# MINERvA's Flux Prediction

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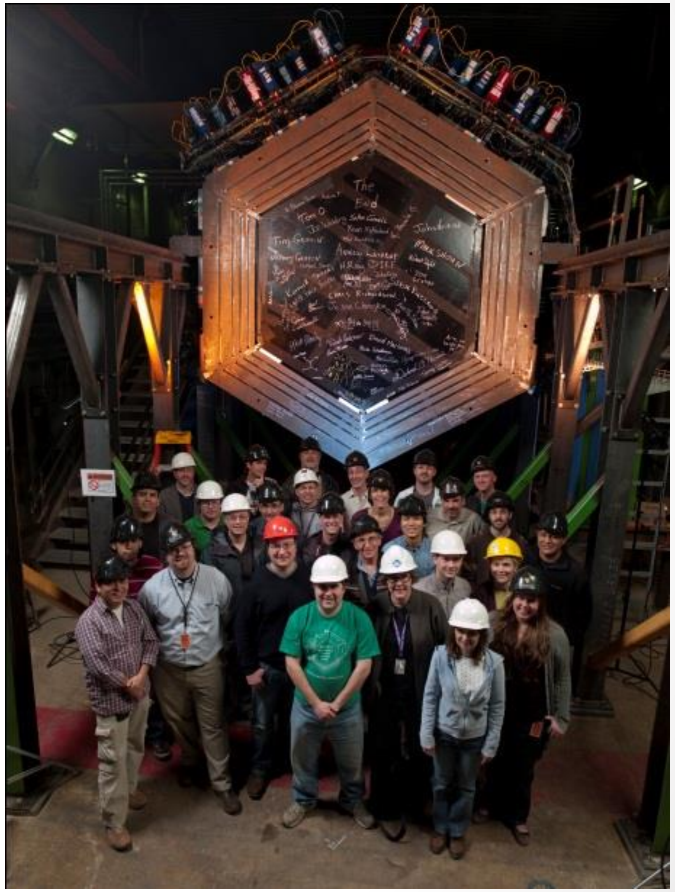
On behalf of MINERvA Collaboration

# **M**ain **IN**jector **E**xpe**R**iment **v-A**

## aka MINERvA

- MINERvA is a neutrino scattering experiment at Fermilab
- Collaboration of about 65 nuclear and particle physicists from more than 20 institutions
- NuMI beam is used to measure cross section for neutrino-nucleus interactions
- Detector includes several different nuclear targets which can be used to measure nuclear effect

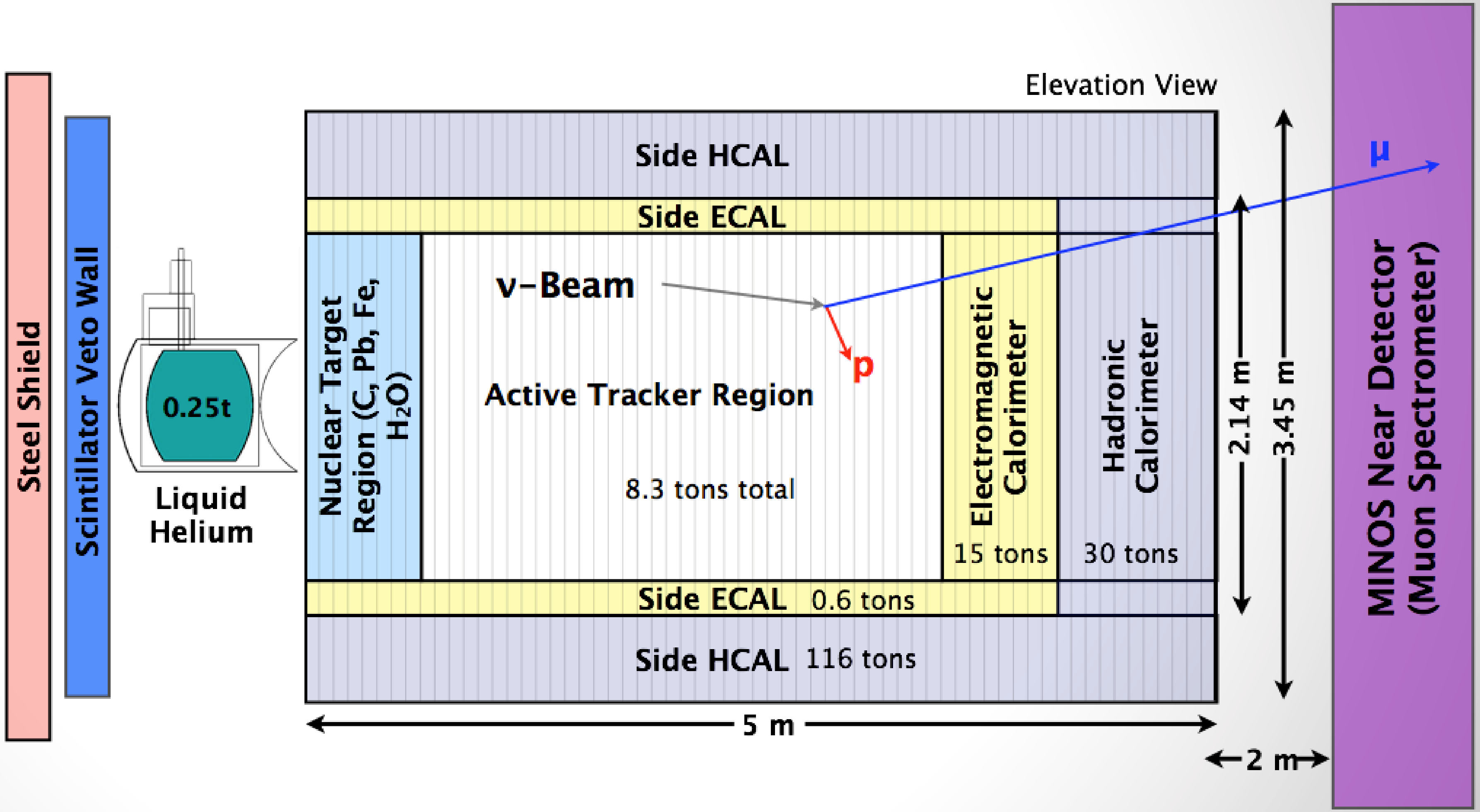


# MINERvA Detector

120 modules of 4 types:

- nuclear targets
- scintillator
- ECal
- HCal

MINOS near detector as muon spectometer



# MINERvA's Flux Prediction

Previous analyses used flux prediction known as Generation 0 and Generation 1

| **Flux** | **Analysis** | **Reference** |
|---|---|---|
| Generation 0 | $\nu_\mu$ CCQE | PRL 111 (2013) 022502 |
| Generation 0 | anti $\nu_\mu$ CCQE | PRL 111 (2013) 022501 |
| Generation 1 | CC target ratios | PRL 112 (2014) 231801 |
| Generation 1 | Coherent $\pi$ | PRL 113 (2014) 261802 |
| Generation 1 | $\nu_\mu$ muon+proton | PRD 91 (2015) 071301 |
| Generation 1 | anti $\nu_\mu$ CC$\pi^0$ | PLB 749 (2015) 130-136 |

Generation 2 includes many improvements:

- Geometry
- Focusing uncertainties
- Additional hadron production data
- Better accounting for beam attenuation
- New framework allows to use MIPP thick target data
- And allows predictions of the flux for NOvA and uBooNE

# MINERvA @ NUINT15

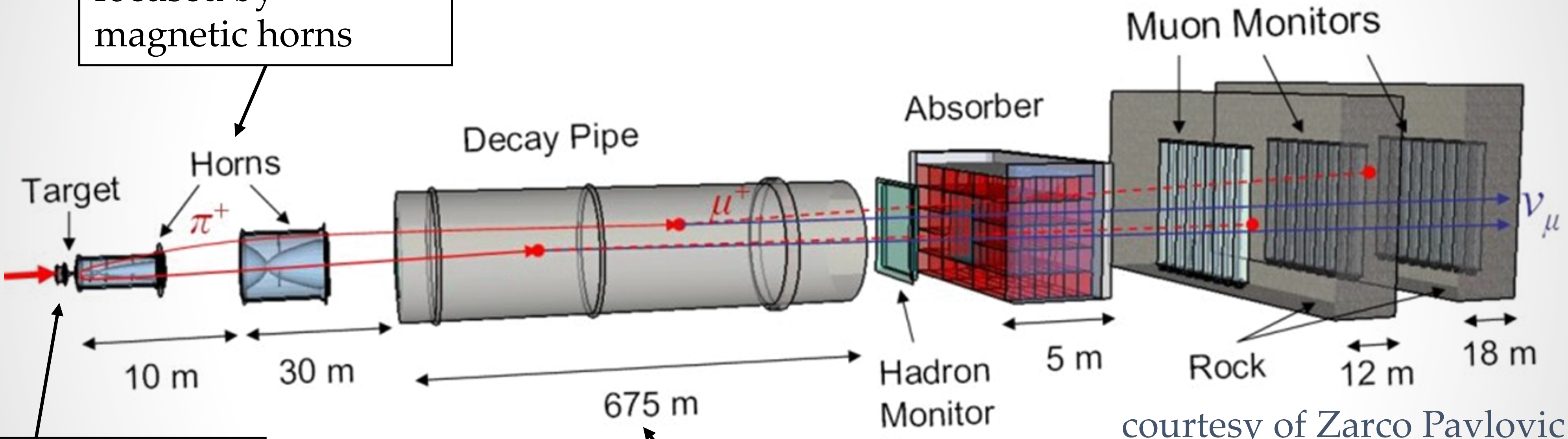
There are many improvements in our understanding of NuMI beam. Do not miss other MINERvA's talk to see how it affects our results:

| Talk | Speaker | Date | Flux |
|---|---|---|---|
| $\nu_e$ CCQE results | J. Wolcott | Tue, 14:05 | gen1 with ν-e constraint |
| $\nu_\mu$ CCQE update | M. Betancourt | Tue, 14:30 | gen1 for muon + proton<br>gen2 update on previous CCQE |
| Search for MEC | P. Rodrigues | Tue, 15:25 | gen2 |
| DIS in nuclear targets | J. Mousseau | Thu, 10:15 | gen1 |

# NuMI Beam

NIM A806 (2016) 279-306

Pions and kaons are focused by magnetic horns




courtesy of Zarco Pavlovic

120 GeV protons strike graphite target and meson mess is created

Pions and kaons decay (note, they can also interact!)

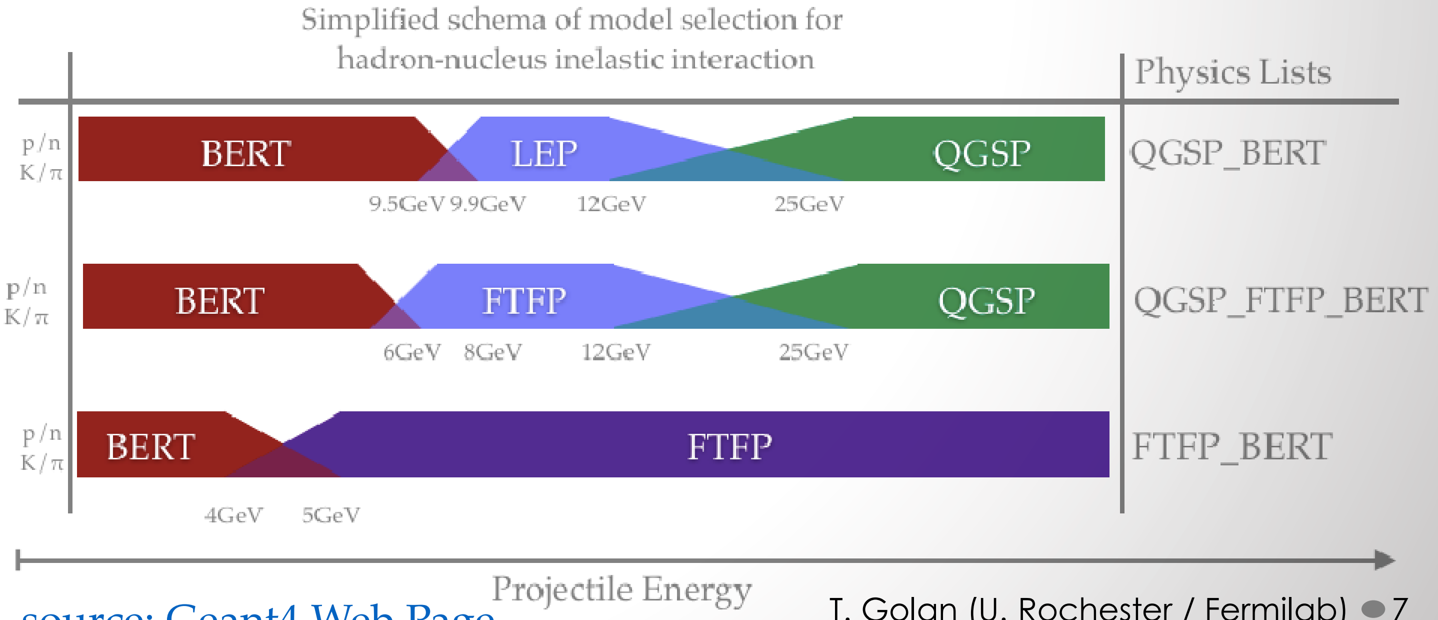
Need to understand each step since proton hits the target to neutrino production

# NuMI Beam Simulation

- Flux simulation starts with a Geant4 simulation of the NuMI beamline (G4NuMI)
- Geant 4.9.2p03 is used with FTFP_BERT hadronic physics list
- The results of the simulation are corrected by external data
- Similar approach to the one T2K used (Phys. Rev. D 87, 012001 (2013))

