Calculating the NuMI Flux

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On behalf of the MINERvA Collaboration

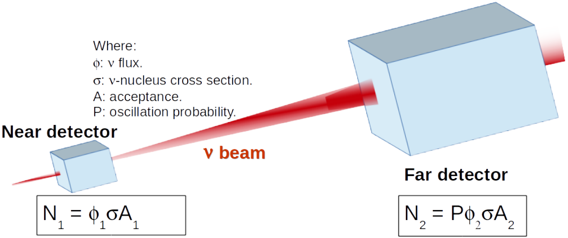
December 18, 2015

WILLIAM & MARY
CHARTERED 1693

Why is predicting the neutrino flux important?

Neutrino Oscillation Strategy

Two separated detectors sharing the same ν beam.



The oscillation probability is:

$$P = \left(\frac{N_2}{N_1}\right)\left(\frac{A_1}{A_2}\right)\left(\frac{\phi_1}{\phi_2}\right)$$

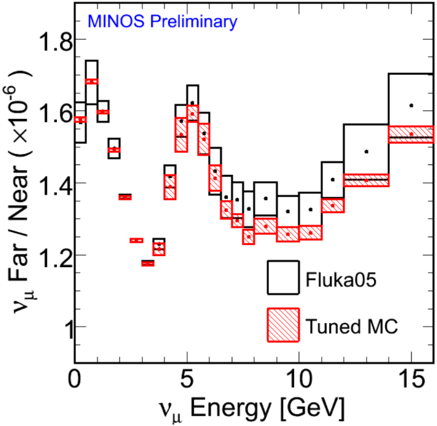
- ϕ just partially cancels.
- If the detectors are different σ does not cancel.

Partial Flux F/N Cancellation

Example: Flux ratio between the MINOS Far detector (FD) and the MINOS Near detector(ND).

The fluxes are not the same:

- ND sees a distributed ν source.
- FD sees a point ν source.

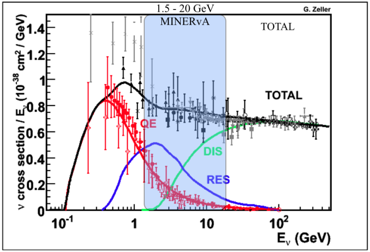


Phys. Rew. D77 (2008) 072002.

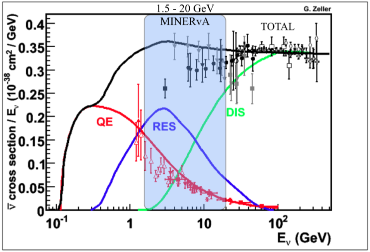
Neutrino Cross Sections

- Cross sections between 0.1-20 GeV are not well known, but important in the regime of oscillation experiments
  - Essential for experiments (NOvA, DUNE)
- Because DUNE will consist of LAr, we have to understand the effects of the nucleus
  - Large errors in cross section measurements and disagreements between experiments lead to systematic uncertainties in oscillation measurements

Neutrino



Antineutrino

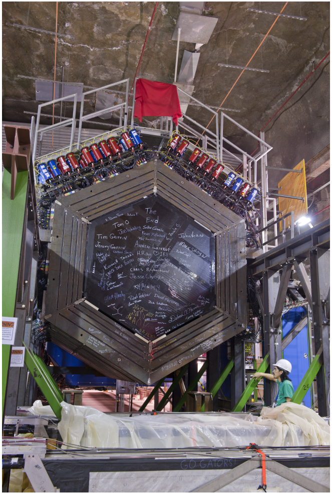


J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

MINERvA

MINERvA is a dedicated ν-nucleus cross section experiment covering 1-20 GeV:

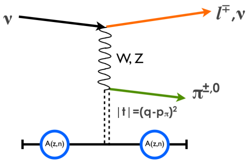
- High statistics of ν and $\bar{\nu}$ measurements..
- Inclusive and exclusive channels (quasi-elastic, coherent pion production, DIS, etc.)
- Several nuclear targets (C, Fe, Pb, water and He) in the same beam line to take simultaneous measurements.

