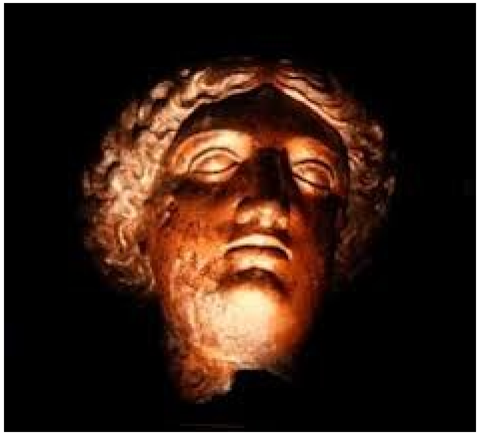
Meeting on Neutrino Flux Prediction



Constraining the Neutrino Flux: MINERvA

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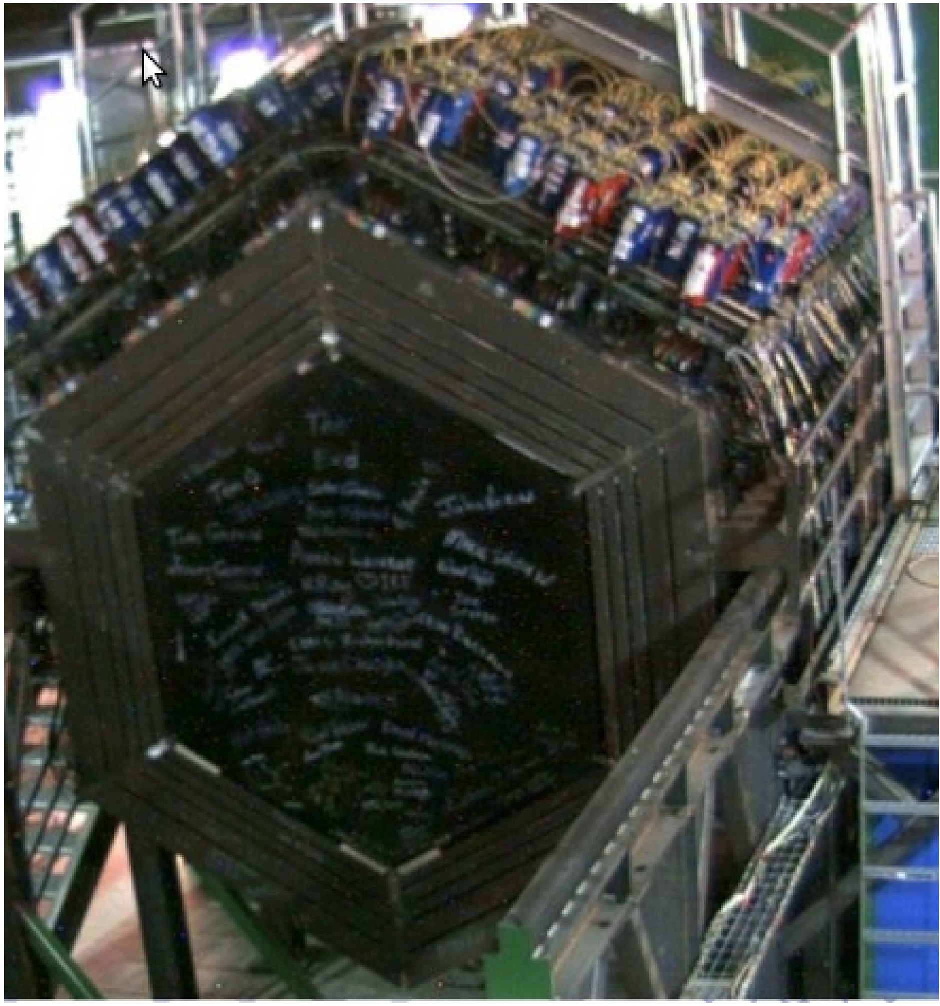
College of William and Mary
Sept 22, 2014

MINERvA

Our main goals are to measure:

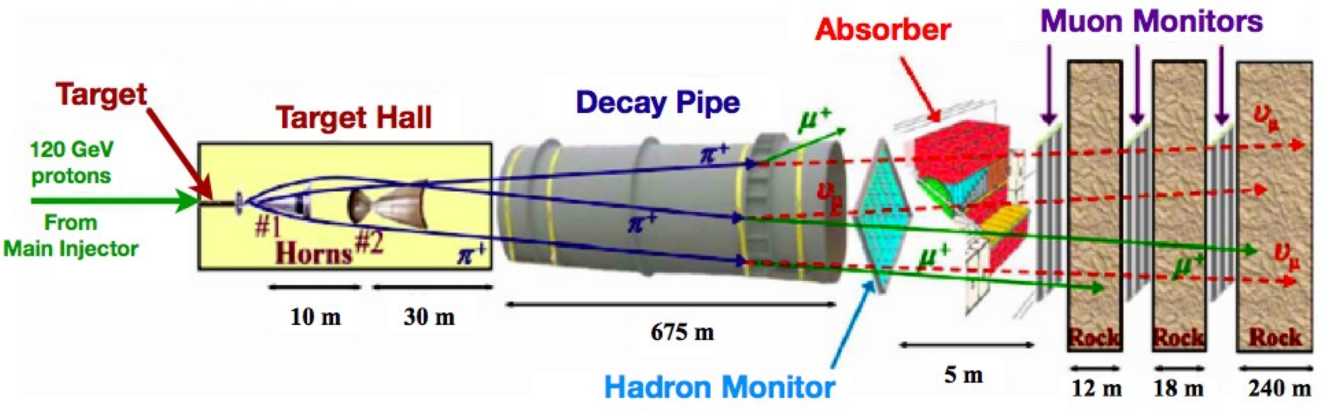
- ***Neutrino-nucleus cross sections of exclusive and inclusive final states.***
- ***The nuclear effects on the ν-A interactions and form factors and structure functions.***

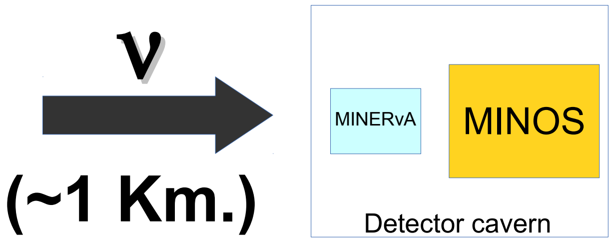
To produce high precision measurements of absolute cross sections...

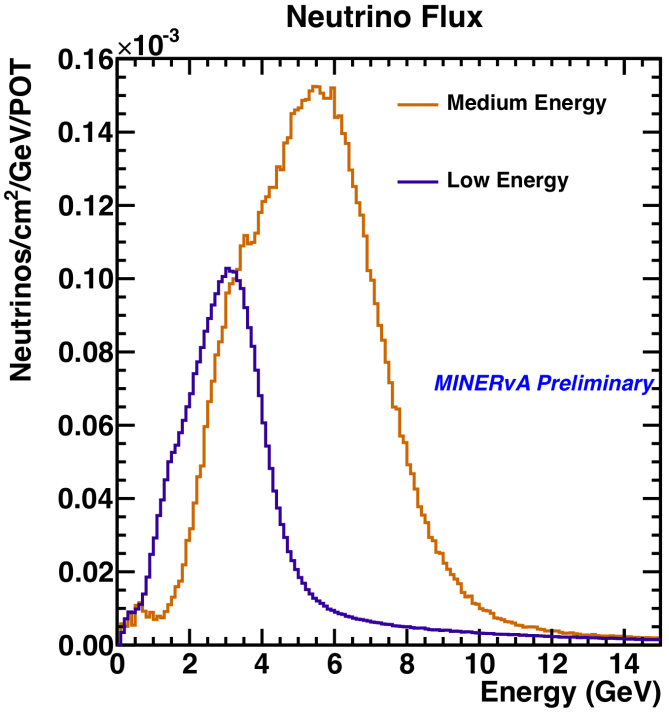


→ We need to know our flux

MINERvA







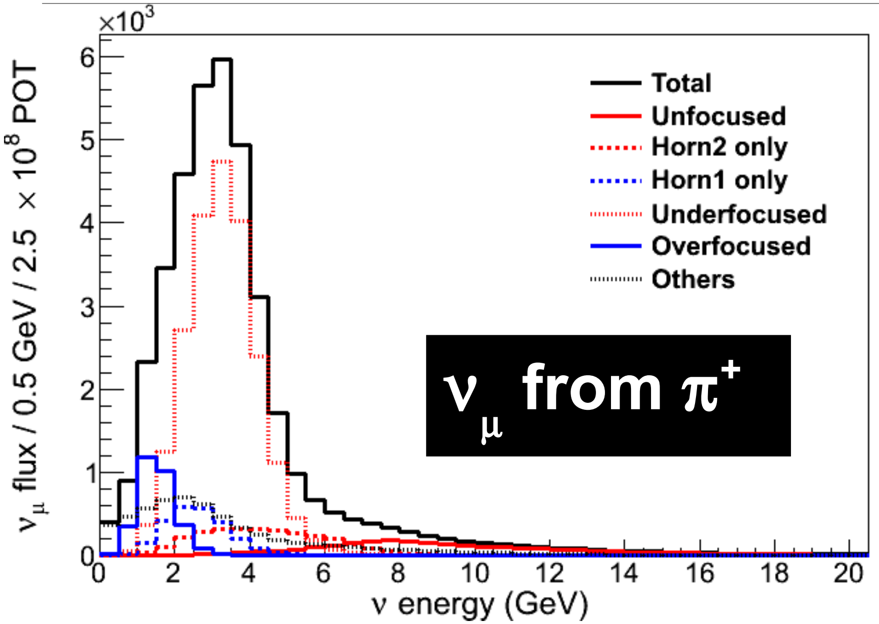
Two basic source of uncertainties:

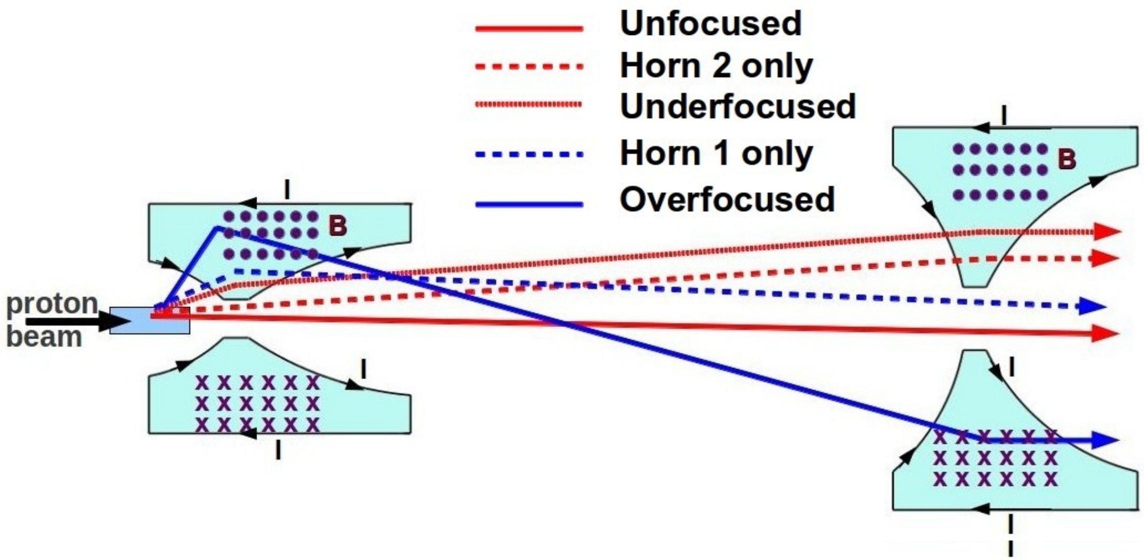
- The description of the focusing components in the Monte Carlo is uncertain or incomplete.
- The theory of the hadronic interactions is not complete (MC needs a model).

- *Flux simulation uses: geant4_9_2p03.*
- *Hadronic model: FTFP_BERT.*

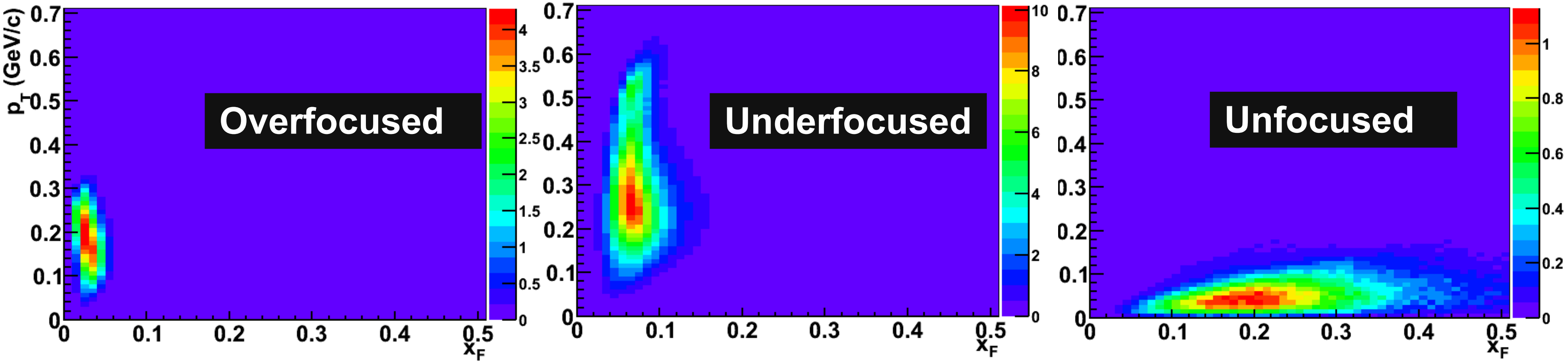
Understanding the Flux

Focusing Components





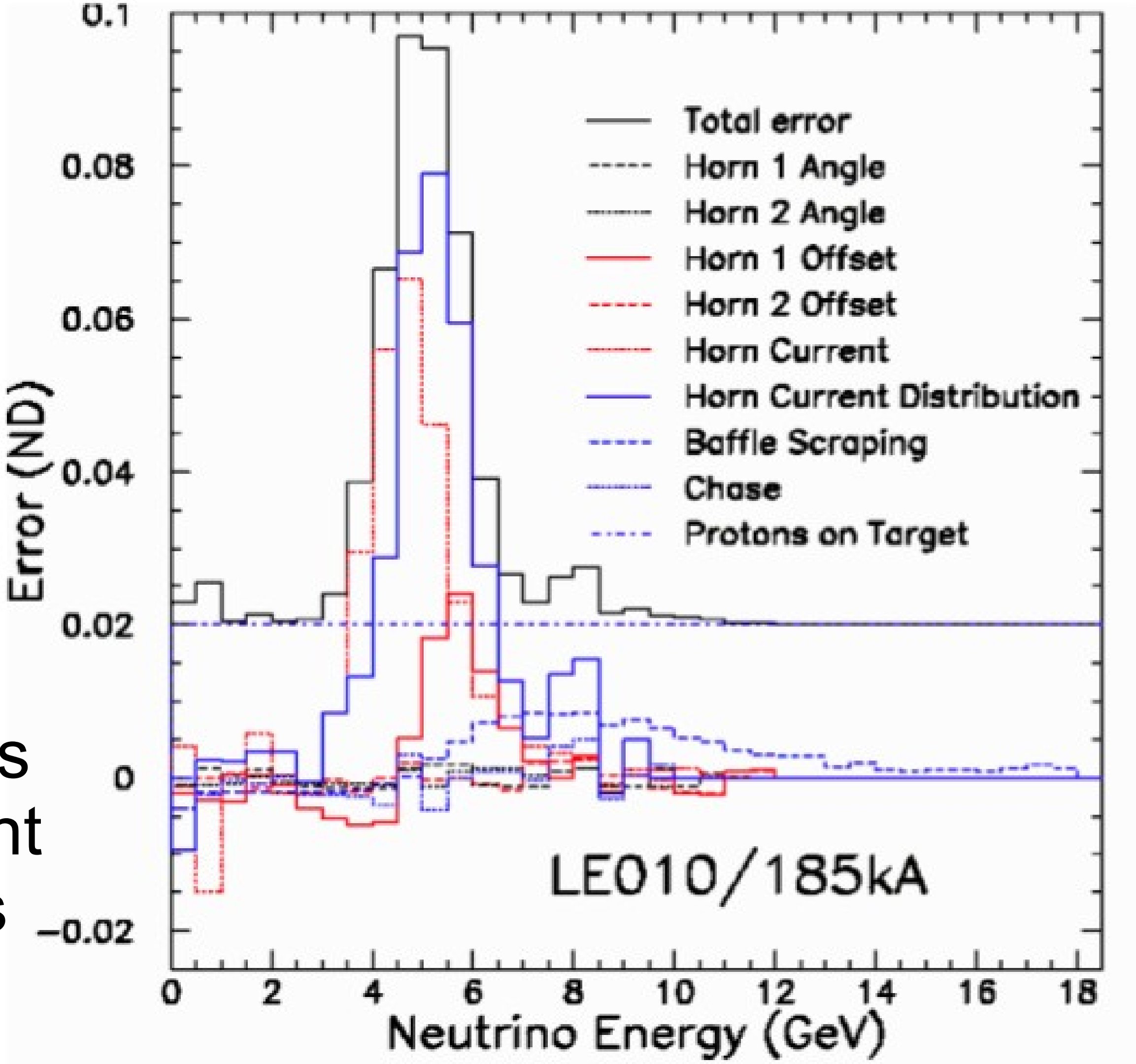
- Underfocused components are most prevalent in the focusing peak.
- Unfocused components are most prevalent in the tail.



