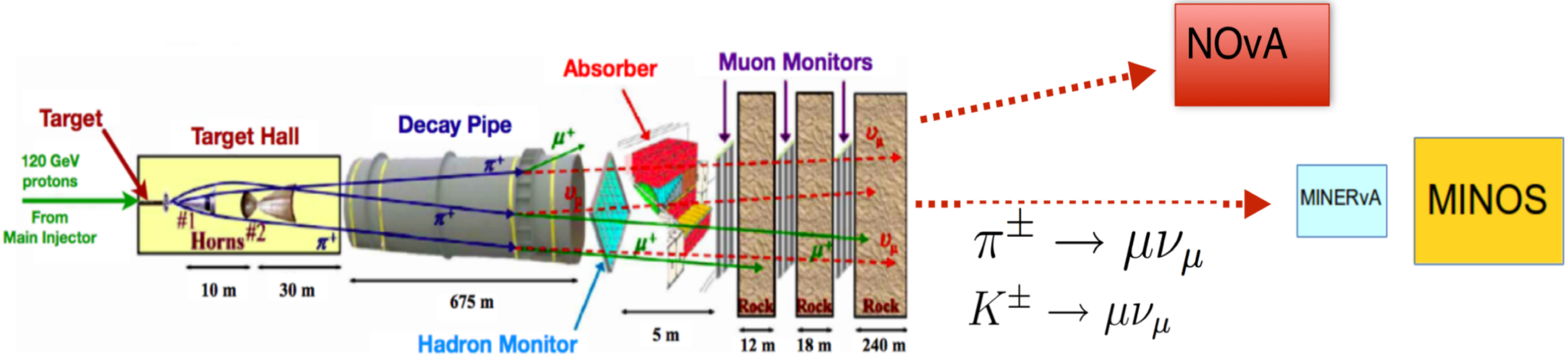
The uncertainties are dominated by the uncertainties from flux

Why is it so hard to determine the flux ?

Two Challenges:

Hadron production uncertainties: Incomplete knowledge of the physics of the hadronic interactions that makes the simulation rely on phenomenological models. Use external data from NA49, MIPP to tune the flux. 158 GeV data cross-section scaled to 120 GeV using FLUKA. Big discrepancies between hadronic models.

Beam Focusing Uncertainties: Details of beam geometry such as target longitudinal position, alignment, materials, etc. Even a single mm shift effect can have an effect on the flux.



$$\pi^\pm \rightarrow \mu\nu_\mu$$
$$K^\pm \rightarrow \mu\nu_\mu$$

MINERvA Strategy for Predicting the Flux

1. Calculate the a-priori flux

- g4numi (GEANT4-NuMI) simulates the beam
- Correcting the hadron production in the beam line to constrain to external hadron production data.

Accounting for focusing and hadron production uncertainty.

2. Use in-situ measurements

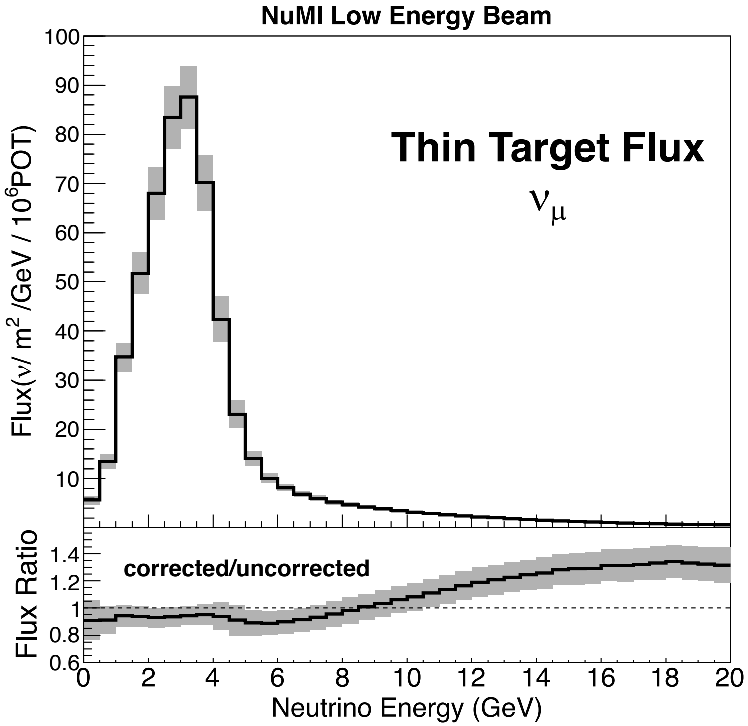
Checking our results with the low recoil event rates (low – nu method): flux shape measurement.

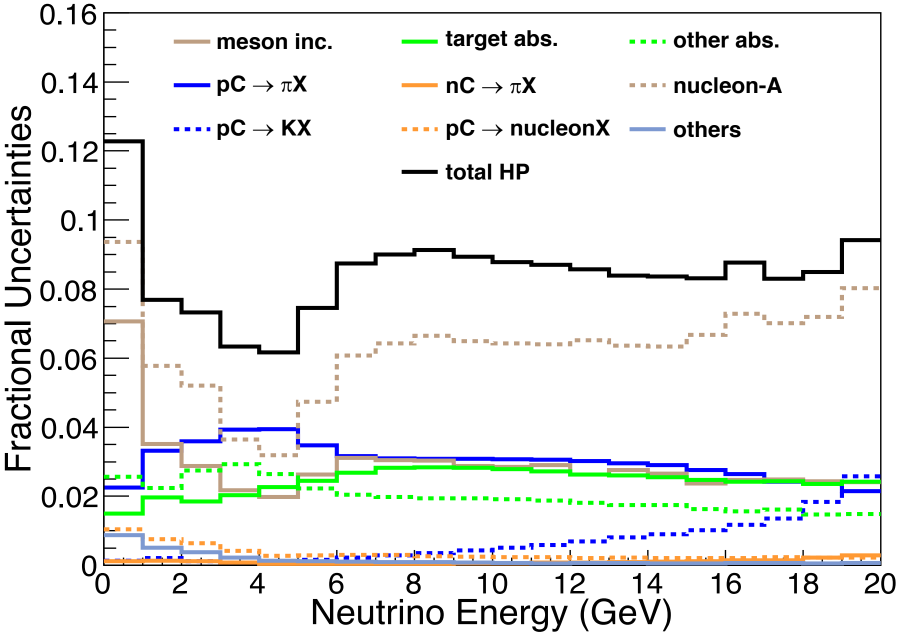
Applying an additional constraint from the neutrino-electron scattering events: flux normalization

A Priori Flux Results for Low Energy mode

Phys. Rev. D 94, 092005 (2016)

- After simulating using Geant4, correct with NA49 measurement which uses a thin target with an incident proton momentum of 158 GeV/c.
- The hadron production is the main source of uncertainties. Applied all relevant existing data to constrain the flux to reduce the uncertainties.



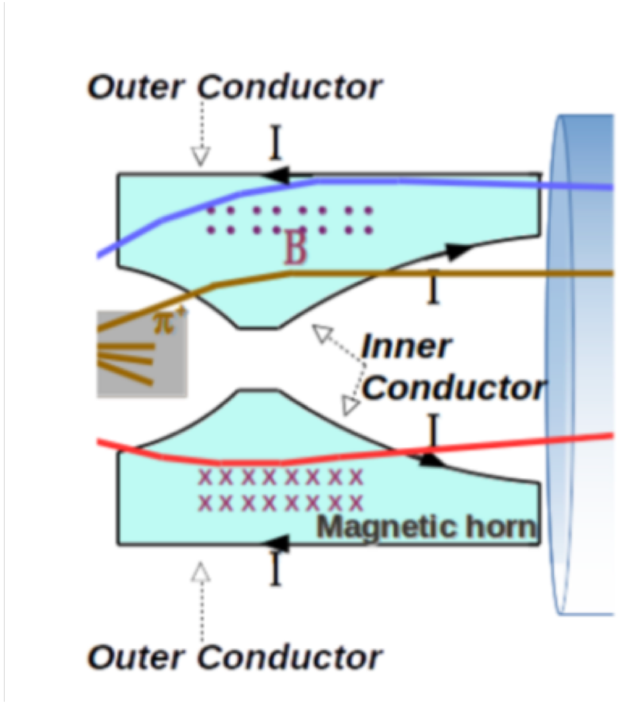


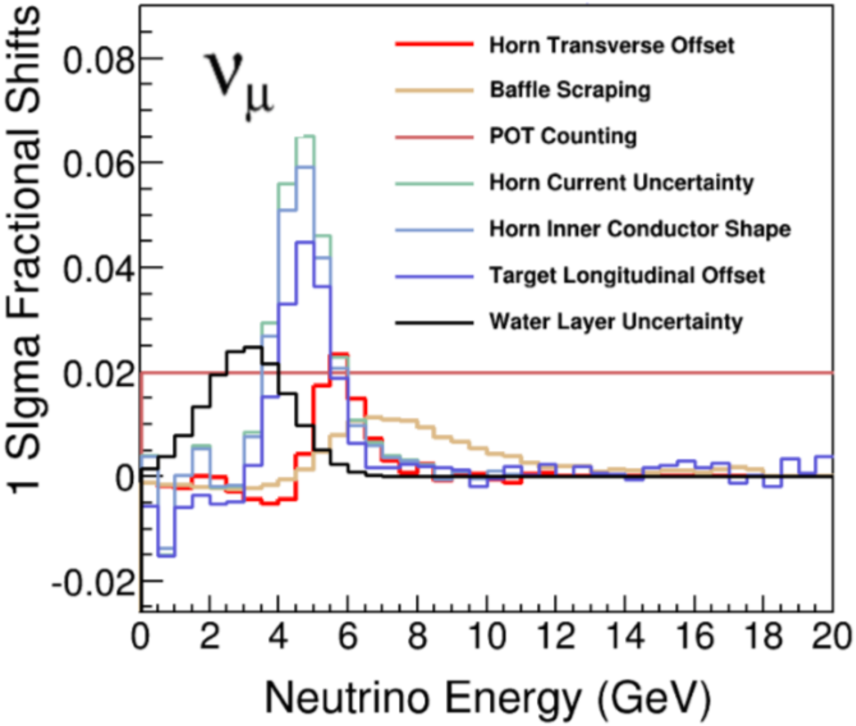
Uncertainties originating from different hadron interaction

Focusing Uncertainties: Low Energy Mode

The small uncertainties are due to the great effort from the ***NuMI Beam group***

Small in comparison with the hadron production uncertainties





Large number of geometric details can affect the neutrino energy distribution and these details must be precisely measured and incorporated in the neutrino beam simulation.

Low-ν Flux

Main idea is to measure the neutrino flux using a standard-candle process (low- ν events)

The CC Inclusive cross section for neutrinos can be expressed in terms of neutrino energy (E_ν) , energy transferred to the nucleus (recoil energy or ν) and Bjorken scaling variable (x) as:

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi}\left(\int_0^1 F_2 dx - \frac{\nu}{E_\nu}\int_0^1 [F_2 \mp xF_3]dx + \frac{\nu}{2E_\nu^2}\int_0^1\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right]dx + \frac{\nu^2}{2E_\nu^2}\int_0^1\left[\frac{F_2}{1+R_L} \mp xF_3\right]dx\right)$$

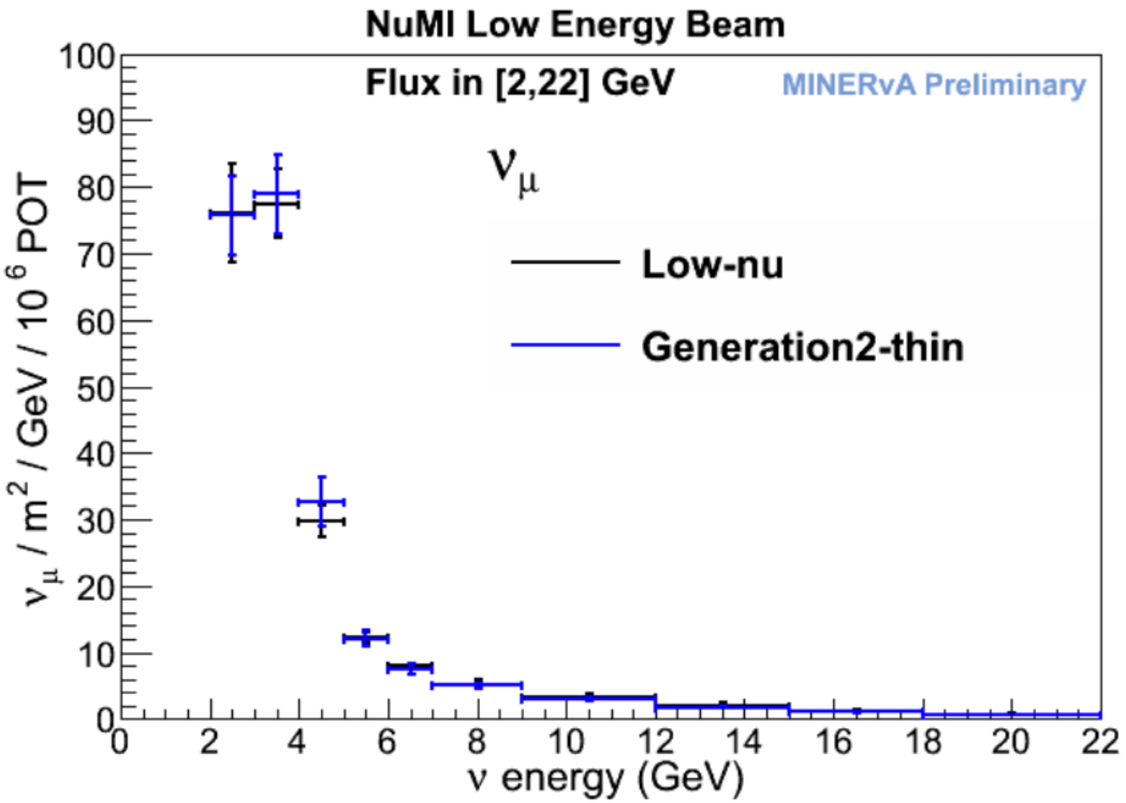
At limit $\nu_o << E_\nu$ (low- ν sample) → $\boldsymbol{\sigma}$ ($\nu < \nu_0$,E) const in neutrino energy

Measurement of low-ν interaction rate as a function of neutrino energy is equivalent to a measurement of the shape of the neutrino flux

$$N(\nu < \nu_0, E) = \boldsymbol{\phi}(E) \times \boldsymbol{\sigma}(\nu < \nu_0, E) \propto \boldsymbol{\phi}(E)$$

Phys. Rev. D 94, 112007 (2016)
Phys. Rev. D 95, 072009 (2017)

Generation2-thin and Low-nu Flux Comparison



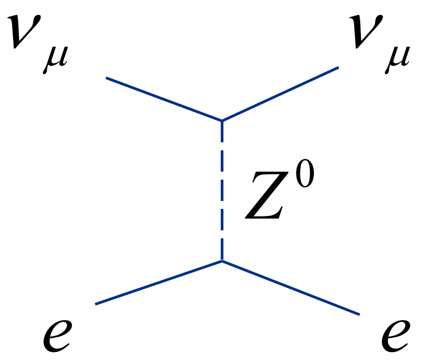
The thin-target and low-ν flux agrees well.