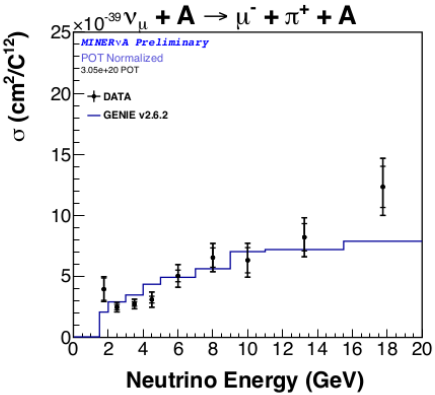


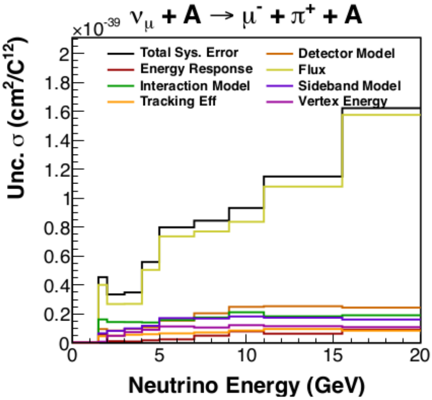
MINERvA Needs the Flux!

Example: Coherent $\pi^{\pm}$ production.
Phys. Rev. Lett. 113, 261802 (2014)

- The uncertainties on our results are dominated by the uncertainty in the flux.



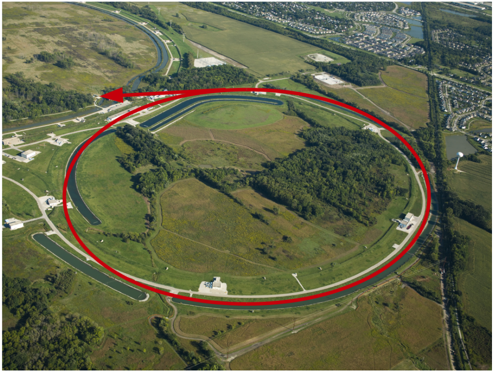




NuMI and Neutrino Experiments

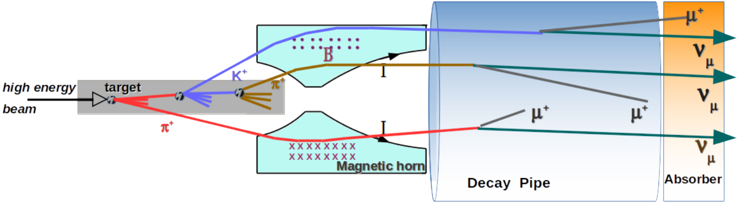
NuMI provides neutrinos to different experiments for the high intensity program at Fermilab since 2005

- On-Axis: MINOS, MINERvA, ArgoNeuT, PEANUT.
- Off-Axis: NOvA.
- Booster experiments receive small amount of off-axis NuMI beam.



Why is it so hard to estimate the flux?

How to Make a Conventional Neutrino Beam



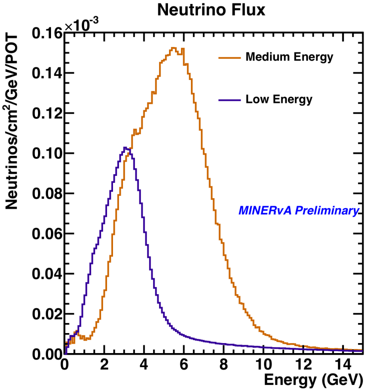
Using short lived particles to make neutrinos... we need:

- a very intense proton beam colliding with a target.
- a production of π's and K's in the target.
- a system to focus the π's and K's.
- an extended decay region.
- absorbers for the remaining hadrons.

NeUtrinos at Main Injector Beam

NuMI has produced two neutrino beams:

- Low Energy (LE) in 2005-2012.
- Medium Energy(ME) in 2013 - present.



ME mode is produced by:

- Moving the target position upstream
- Moving the horn 2 downstream.

Beam Power:

- LE $\approx 250kW$.
- ME $\approx 400kW$.

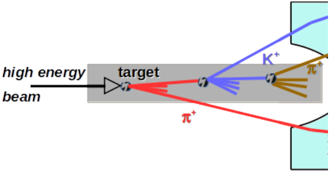
In this talk, I will be focused on muon neutrino in LE.

The NuMI Target

- Rectangular graphite rod.
- Segmented in "fins" + Budal beam monitors.
- Cooled by water in pipes, and enclosed in helium container.

	LE	ME
Cross Sectional view	6.4 x 15 mm^2	7.4 x 63 mm^2
Segment length	20 mm	24 mm
"Fins"	47	48
Budal Monitors	1	2
Total Length	960 mm ($\approx 2\ \lambda$)	1200 mm ($\approx 2.5\ \lambda$)

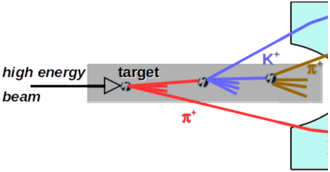
Hadronic Cascade in the Target



Pions, kaons, protons and other particles are created in cascade of hadronic interactions in:

- The primary beam interactions in the target (proton on carbon).
- Secondary and tertiary interactions in the target (proton, π, K, etc. on carbon).
- Interactions outside of the target (proton, π, K, etc. on aluminum, iron, helium, etc).