x_F: Feynman-x, $x_F = 2p_L^{CM}/\sqrt{s}$

Focusing Uncertainties

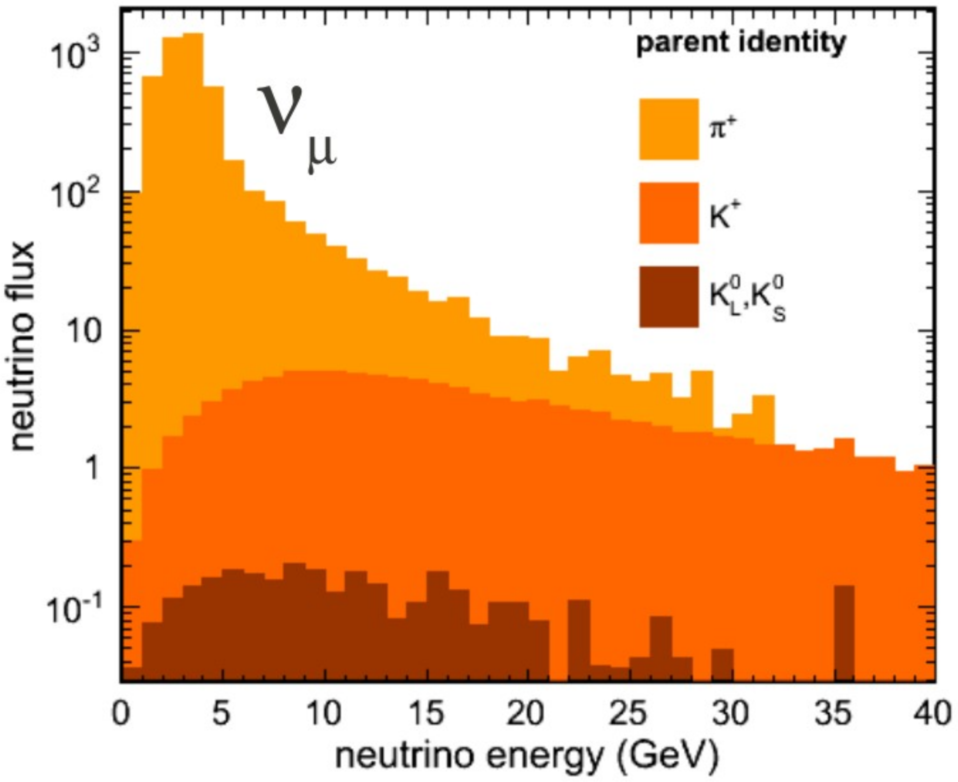
- These uncertainties are bigger in the falling edge of the focusing peak.
- We are revisiting these values with our MC flux simulation.
- One of the preliminary results indicates that the horn current distribution in the conductors is smaller than we assume.



Z. Pavlovich, "Observation of disappearance of muon neutrinos in the NuMI beam", PhD thesis, UT Austin 2008

Neutrino Parents

Parents

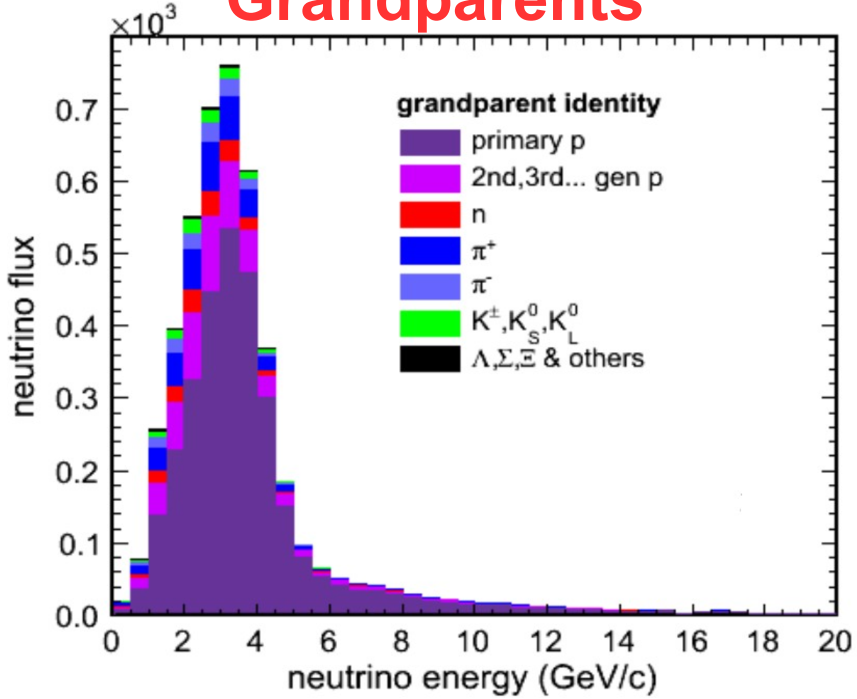


- <25 GeV, π's parents are dominating.
- >25 GeV, K's are dominating.

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%**

Grandparents



Multi-prong Approach to Constrain the Flux

- External hadron production (HP) data:
  - Thin target.
  - MIPP Numi Target.

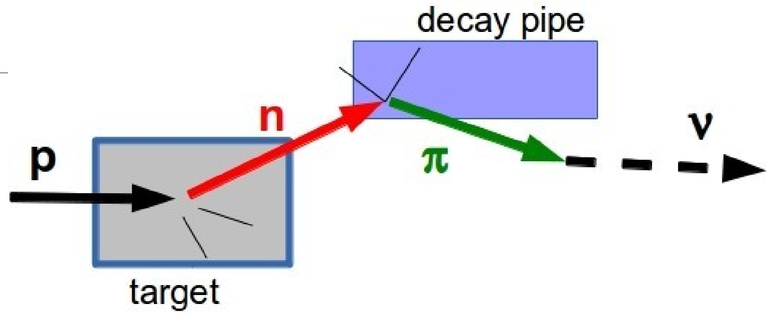
In-situ measurements:

- $\nu -$ atomic electron interactions (JETP, Dec20, 2013).
- Low-nu method.
- Special runs varying some beam parameters.

Redundancy and complementarity will improve our accuracy...

HP Constraints on the Flux

HP Correction Procedure



- The cascades that lead to ν's are tabulated at generation. The kinematics and the material of the cascade are saved.

- Then a correction the primary beam attenuation in the target is applied.

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

L: distance travels in the target

ρ: target density.

- Interactions of a proton on carbon between $p_{incident}$ in [12, 120] GeV/c producing a particle (NA49-like) are reweighted using NA49 (pC @ 158 GeV) as:

$$f_{Data}(x_F, p_T, E)/f_{MC}(x_F, p_T, E)$$

$$f = E\,d^3\sigma/dp^3$$

- Energy scaling corrections are calculated by scaling the Data by Fluka and checking by comparing to NA61 pC @ 31 GeV *[Phys.Rev. C84 (2011)034604].*

- Currently, interactions on Al, Fe, He and Air are treated as if on C.

Multi-Universe Technique to Evaluate Systematics

- The “multi-universe” method is the creation of a statistical ensemble of individual randomly generated universes.

- Each “universe” chooses a value for specific parameters from the range of possible values:
  - Neutrino flux.
  - MINERvA detector.
  - Cross-sections.

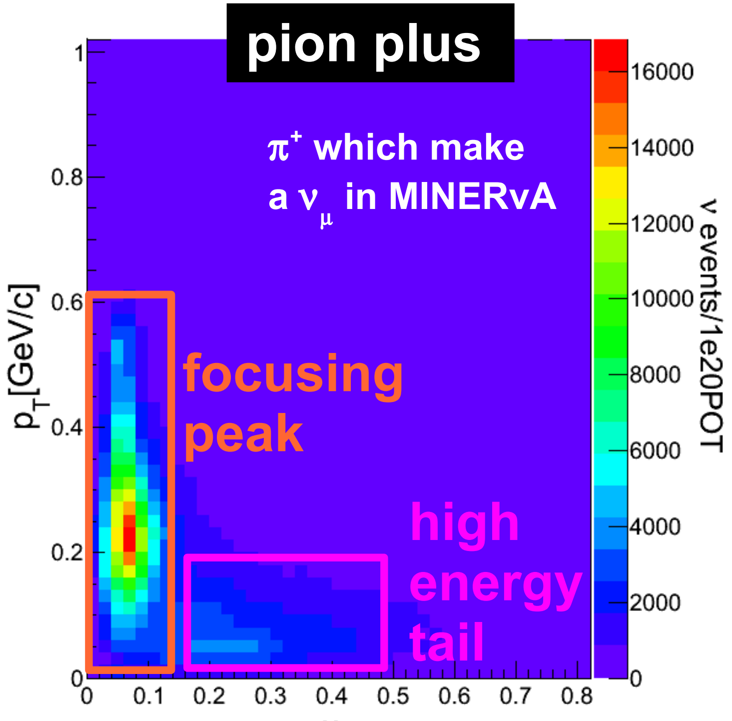
- Measurements are repeated in each individual universe and the statistical variations are used to evaluate systematic uncertainties.

- When constrained by data, HP uncertainties are calculated by taking the data's uncertainty and adding the uncertainty from the energy scaling.
- Where no data is available, model spread is used to calculate the uncertainty.

Datasets Used

- NA49 pC @ 158 GeV (p$_T$ dependence)
  - $\pi^\pm$ production for xF < 0.5 *[Eur.Phys.J. C49 (2007) 897]*
  - $K^\pm$ production for xF < 0.2 *[G. Tinti Ph.D. thesis]*
  - p production for xF < 0.95 [*Eur.Phys.J. C73 (2013) 2364]*
- Barton pC @ 100 GeV (0.3< p$_T$ <0.5 GeV/c)
  - $\pi^\pm$ production for xF > 0.5 *[Phys.Rev. D27 (1983) 2580]*
- MIPP pC @ 120 GeV
  - – K/π + NA49 extend kaon coverage to xF < 0.5 *[A. Lebedev Ph.D. thesis].*

Hadron Production

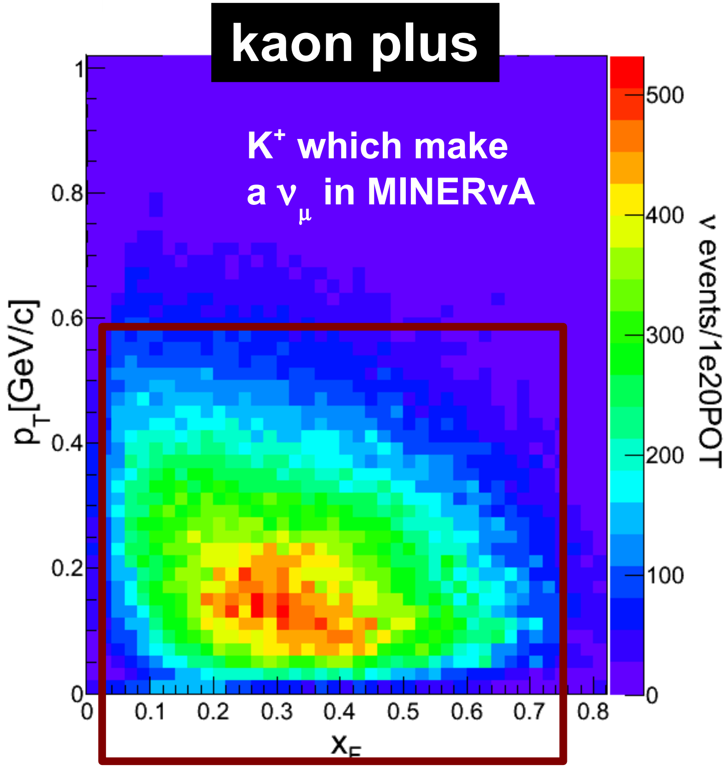


pion plus

π^+ which make a ν_μ in MINERvA

focusing peak

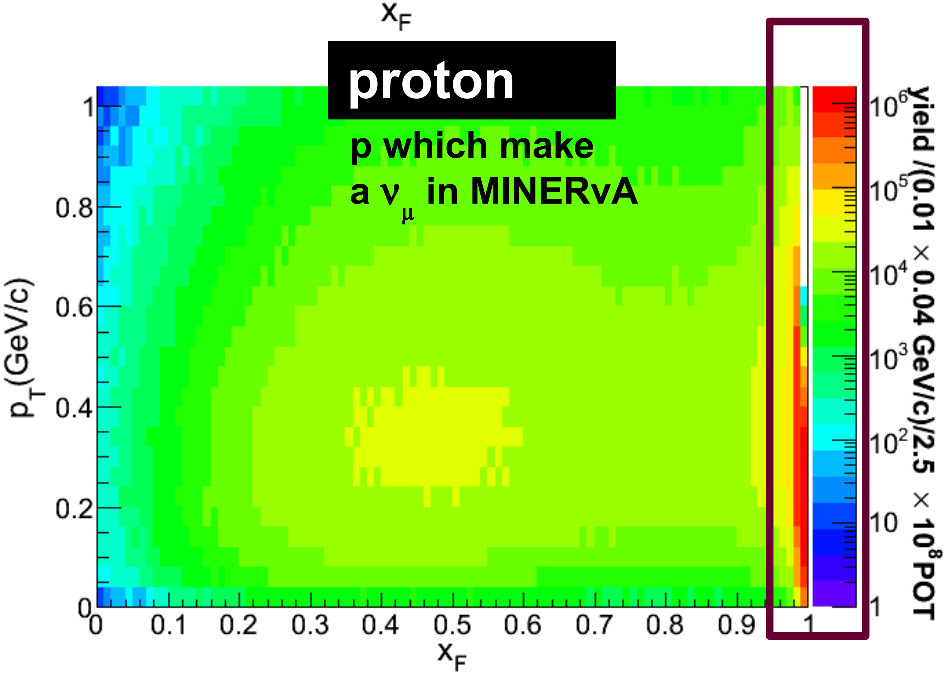
high energy tail



kaon plus

K^+ which make a ν_μ in MINERvA

broader range



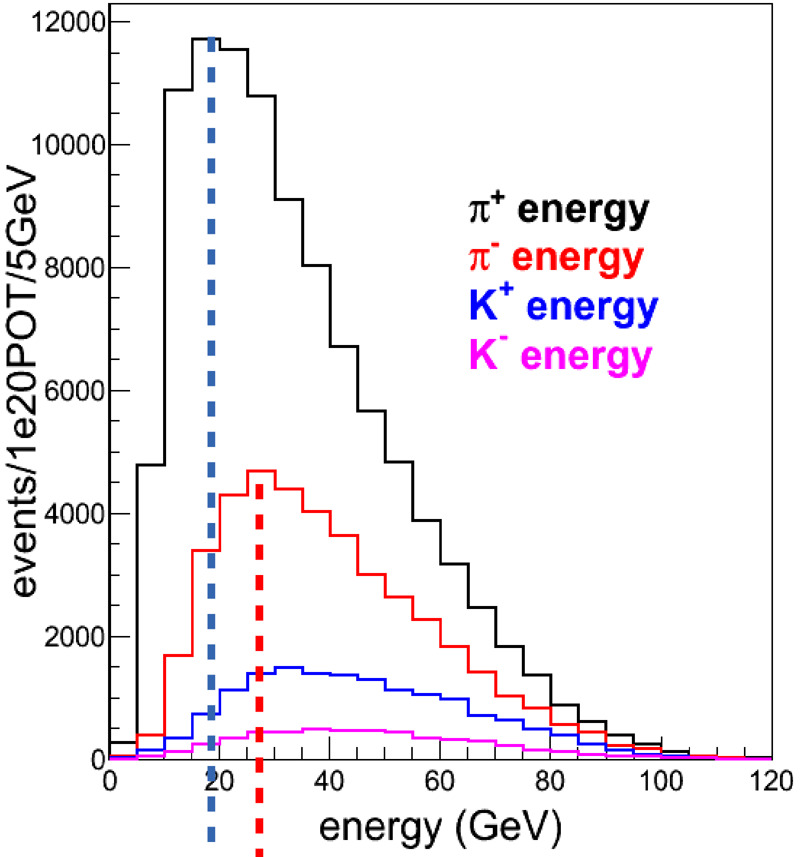
proton

p which make a ν_μ in MINERvA

Many of them with high momentum (quasi-elastics).