MINERvA published the flux prediction for Low Energy NuMI beam based on thin target correction.

Neutrino-Electron Scattering:

Besides cross section measurements MINERvA is pioneering the use of a standard candle for flux estimation: neutrino scattering on electrons.

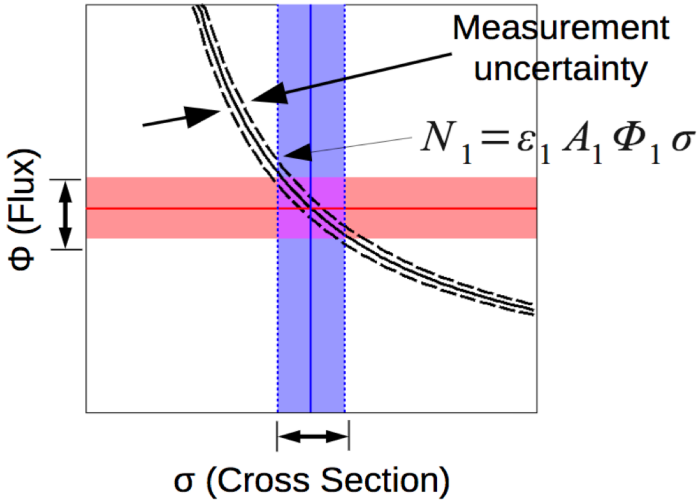
- Let's use well-known reaction to measure the flux
- Standard electroweak theory predicts it precisely
  - Point-like scattering
- Very small cross section (2000 times smaller than ν-nucleon scattering)



MINERvA

$$\boldsymbol{\sigma} = \frac{N}{\varepsilon \, A \, \Phi}$$

Flux uncertainty goes into the cross-section uncertainty



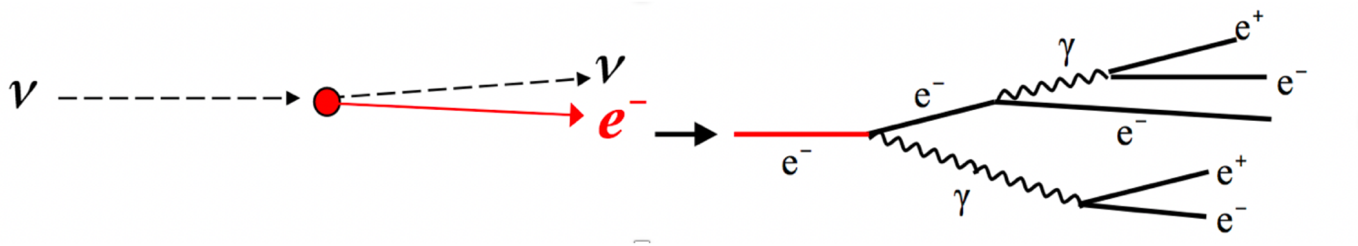
$\nu_\mu + e \rightarrow \nu_\mu + e$

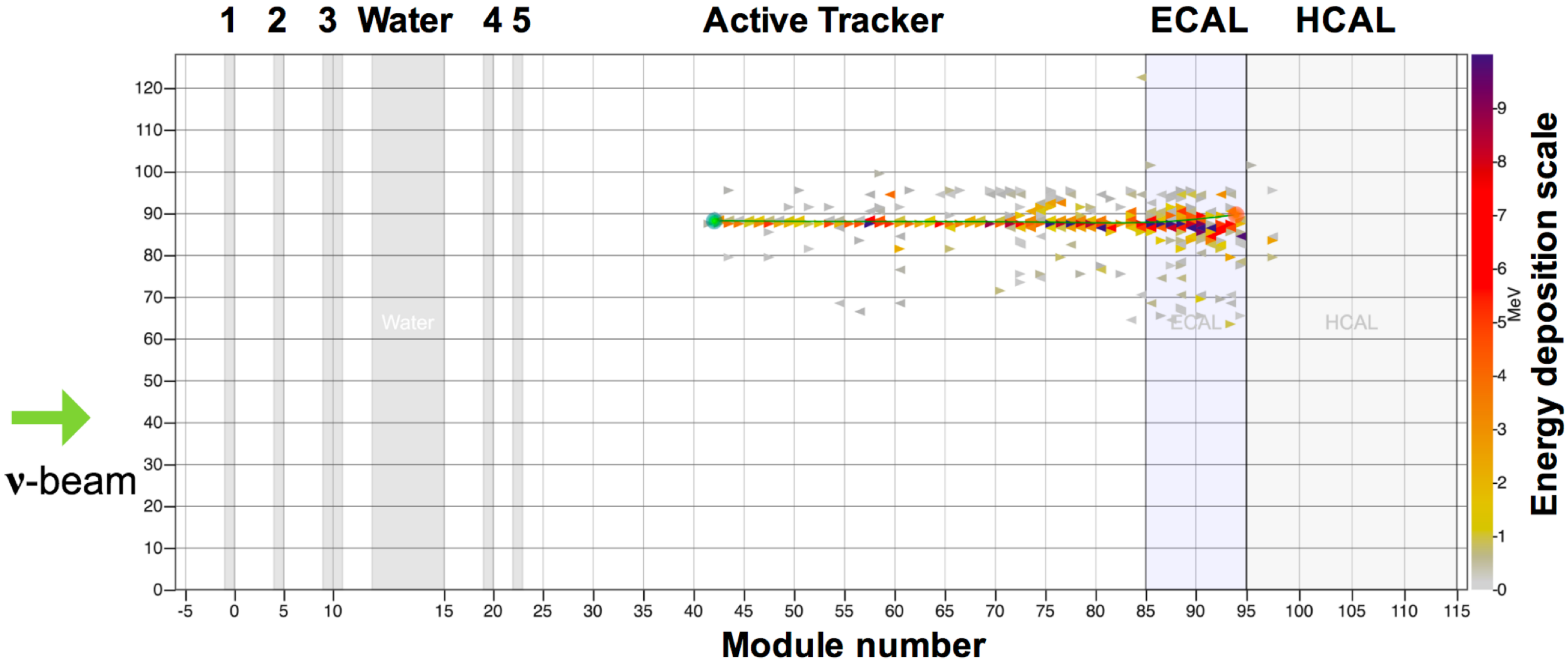
$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$

- Useful to constrain Flux:
  - Total events: constraint on integrated flux

Experimental Signature:

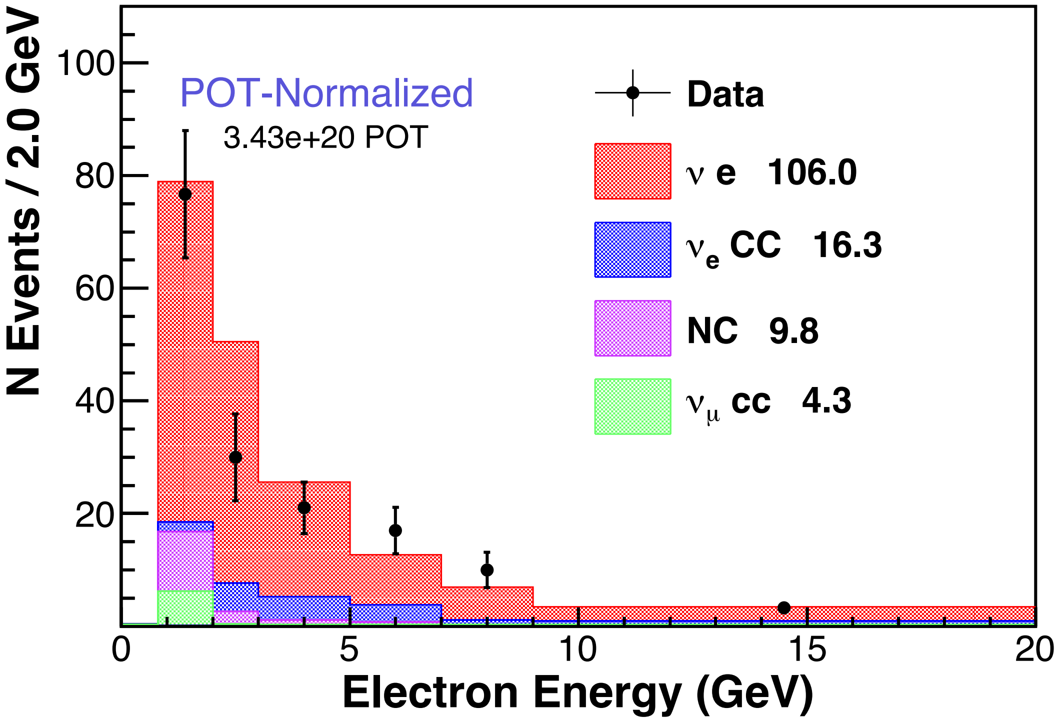
- Very forward single electron final state.
- Electromagnetic shower process is stochastic





ν-e Scattering at Low Energy

Phys. Rev. D 93, 112007 (2016)



Dominant sources of Uncertainties:

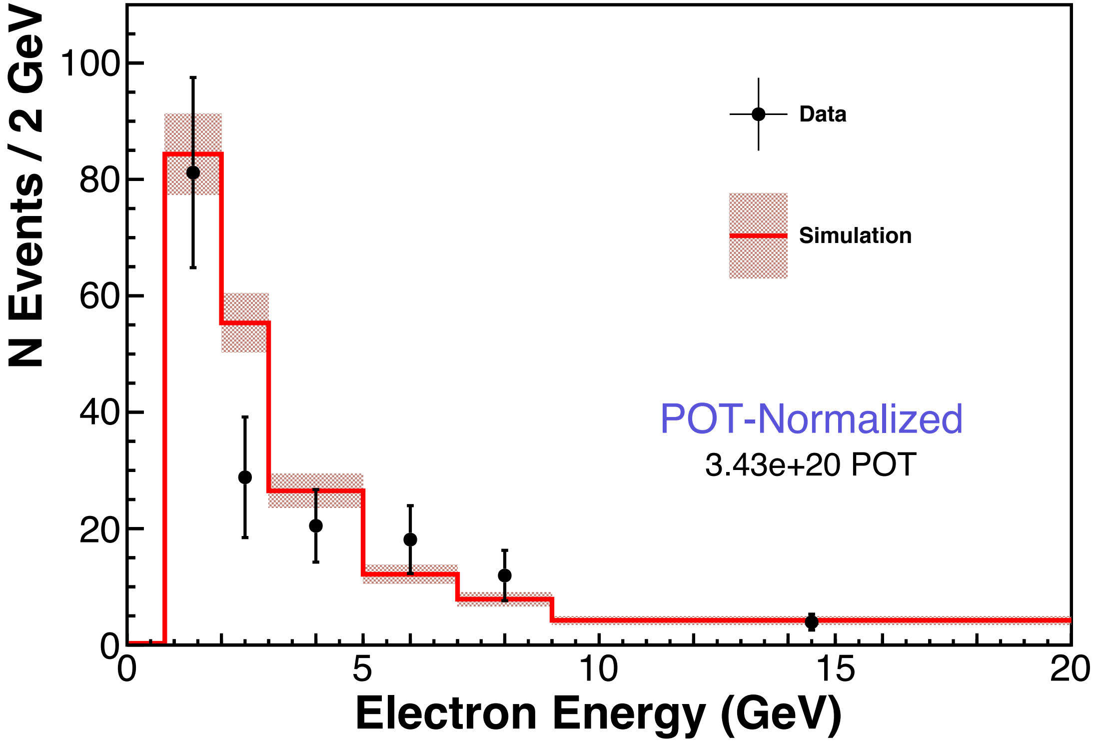
- The largest uncertainty in the background prediction comes from the background cross section models, although it is significantly reduced by the sideband tuning
- For $E_e < 7$ GeV: the ν_e CCQE cross-section shape as a function of Q^2 is not known.
- Uncertainty in the electron energy scale (4%), which is determined by comparing the agreement between data and simulation for the Michel electron candidates.