Hadronic Cascade in the Target



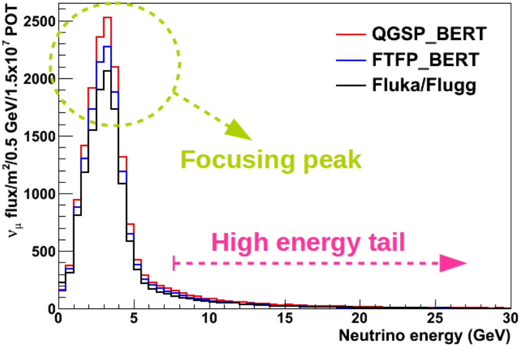
- But... these interactions are non-perturbative QCD.
- The simulation uses a model.

Then, we need data to constrain the model

MINERvA uses geant4 (geant4.2.p03) and FTFP_BERT as hadronic model.

Model Discrepancies

Big discrepancies between predictions from hadronic models

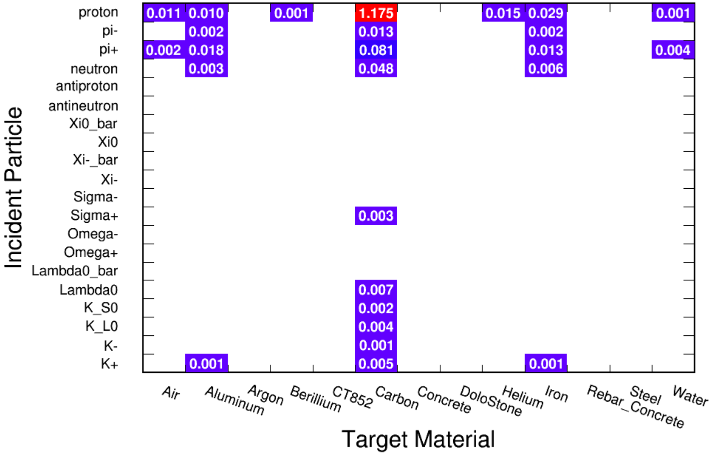


- The flux spectrum shows a focusing peak around 3 GeV.
- A long high energy tail goes up to 120 GeV.

Hadronic Interactions in NuMI LE

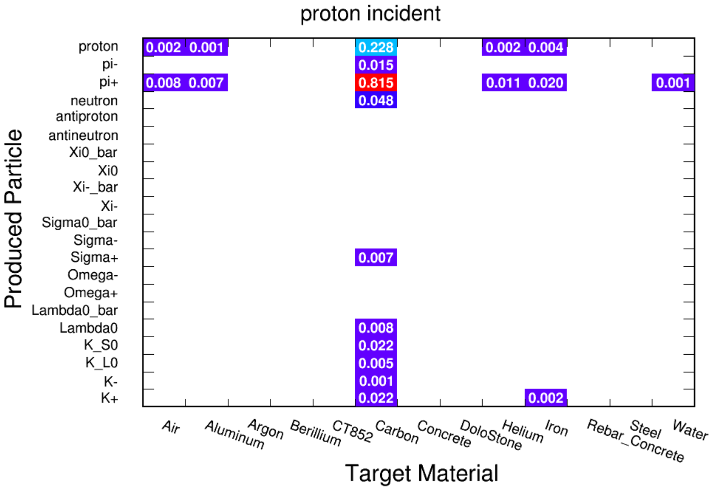
<number of hadronic interactions> per ν_μ in [0,20] GeV

Incident particle vs target material (<0.001 not shown)



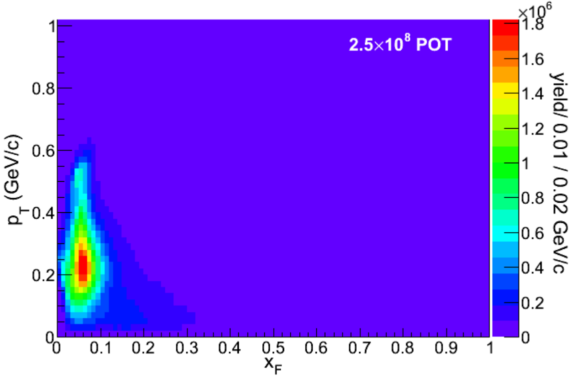
Hadronic Interactions in NuMI LE

<number of hadronic interactions> per ν_μ in [0,20] GeV



Hadronic Interactions in NuMI LE

π^+ produced by the primary proton beam:
(x_F: Feynman-x, $x_F = 2p_L^{CM}/\sqrt{s}$)