BERT – Bertini intranuclear cascade

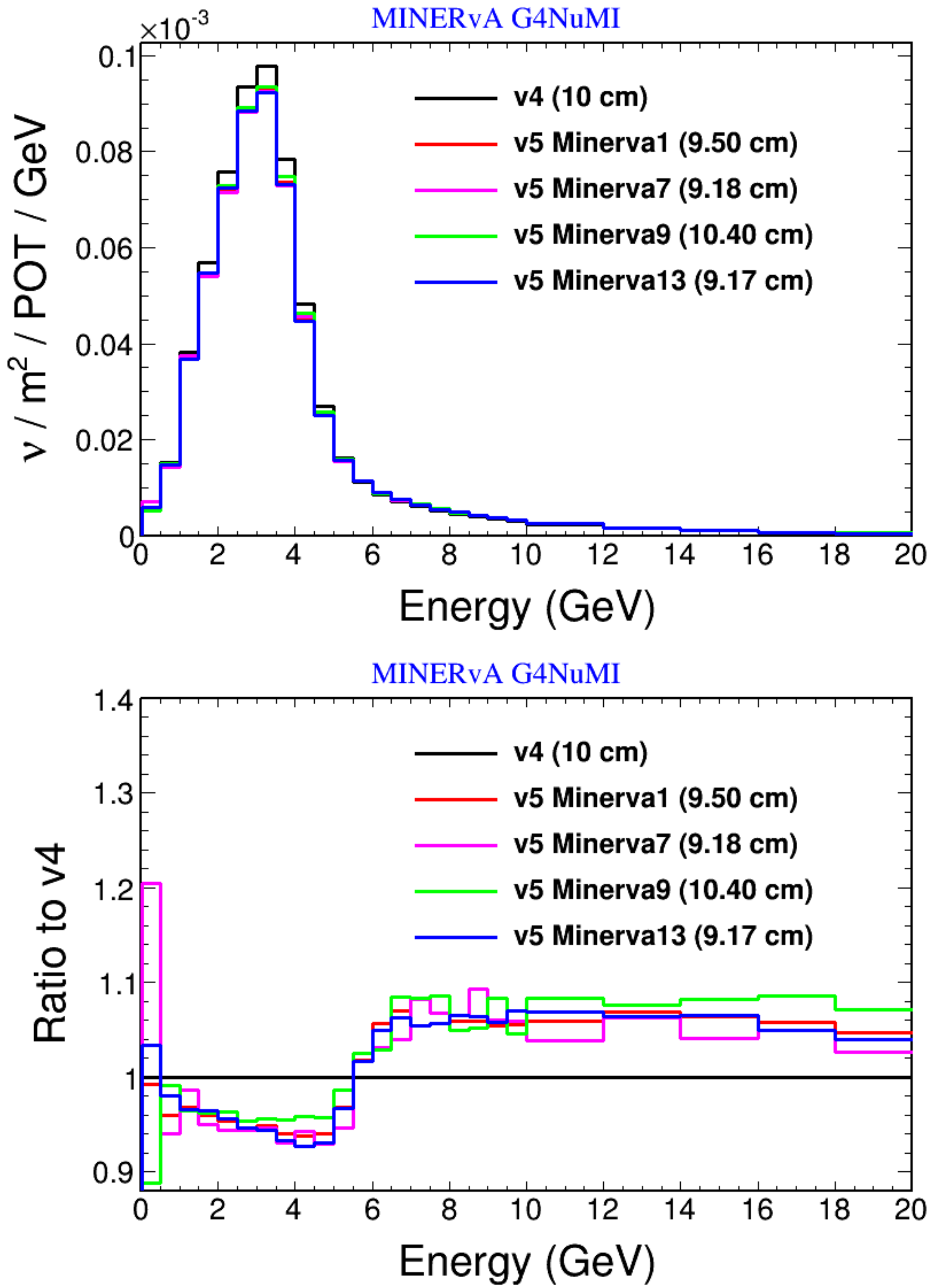
FTFP – The FRITIOF Precompound




source: Geant4 Web Page

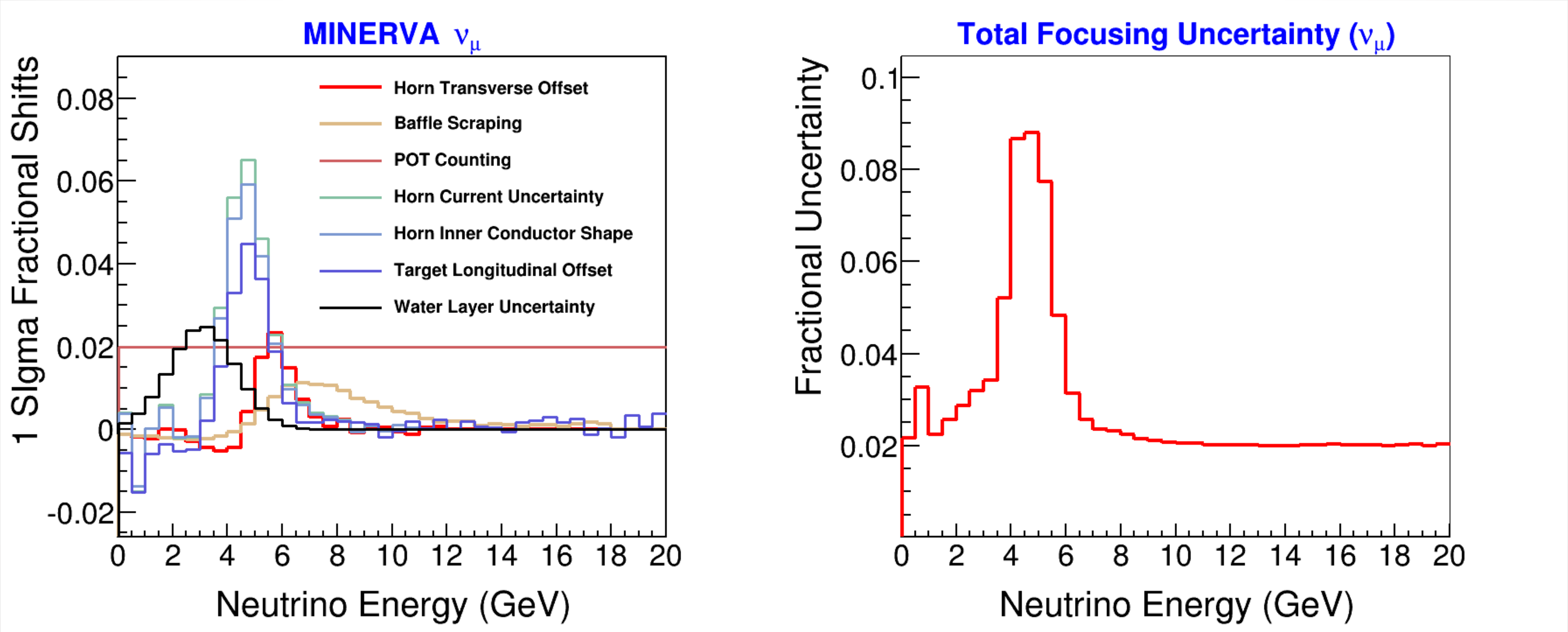
# Geometry improvements

- Thin layer (1.0 +/- 0.5mm) of cooling water around the inner conductor
- Beryllium windows (0.5 mm each) at the entrance and at the exit of NuMI baffle
- Argon instead of Air inside the magnetic horns
- The longitudinal target position

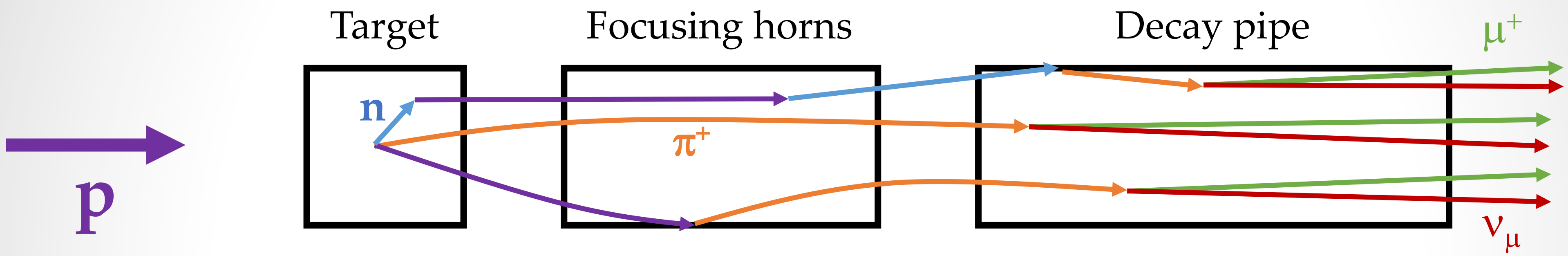


# Focusing uncertainties

Horn geometry and water layer was (re)studied to evaluate focusing uncertainty



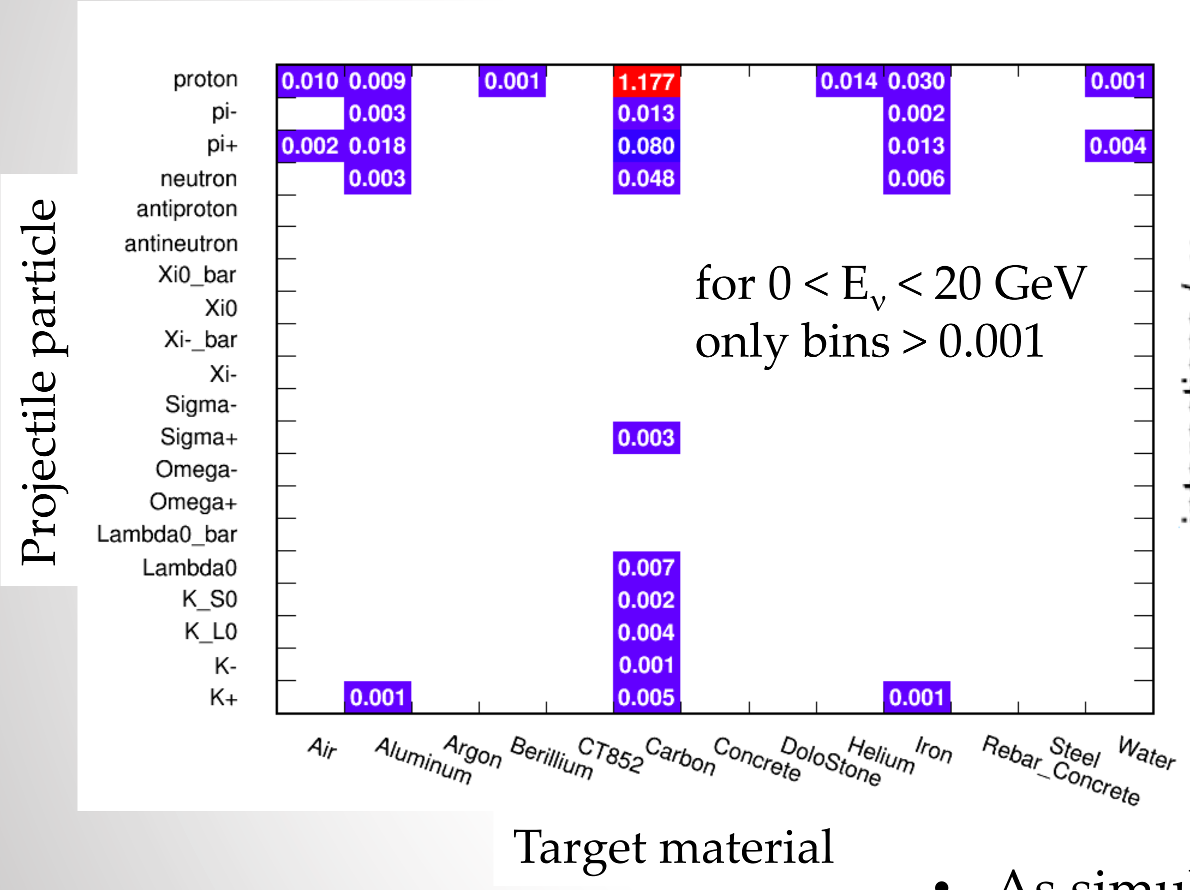
# Hadron interactions

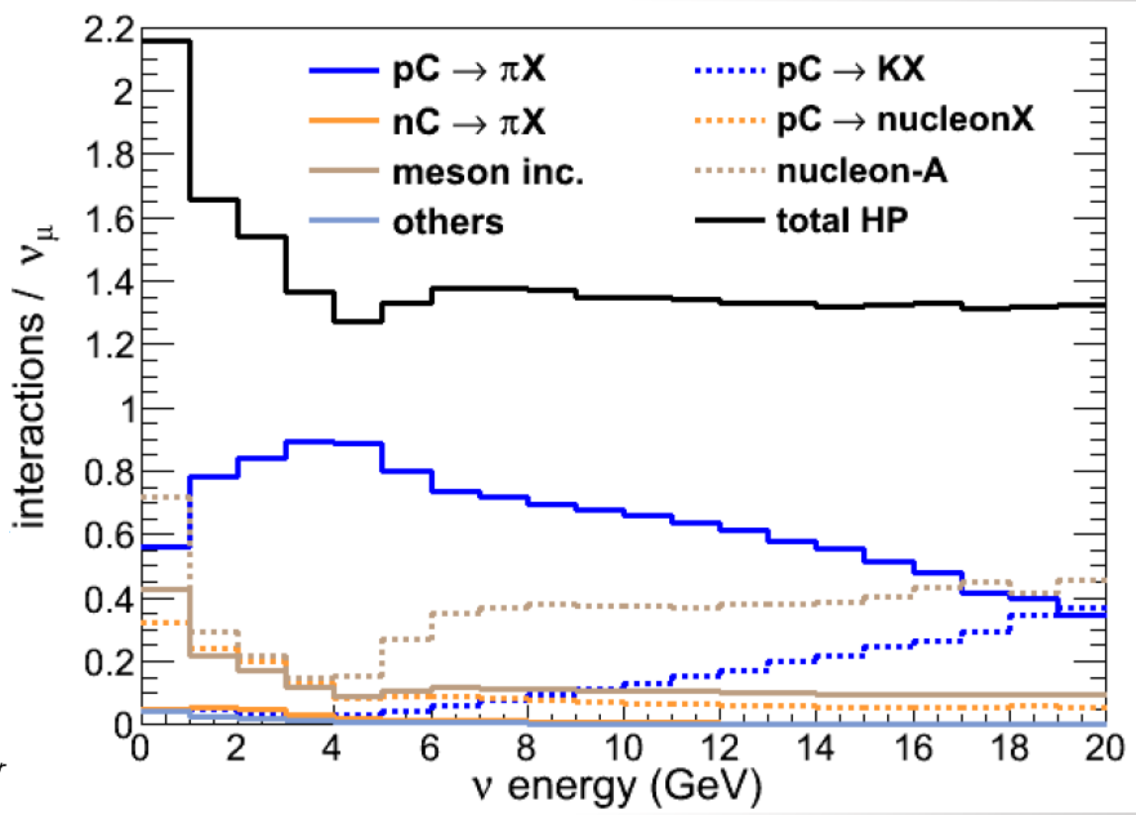



- All interactions leading to neutrino production are stored in ntuple
- Including whole kinematics and material
- This information is used to apply corresponding data for our reweighting procedure