ν-e Scattering at Low Energy

After Bkg subtraction and Eff correction

ν-e scattering events after background subtraction and efficiency correction:
135 ± 12.2 (stat) ± 5.1 (sys)

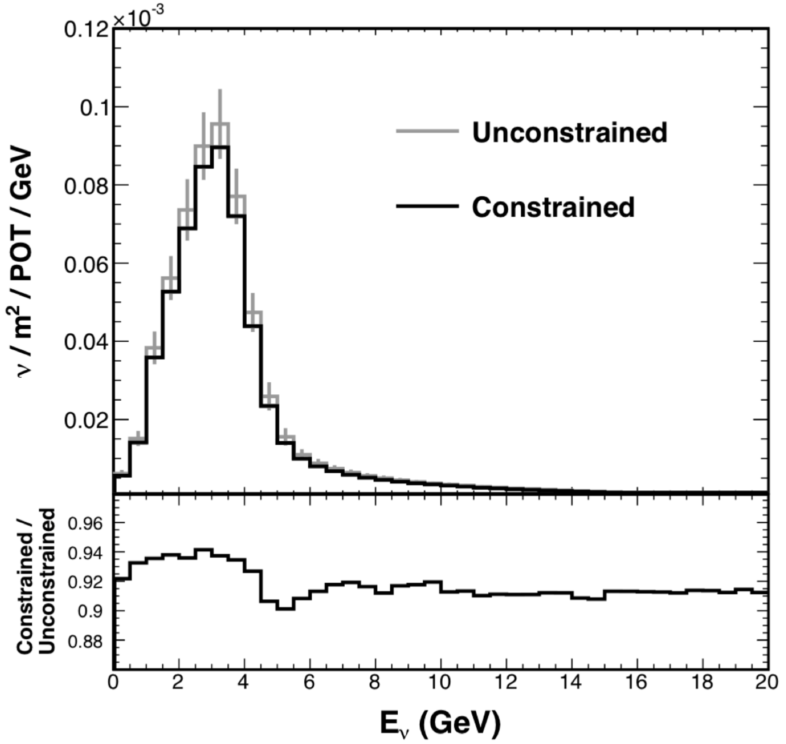
Because the cross section is known, a measurement of the rate of neutrino-electron scattering is used to constrain the a-priori flux.



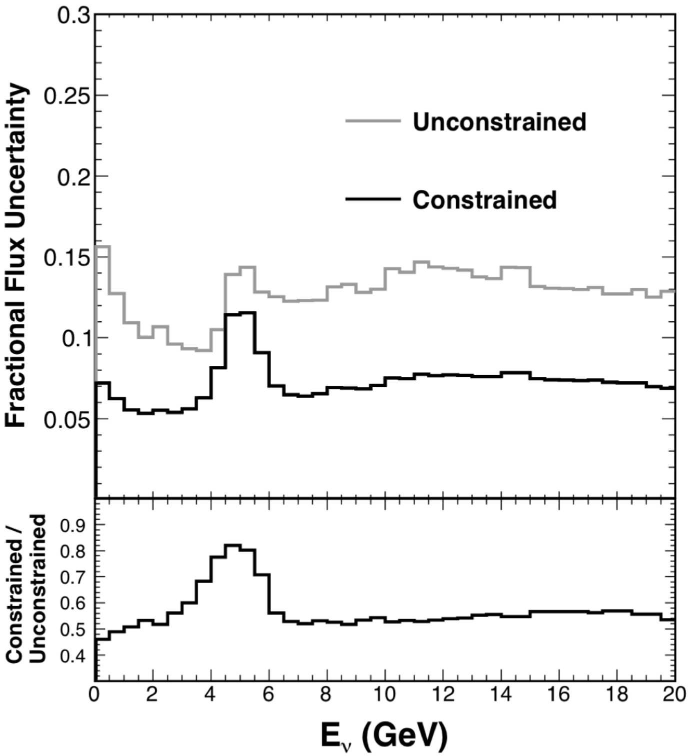
The effect of the constraint is to change the flux such that the predicted MC spectrum is closer to the data measurement.

ν-e Scattering Constraint on Flux at Low Energy:

Flux change after ν-e constraint



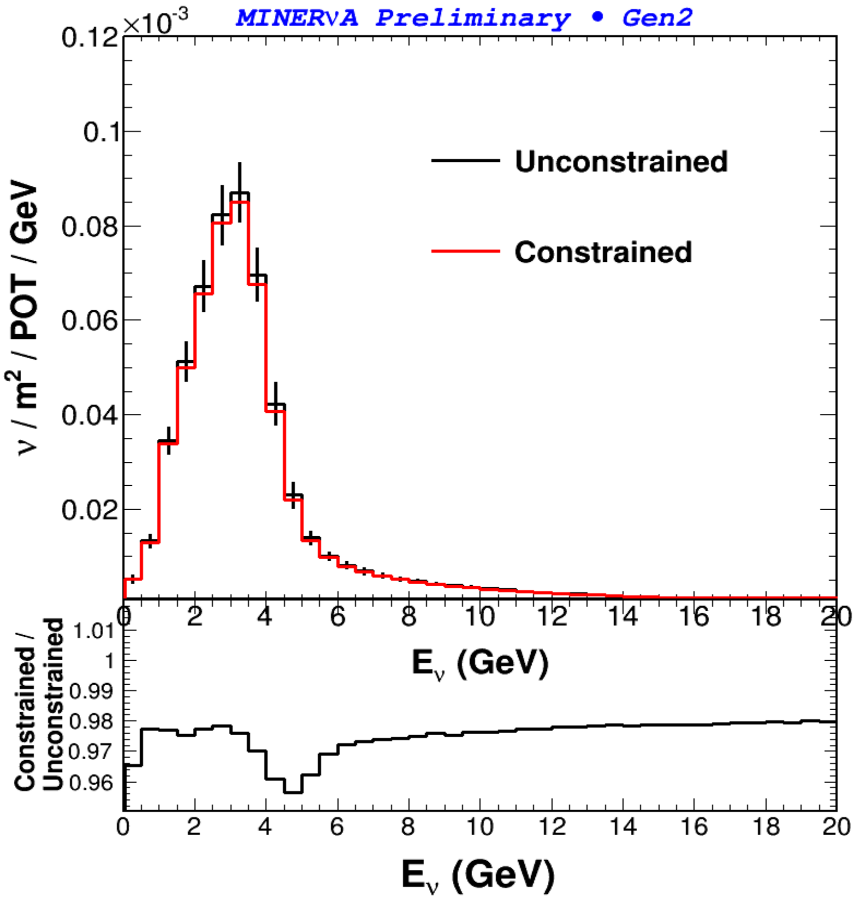
Fractional Uncertainty change after ν-e constraint



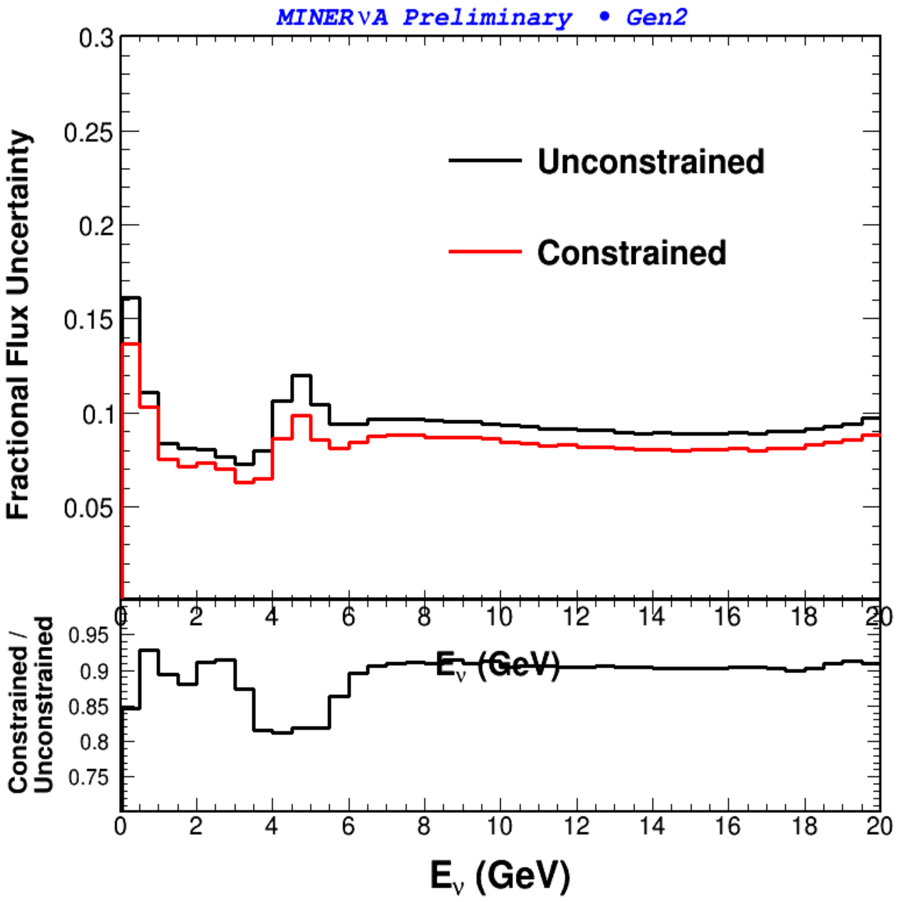
These plots are from original publication (Phys. Rev. D 93, 112007 (2016)) was before the state of the art hadron production measurement constraint (called "PPFX", now used by NOvA and MINERvA). The updated plots are in the next slide.

ν-e Scattering Constraint on Flux at Low Energy:

Flux change after ν-e constraint

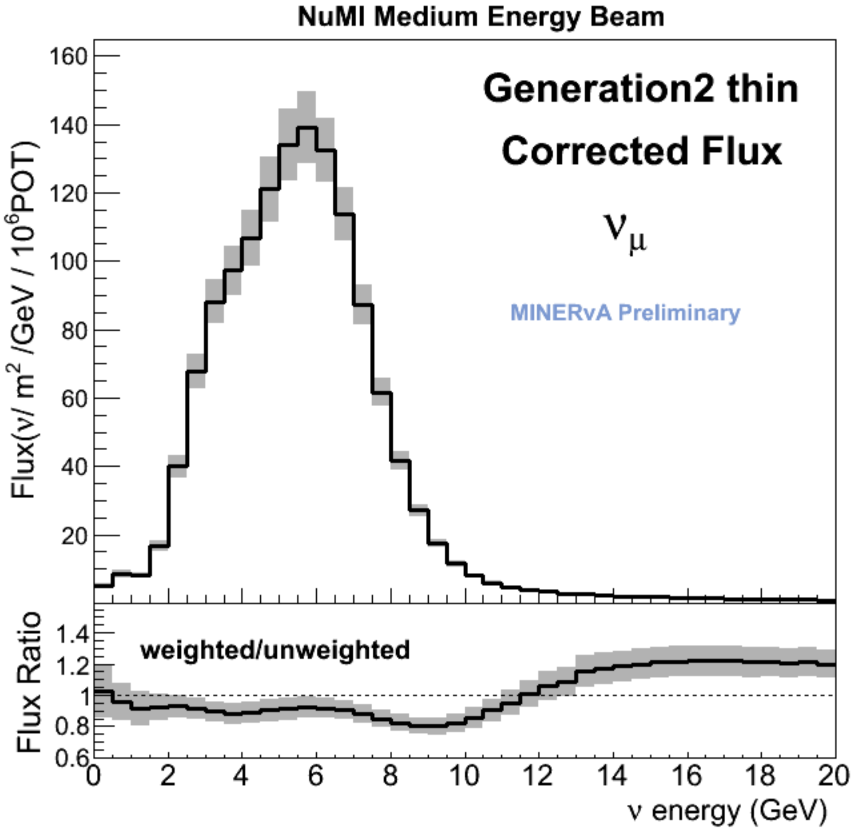


Fractional Uncertainty change after ν-e constraint



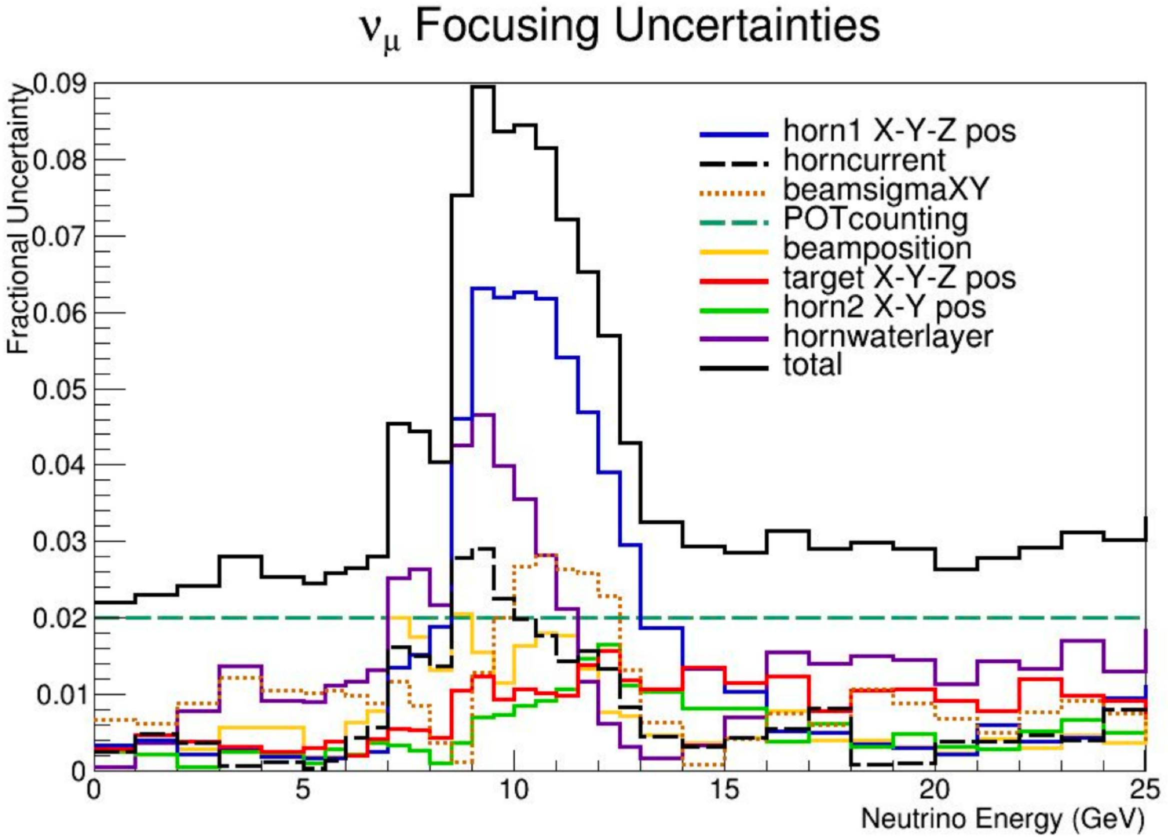
The flux uncertainty at the peak changed from 8% to 7%.