Interactions in the Target

π(K)'s that interact in the target

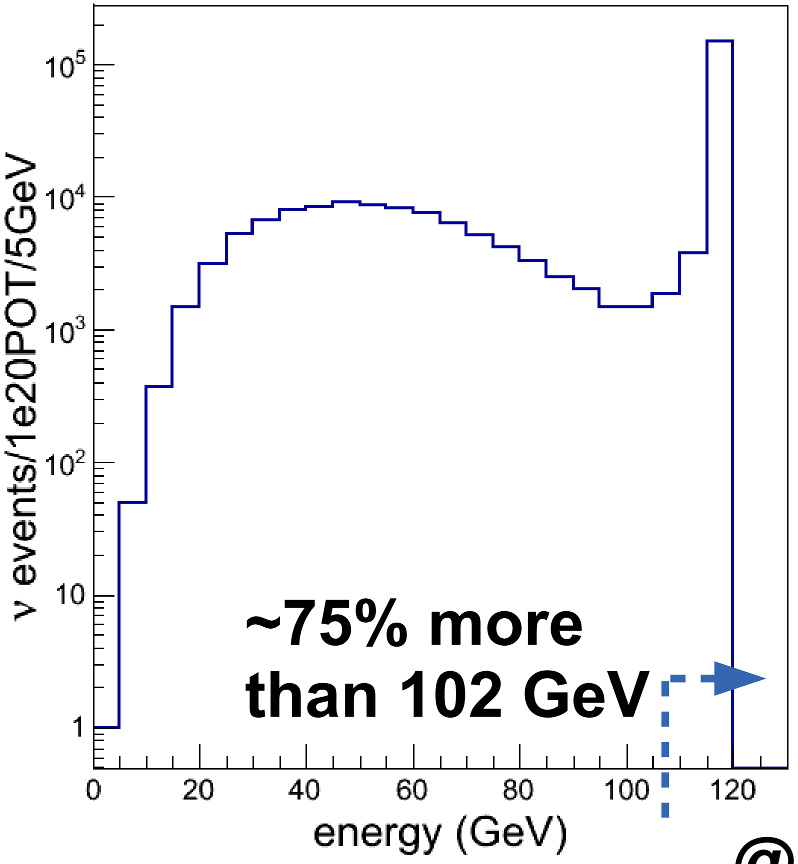


~30 GeV

~20 GeV

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

protons that interact in the target



~75% more than 102 GeV

$$pC \rightarrow pX$$
$$pC \rightarrow pN'n$$

@ 120 GeV

$$pC \rightarrow pX$$
$$pC \rightarrow pN'n$$

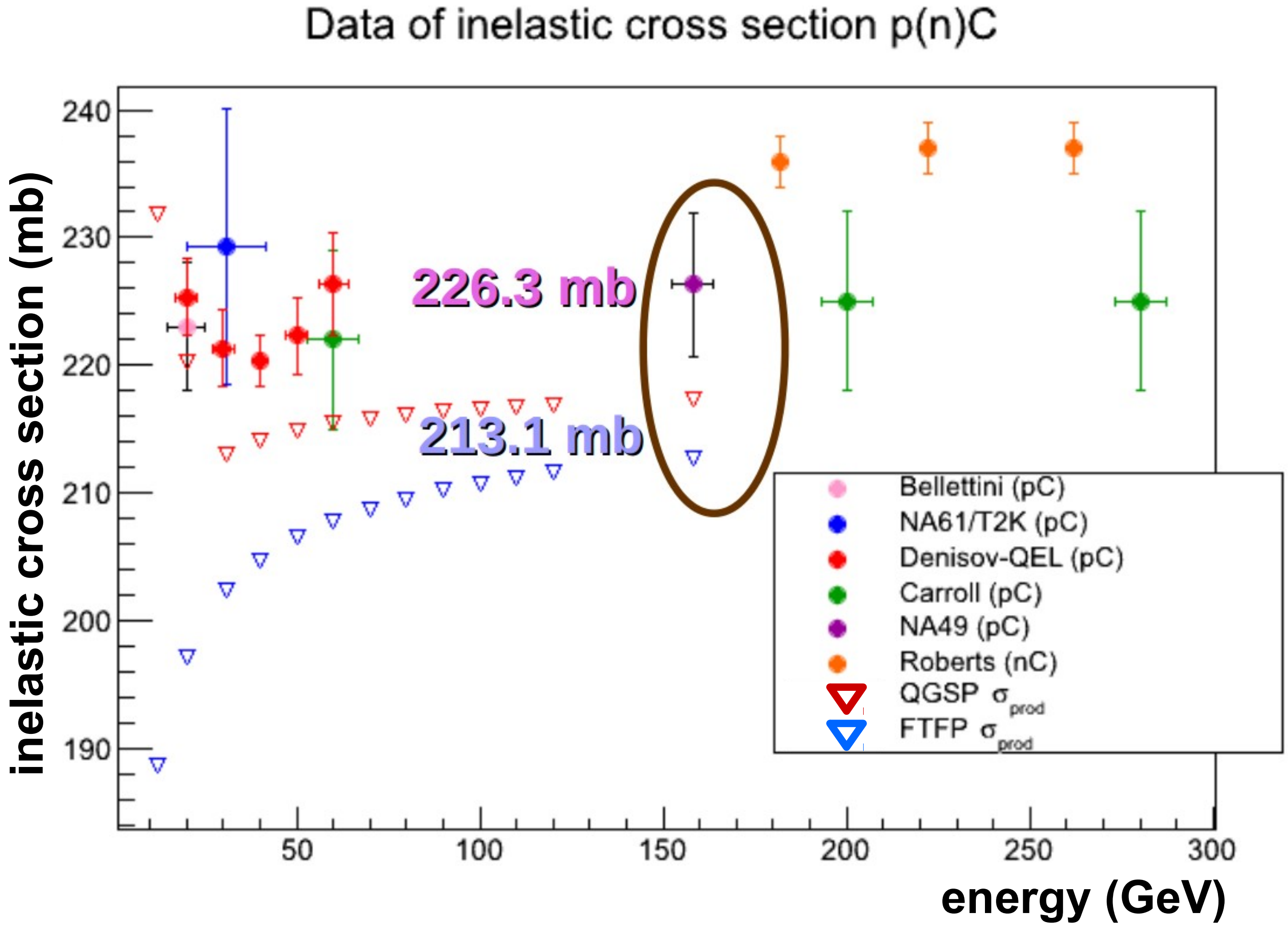
Inelastic Cross Section

- Data – MC inelastic cross section disagreement will lead to discrepancies in:

- beam attenuation.
- Interaction position.

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

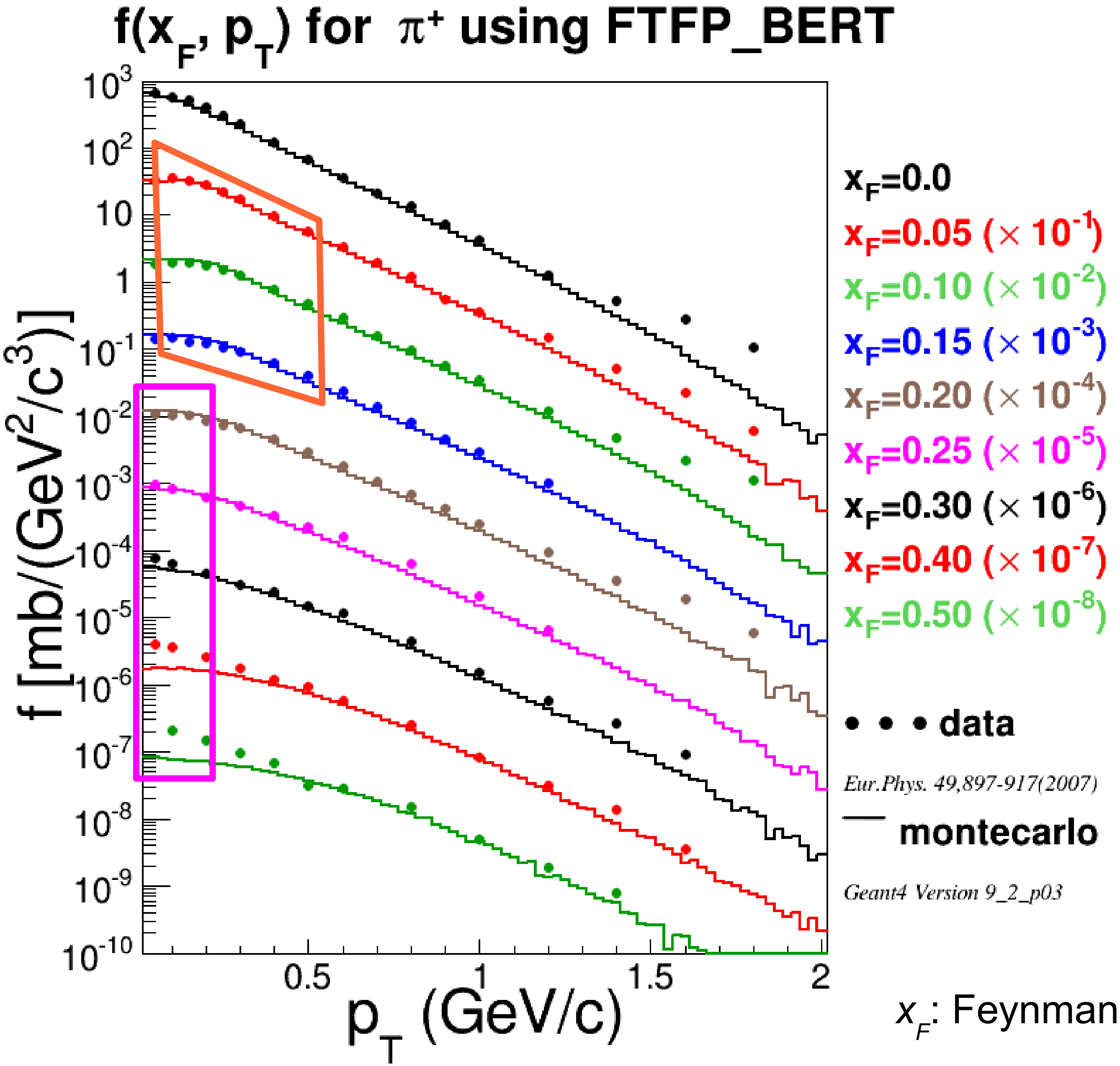
- Effect of 5% correction down.

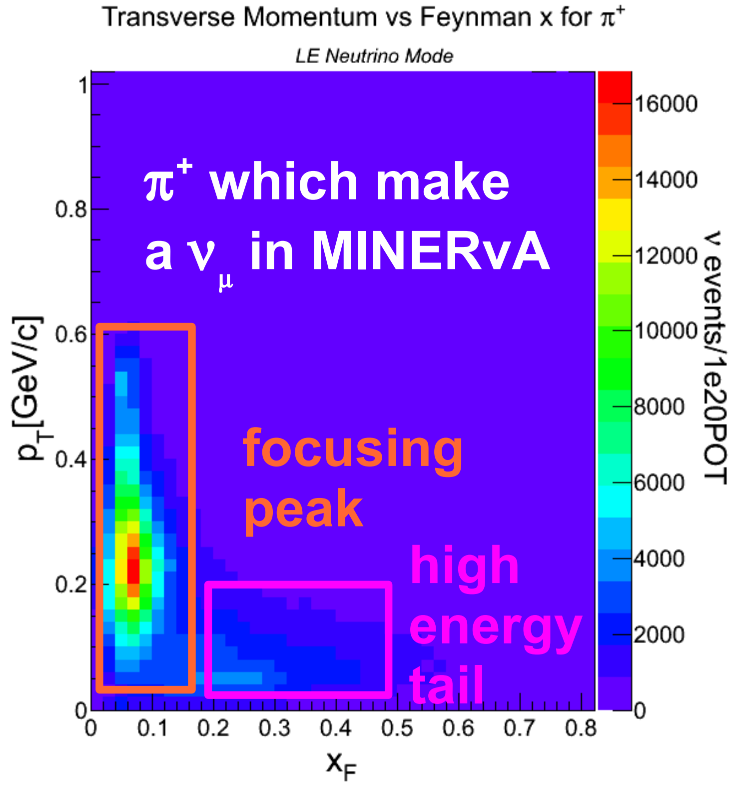


- σ_{prod} has the quasi-elastic component subtracted from total inelastic looking at the final state particles.

NA49 for pC->p$^+$X

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



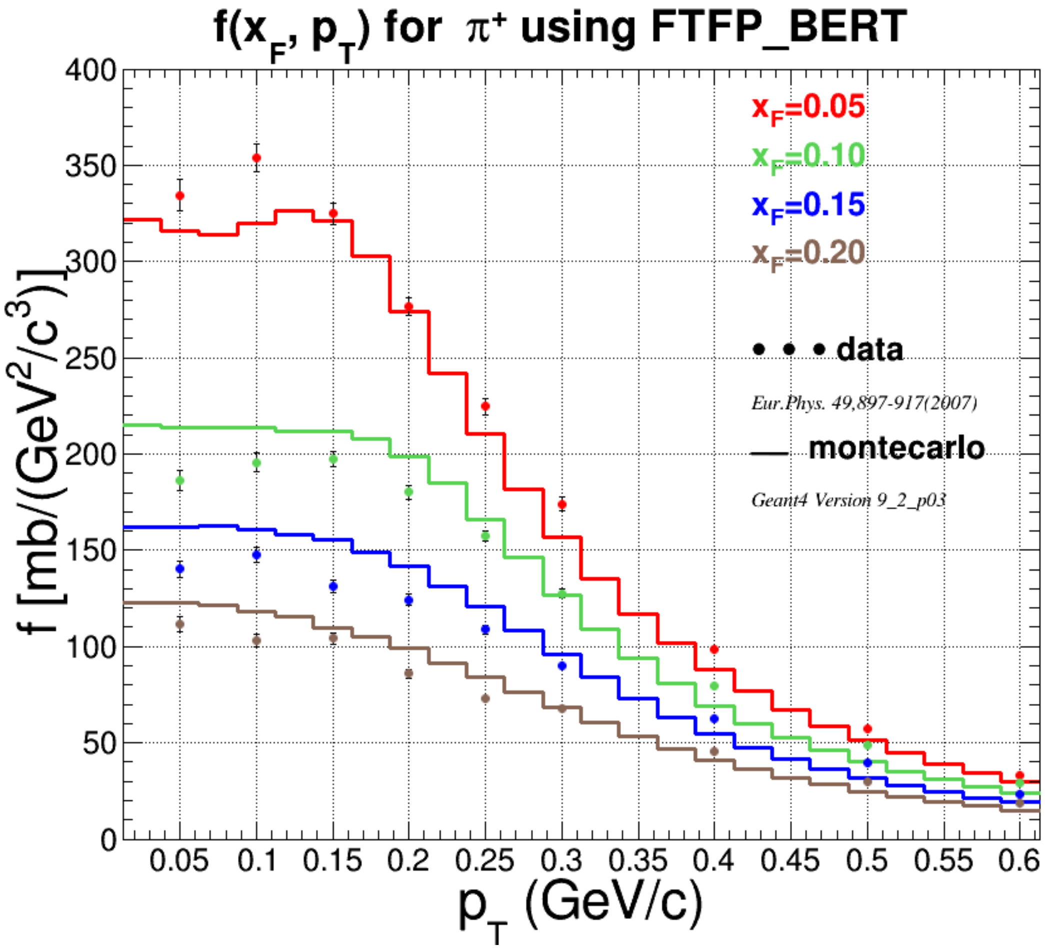


Uncertainties
7.5% systematic
2-10% statistical

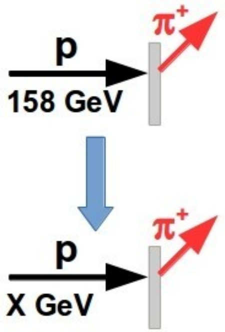
x_F: Feynman-x, $x_F = 2p_L^{CM}/\sqrt{s}$

NA49 for pC->p^+X

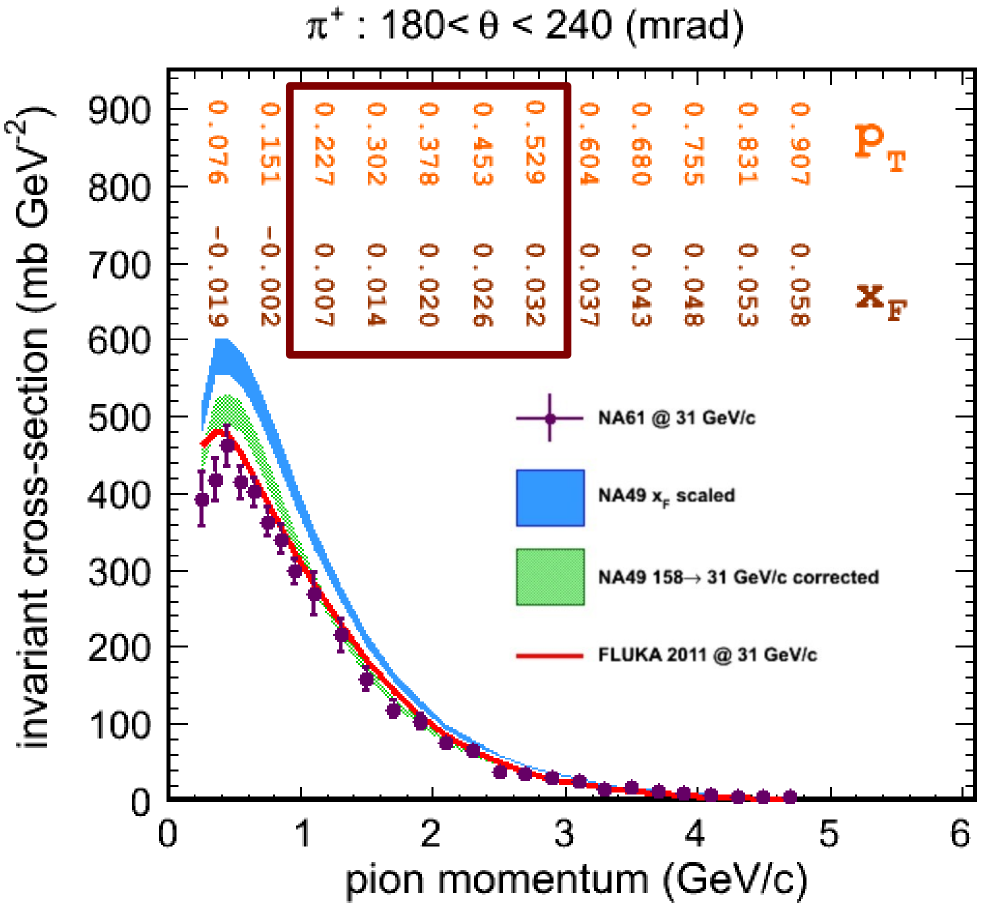
- A closer view will show the real disagreement:

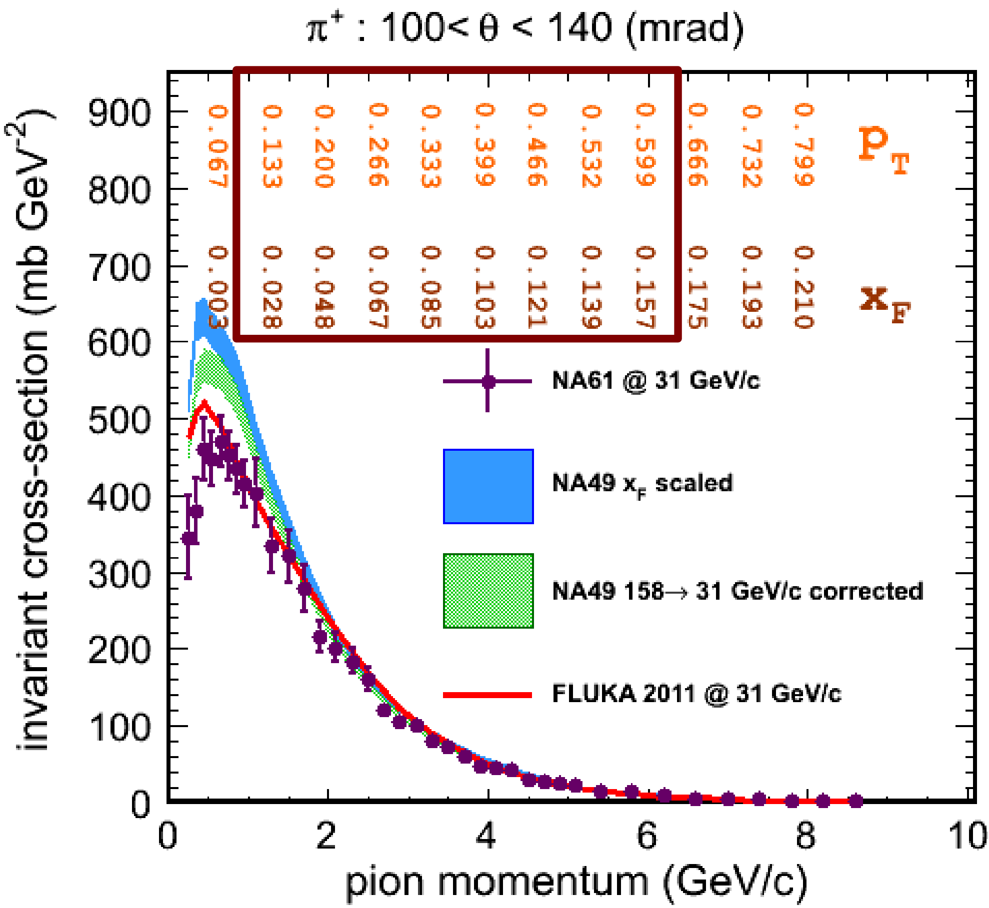


Energy Scaling Correction



- Energy scaling correction needs to be applied to apply one data set at one energy to another.





- The energy scaling from NA49 (158 GeV) to NA61 for T2K (31 GeV) has been used to test this scaling procedure.

Q: How much reweighting do we do?

A: We constrain about 70% of interactions using HP data.

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%

What doesn't HP data cover?

ν_μ 0<E<30 GeV

Total interactions / event = 1.463

- For incident protons

interactions / event

produced particle	**unconstrained**	**all**
p	0.108	0.236
π±	0.015	0.877
K±	0.002	0.031
Ks KL	0.028	0.028
n	0.049	0.049

possible to address

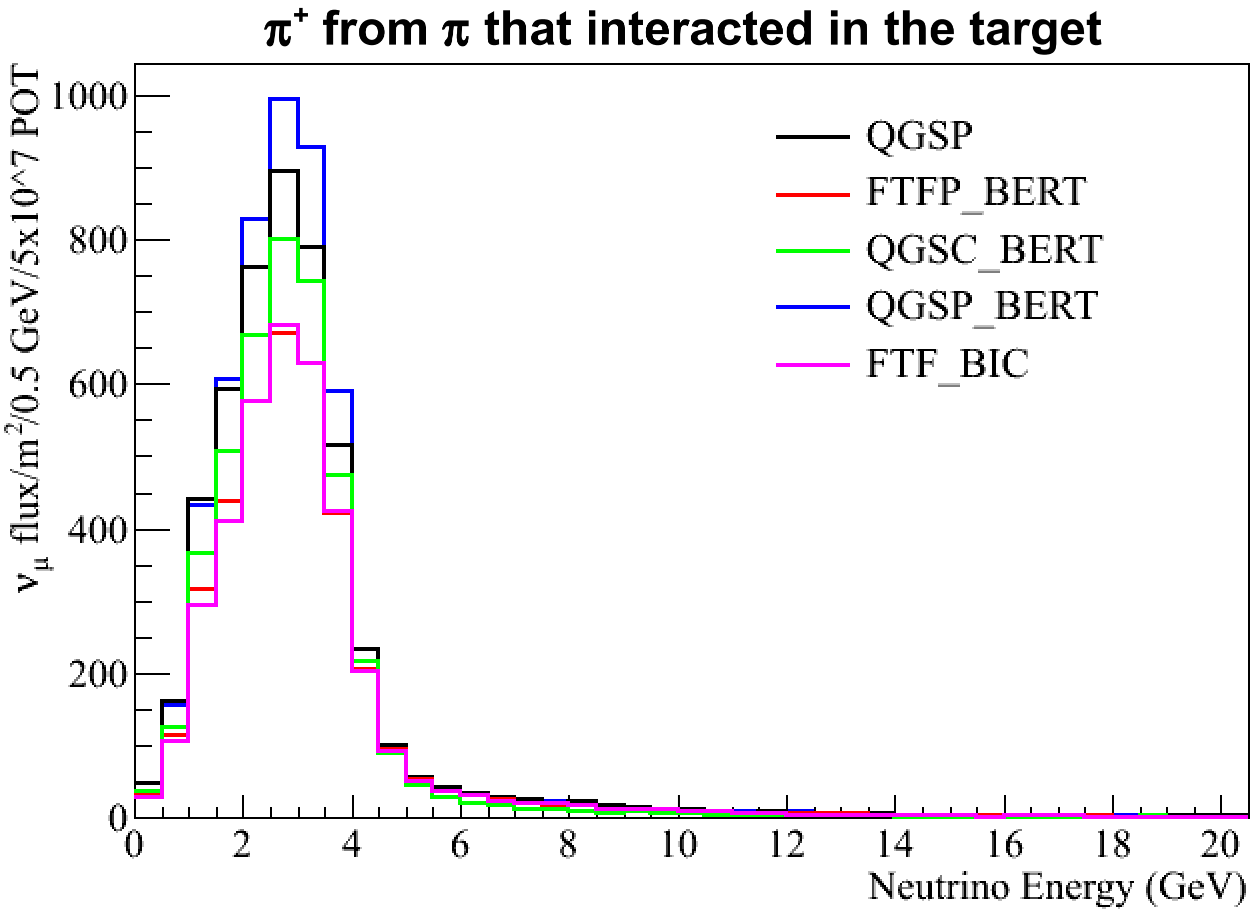
- Other incident particles

incident particle	interactions/event
π±	0.134
n	0.057
K±, Ks KL	0.018
all others	0.013

possible to address

No HP Data Set Available

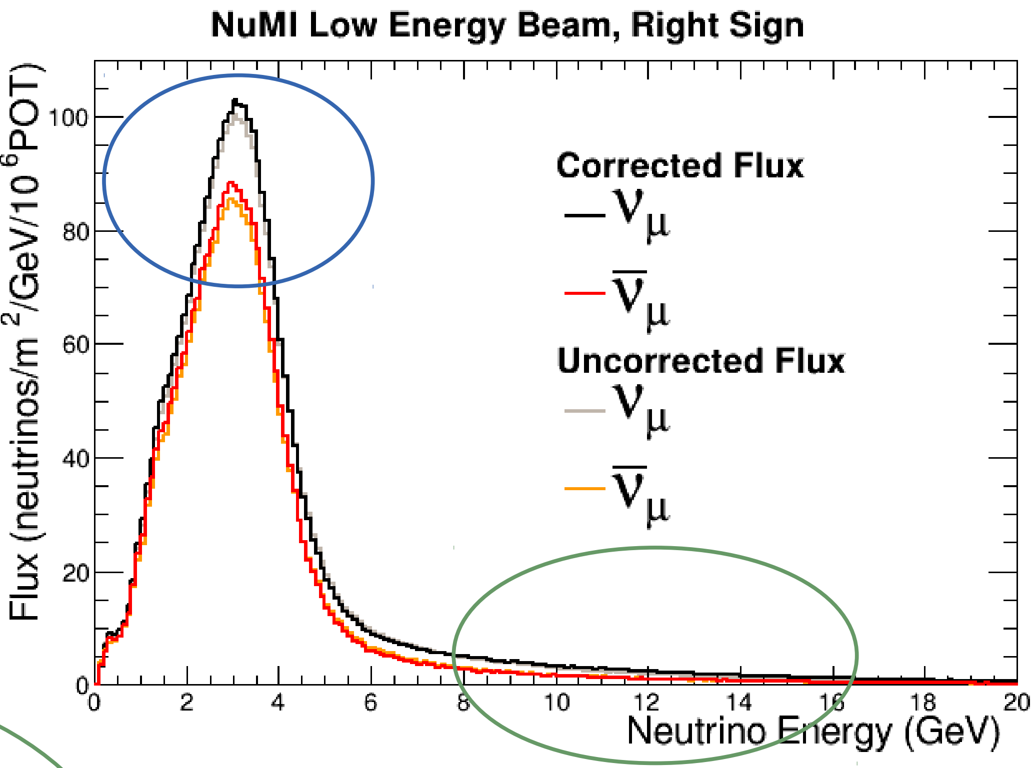
- We use a model spread to account the uncertainty when we do not have data available.

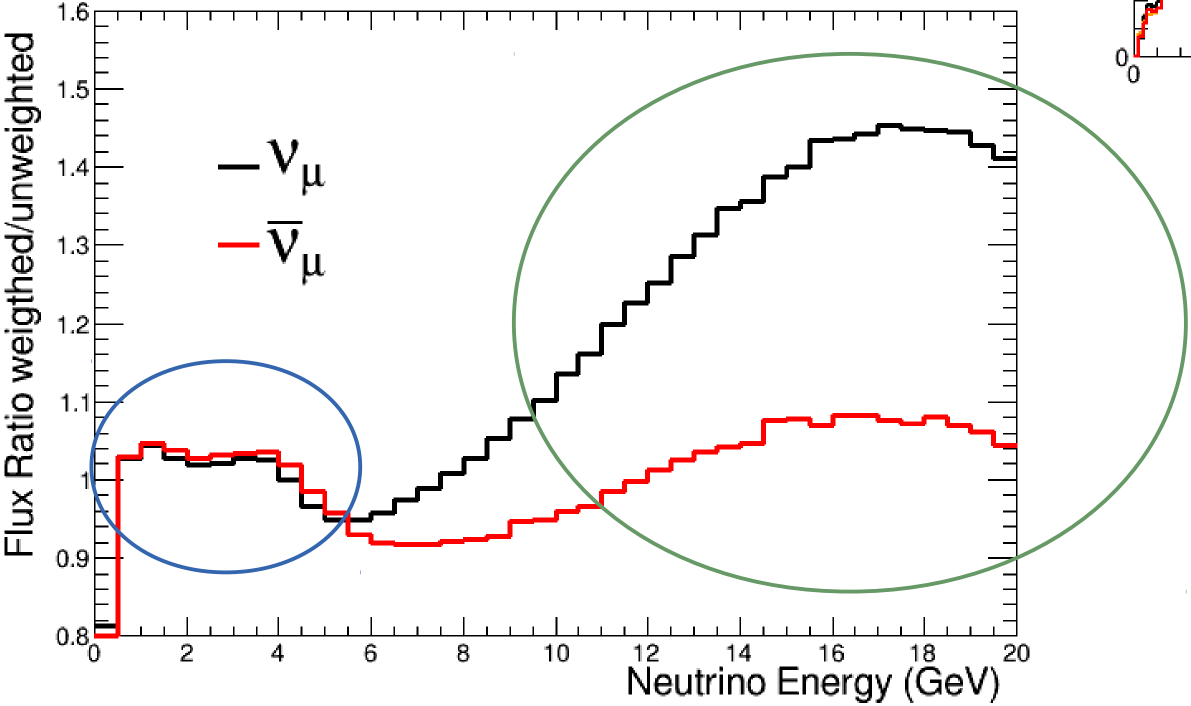


- This is done separately for each type of interaction.

Results using the HP Procedure

- The correction is small around the focusing peak.



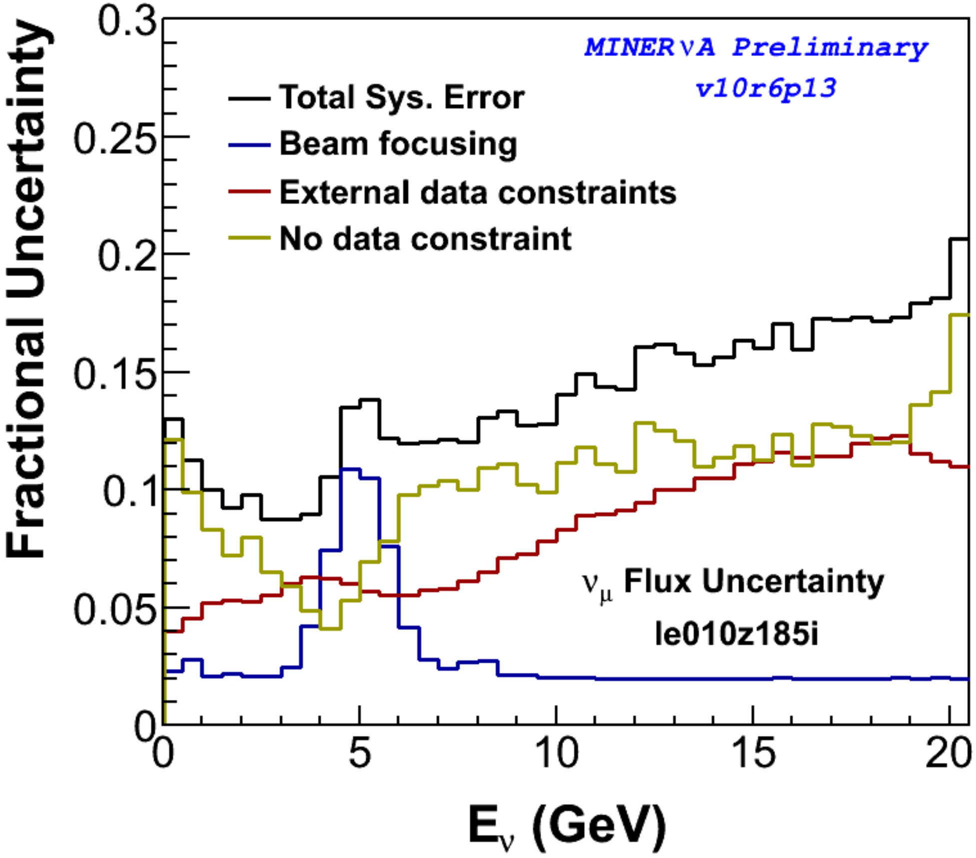


- But it becomes significant at intermediate energies for muon neutrinos in FHC.