# What interacts where

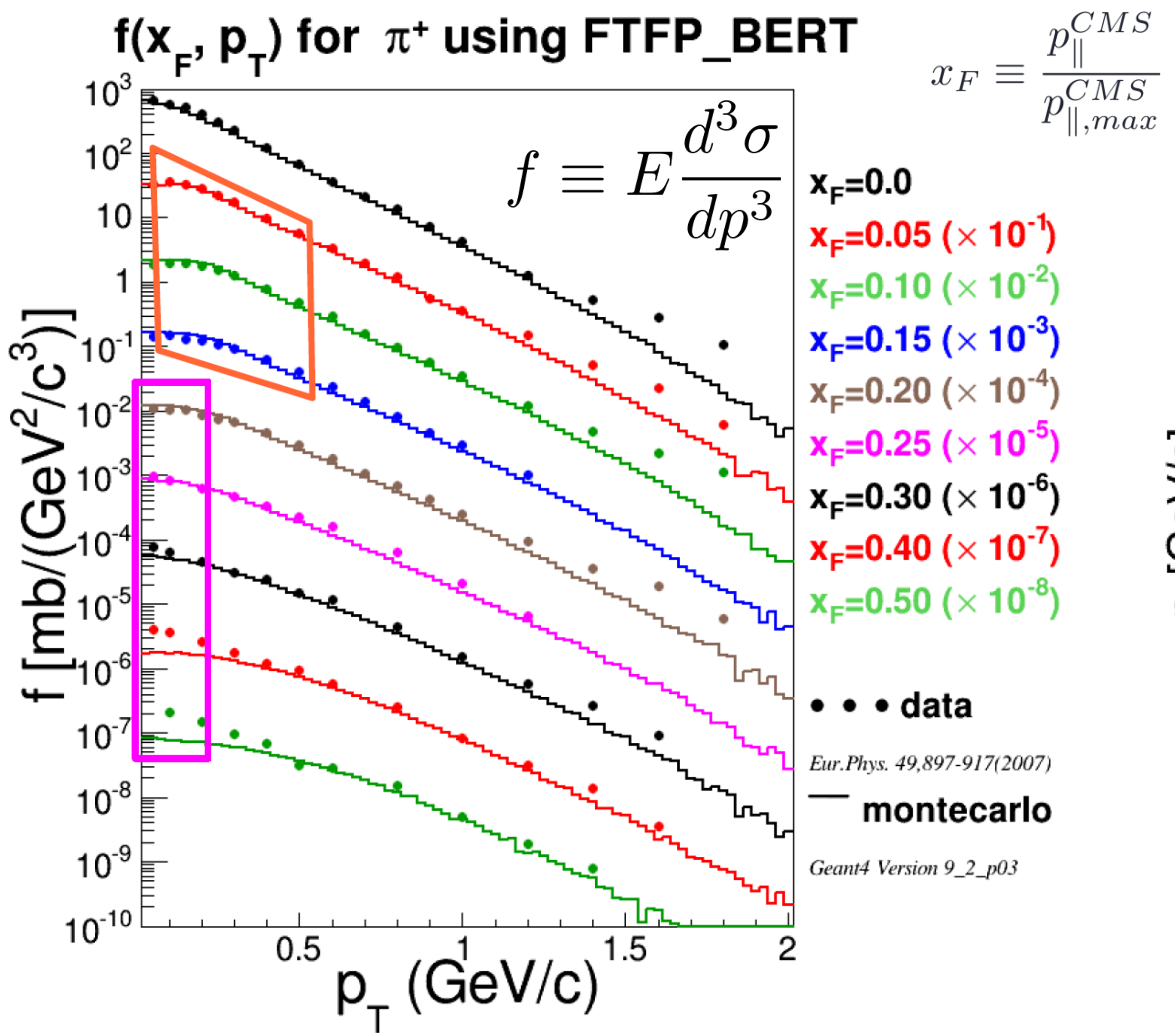
**Number of interactions per neutrino at the detector**



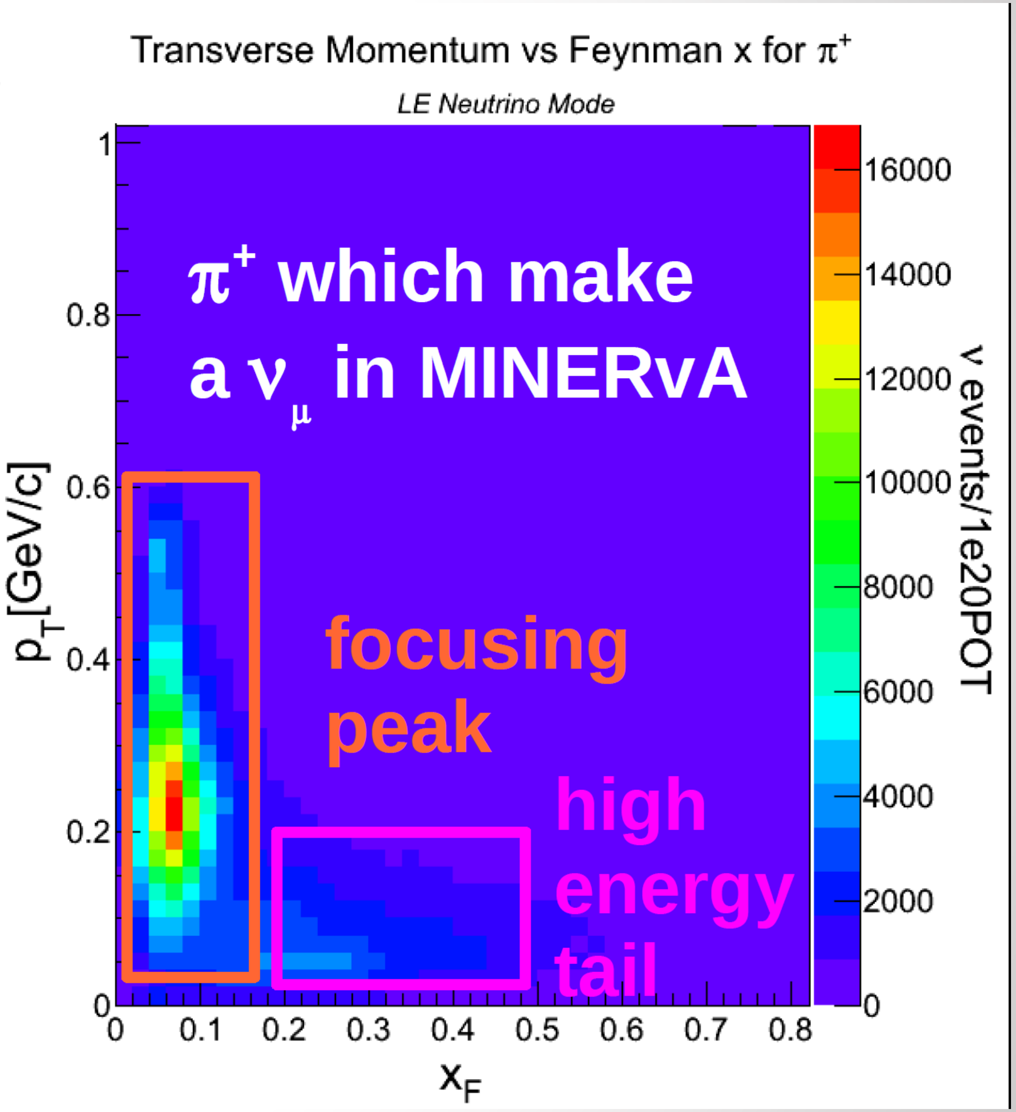




- As simulated by g4numi
- Most of it is covered by NA49 and MIPP data

# NA49 data



f(x_F, p_T) for π⁺ using FTFP_BERT
$x_F \equiv \frac{p_{\parallel}^{CMS}}{p_{\parallel,max}^{CMS}}$
$f \equiv E\frac{d^3\sigma}{dp^3}$
f [mb/(GeV²/c³)]
p_T (GeV/c)
x_F=0.0
x_F=0.05 (× 10⁻¹)
x_F=0.10 (× 10⁻²)
x_F=0.15 (× 10⁻³)
x_F=0.20 (× 10⁻⁴)
x_F=0.25 (× 10⁻⁵)
x_F=0.30 (× 10⁻⁶)
x_F=0.40 (× 10⁻⁷)
x_F=0.50 (× 10⁻⁸)
• • • data
Eur.Phys. 49,897-917(2007)
— montecarlo
Geant4 Version 9_2_p03

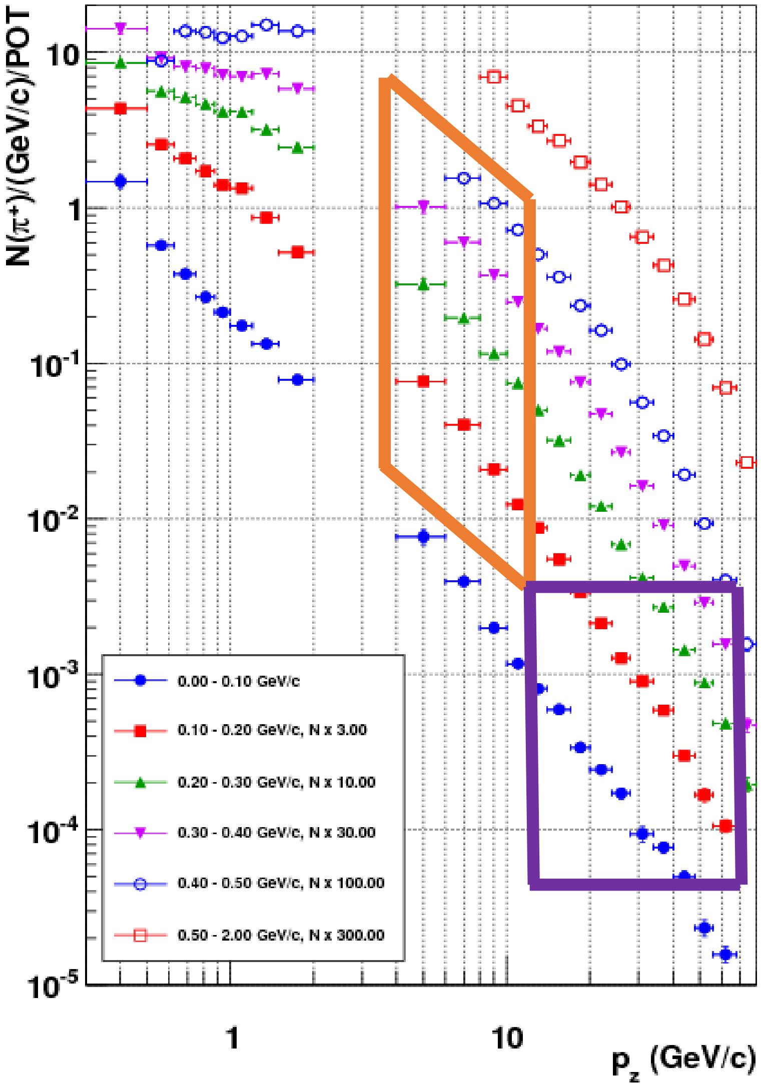
Transverse Momentum vs Feynman x for π⁺
LE Neutrino Mode
π⁺ which make a ν_μ in MINERvA
focusing peak
high energy tail
p_T[GeV/c]
x_F
ν events/1e20POT

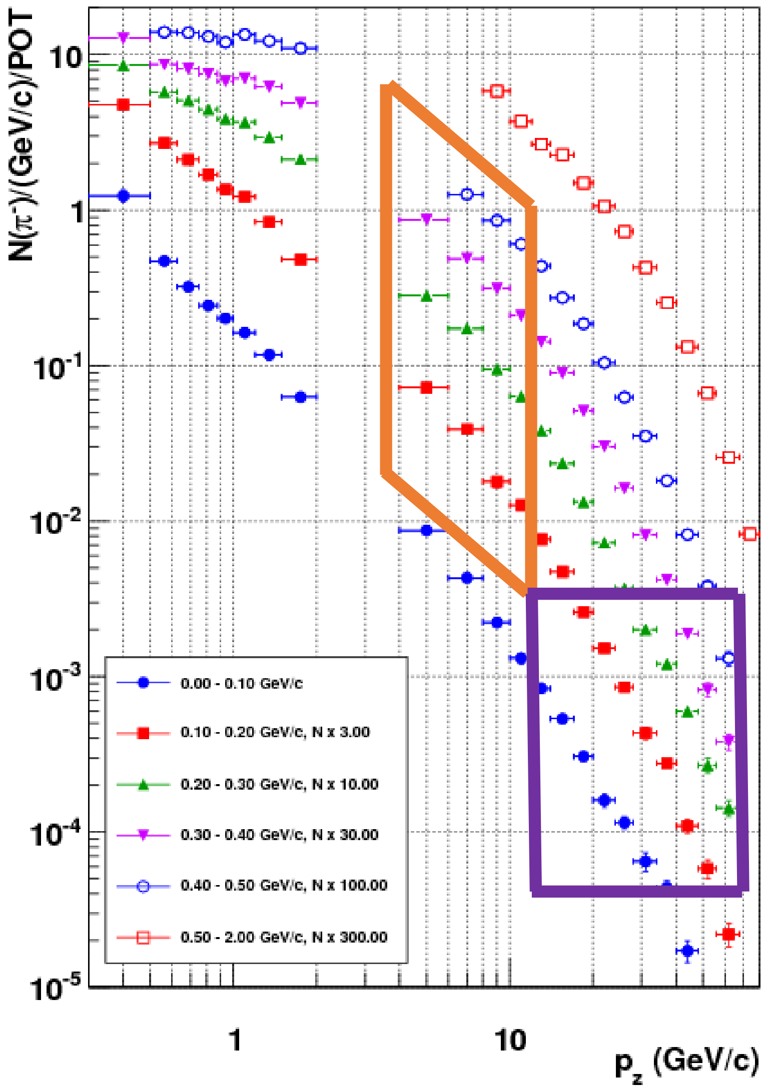
# MIPP data

- MIPP is hadron production experiment located at Fermilab
- Pions yields off the NuMI target are measured
- Ratios of kaon/pion yields are measured on thin target and NuMI replica

Low Energy Focusing Peak

Low Energy High Energy Tail




PRD 90 (2014) 3, 032001

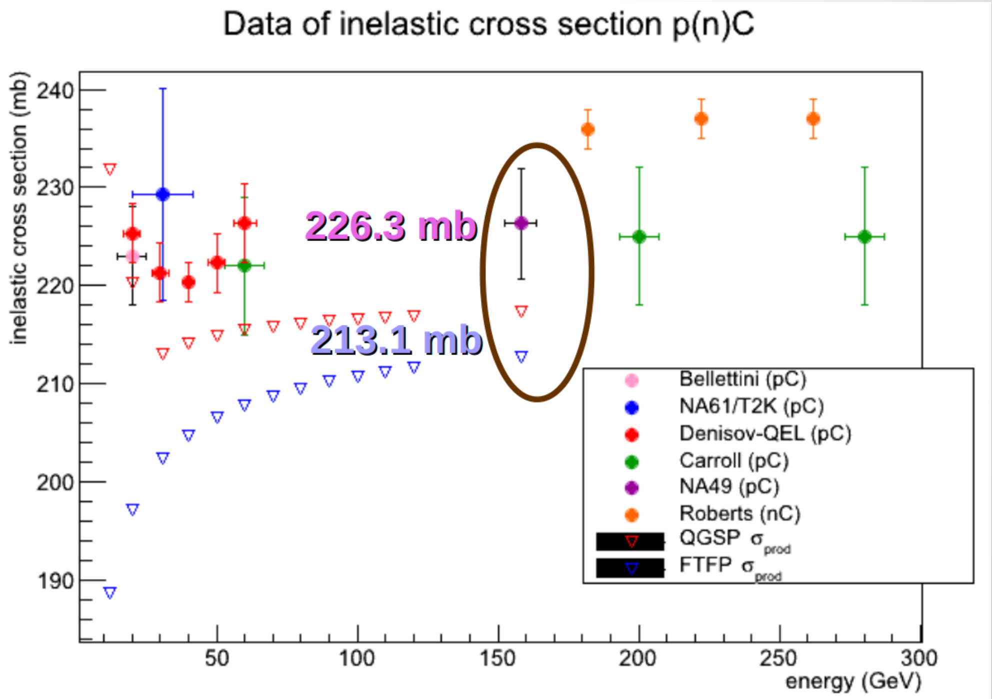
# Reweighting

- Using external hadron production data events are weighted by:

$$w_{HP} = \frac{f_{data}(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}, \quad f \equiv \frac{1}{\sigma} E \frac{d^3\sigma}{dp^3}$$

- The beam attenuation (due to mismodeling of total inelastic cross section) is taken into account by applying a second weight (for each volume):