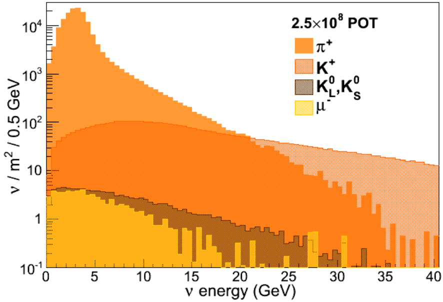


π^+ projectile:

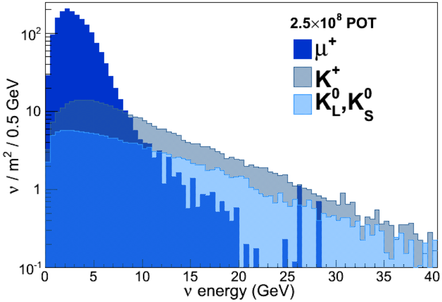
Material	Air	Al	C	Fe	Water
<interactions>/ν_μ	0.002	0.017	0.079	0.013	0.004

Parent Identity

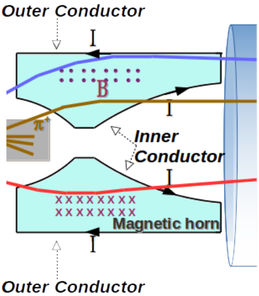
Muon Neutrino

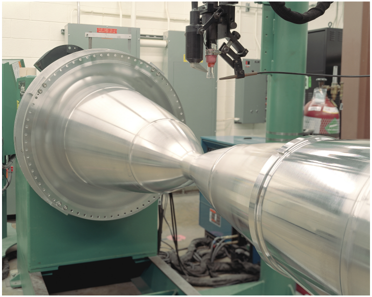


Electron Neutrino



NuMI Focusing

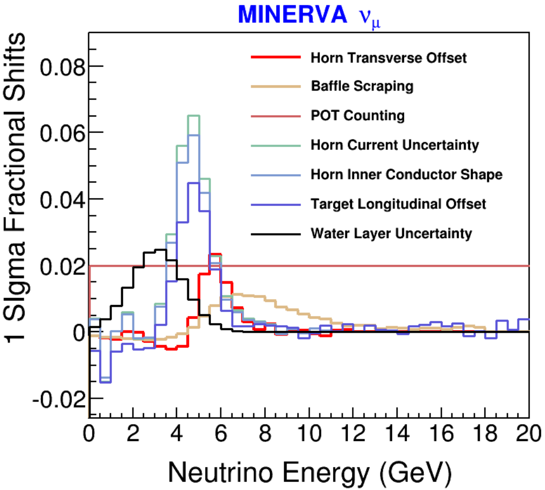




- A $\sim$ 200 kA current is pulsed through two aluminum horns to create a toroidal magnetic field.
- The current passes through a conductor (Al). Inner conductor is 2mm-4mm thick.
- Every charged particle traveling by the horns feel a p_T kick.

Focusing Uncertainties

This small uncertainties is due to the great effort from the NuMI Beam Group.

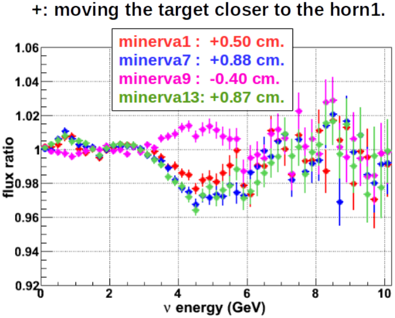


- Small in comparison with the hadron production uncertainties.

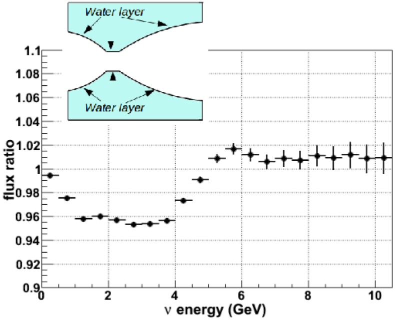
Geometric Effects in the Horn Simulation

Small inaccuracies in the horn geometry can lead to a bad flux prediction

The relative distance target - horn:



1 mm cooling water layer around the horn inner conductor:



Additionally, a new horn model has been implemented (P.Lebrun) and it shows significant effect on the flux.