Medium Energy Flux for MINERvA:



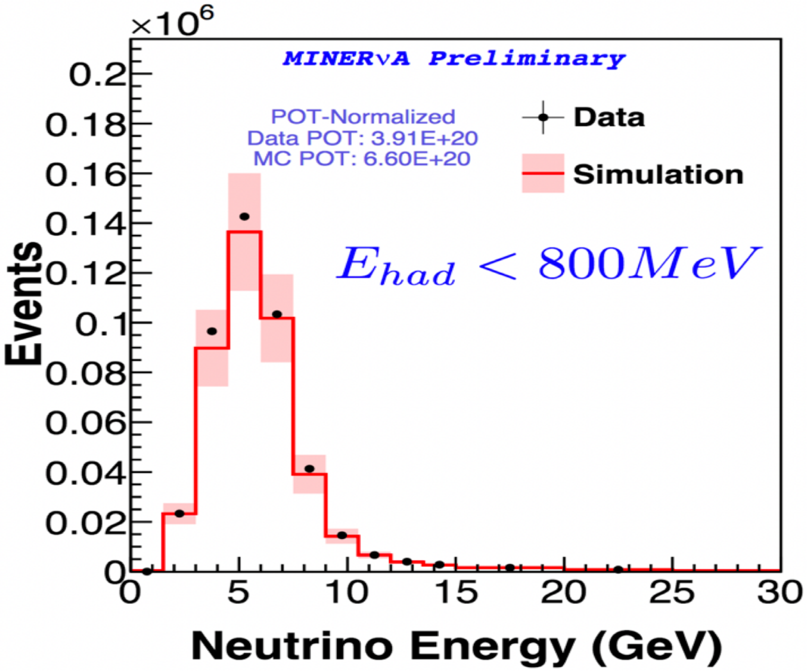
- Hadron production and detailed beamline geometry is simulated using GEANT4
- Corrects GEANT4 predicted hadron production using world hadron production data
- Thin target (NA49) dataset used for constraining hadron production in target

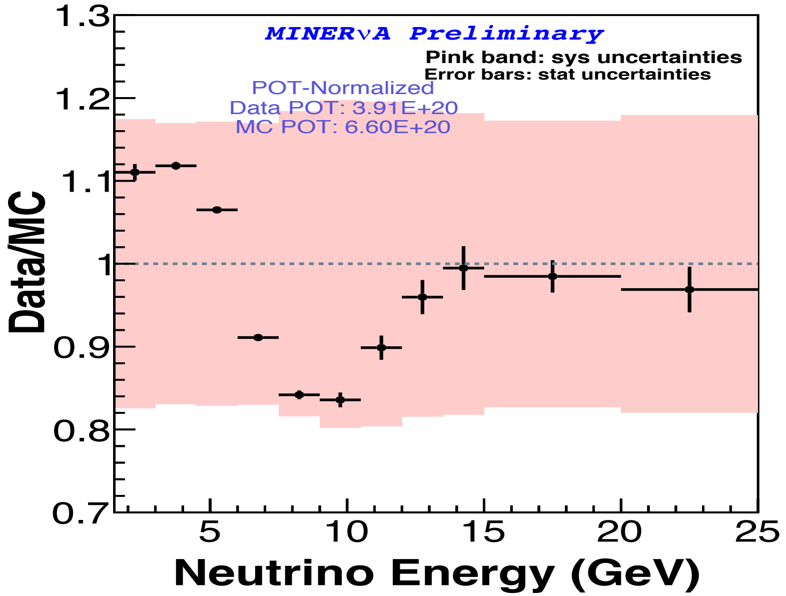
Medium Energy Focusing Uncertainties:



After the development of PPFX (Package to Predict the Flux), our flux predictions for the ME NuMI beam was supposed to work.

Comparison of Data to MC





- The data/mc ratio shows the squiggle shaped discrepancy in the focusing peak region of the flux.
- These are events with low hadronic recoil energy so we believe the discrepancy is coming from our flux-predictions and not cross-sections.

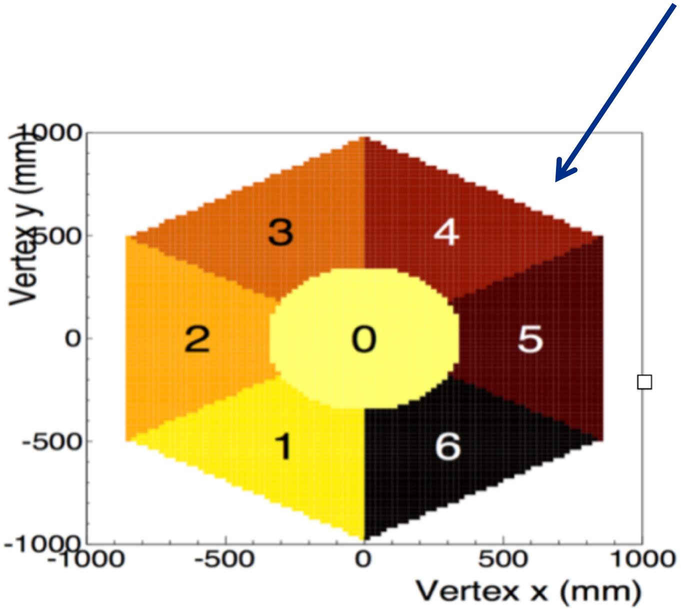
Look at our focusing systems on which our flux prediction depends on, we believe that one or combination of more than one focusing parameters caused the discrepancy (wiggle) in our flux prediction.

Flux Fit with focusing Parameters

Approach:

Problem in Flux Prediction: Possibly mismodeling of NuMI Focusing system

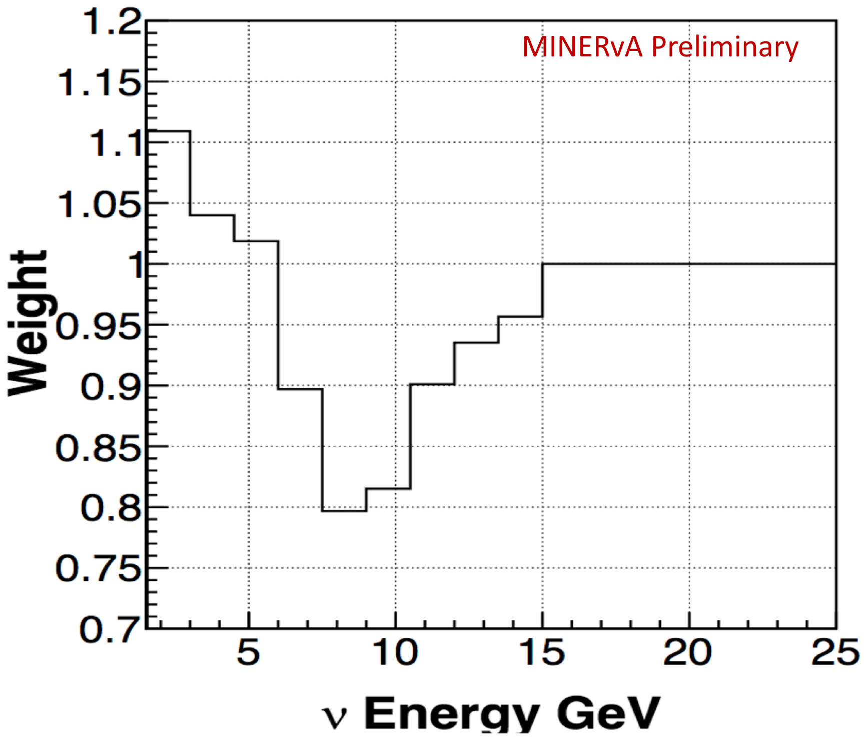
- Fit low nu MC to data by varying the focusing parameters and (look at the shifted parameters to understand the discrepancy)
- Shifting of a focusing parameter, by some amount do not produce uniform effect across the lateral face of the detector. Fit in different ***daisy bins*** of MINERvA detector and merge them later

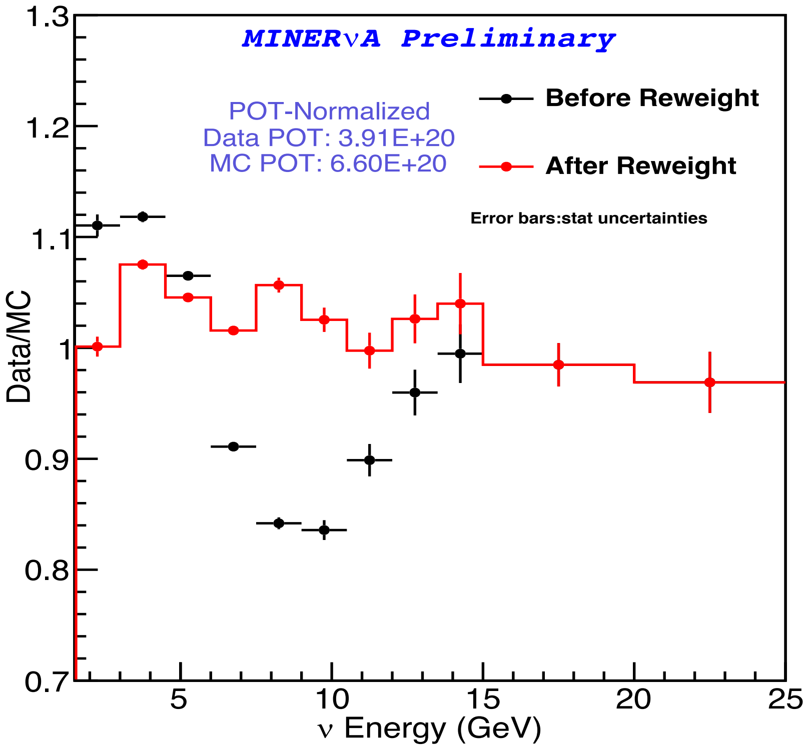


Parameter	Nominal Value	New Value	Sigma Value
Beam Position (X)	0 mm	-0.2±0.12 mm	1 mm
Beam Position (Y)	0 mm	-0.53±0.14 mm	1 mm
Beam Spot Size	1.5 mm	1.22±0.07 mm	0.3 mm
Horn Water Layer	1 mm	0.895±0.16 mm	0.5 mm
Horncurrent	200 kA	197.41±0.76 kA	1 kA
Horn1 Position (X)	0 mm	0±0.17 mm	1 mm
Horn1 Position (Y)	0 mm	-0.39±0.17 mm	1 mm
Target Position (X)	0 mm	-0.32±0.17 mm	1 mm
Target Position (Y)	0 mm	1.65±0.5 mm	1 mm
Target Position (Z)	-1433 mm	-1419.44±1.83 mm	3 mm

Flux Fit

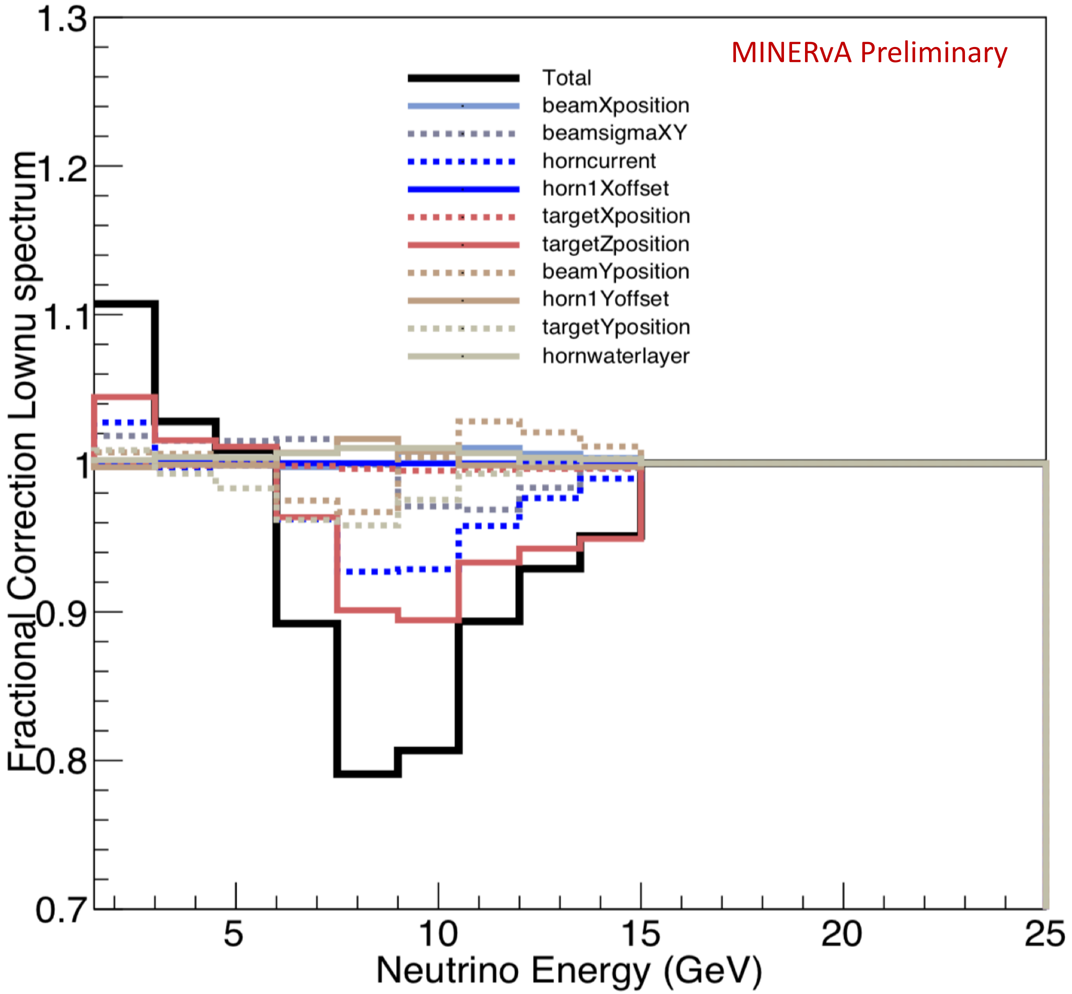
- Returns a weight function which is the function of shifted focusing parameters returned by the fit.
- It seems to fix the wiggle problem. But this causes really large shift in target longitudinal position and horn current.