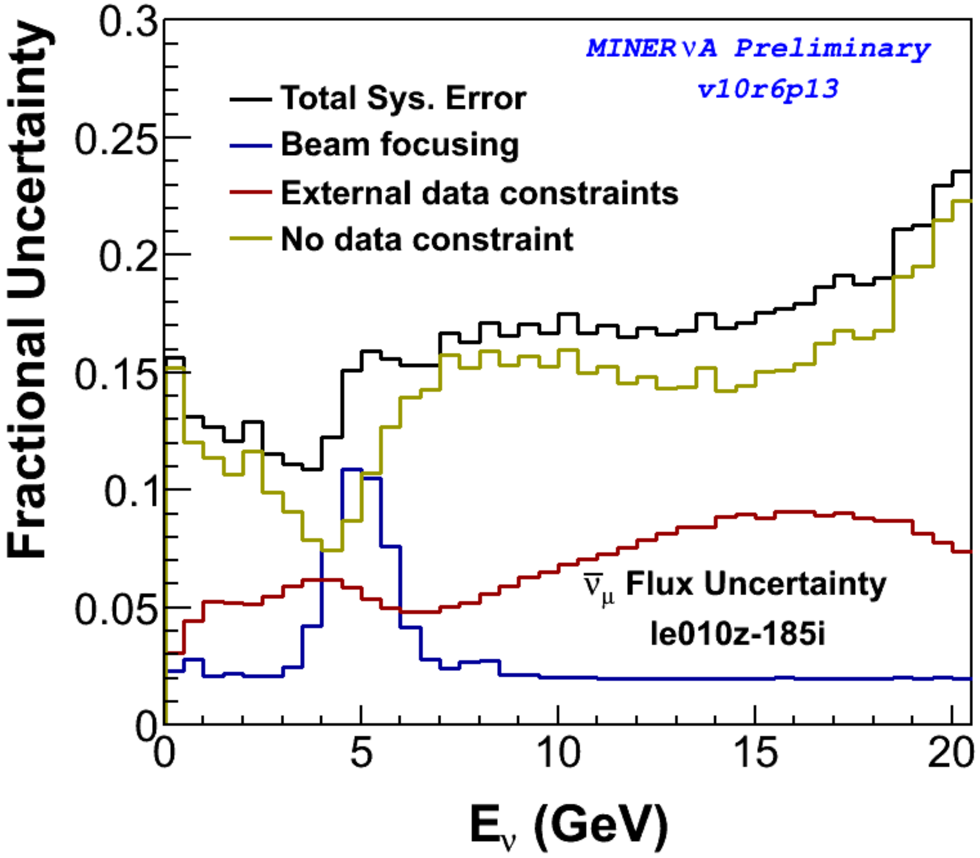
Flux Uncertainties FHC

- Unconstrained HP uncertainties dominate.

ν_μ **LE010Z185i**



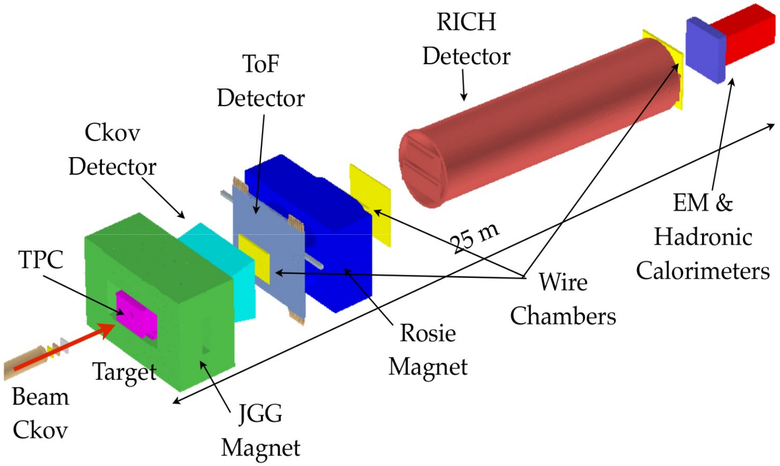
$\bar{\nu}_\mu$ **LE010Z-185i**



Work in Progress

Steps towards to Incorporate MIPP Data

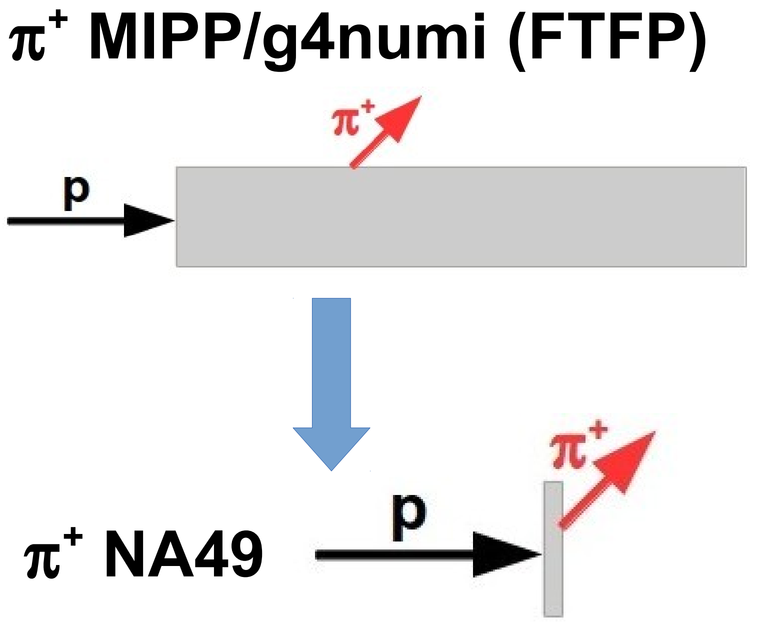
- MIPP data from the NuMI target measurements gives us the opportunity to improve the HP constraint.



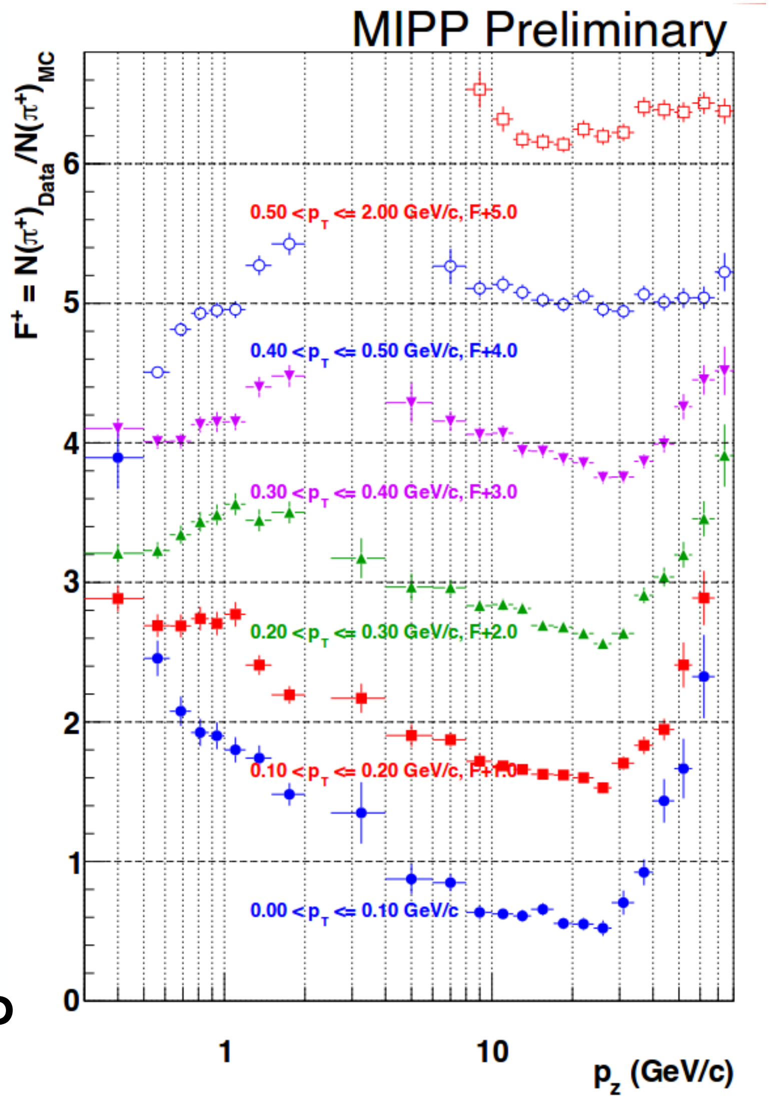
- We are working to understand the MIPP data in comparison with the thin target data.

- Currently, our strategy for HP constraints is to combine MIPP and thin target data.

Steps towards to Incorporate MIPP Data



MIPP/g4numi (FTFP)

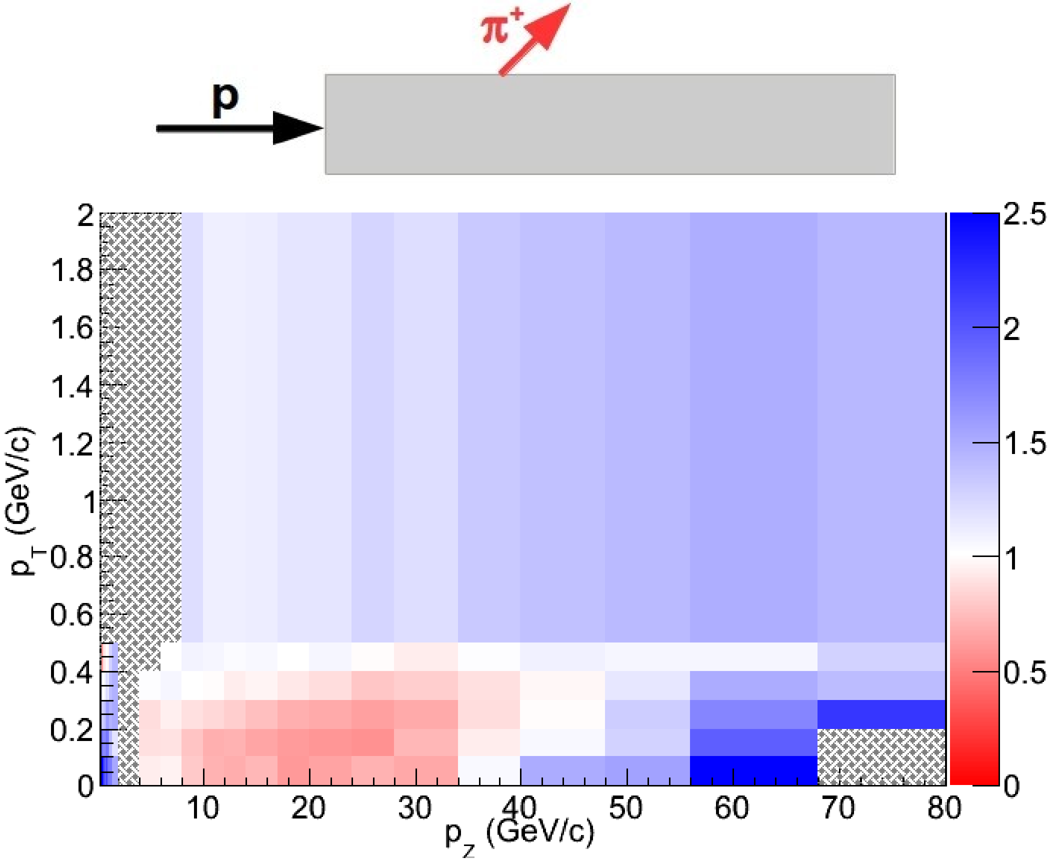


- Using MIPP will help to reduce the uncertainties from interactions when we do not have data inside the target, then we expect a significant reduction in the final HP uncertainties.

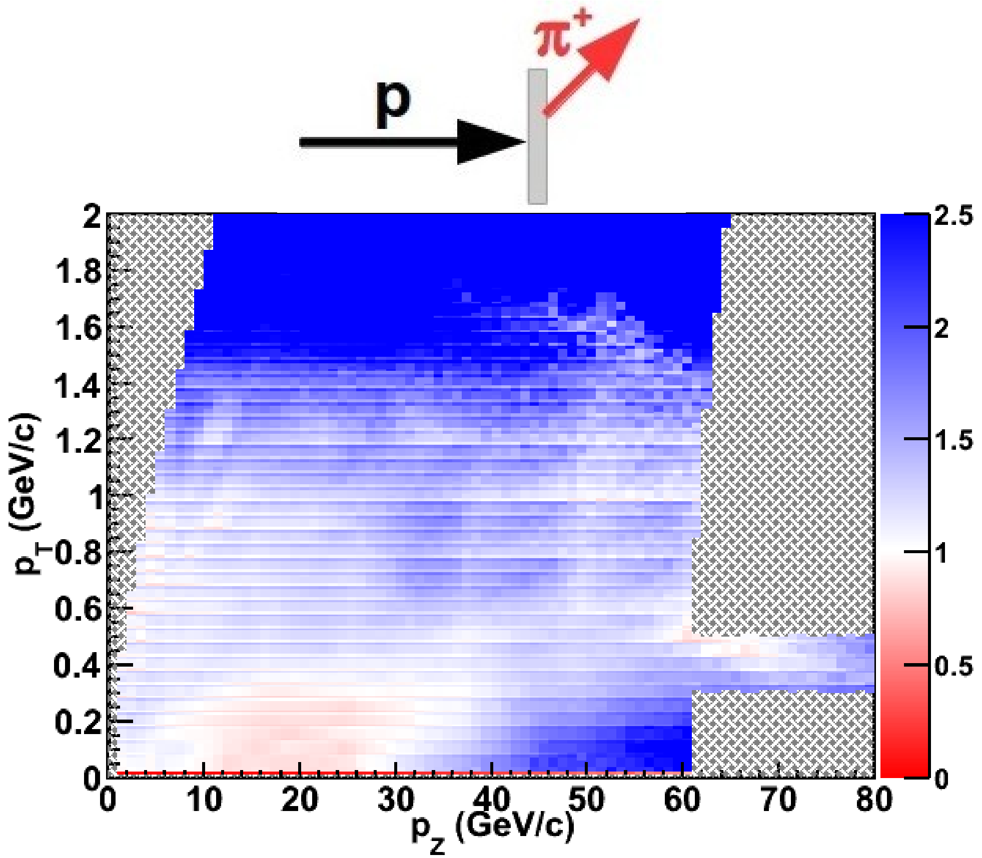
(J. Paley, FNAL JETP, Apr 2014)

Steps towards to Incorporate MIPP Data

π^+ MIPP/g4numi (FTFP)
(Data from J. Paley, FNAL JETP, Apr 2014)



π^+ NA49 + Barton, energy scaled to 120 GeV using Fluka.



- Any discrepancies between these two datasets have to come from secondary interactions in the target.

In-situ Measurements

MINERvA

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

Flux uncertainty goes into cross-section uncertainty

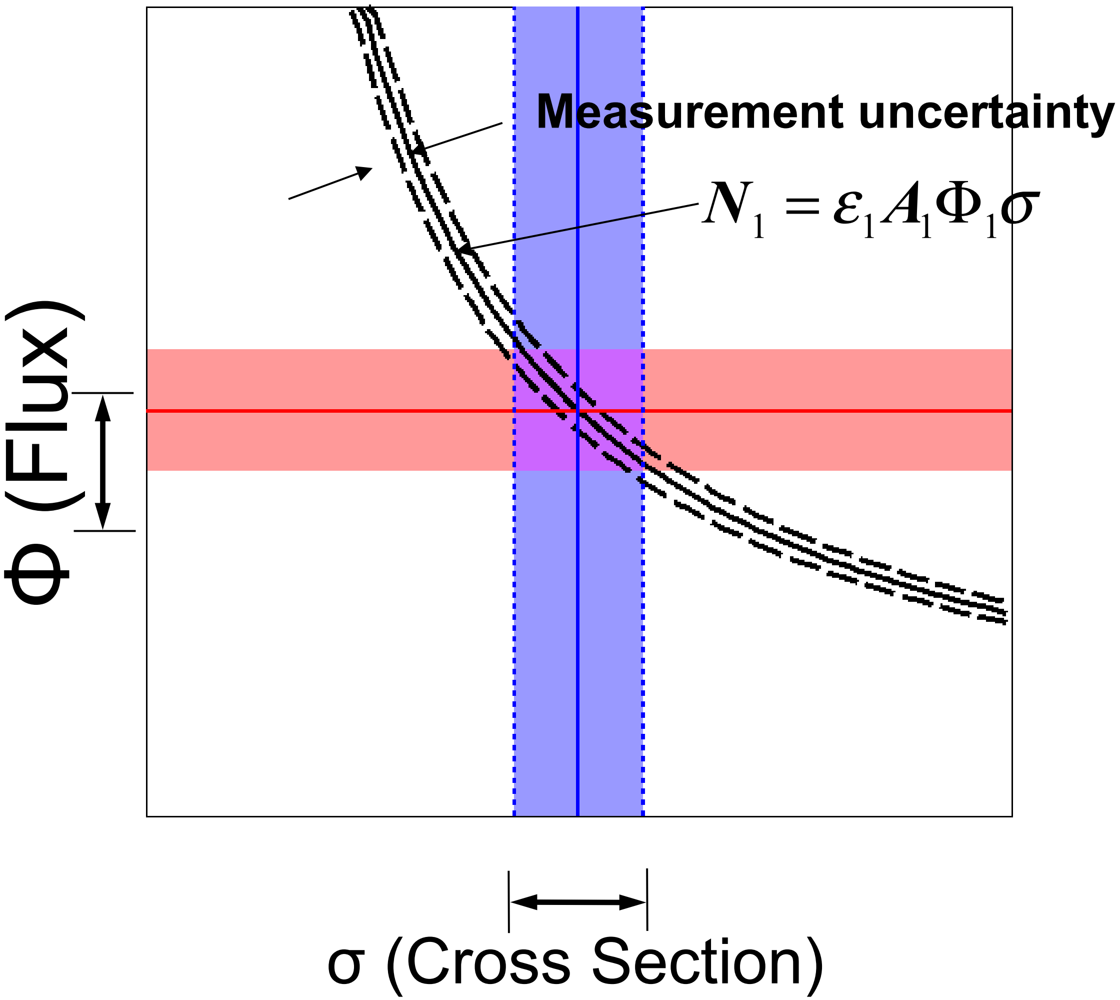
Flux constraint using MINERvA

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

Cross-section uncertainty goes into flux uncertainty

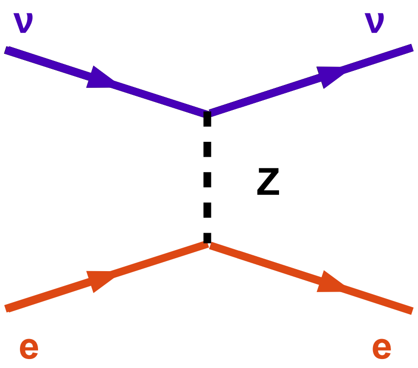
N: Events
ε: Efficiency
A: Acceptance
σ: signal cross section