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



# Uncertainties

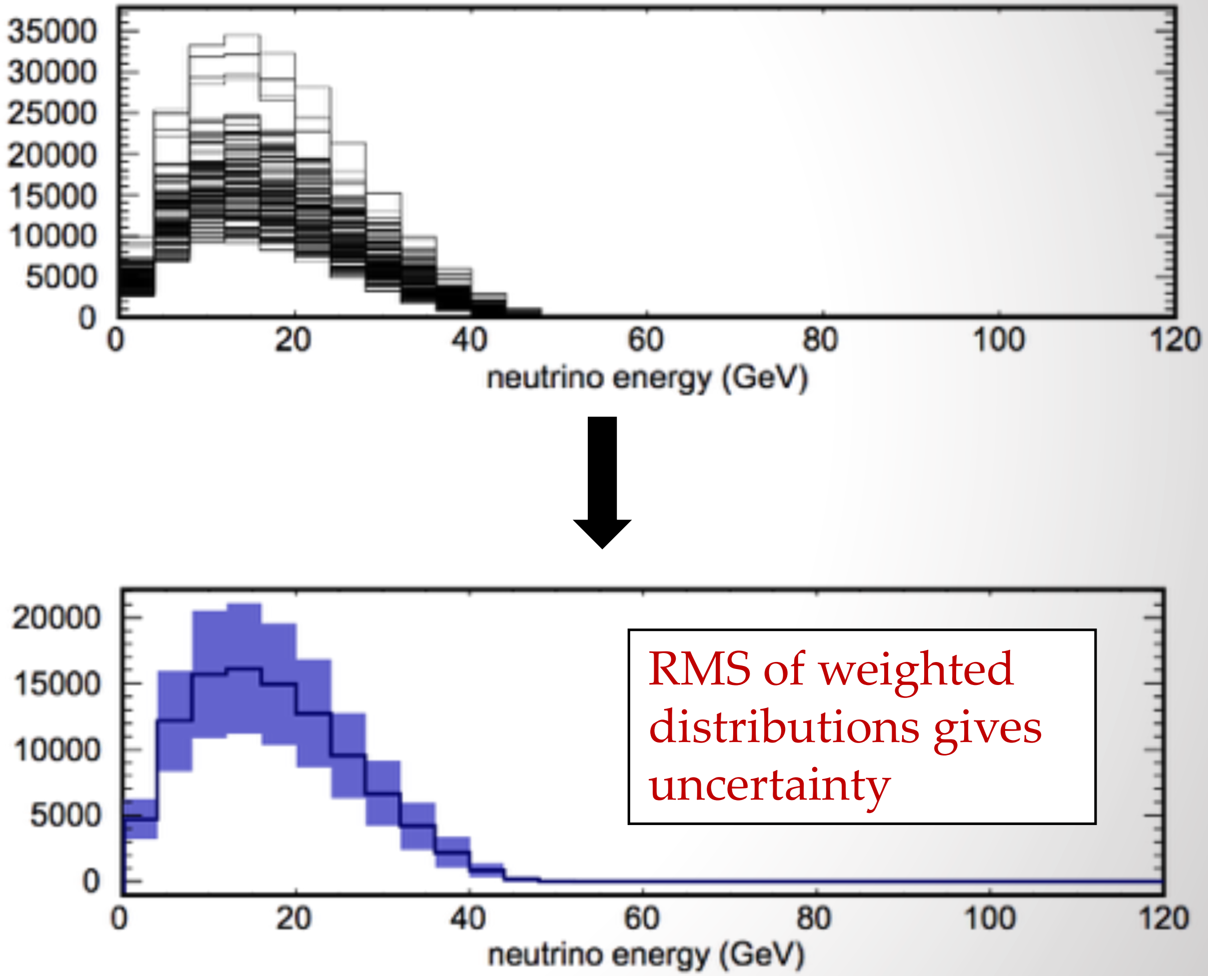
by M. Kordosky

- „Many-Universes” method is used to propagate external data uncertainties to our flux

$$w_u = w_{att,u} \cdot \prod_i w_{HP,u,i}$$

for each universe (u) data central value is randomly shifted according to uncertainty

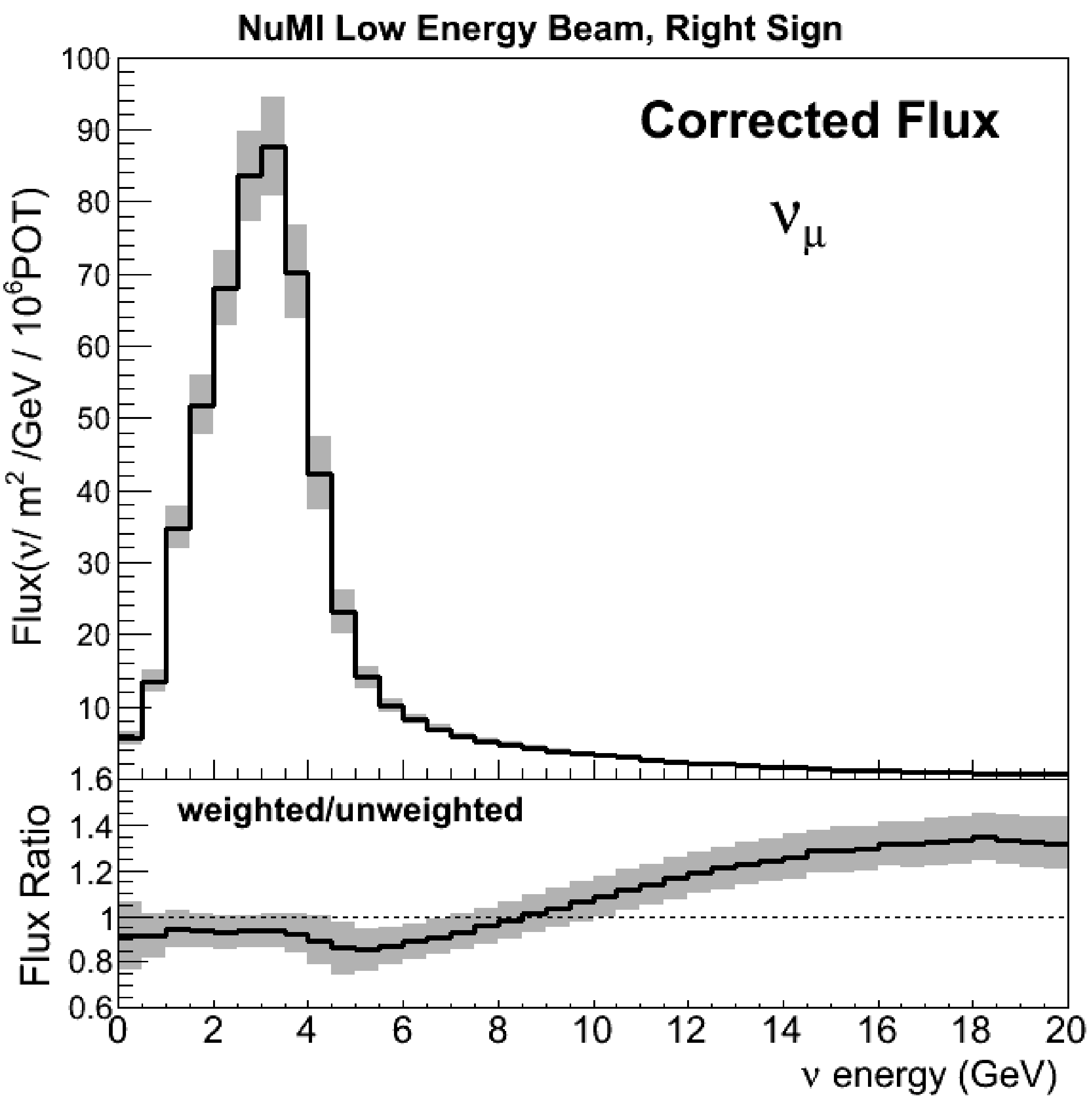
product of HP weights for all reweightable interactions (i)

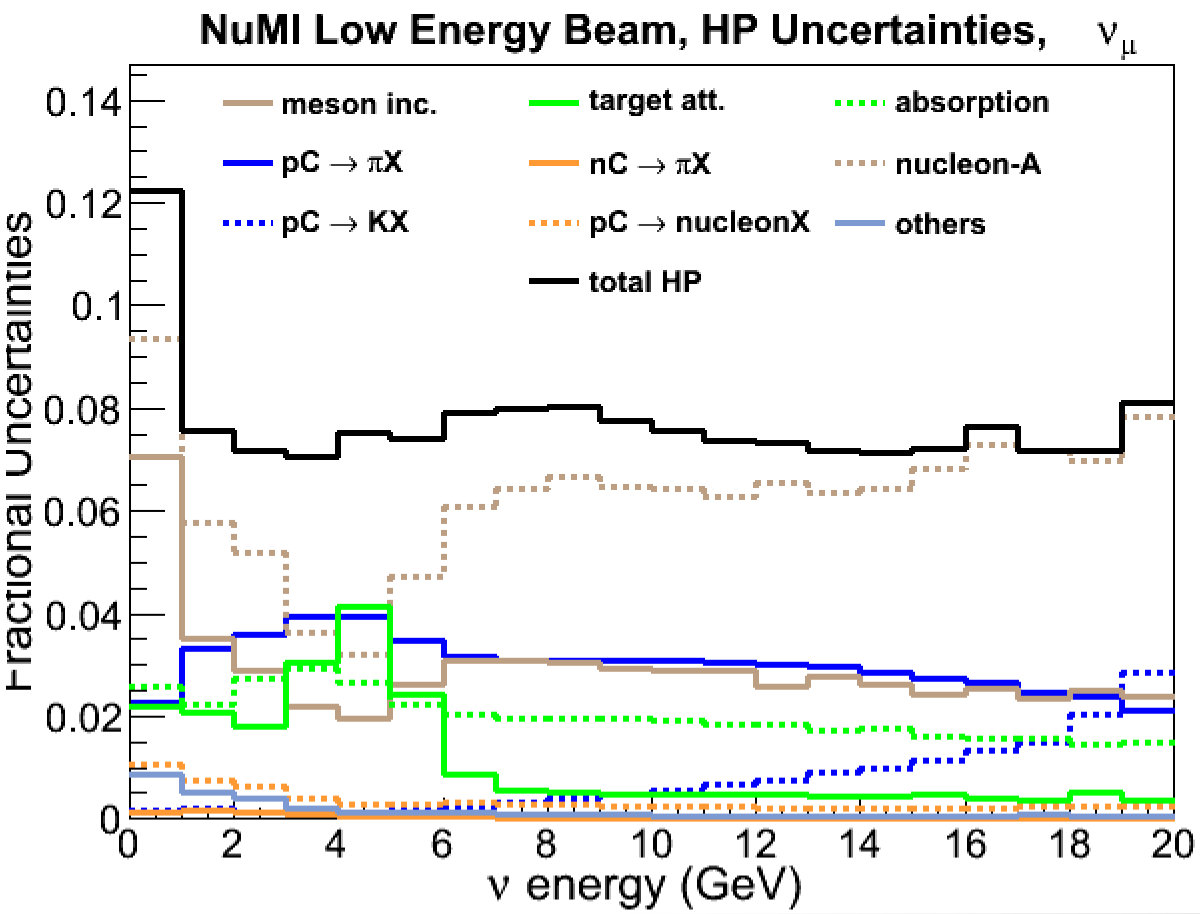


# It is time for results

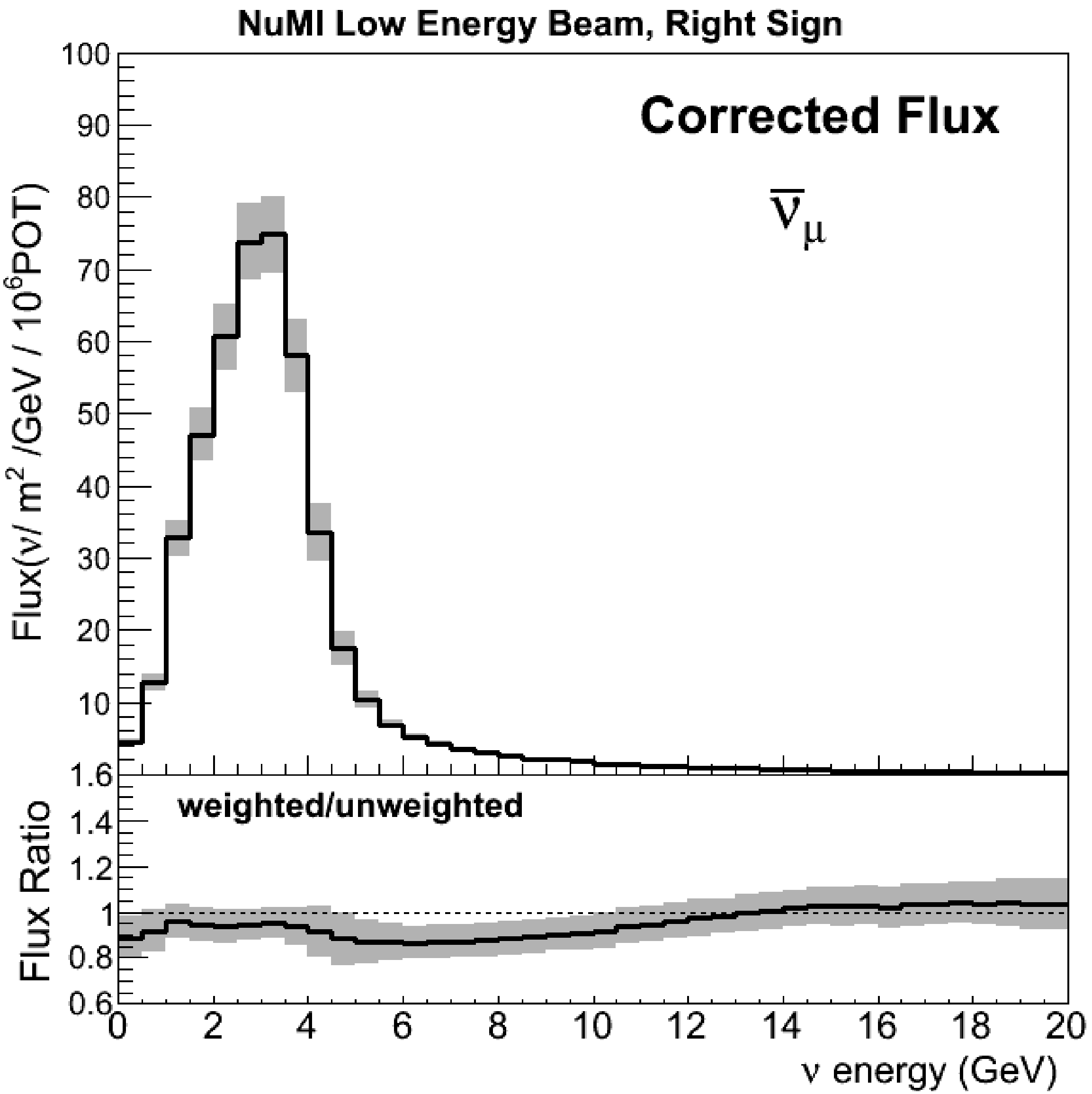
- Plots presented in this talk include all geometry improvements
- They include thin target hadron production data correction
- They do NOT include thick target hadron production correction
- The thick target data will be discussed at Joint Experimental-Theoretical Physics Seminar at Fermilab (aka Wine&Cheese) by L. Aliaga on Dec 17 (and in his PhD thesis!)