Flux Fit with Focusing Parameters

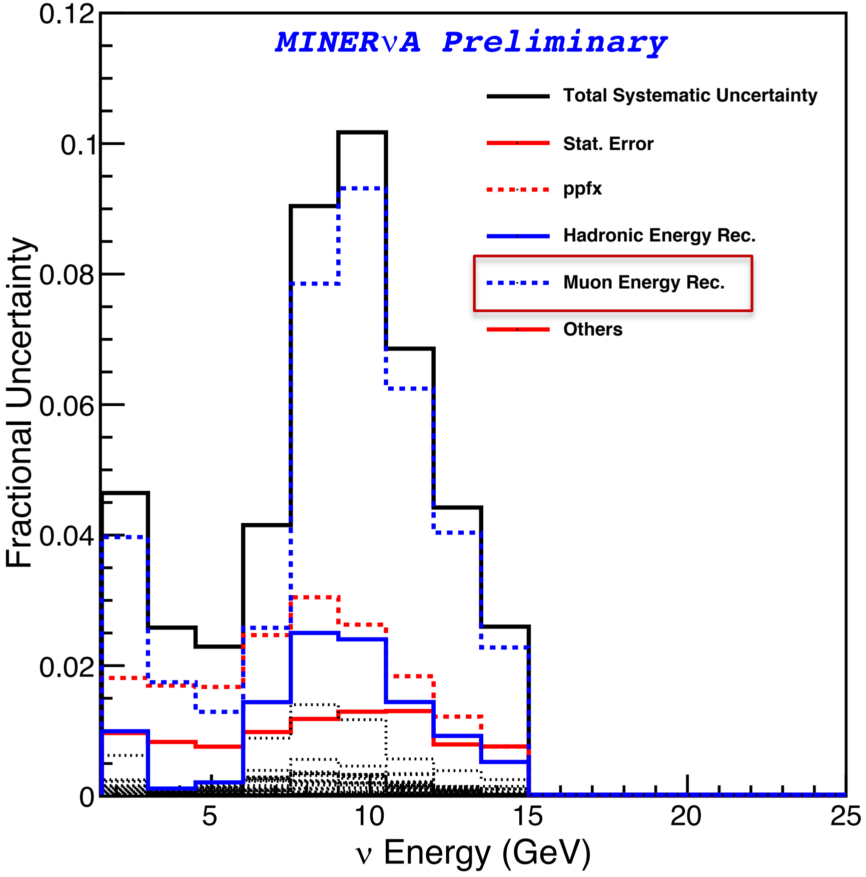
Decomposed the correction returned by the fit into various components and observe that shift in *TargetZ* and *Horn Current* are major contributors of overall correction



This is not the end!

Uncertainties on Flux Fit

- Uncertainty on Flux fit as we vary MINERvA Systematics comes mainly from Muon Energy Reconstruction Systematics.
- At the falling edge of focusing peak, the change in flux is around 9%. This means 1 sigma change in muon energy means 9% change in the flux.
- Data/MC discrepancy at the peak value. Motivated us towards studying a what 2 sigma shift in Muon Energy Reconstruction would do.
- The study showed that shifting the Muon Energy Scale by -2 Sigma would almost follow the shape of the wiggle.
- Add the muon energy scale as a fitting parameter that can float and one can see the correlations among the parameters



Introducing the Muon Energy Scale as fit parameters

For the purpose of fitting:

MINOS Range

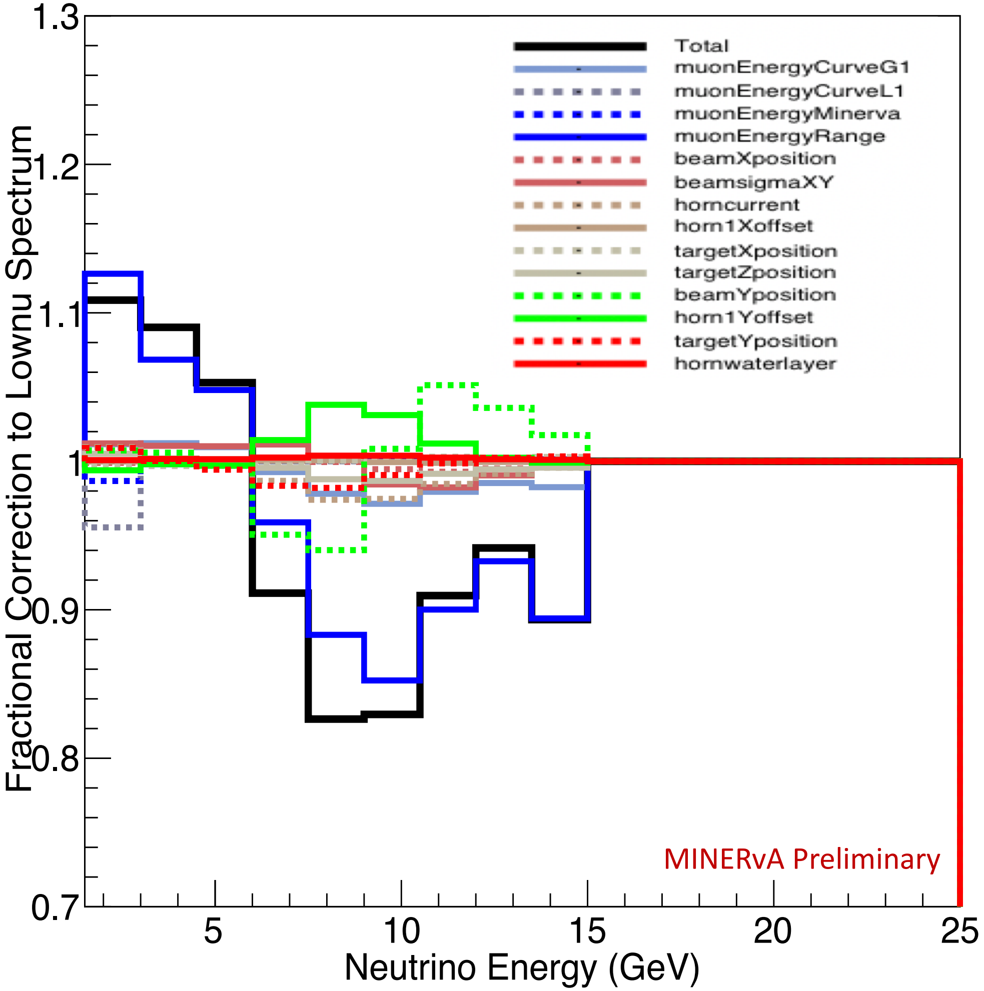
- **1 parameter (MuonEnergyRange)**

MINOS Curvature

- **MuonEnergyCurveG1**
- **MuonEnergyCurveL1**

MINERvA Systematics

- **1 Parameter(MuonEnergyMinerva)**



The effect of the parameter changes on the low nu prediction is shown at left.

Muon Energy Range is the biggest contributor !

This analysis uses data from the MINOS detector, but it is not endorsed by the MINOS+ collaboration.

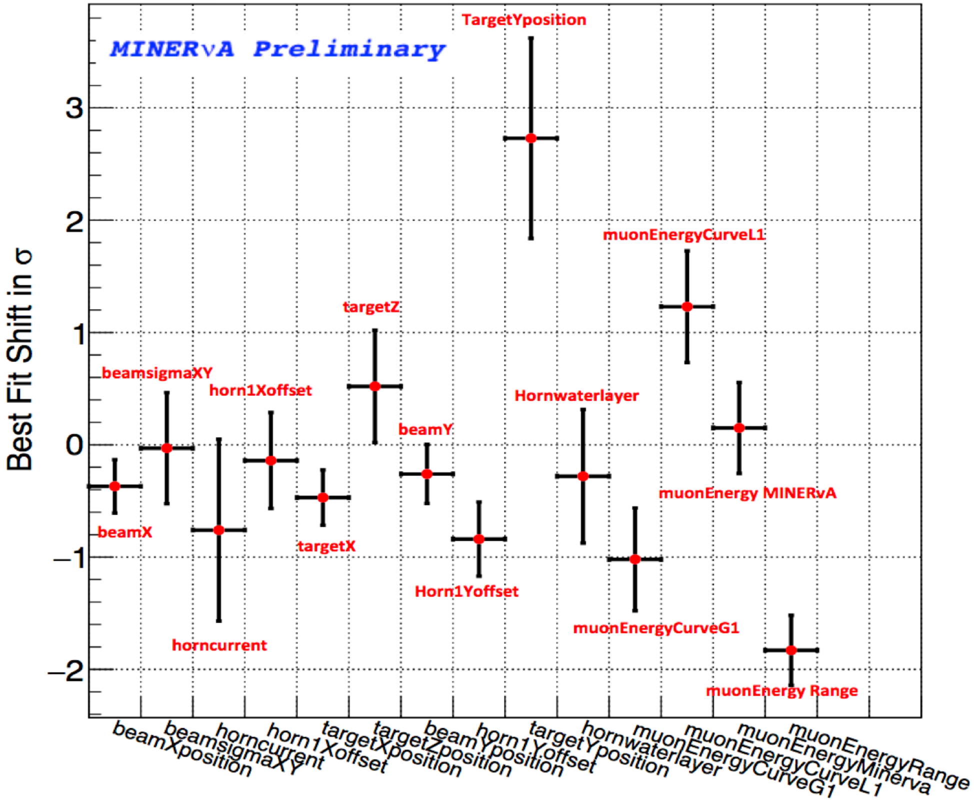
Best Fit Values:

Re-do the fit by putting Muon energy scale as fit parameters along with focusing parameters.

- When we add four muon energy scale parameters to the fit, all of the focusing parameter best fit values are within their standard uncertainties, except for target y position.

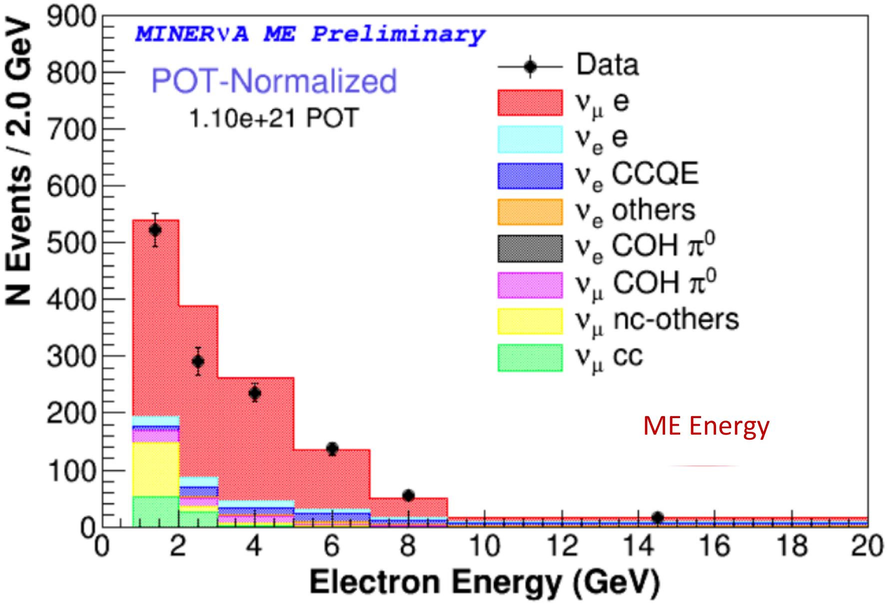
- We believe the pull of the target y position is trying to fix a small up/down asymmetry in the daisy bins, and *we are investigating further.* The effect of the target y shift on the flux averaged over MINERvA is very small

- The parameter with the biggest effect on data/MC agreement is the muonEnergy Range parameter, which is pulled by 1.8 sigma



This analysis uses data from the MINOS detector, but it is not endorsed by the MINOS+ collaboration.