(J. Park, FNAL JETP, Dec 2013)

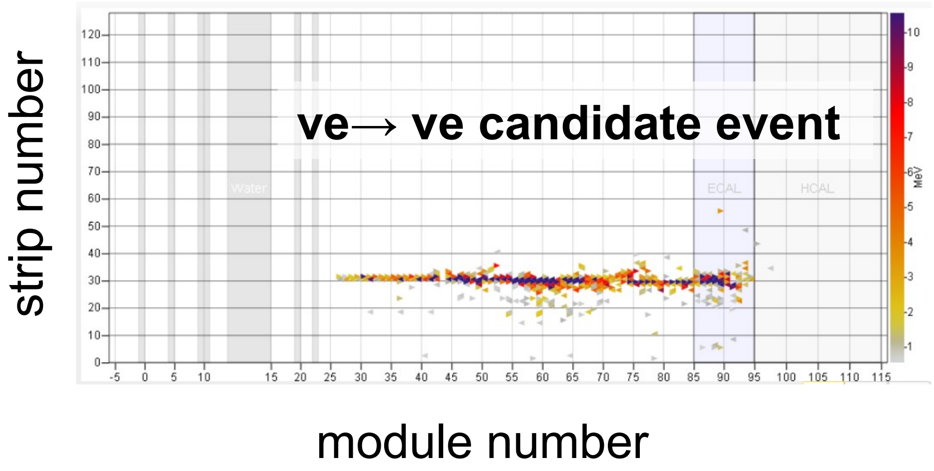


- **Flux and cross-section are anti-correlated**

ν – e scattering

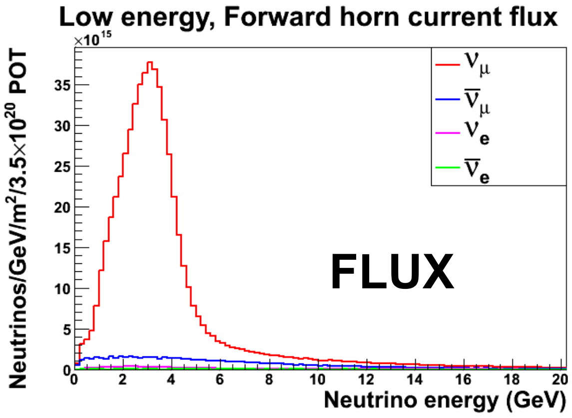


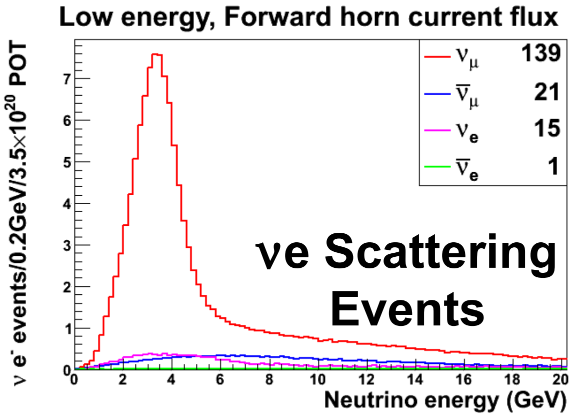
- Neutrino scattering on electrons is a standard candle:
  - Standard electroweak theory predicts it precisely.
  - Signal is a single electron moving in beam direction.
  - Process cross section is smaller than nucleus scattering by a factor of 2000.
  - Statistically limited.

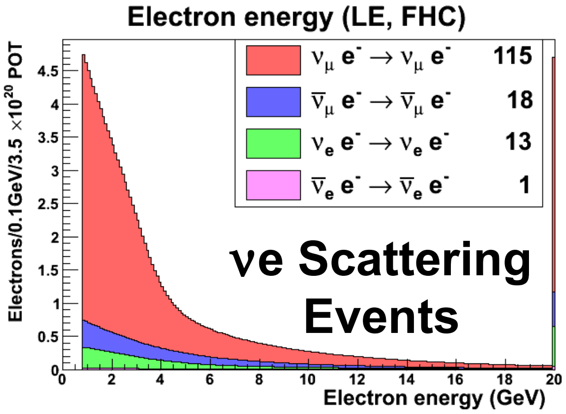

νe→ νe candidate event

- By improving MINERvA's flux normalization uncertainties, this helps to reduce uncertainties on MINERvA’s absolute cross-section measurements

ν – e Scattering
(J. Park, FNAL JETP, Dec 2013)

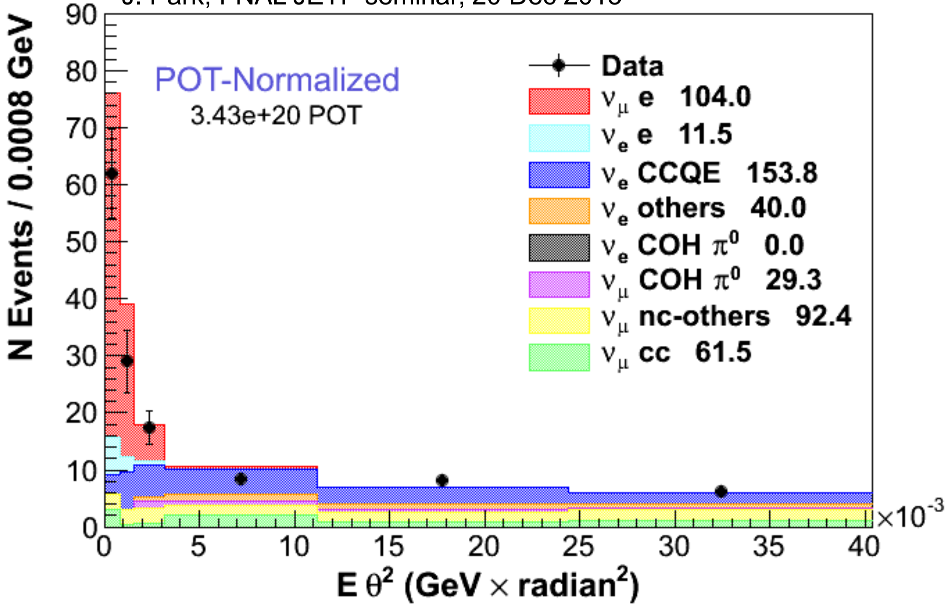






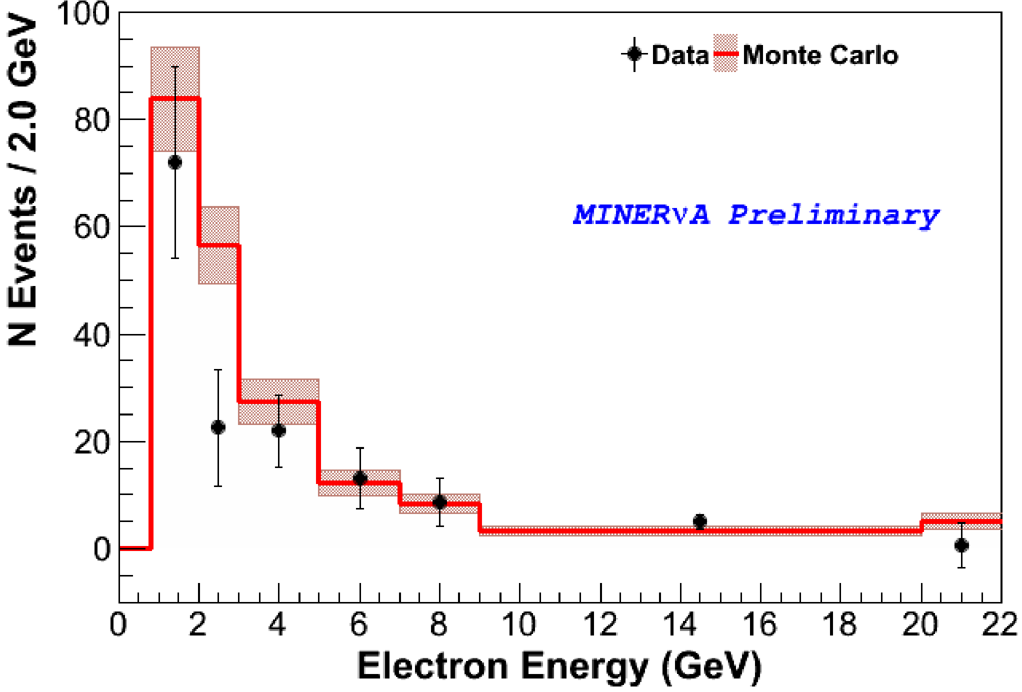
- > 0.8 GeV (high background rate)
- Predict 147.5 ± 22.9(~15.5%) signal events for 3.43×10^{20} (POT)
- 123.8 ± 17.0 (stat) ± 9.1 (sys) events with total uncertainty: 15% (after background subtraction).

J. Park, FNAL JETP seminar, 20 Dec 2013



ν – e Scattering as Constraint

(J. Park, FNAL JETP, Dec 2013)

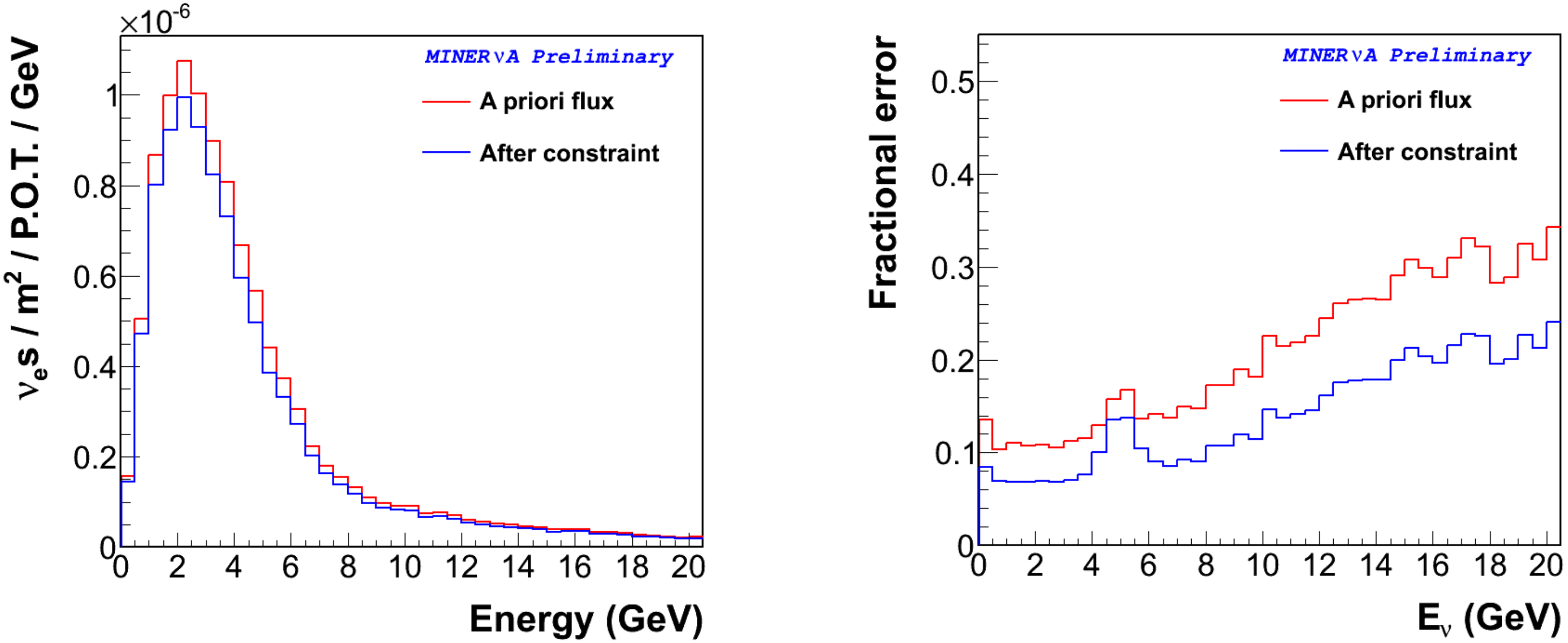


Observed ν-e scattering events give a constraint on flux with similar uncertainty as current flux uncertainty, consistent with prediction

- For each universe, we can evaluate it's consistency with the measured neutrino-electron results and calculate a likelihood of that universe, given that universe's flux.
- We then use this likelihood to weight universes: more consistent universes will have a higher weight and vice versa.

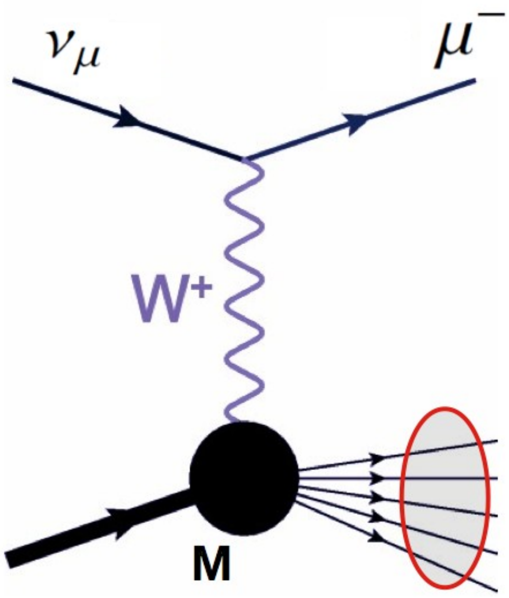
ν_e CCQE cross section (J. Wolcott, NuFact 2014)

- Using ν – e results, we can apply an additional constraint to the flux.
- Here, the a priori is the HP corrected flux.



- Reduction of 5-10% in the flux prediction and 5-10% in predicted uncertainty as well.

Low nu



- Charged-current scattering with lower hadronic recoil energy is another standard candle.

- Differential cross section can be expressed as:

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

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

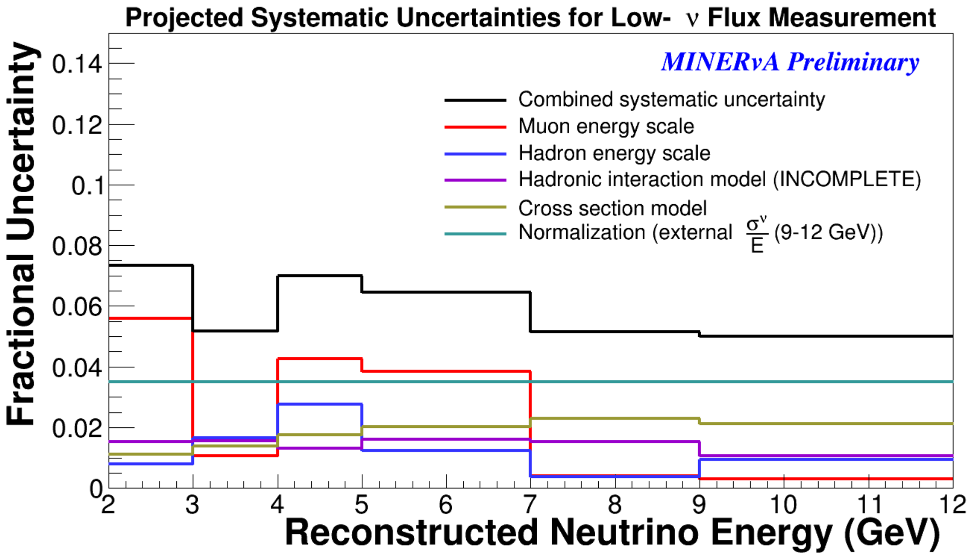
- Gives a good measurement of flux shape.