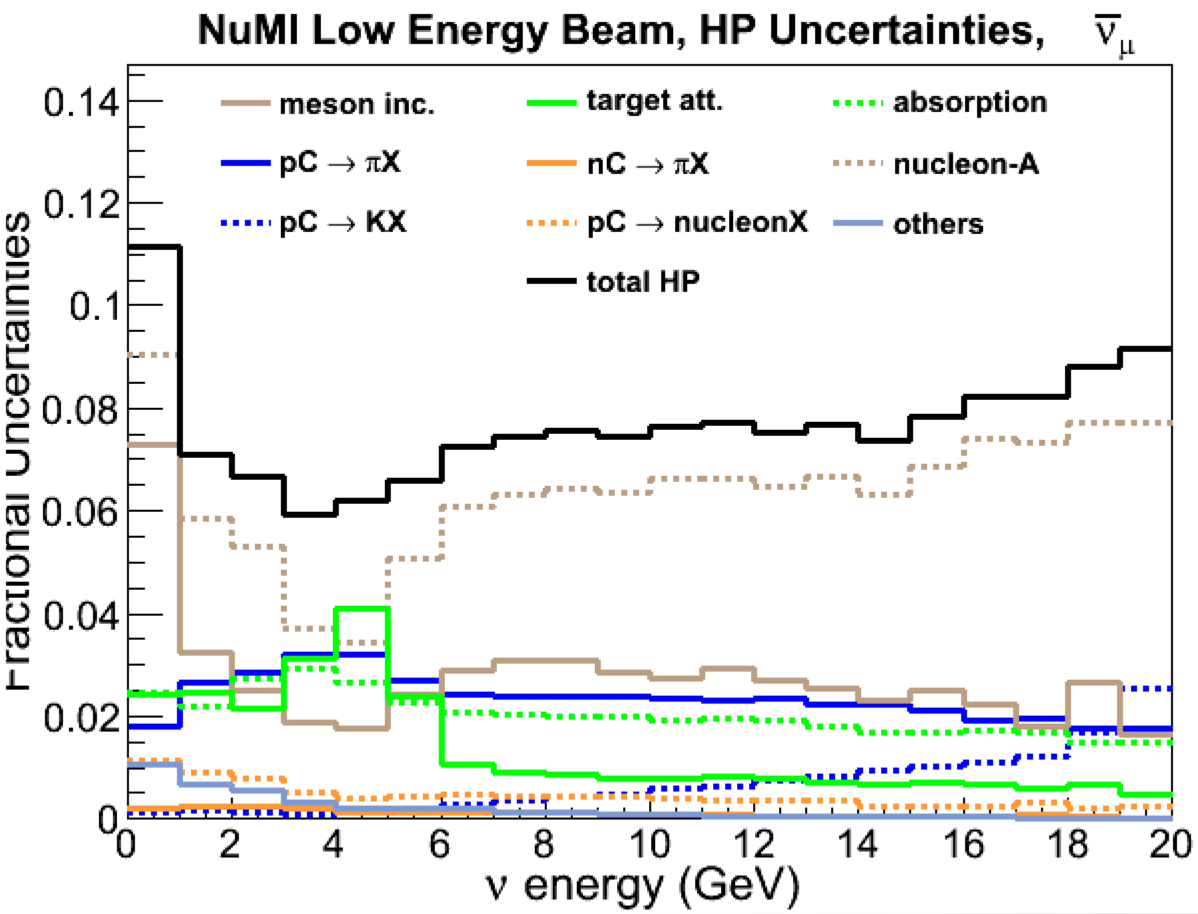
# Muon Neutrino



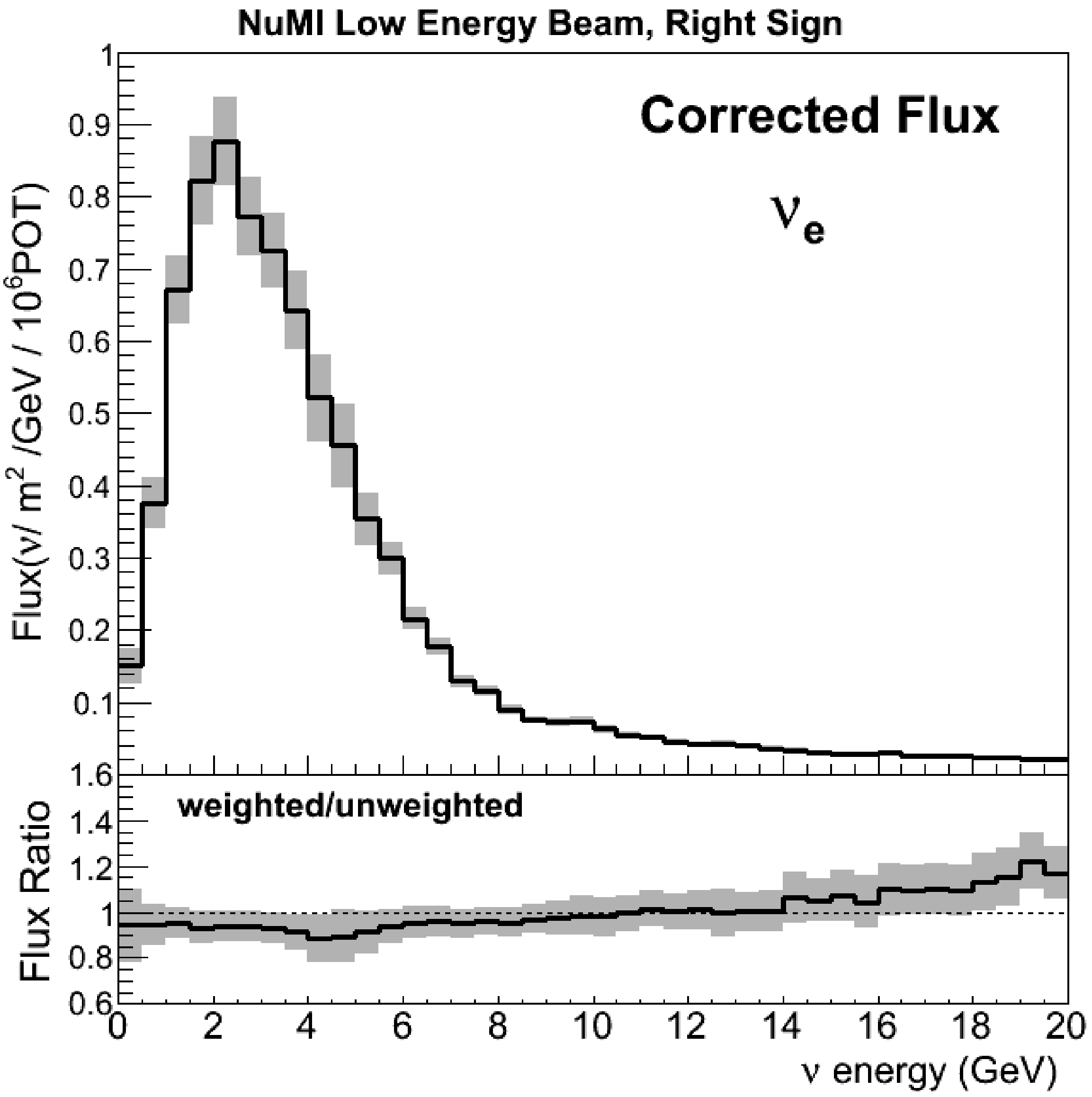



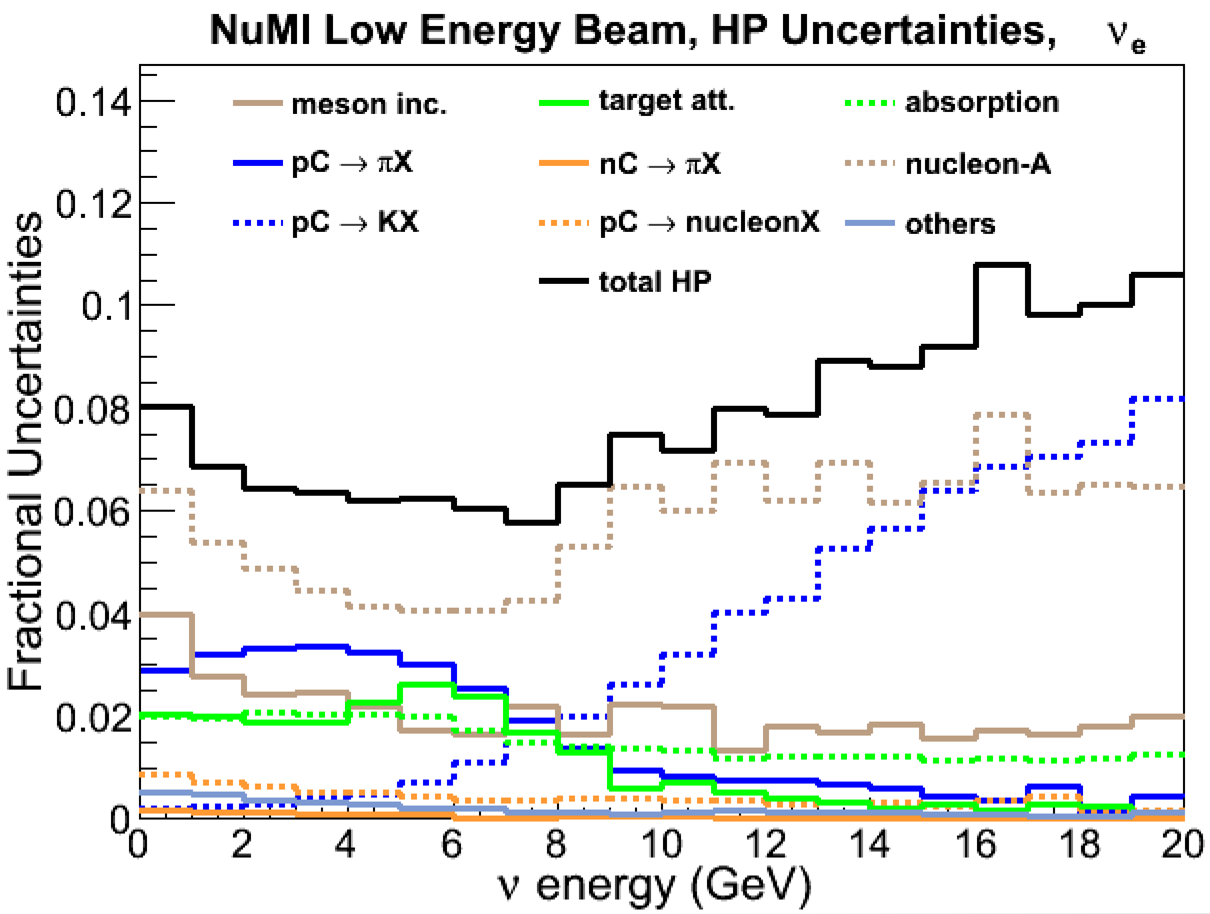
# Muon Anti-Neutrino



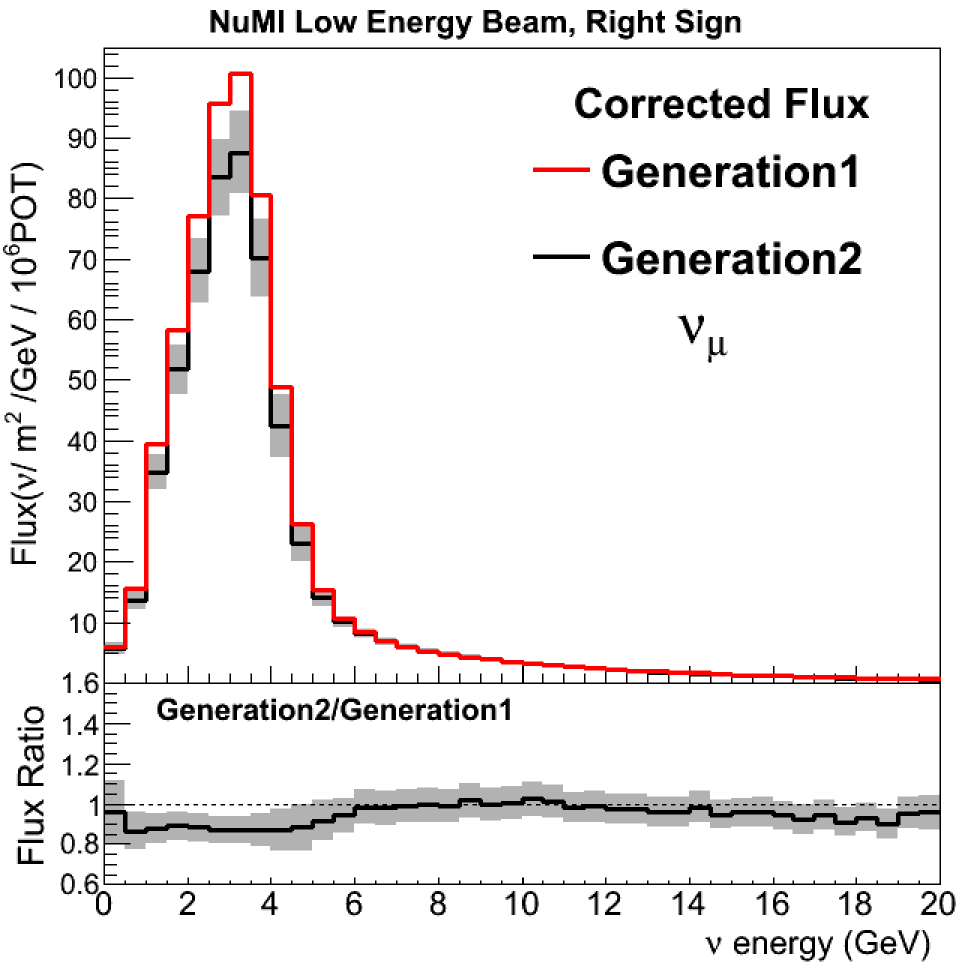



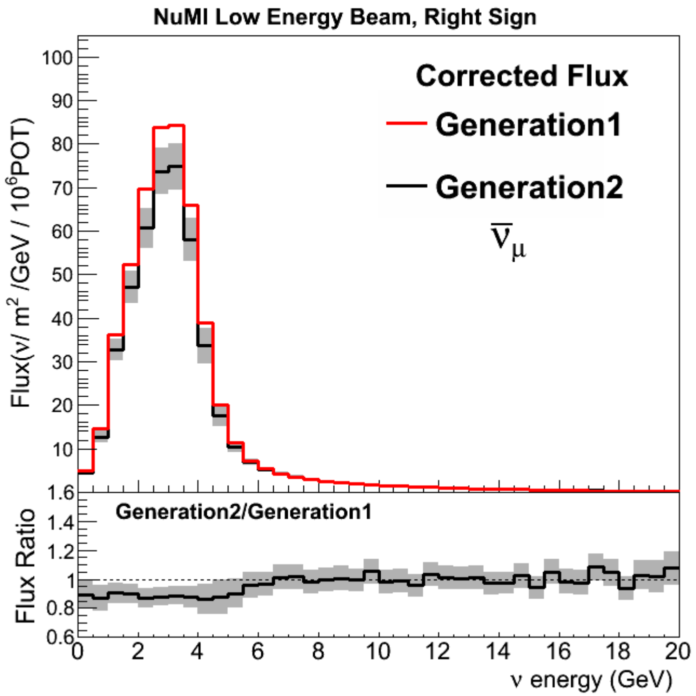
# Electron Neutrino

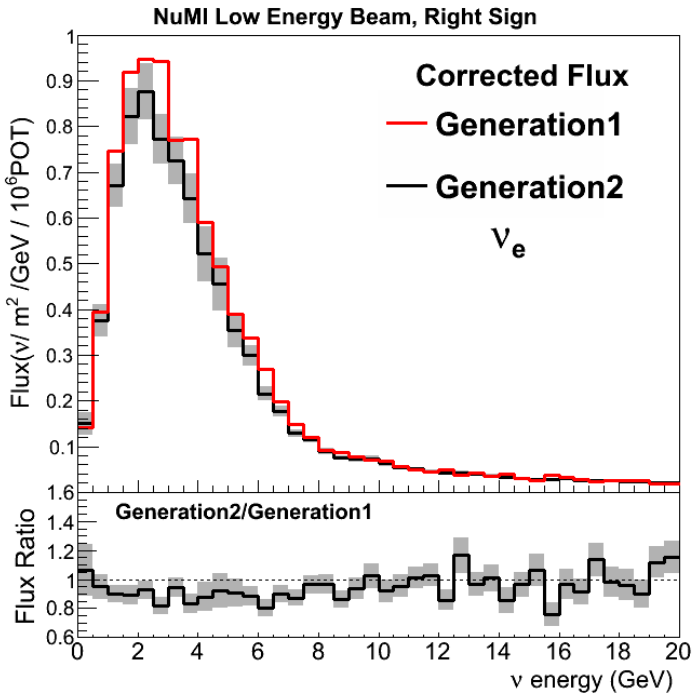


# Flux comparisons

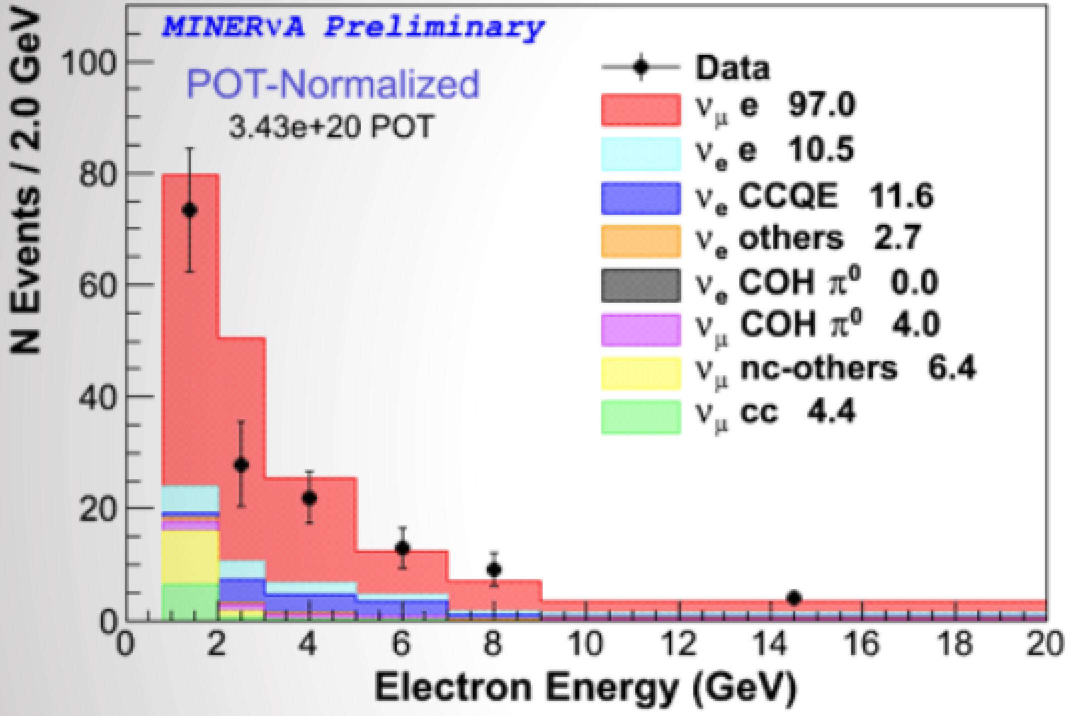


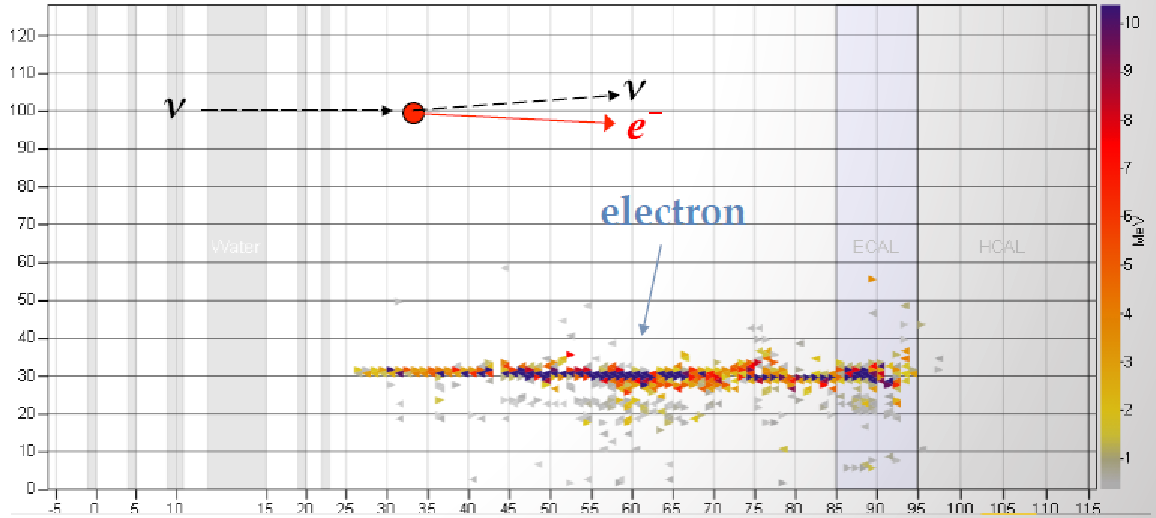
# ν-e scattering constraint

First analysis which uses this constraint: $\nu_e$ CCQE, see J. Wolcott talk on Tue

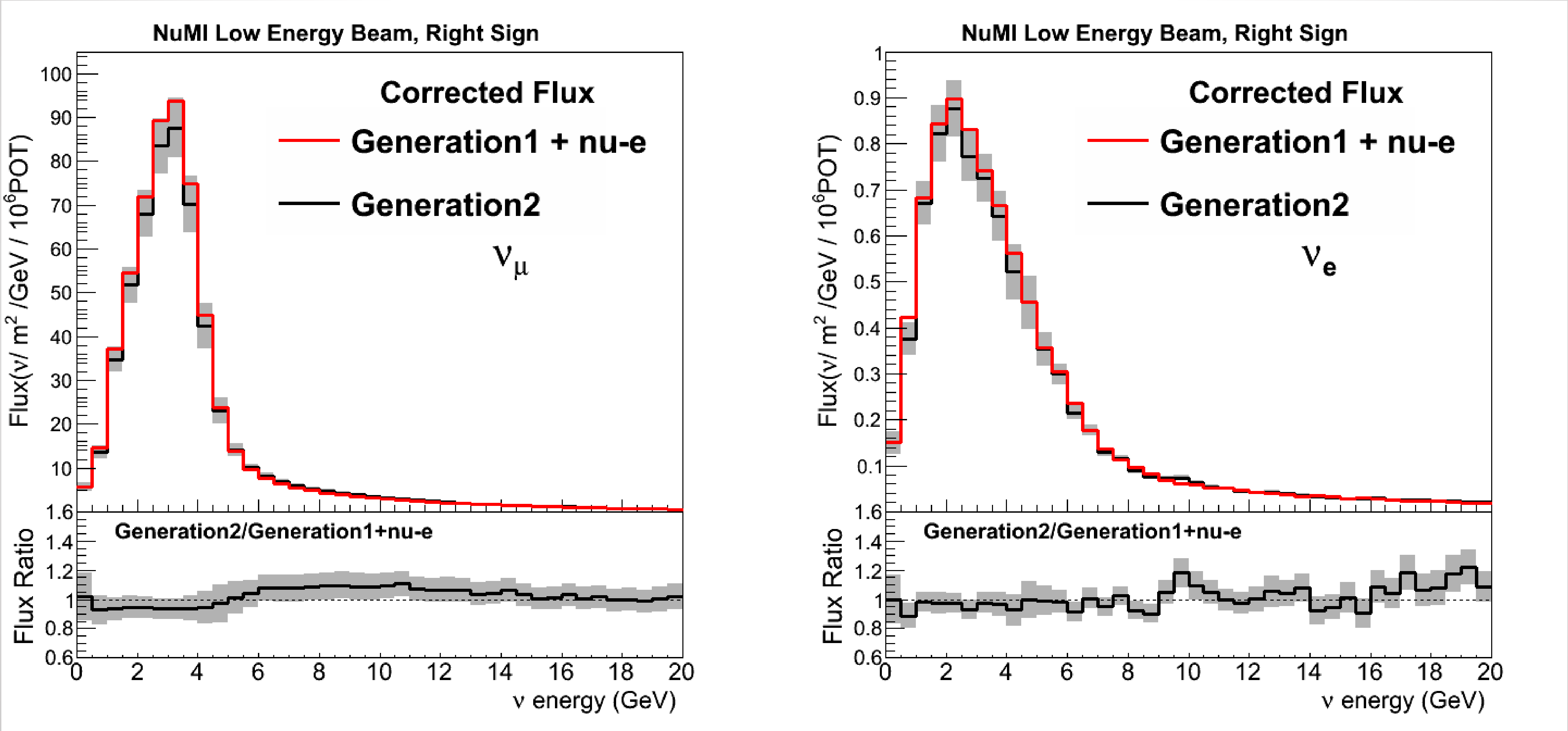



Predicted number of signal events is higher than indicated by data (weighting up universes that agree better with data)