ν-e Scattering at Medium Energy

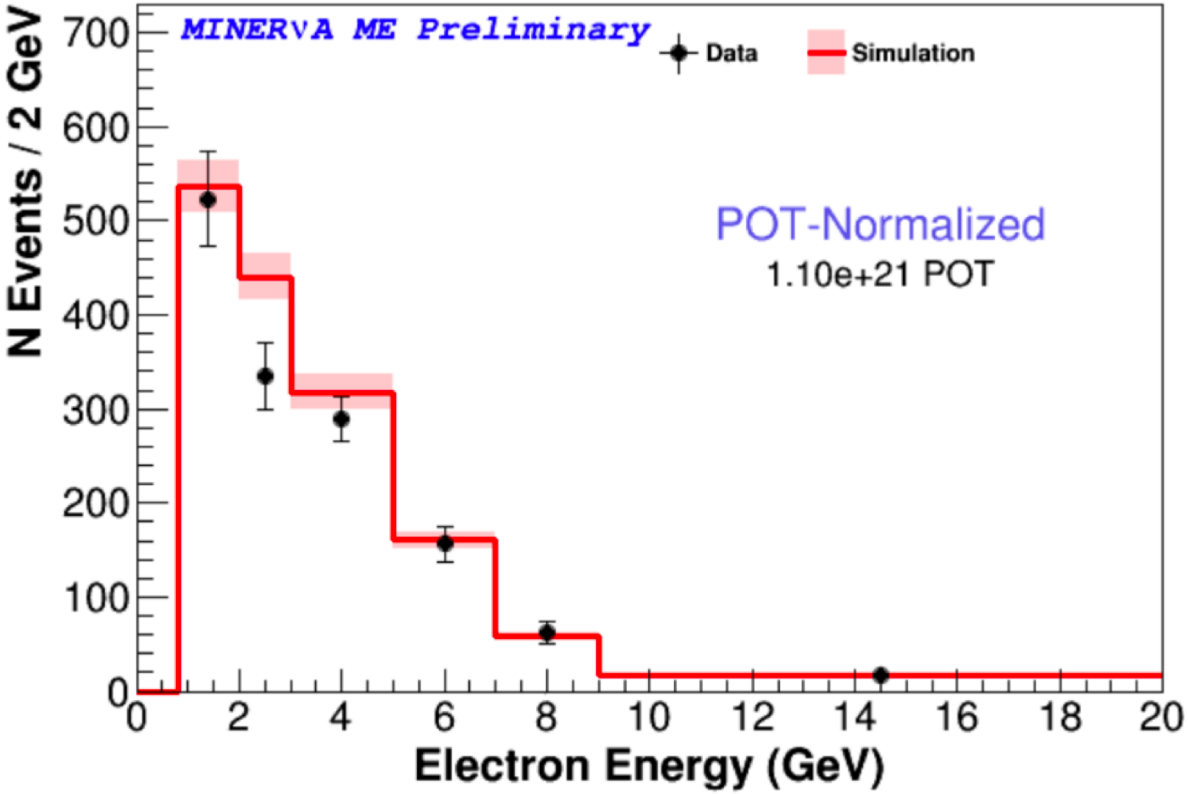


Work in Progress

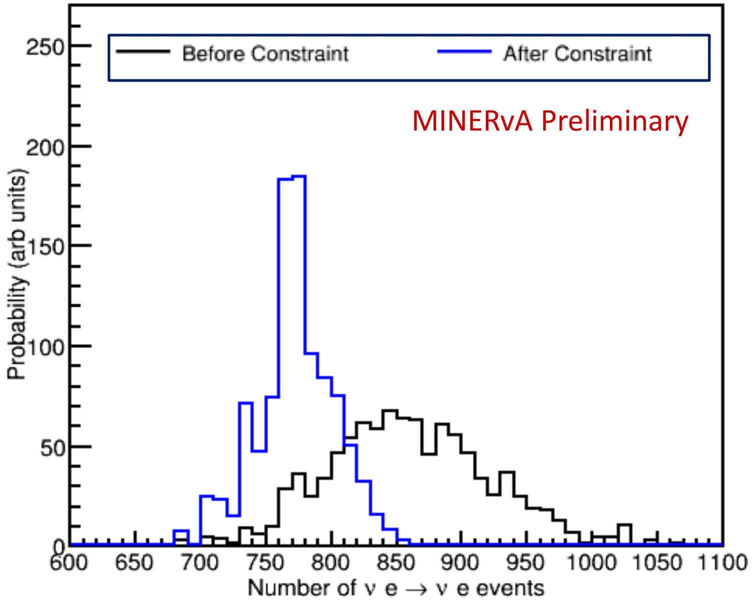
- Large Statistics
  - POT_Low Energy : 3.4×10^{20}
  - POT_Medium Energy : 12×10^{20}
- Improved overlay of data and simulation in existing Medium energy Minerva framework.
- In the process of finalizing systematics
- Flux constraint work on going

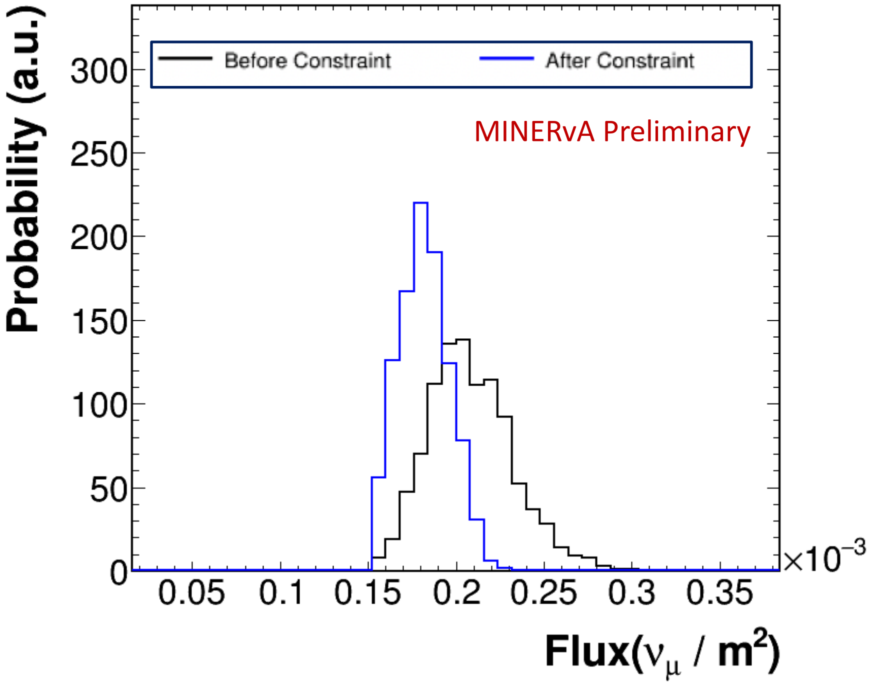
ν-e Scattering at Medium Energy

After Background Subtraction and eff correction



ν-e scattering constraint at Medium energy:

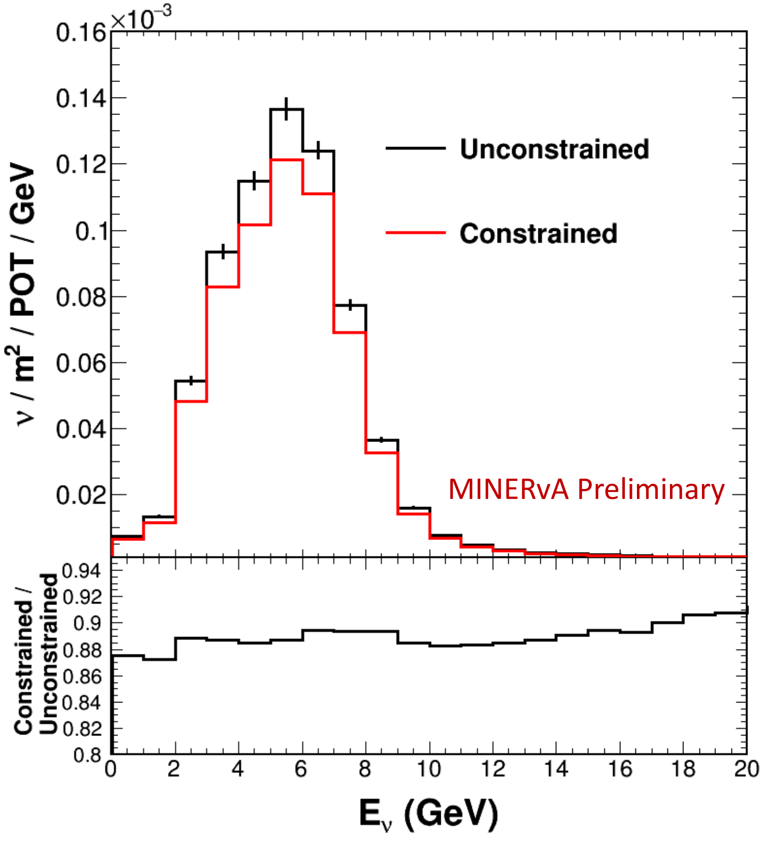




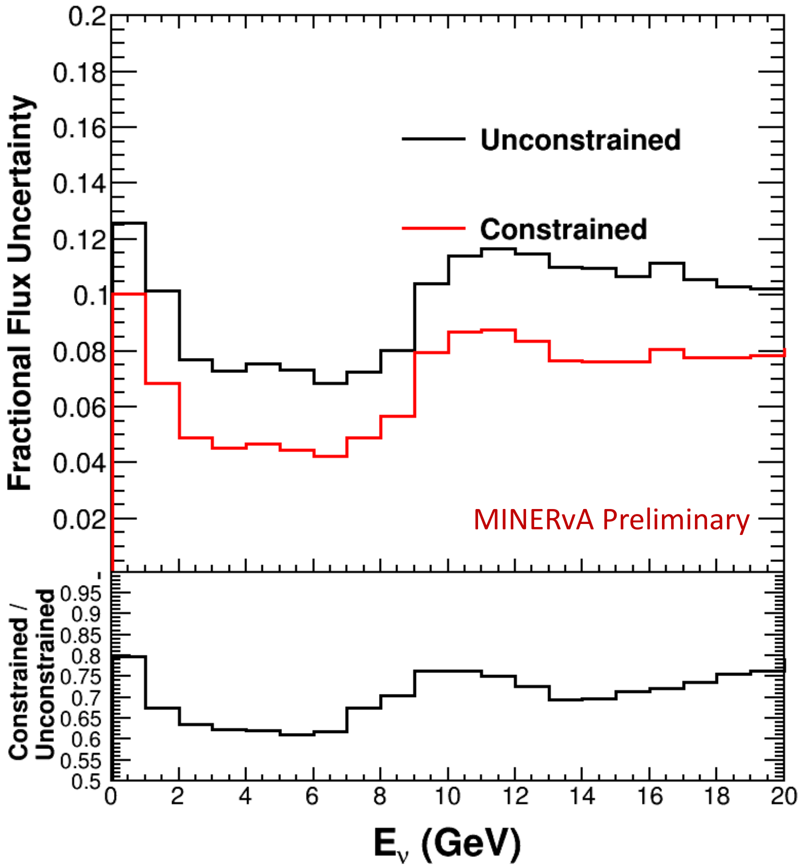
Predicted number of neutrino-electron scattering events changes after applying the flux constraint.

Muon-neutrino flux integrated between 2 – 20 GeV as a function of neutrino energy before and after the constraint

Flux Constraint using ν-e scattering:



ν_μ flux as a function of neutrino energy before and after the constraint



With the current a-priori flux, fractional Flux Uncertainty reduces after the ν– e scattering constraint

Conclusion:

A word about our Medium energy Analysis results shown yesterday

- *A priori flux with no focusing or muon energy scale uncertainty*
- *On top of our standard a priori flux + muon energy scale uncertainties, we took 100% of the weight returned by the focusing only fit as an additional uncertainty.*
- *The collaboration is still determining the best flux / muon energy scale values and uncertainties for our upcoming publication*

- Low Energy MINERvA flux predictions is final and is being used for many cross section measurements (as we saw on Tuesday).
- We are working on improving our medium energy flux predictions for our upcoming publications.
    - Using the Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering in Medium Energy data
    - High-ν Analysis
- MINERvA is pioneering flux techniques that can be used by other experiments such as DUNE.

STAY TUNED !

THANK You !

BACKUP

PPFX

PPFX: Package to Predict the Flux

- Experiment independent NuMI reweighting package.
- Applying all relevant data and remove model spread.
- Handle correlated uncertainties.
- Account for the attenuation of particles passing through
- NuMI materials.
- Use "many universes" technique for the uncertainty
- propagation.
- This is an external package for MINERvA framework.
- PPFX is able to calculate the HP corrected NuMI flux for

any detector

Chi2 minimize for getting the fit

$$\chi^2 = (Data - MC)^T . C_{TOT}^{-1} . (Data - MC)$$

$$C_{TOT}^{-1} \rightarrow Total\ Covariance\ Matrix$$

- Total Covariance Matrix is given by:

$$C_{TOT} = C_{DATA} + C_{MC,weight} + C_{MC,syst}$$

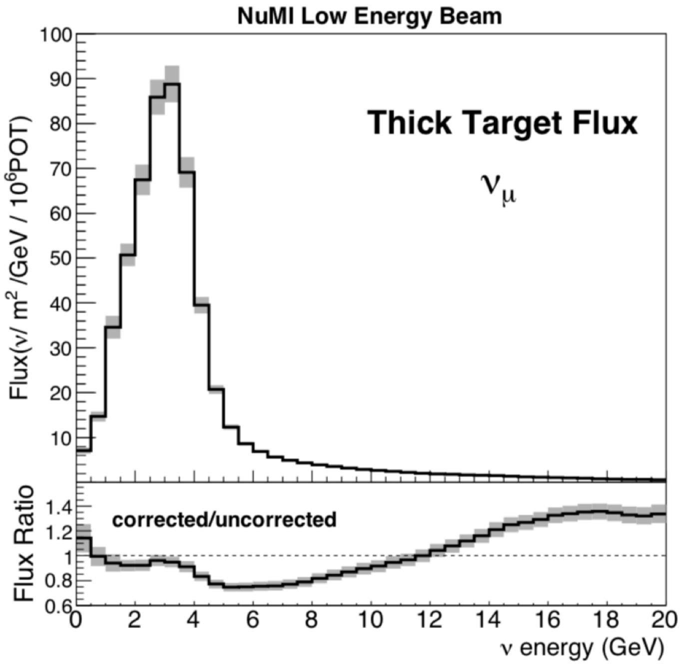
$$C_{MC,weight}[i,i] = MC_i \times (\frac{\delta w_i}{w_i})^2 \times w_i$$