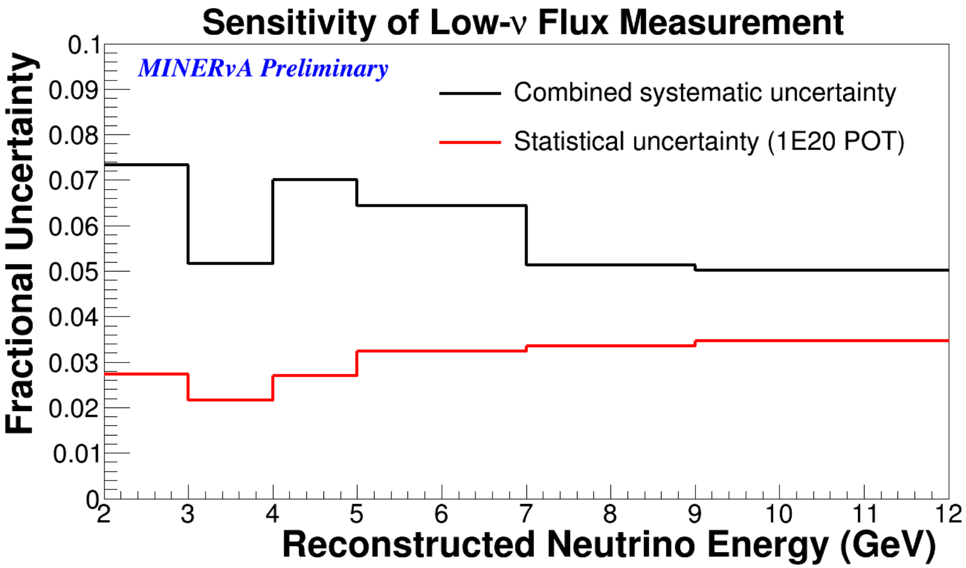
- Normalization tied to external measurements at high energy. NOMAD σ_{tot} (9-12 GeV on carbon).

- Challenge lies in correctly measuring the hadronic energy of the system.

Expected Uncertainties (L.Ren APS 2014)

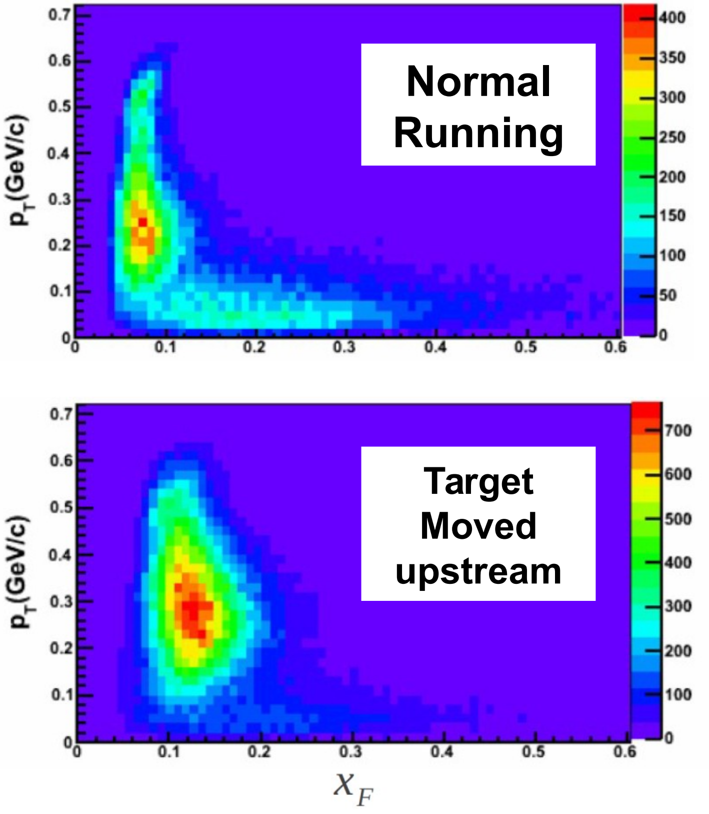
No results yet, but preliminary estimates of systematic uncertainty are promising

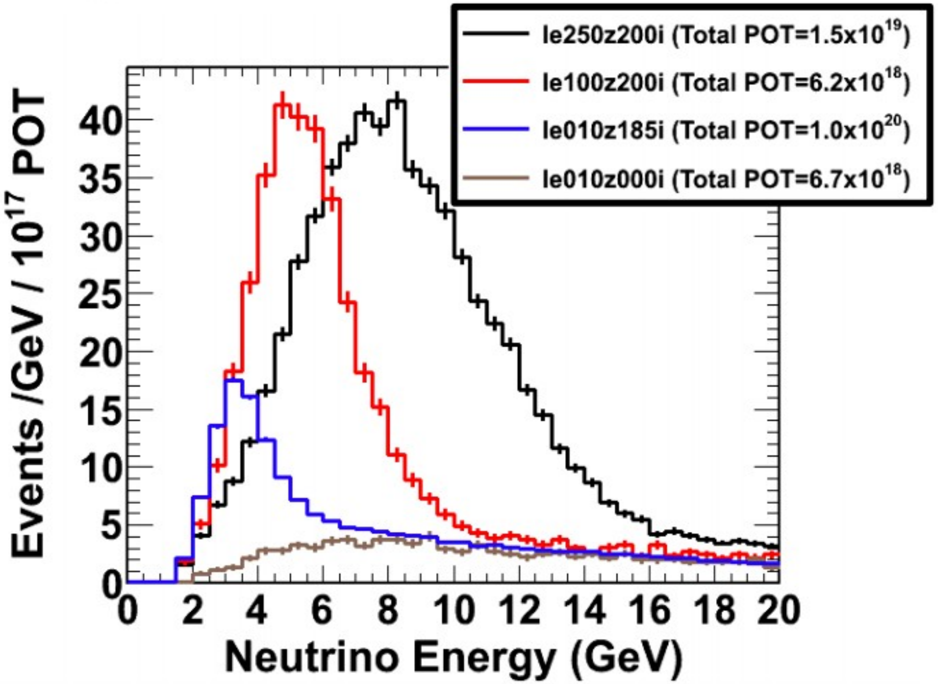




Special Runs

- We use almost 10% of out total neutrino beam exposure in alternative focusing geometries:
  - Changing the horn current.
  - Changing the relative distance between the target and the first magnetic horn.





- The purpose is disentangle hadron production uncertainties from focusing uncertainties.

Special Runs

- The idea is to tune the hadron production to match the observed data with MC in Minerva.

- MINERvA performs this using low nu samples for different beam modes.

- Challenge: It assumes that all the remaining discrepancies Data-MC come from the flux, and assumes all detector systematics are totally understood.

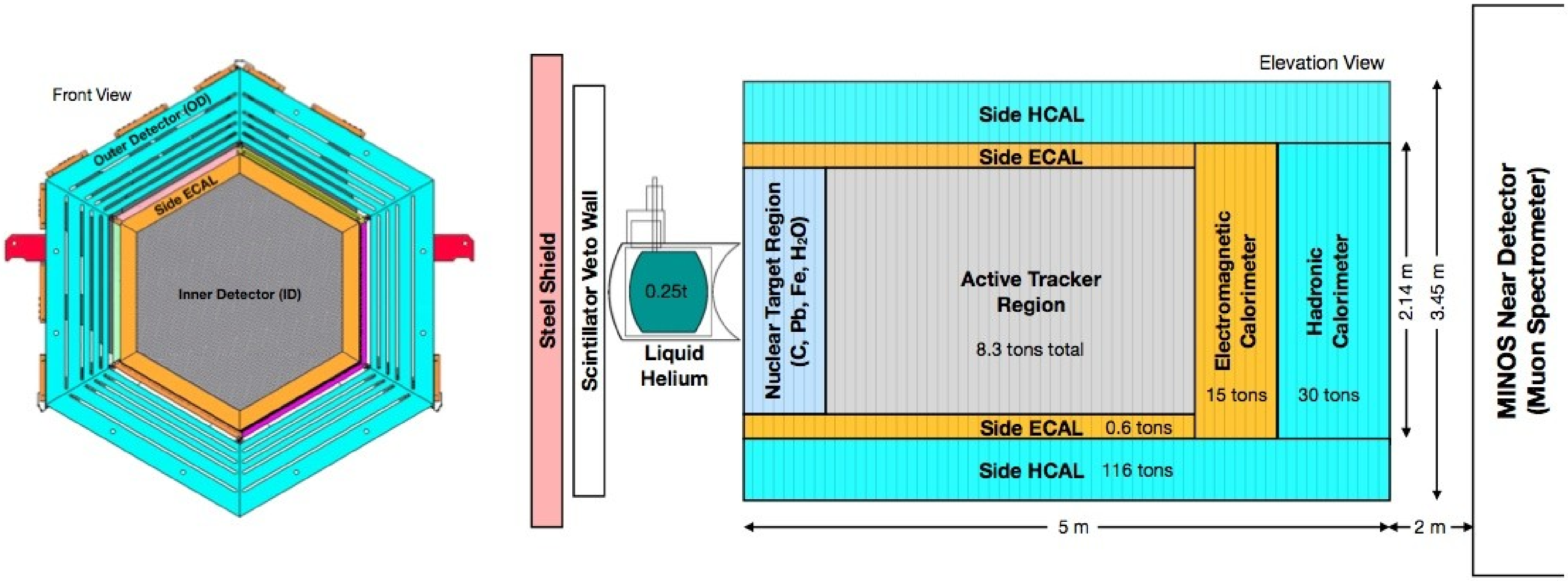
Conclusions

- For MINERvA it is crucial to have a precise measurement of the flux with small uncertainties to deliver ν cross sections.
- We are following different and independent approaches to constrain the flux.
- These approaches are converging to give our best possible result.
- Stay tuned for results.

backup

Minerva...

- Active region made of plastic scintillator (CH).
- Nuclear targets to study the A dependency of the ν-cross section.
- EM and hadronic calorimeter.

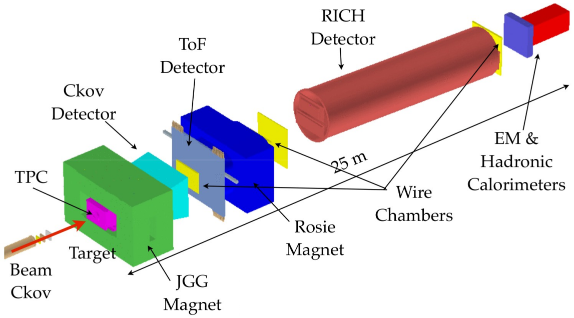


- 120 modules ~32K channels.
- X, U, V orientation (600).

MIPP Data

- MIPP yields of π^+ and π^- in a wide kinematic range using a spare Numi target (Phys. Rev. D 90, 032001 (2014))

- Low bin errors: between 5%-10%.

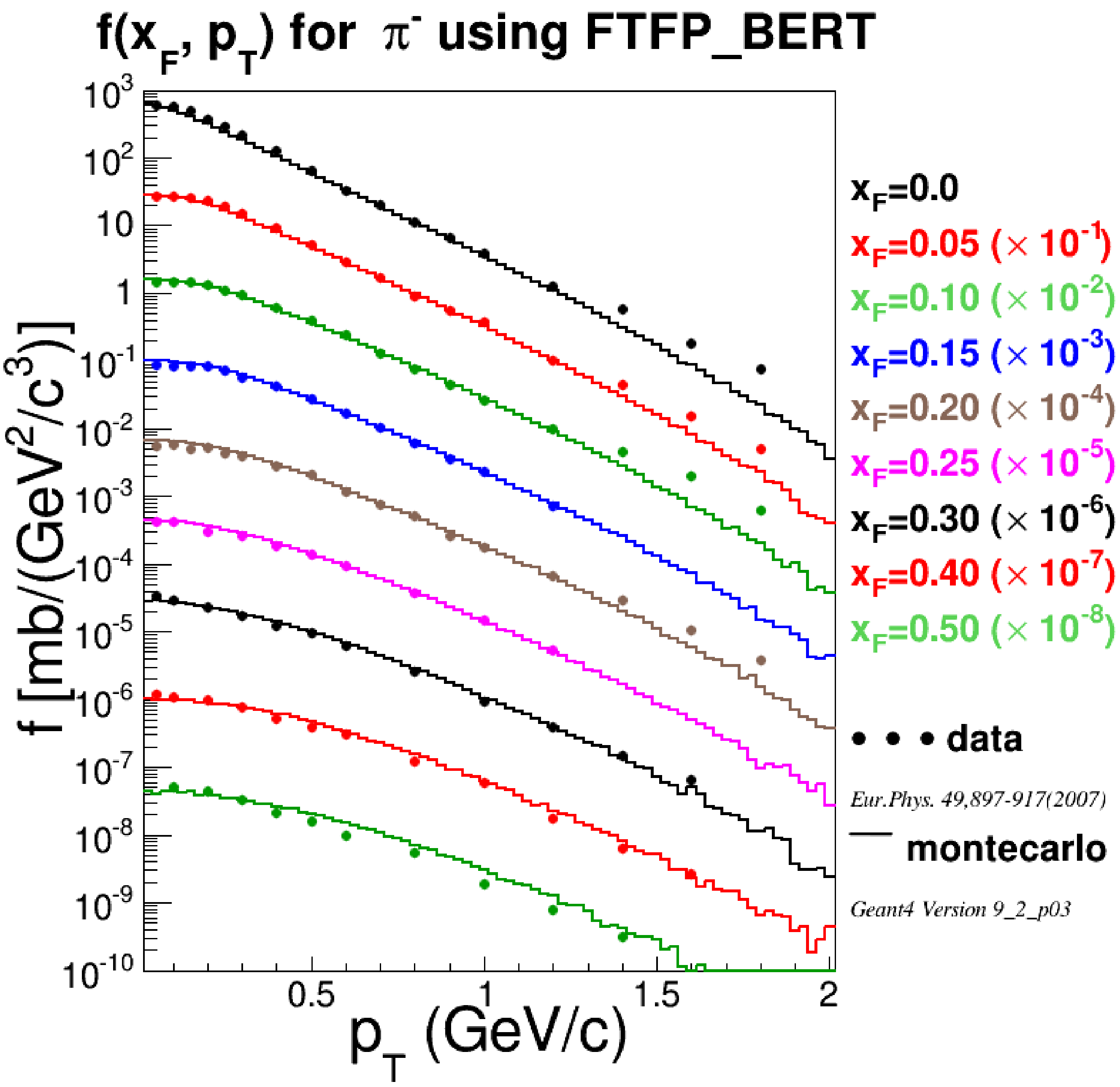


- Understand the impact of MIPP in the flux prediction.

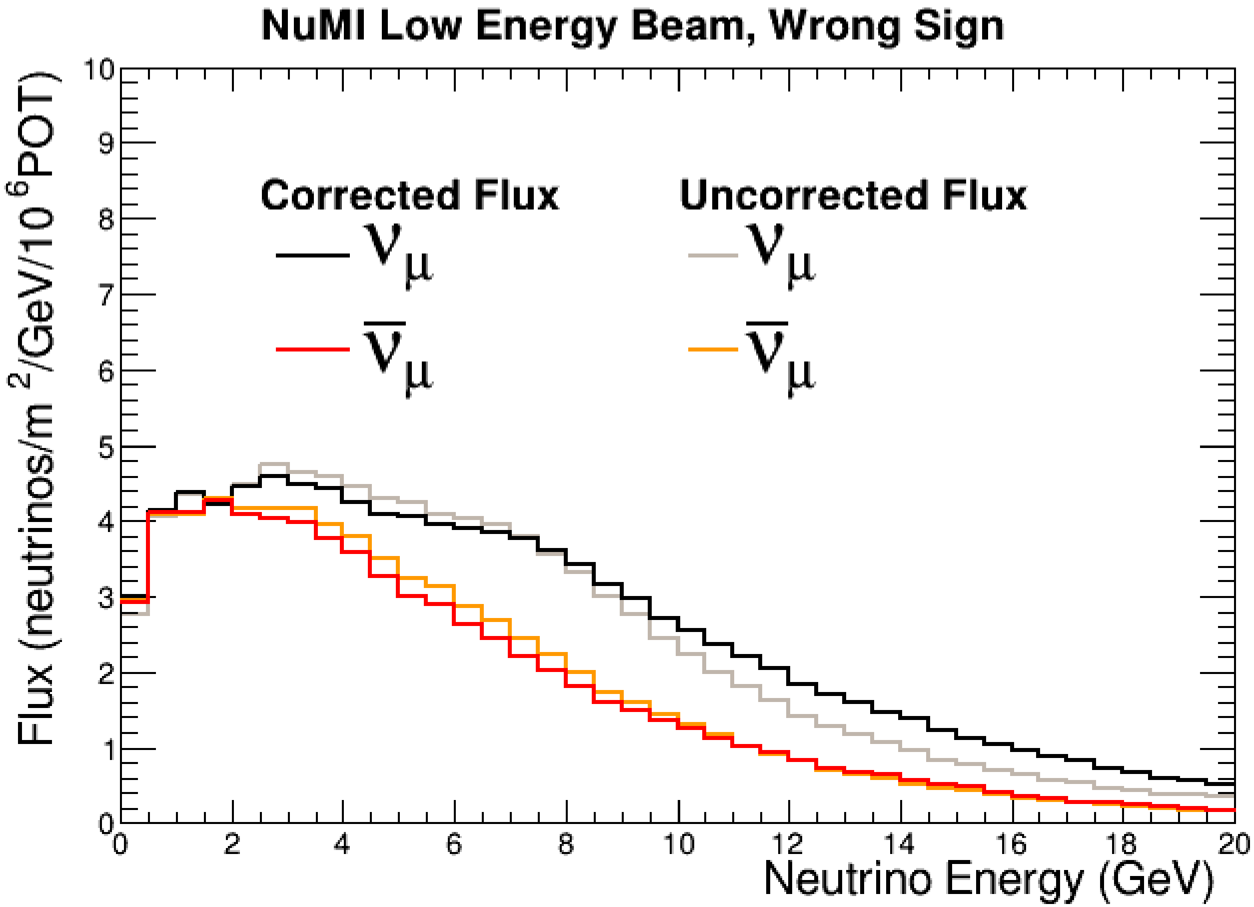
- It is possible to extend the results for high energy kaons.