- Electroweak theory predicts precisely cross section for neutrino-electron scattering
- Experimental signature is a very forward single electron in the finale state



# ν-e scattering constraint



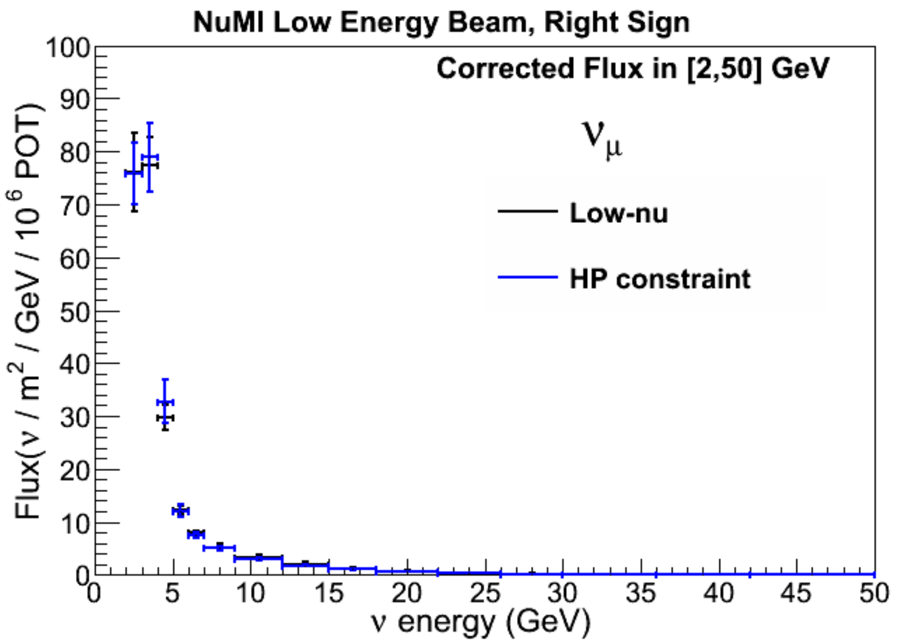
# Low-ν constraint

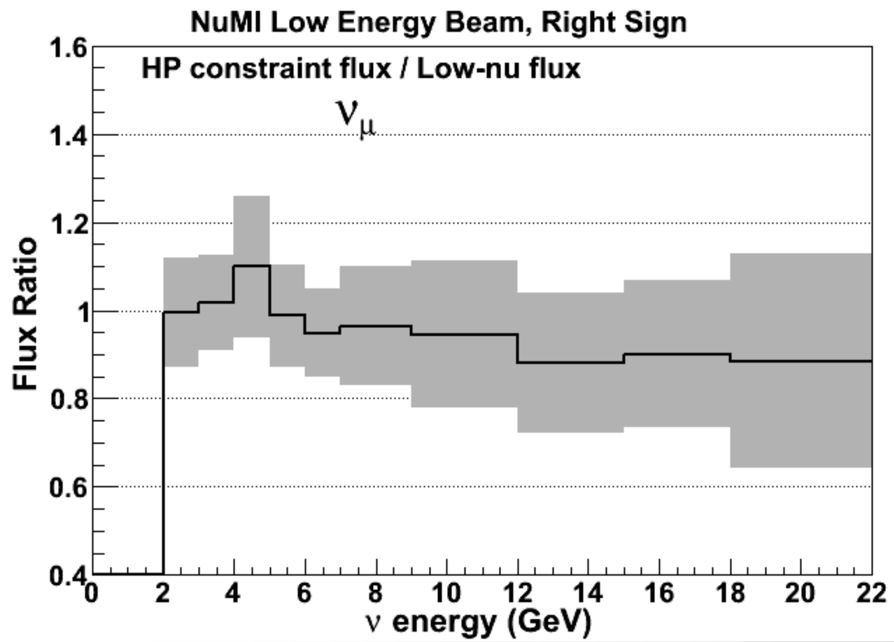
- Differential cross section can be approximated by

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

- It is constant for: $\frac{\nu}{E} \to 0$

- It can be used to constraint flux prediction
- At high energies normalization is fixed using high precision cross section measurements (like NOMAD)