$C_{MC,systematics} \rightarrow$ Covariance matrix from MC systematics

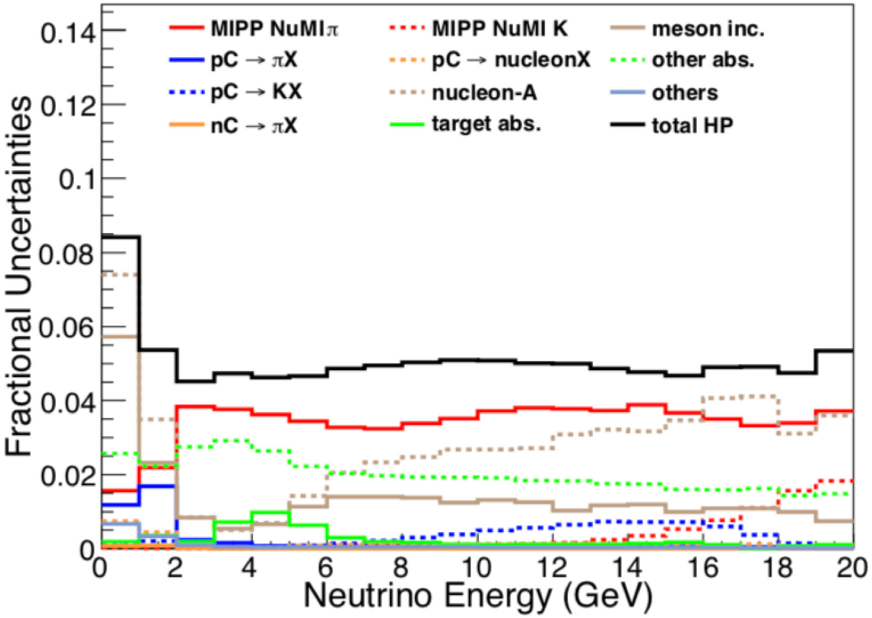
$C_{DATA} \rightarrow$ Covariance matrix from Data

Thick target flux for low energy mode:

The other measurement, from MIPP [4], uses an actual NuMI LE target and 120 GeV/c protons.

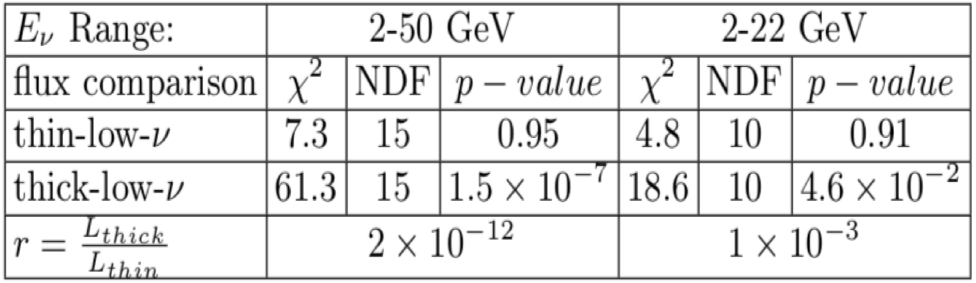


The predicted thick target ν_μ flux at the MINERvA detector for the low energy, ν_μ focused, beam configuration. The ratio plot shows the effect of correcting the flux simulation using thick and thin target hadron production and attenuation data. The error band includes uncertainties due to hadron interactions, beam geometry and beam focusing.



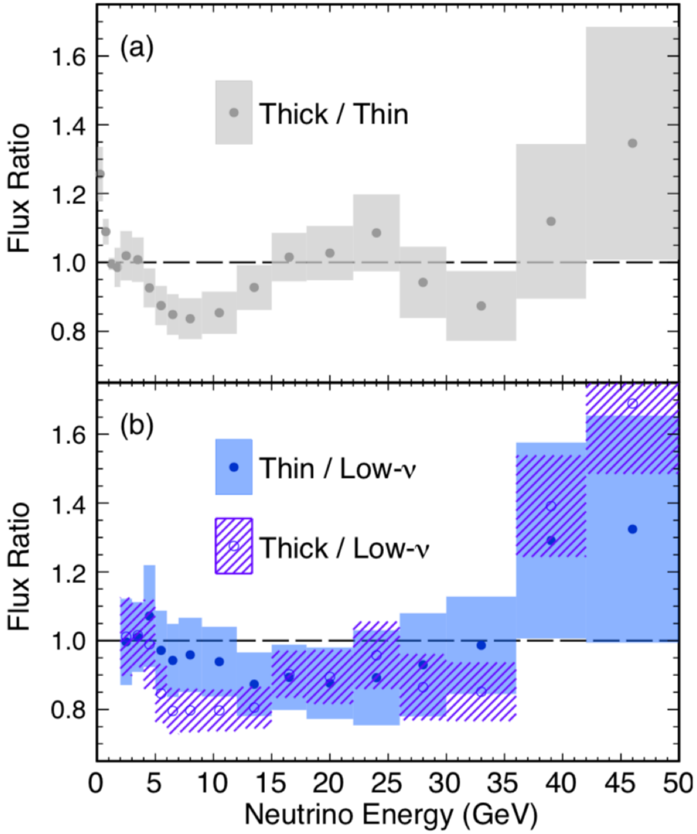
Uncertainties on the NuMI low energy ν_μ"thick target flux" that originate from the different hadron interaction categories The label "nucleon-A" refers mainly to nucleons interacting in material that is not carbon , and "meson inc." refers to mesons interacting on any material in the beamline; "target abs." and "other abs." refer to absorption in the target and other materials (Al, He, Fe).

Comparison of thin and thick to low-nu flux



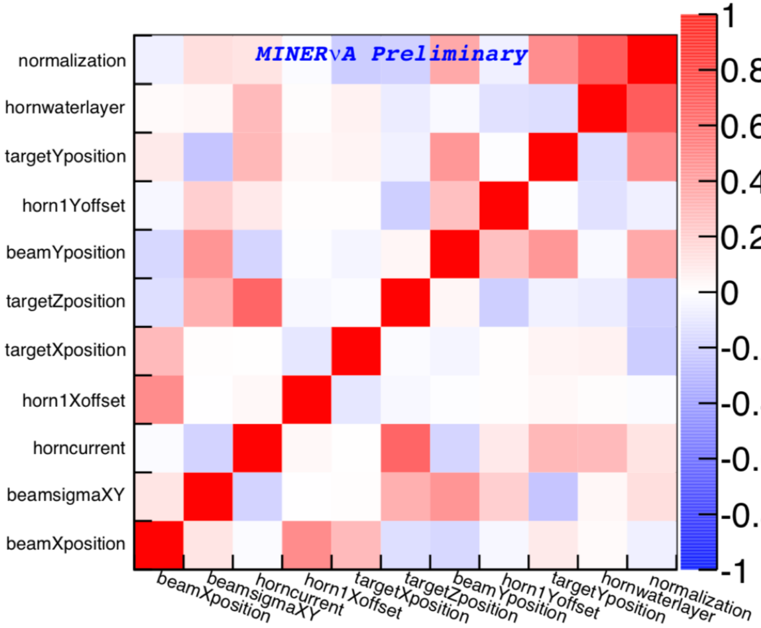
E_ν Range:	2-50 GeV			2-22 GeV		
flux comparison	χ^2	NDF	$p - value$	χ^2	NDF	$p - value$
thin-low-ν	7.3	15	0.95	4.8	10	0.91
thick-low-ν	61.3	15	1.5×10^{-7}	18.6	10	4.6×10^{-2}
$r = \frac{L_{thick}}{L_{thin}}$	2×10^{-12}			1×10^{-3}		

Results from a χ2 comparison of the thick- and thin target constrained fluxes with the low-ν flux.



Ratios of flux predictions. (a) The flux predicted using data from thick target experiments divided by the flux prediction that uses only thin target data. (b) The thin and thick target flux predictions divided by the in situ flux measured using the low-ν technique. The error bands on each curve account for uncertainties in the numerator and denominator, including the effect of significant correlations between the thick and thin target predictions.

Correlation Matrix



General Trend:

- **Strong correlation between targetZ and horn current. (Refer to back up slide as well)**
- **X offsets and Y offsets of focusing parameters are positively correlated.**
  - **Should be since (x offset in target position should have similar effect as x offset in beam position and so on)**

Muon Energy Scale as Fit Parameters

For the purpose of fitting:

MINOS Range corresponds to 2 % shift

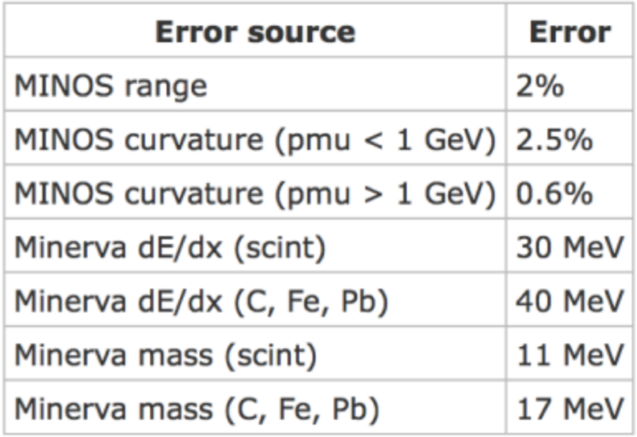
- **1 parameter (MuonEnergyRange)**

MINOS Curvature corresponds to 2.5% or 0.6% shift 2 parameters

- **MuonEnergyCurveG1 → >1 GeV**
- **MuonEnergyCurveL1 → <1 GeV**

MINERvA Systematics

- **1 Parameter(MuonEnergyMinerva)**



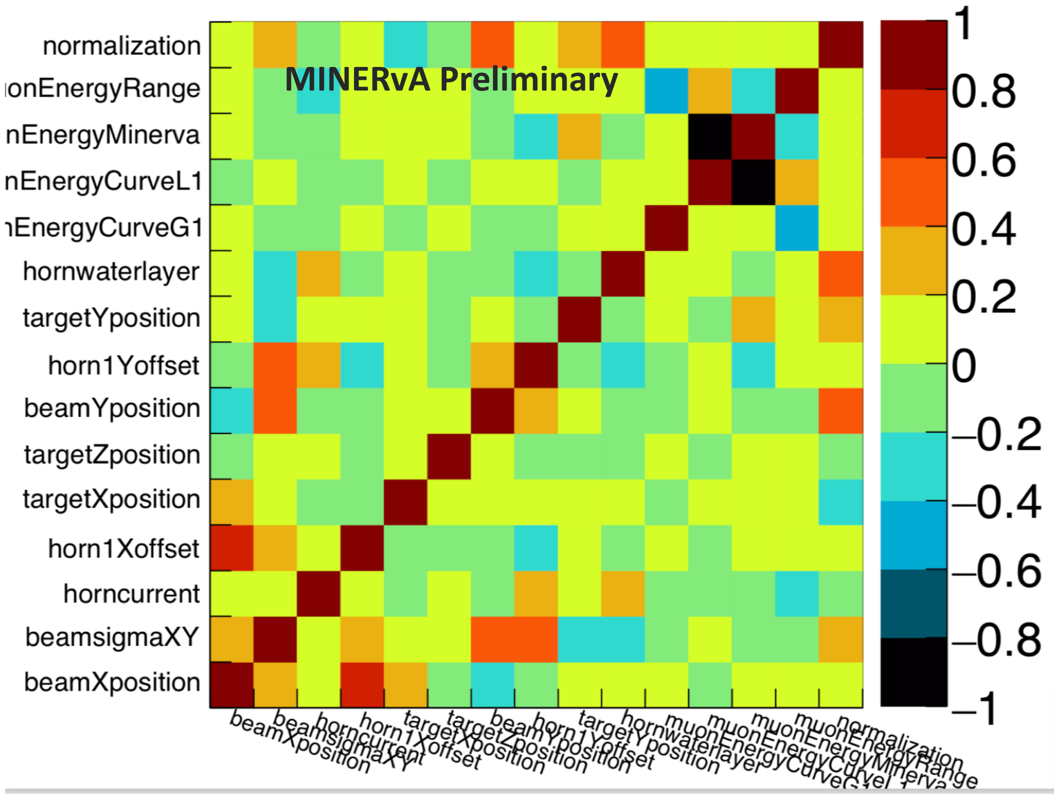
Error source	**Error**
MINOS range	2%
MINOS curvature (pmu < 1 GeV)	2.5%
MINOS curvature (pmu > 1 GeV)	0.6%
Minerva dE/dx (scint)	30 MeV
Minerva dE/dx (C, Fe, Pb)	40 MeV
Minerva mass (scint)	11 MeV
Minerva mass (C, Fe, Pb)	17 MeV

Best shift in sigma:

MINERνA Preliminary

Parameters	Best Fit Shifts in Sigma ± Stat Err ± Sys Err
Beam Position (X)	-0.37 ± 0.22 ± 0.09
Beam Position (Y)	-0.26 ± 0.17 ± 0.2
Target Position (X)	-0.47 ± 0.22 ± 0.11
Target Position (Y)	2.73 ± 0.54 ± 0.71
Target Position (Z)	0.52 ± 0.49 ± 0.1
Horn 1 Position (X)	-0.14 ± 0.41 ± 0.12
Horn 1 Position (Y)	-0.84 ± 0.27 ± 0.19
Beam Spot Size	-0.03 ± 0.35 ± 0.35
Horn Water Layer	-0.28 ± 0.40 ± 0.44
Horn Current	-0.76 ± 0.72 ± 0.37
Muon Energy (By Range)	-1.83 ± 0.2 ± 0.24
Muon Energy (By Curvature for >1 GeV Muons)	-1.02 ± 0.39 ± 0.24
Muon Energy (By Curvature for <1 GeV Muons)	1.23 ± 0.45 ± 0.21
Muon Energy (Minerva Detector)	0.15 ± 0.22 ± 0.34

Correlation Matrix



Muon Energy Range is correlated to almost all other muon energy parameters.