- Combine in a comprehensive strategy with thin target data, low nu, beam fit and ν-e.

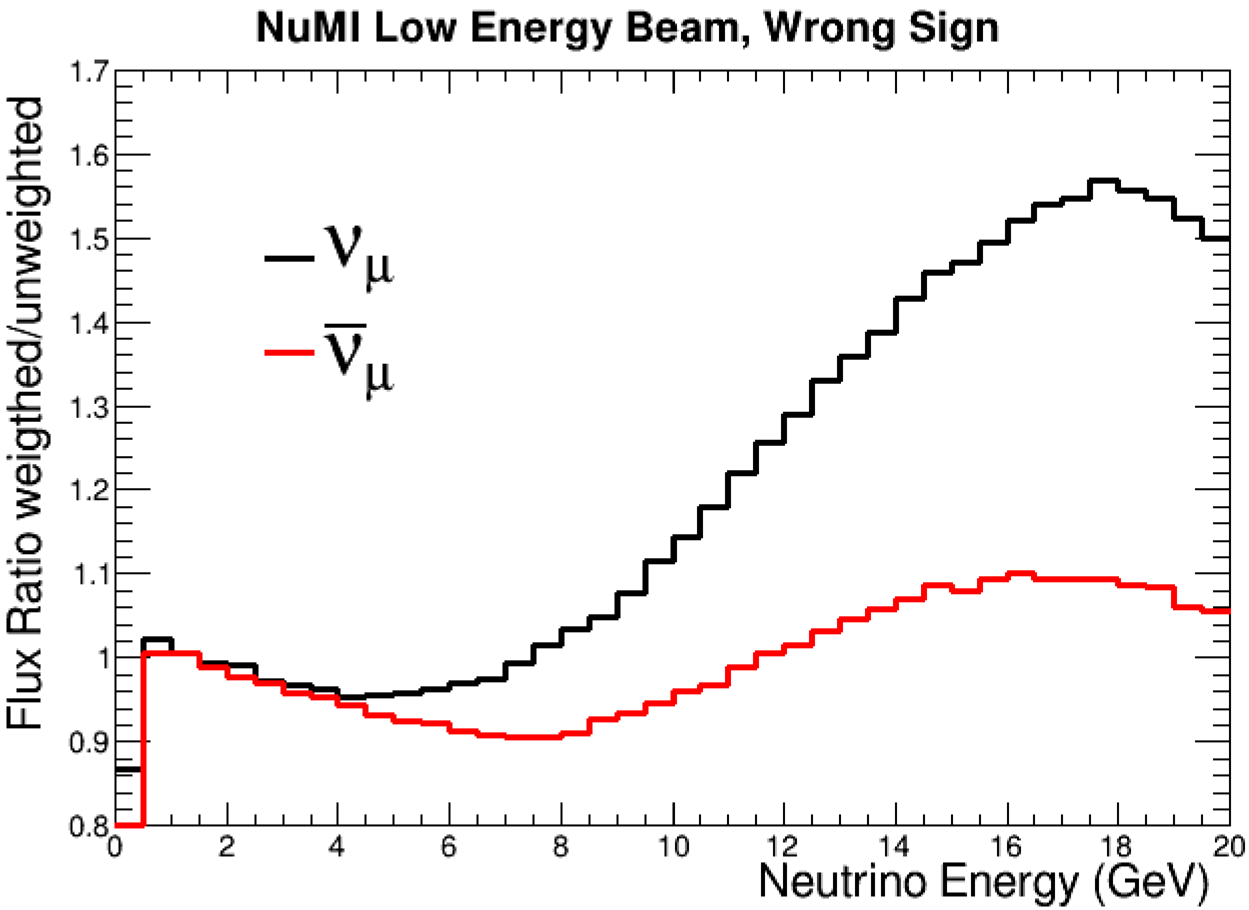
NA49 & Geant4 for pC->π⁻X



Wrong sign for LE010z185i & LE010z-185i



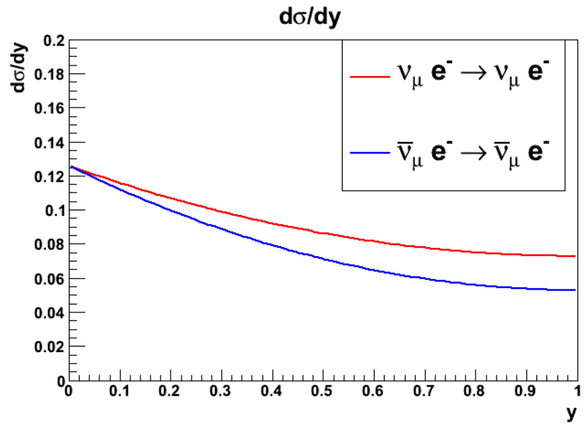
Wrong sign for LE010z185i & LE010z-185i



ν-e Scattering

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F^{\,2} m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

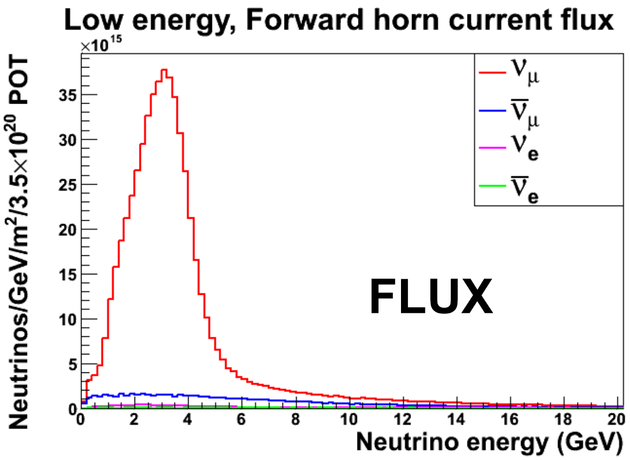
G_F and θ_W: well-known electroweak parameters

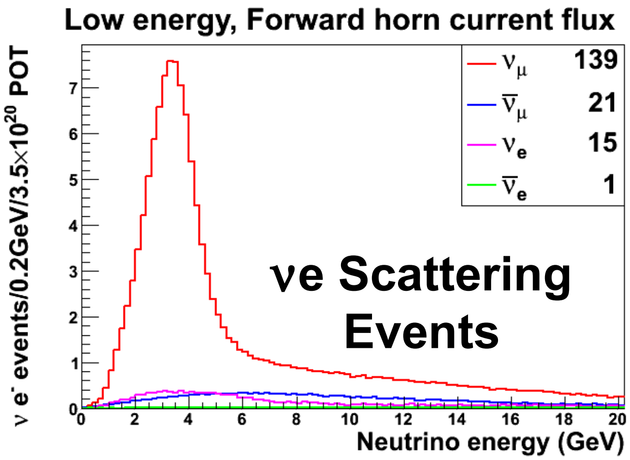


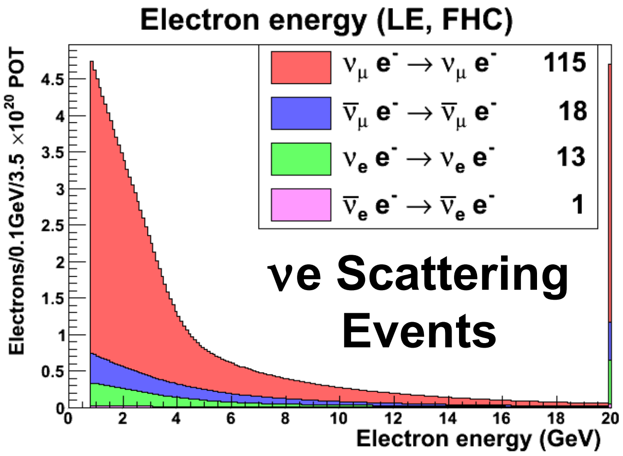
$$\sigma(\nu e) \propto E_\nu$$

$$\frac{d\sigma}{dy}$$

$$y = \frac{\text{(electron KE)}}{\text{(neutrino energy)}}$$

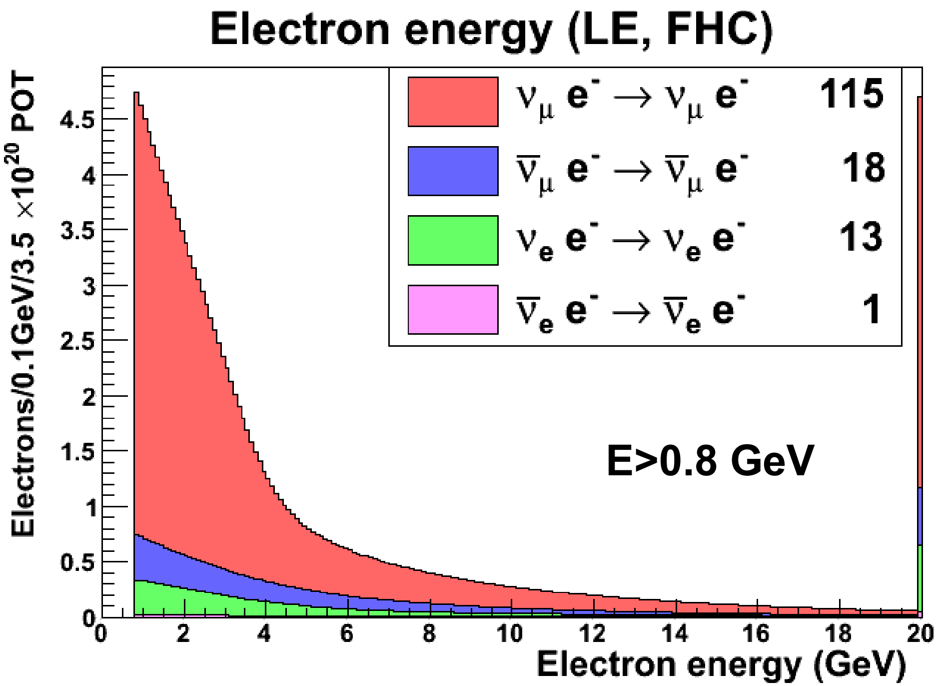






- **E > 0.8 GeV**
  - High background rate and tough reconstruction at low energy
- **Predict 147 signal events for 3.43×10²⁰ Protons On Target (POT)**
  - ~100 events when you fold in (reconstruction + selection) efficiency of ~ 70%
- **Not a large sample in low energy run but still useful to constrain absolute flux**

Signal Events



E<0.8 GeV is not used

- Large background
- Tough reconstruction

- Signal is mixture of $\nu_\mu e^-, \bar{\nu}_\mu e^-, \nu_e e^-$, and $\bar{\nu}_e e^-$ in LE-FHC (neutrino beam)
- ~100 signal events for 3.43E20 POT
- Can't distinguish neutrino type

$$\nu_\mu e^- \text{ and } \bar{\nu}_\mu e^- : 91\%$$

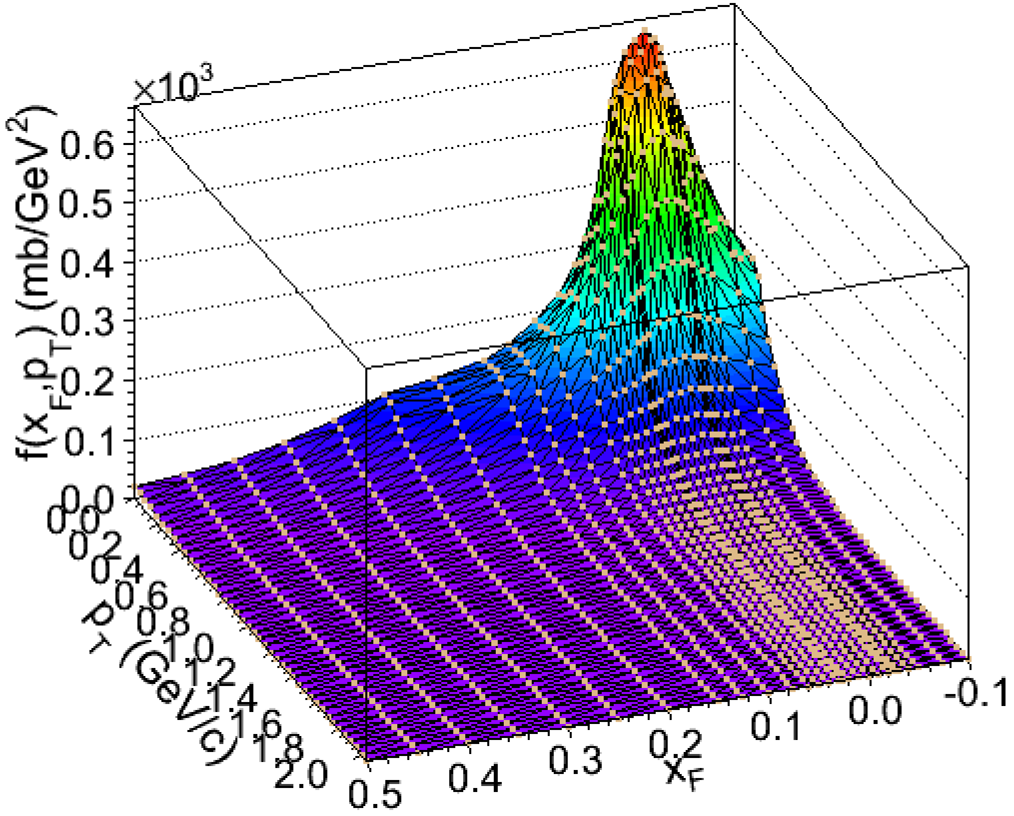
$$\nu_e e^- \text{ and } \bar{\nu}_e e^- : 9\%$$

- Still useful to constrain the flux
  - **Total events: Constraint for integrated flux**
  - **Electron spectrum: Constraint for flux shape**

For remainder of talk,
ν means ν and $\bar{\nu}$

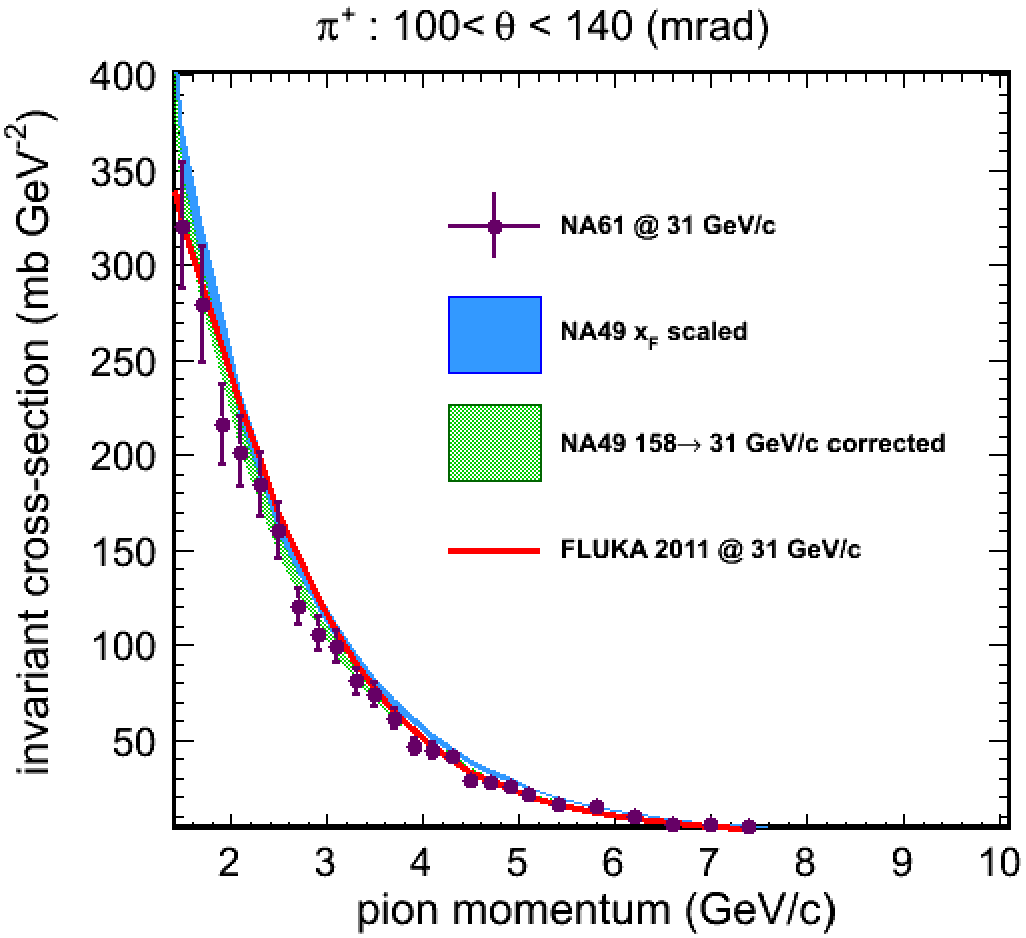
Energy scaling (Fluka ratios)

Interpolated NA49



NA49 – NA61 @ 31 GeVcomparison

zoomed-in



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