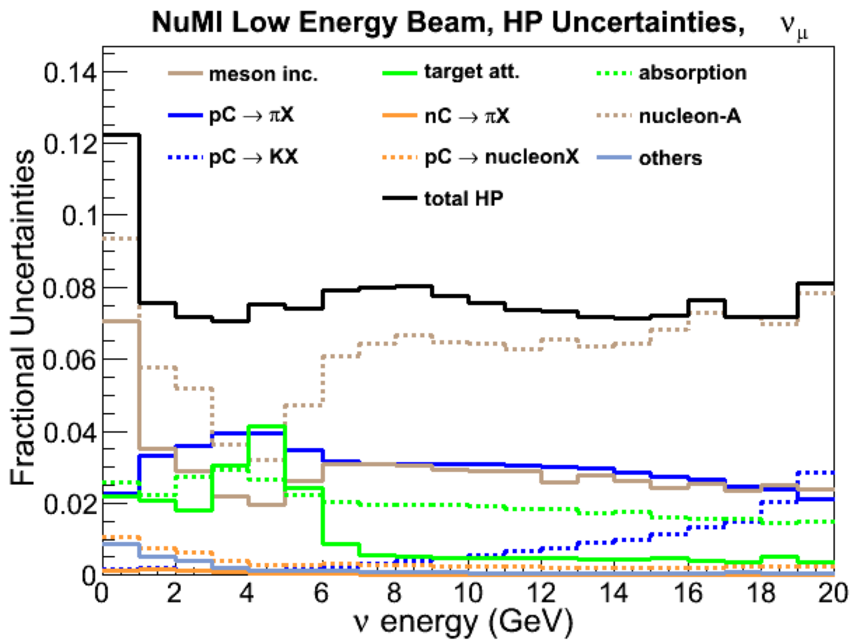


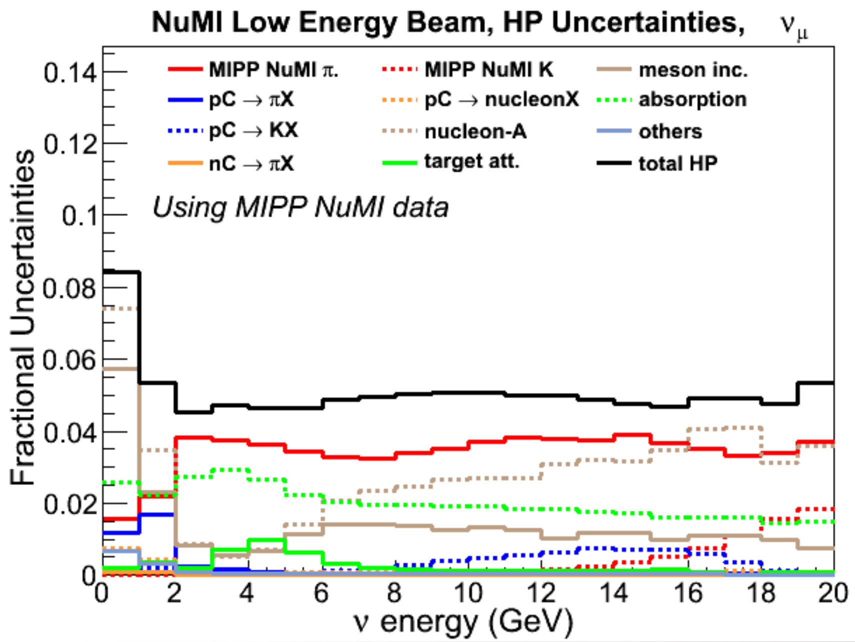




More details on Jan 8 Wine&Cheese by J. Nelson and J. DeVan PhD thesis

# Summary

- MINERvA's flux prediction is significantly improved
- Geometry of NuMI beamline is updated
- Geant4-based simulations are corrected using external hadron production data
- ν-e scattering analysis is done
- Work on low-ν constraint is done as well as inclusion of MIPP thick target data
- Do not miss Wine&Cheese by L. Aliaga on Dec 17 and by J. Nelson on Jan 8



# Backup slides

# Flux playlists

| Beam mode | Playlist | New Z position (cm) |
|---|---|---|
| LE FHC | 1 | 9.50 |
| nominal: | 7 | 9.18 |
| 10 cm | 9 | 10.40 |
| | 13 | 9.17 |
| LE RHC | downstream | 9.50 |
| | 5 | 8.85 |
| | 10 | 9.18 |
| LE 0HC | 6 | 9.18 |
| pME FHC | 2 | 99.57 |
| nom:100cm | 11 | 99.17 |
| pME RHC | 3 | 99.57 |
| | 12 | 99.17 |
| pHE FHC | 4 | 249.57 |
| nom:250cm | 8 | 250.09 |

Table 1: Playlists flux production

# Interaction map legend

pC -> πX: NA49 data scaled using FLUKA (checked by comparing with NA61)

pC -> KX: NA49 data and K/π ratios from MIPP

pC -> NX: NA49 data for nucleon production

nC -> pX: assuming isoscalar symmetry

nucleon-A: for targets other than C

A-scaling is applied for kinemtics covered by data

otherwise 40% assumed

meson-inc: meson as the projectile, educated guess (uncorrelated 40% uncertainty)

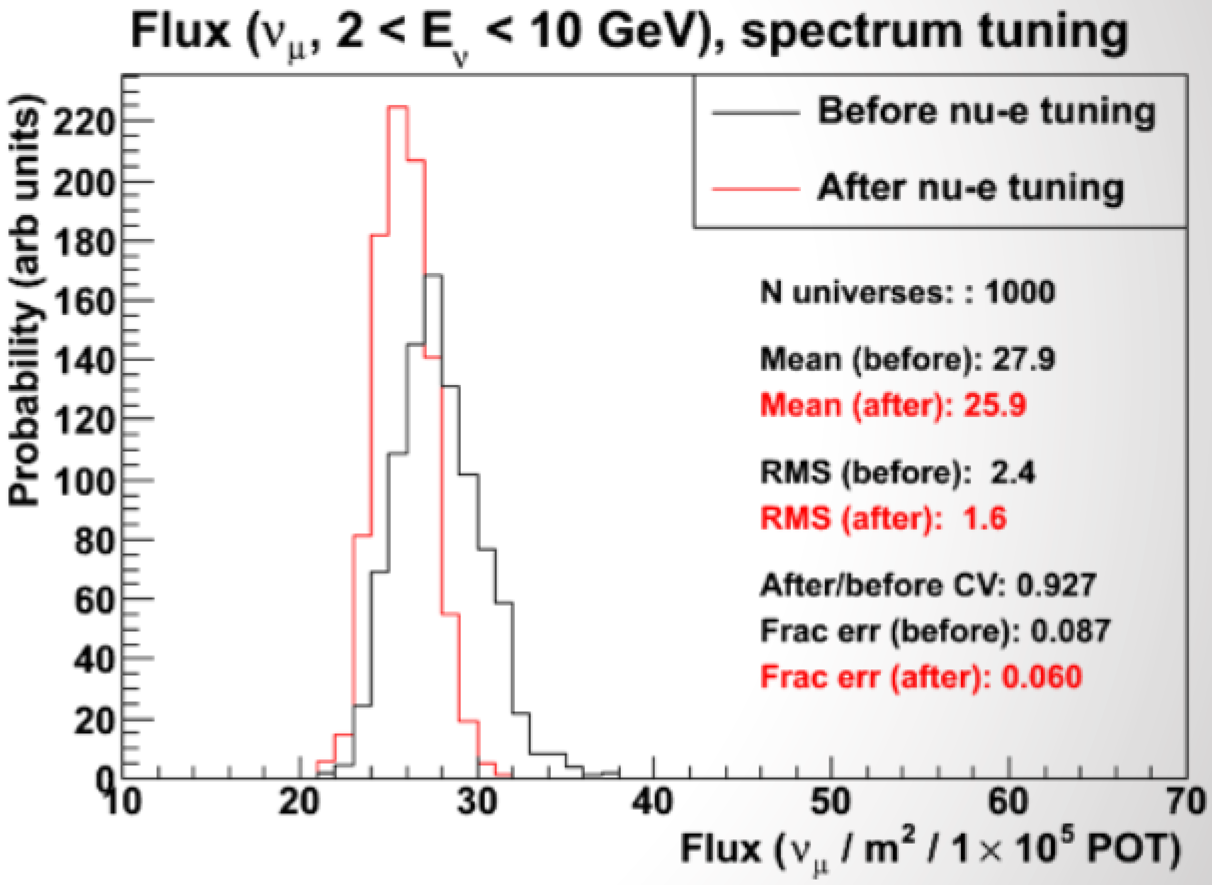
others: anything else, really rare, assuming 40% uncertainty

# ν-e scattering constraint

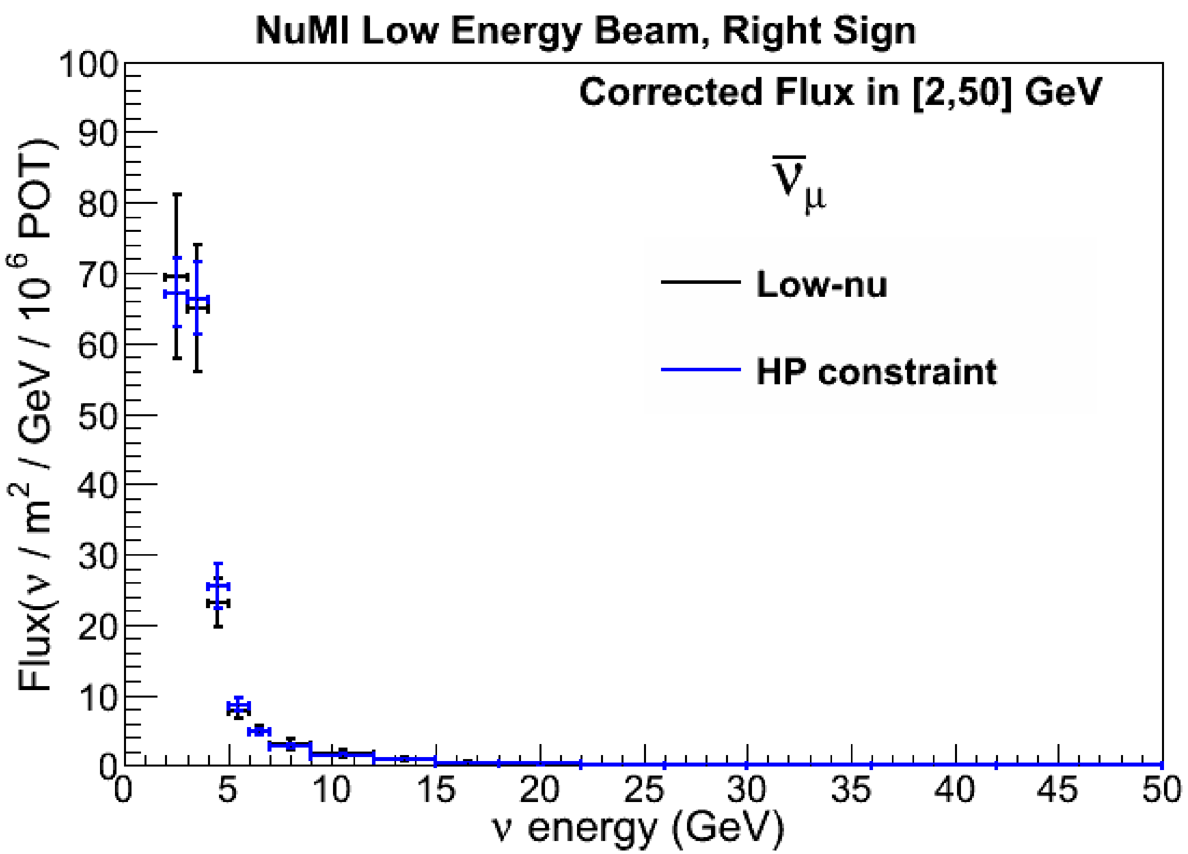
Probability of a universe:

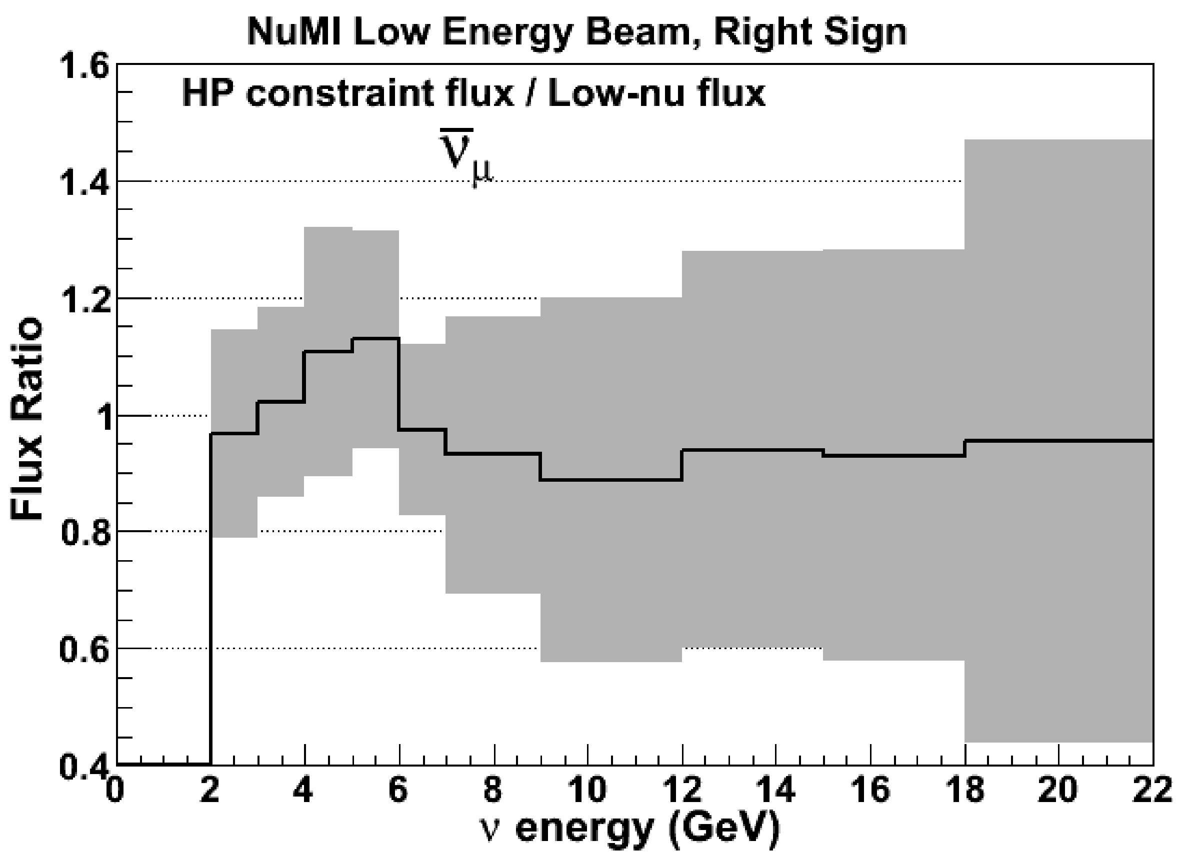
$$f(x,\mu,\sigma)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- μ: data events
- σ: error on data (fraction uncertainty = 13%)
- x: MC events in i-th multi-universe