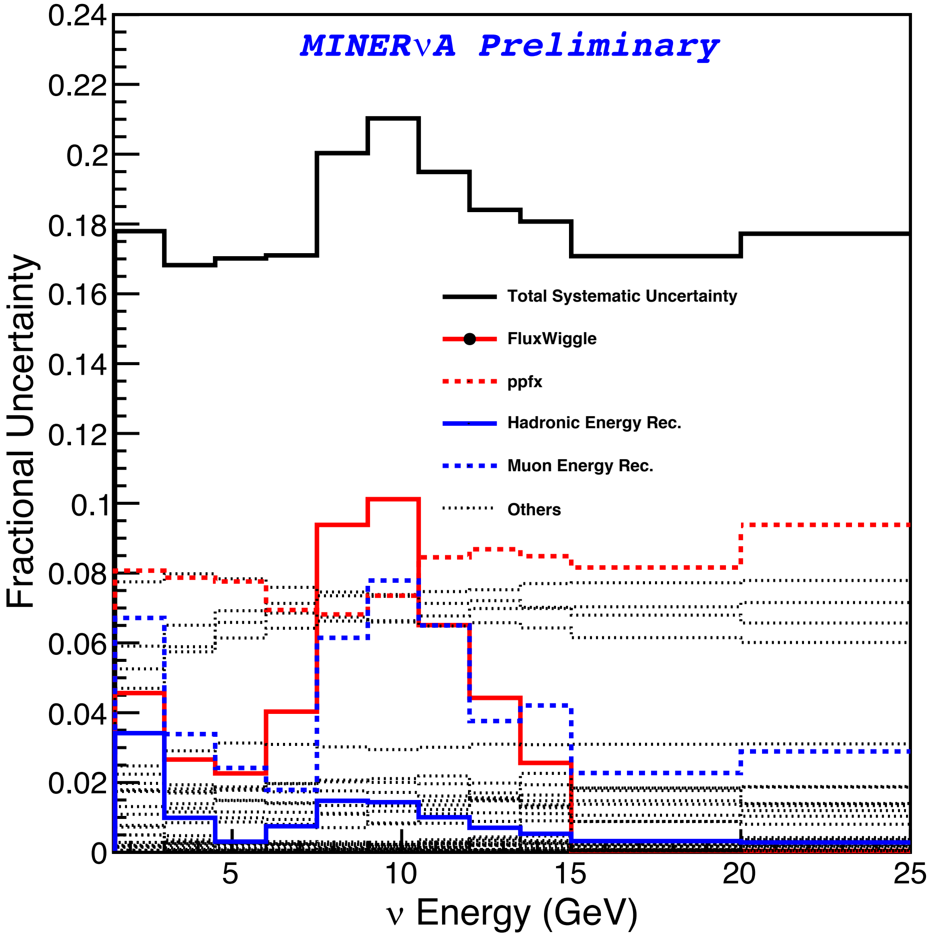
Muon Energy Ranger and Muon Energy Minerva are very strongly correlated (negative).

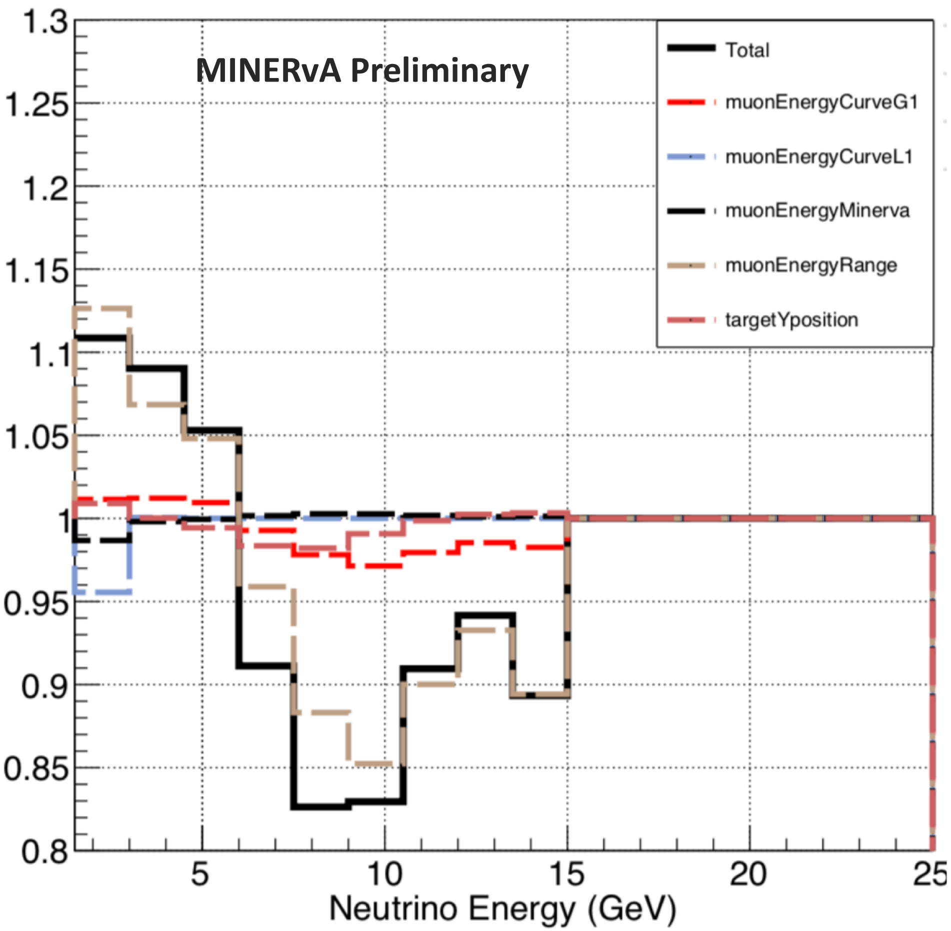
HornCurrent and MuonEnergyRange show some correlation.

TargetY position is relatively strongly correlated to MuonEnergyMinerva compared to other focusing paramters.

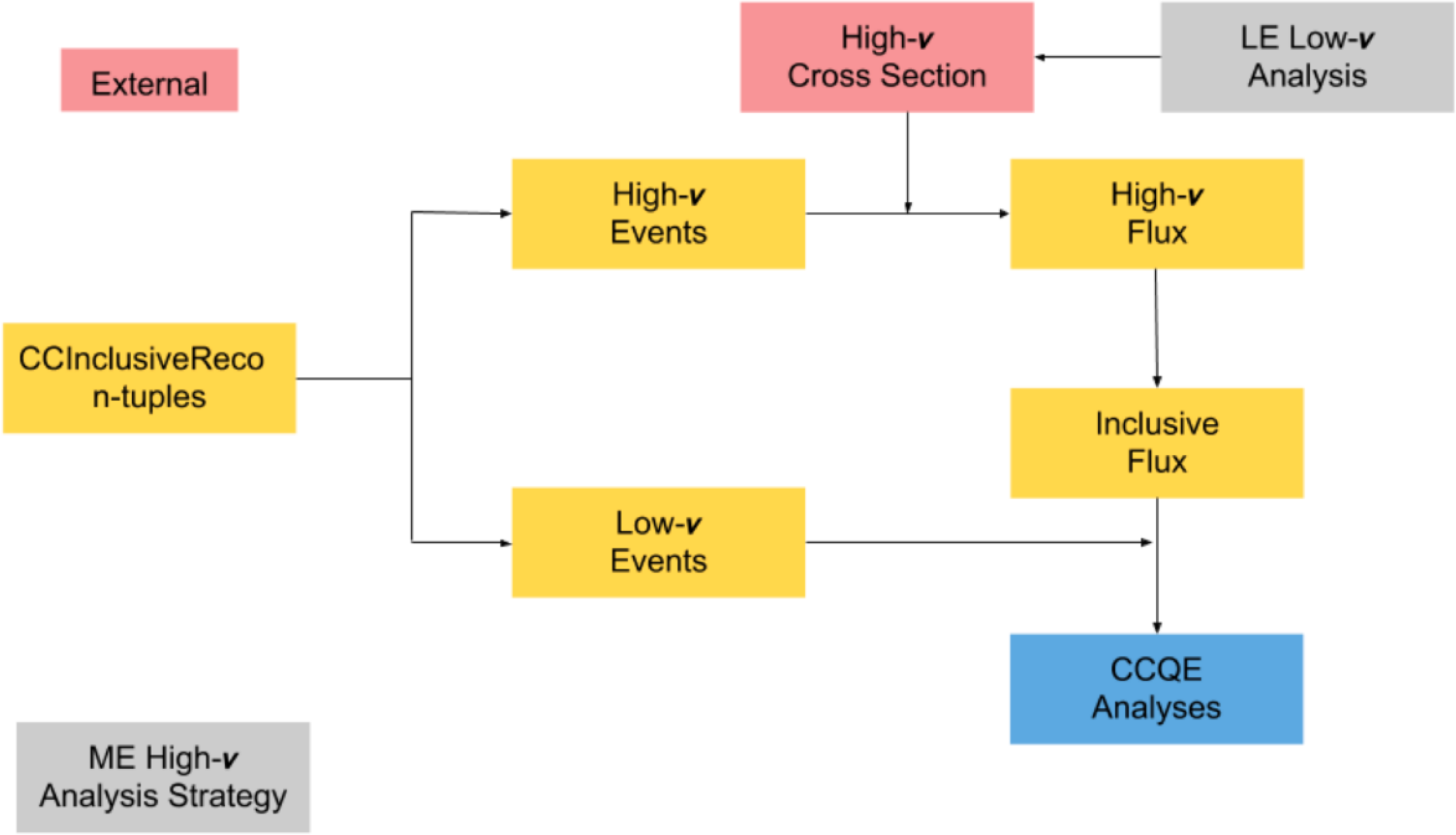
Focusing parameters show their usual correlations (in terms of X and Y shifts and so on).

Fractional Flux Uncertainties:




MINERvA Preliminary
Total
muonEnergyCurveG1
muonEnergyCurveL1
muonEnergyMinerva
muonEnergyRange
targetYposition
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
5
10
15
20
25
Neutrino Energy (GeV)

High-ν Flux Strategy:



External

High-ν Cross Section

LE Low-ν Analysis

High-ν Events

High-ν Flux

CCInclusiveReco n-tuples

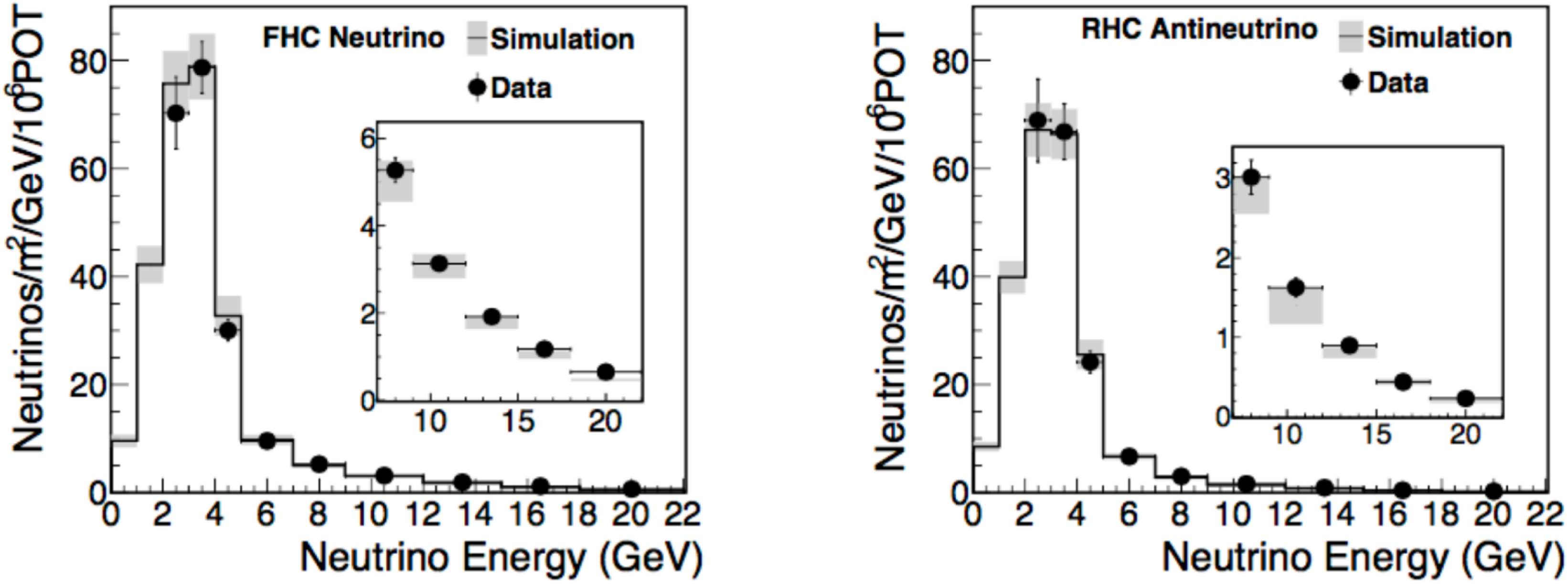
Inclusive Flux

Low-ν Events

CCQE Analyses

ME High-ν Analysis Strategy

Results for Low-ν Flux



Extracted low-nu fluxes comparing with input MC fluxes (hadron production model)