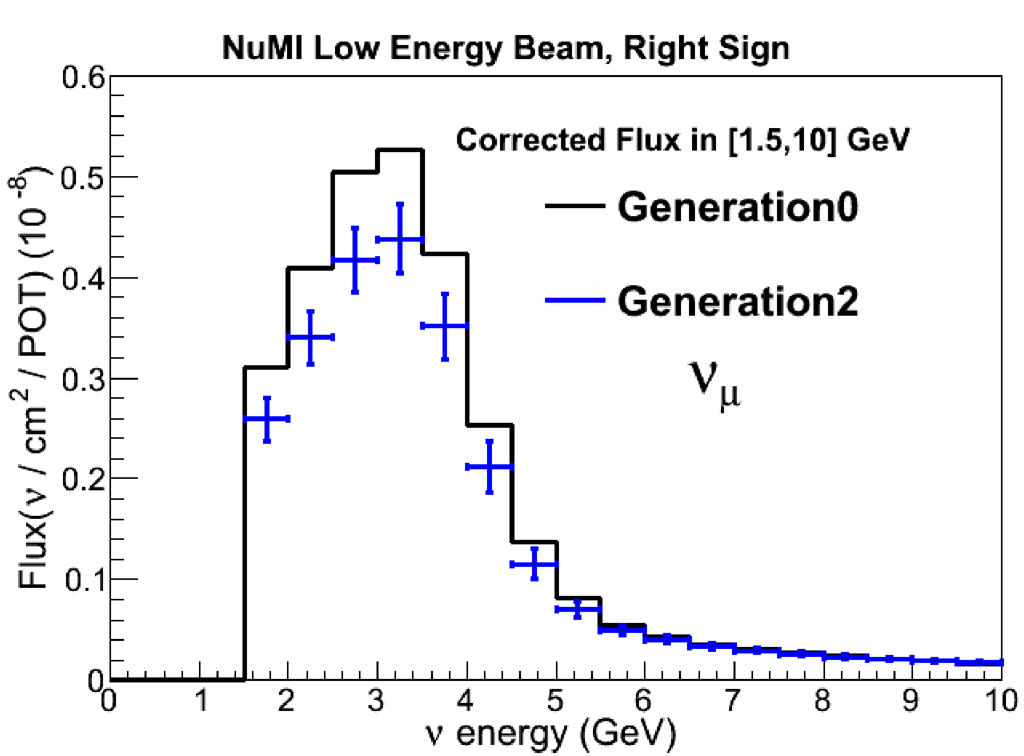


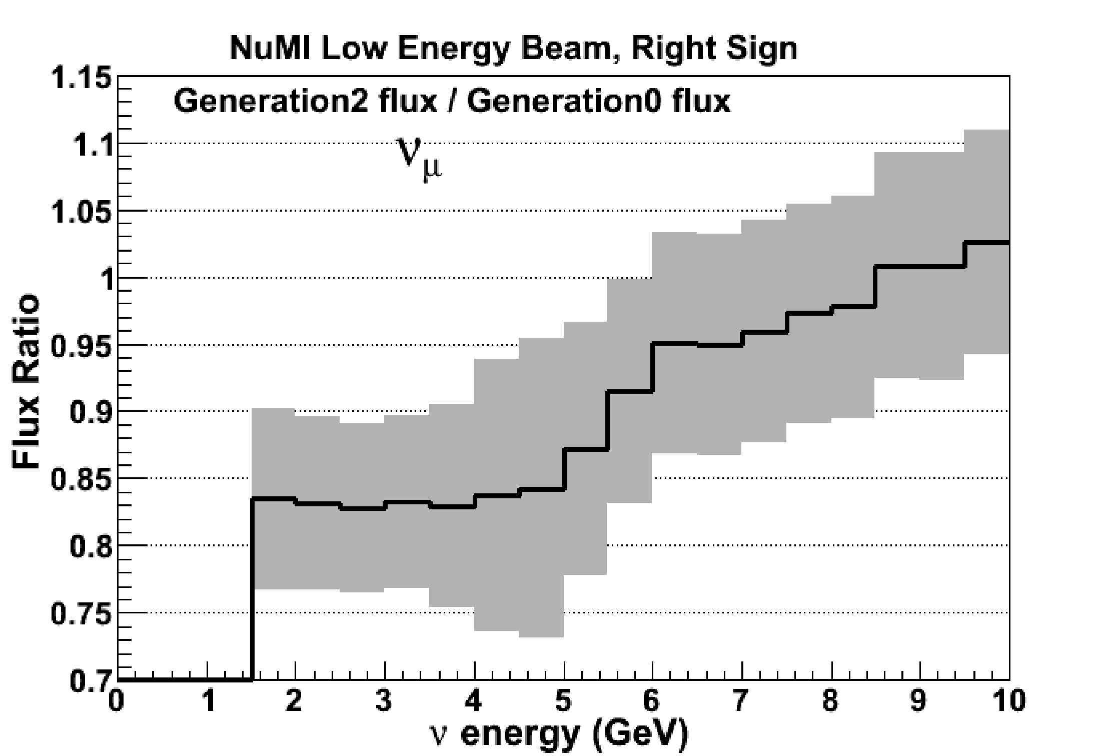
# Low-ν constraint



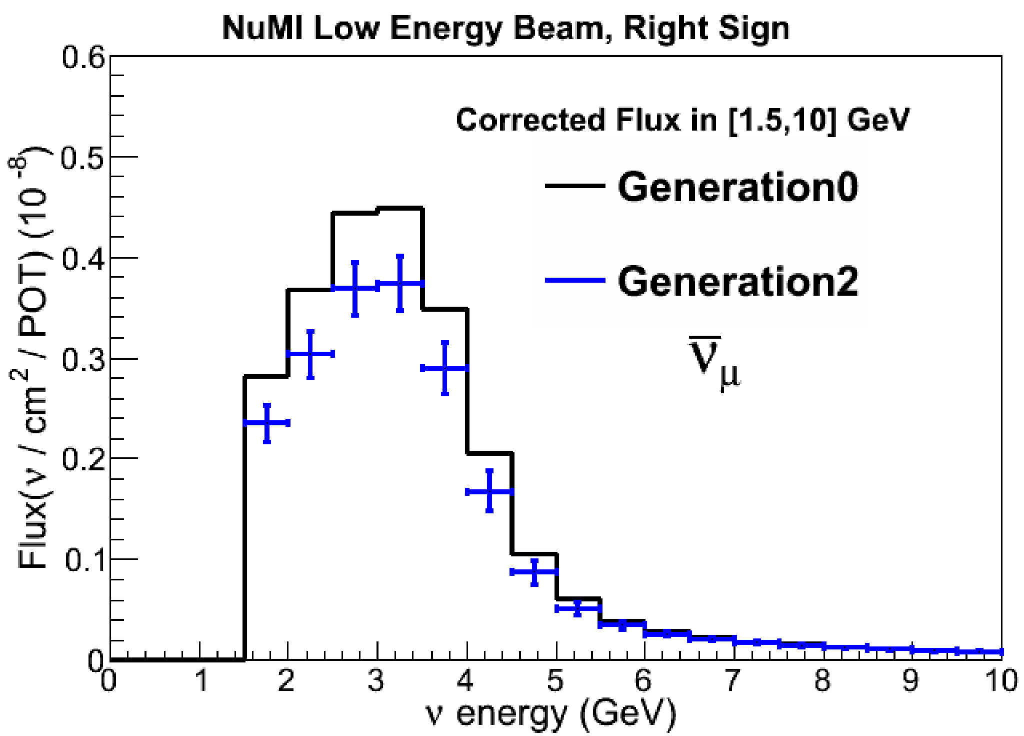



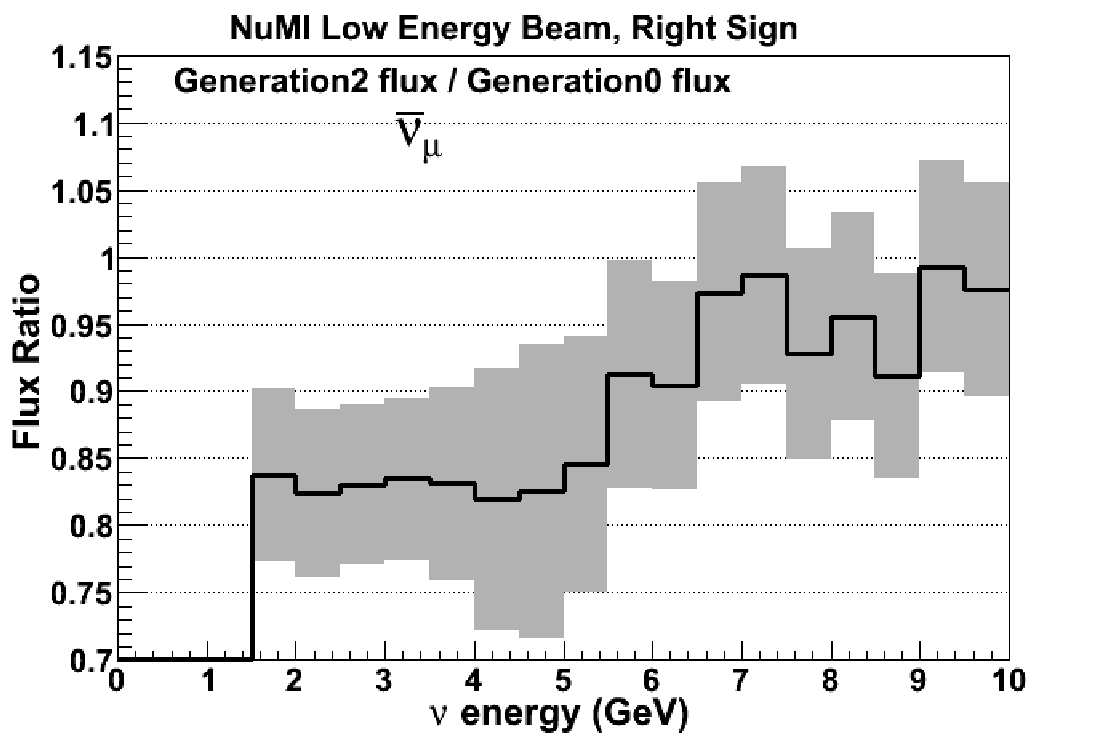
# Gen 0 vs Gen 2 (muon neutrino)



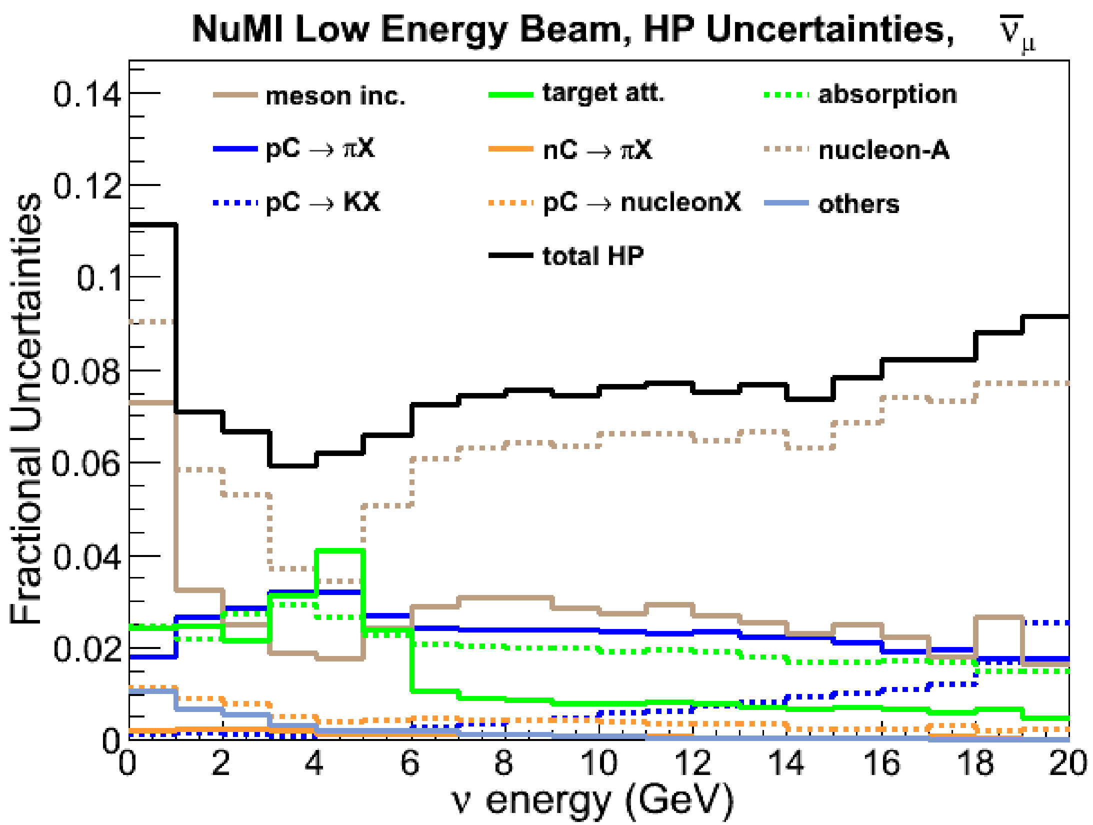



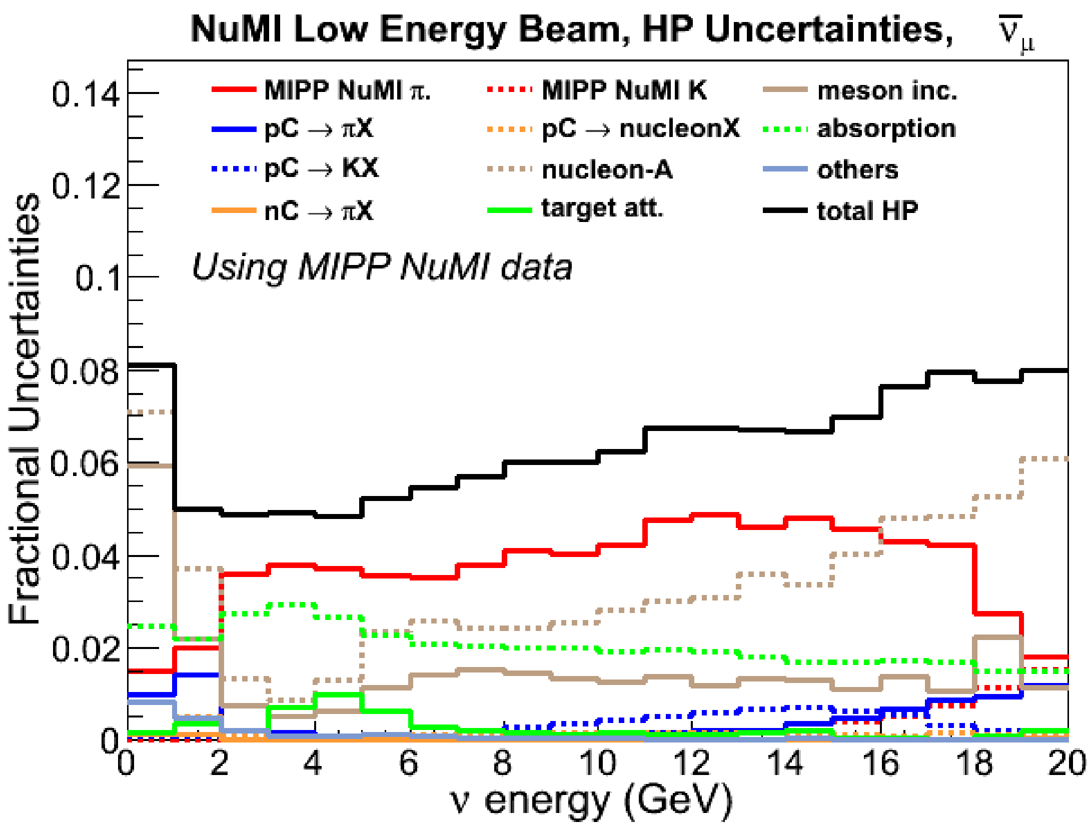
# Gen 0 vs Gen 2 (muon antineutrino)



# MIPP thin data



# MIPP thin data