The Challenge

There are two leading causes of a bad flux prediction:

1. **Focusing system**
   We have studied the horn parameters uncertainties and improved the geometry simulation.
   - Small simulation inaccuracies have a big impact around the focusing peak.
2. **Hadronic interactions**
   We need data to constrain hadron production:
   - The interaction probability of the hadrons on the materials.
   - Probability to produce a hadron in a kinematic bin ((x_F, p_T).

What sort of data do we need?

We need:

- Inelastic cross section of π, K, p, n in [0,120] GeV on carbon, aluminum, helium, etc.

- Yields or differential cross section of:
  - π (specially for the focusing peak).
  - K′s (specially at high energy)
  - and all particles that are part of the hadronic cascade (n,p,K^0, etc.).

What sort of data is available?

What Sort of Data is Available?

Thin target experiments:

- Monochromatic proton, pion or kaons beams on few % interaction length targets.
- Used to measure:
  - The inelastic total cross section.
  - The differential cross sections to produce hadrons.
  - Yields of hadrons produced.

Thick target experiments:

- Monochromatic protons on a long target.
- Used to measure:
  - Yields of hadrons produced.

Data Relevant for the NuMI Flux

Thin target experiments:

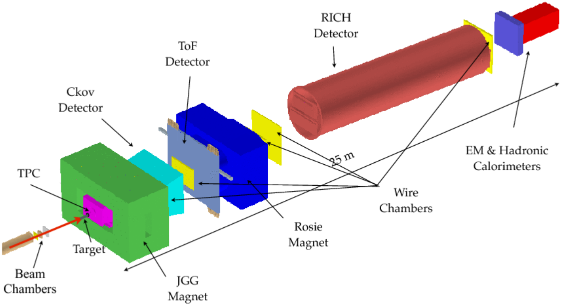
- Inelastic cross section:
  - Belletinni, Denisov, etc. cross sections of pC, πC, πAl etc.
  - **NA49: pC @ 158 GeV.**
  - NA61 pC @ 31 GeV.
- Hadron Production:
  - Barton: $pC \to \pi^{\pm}X$ @ 100 GeV $x_F > 0.3$
  - **NA49: $pC \to \pi^{\pm}X$ @ 158 GeV $x_F < 0.5$**
  - NA49: $pC \to n(p)X$ @ 158 GeV for $x_F < 0.95$
  - NA49: $pC \to K^{\pm}X$ @ 158 GeV for $x_F < 0.2$.
  - NA61: $pC \to \pi^{\pm}X$ @ 31 GeV.
  - MIPP: π/K from pC at 120 GeV for $p_Z > 20GeV/c$

Data Relevant for the NuMI Flux

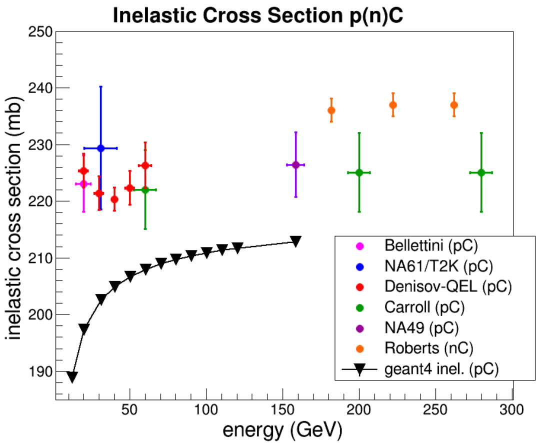
Thick targets experiments:

MIPP: proton on a spare NuMI target at 120 GeV:

- $\pi^{\pm}$ up to 80 GeV/c.
- K/π for > 20 GeV/c.



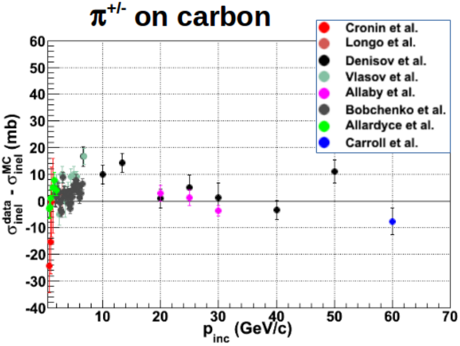
Data - MC Inelastic Cross Sections

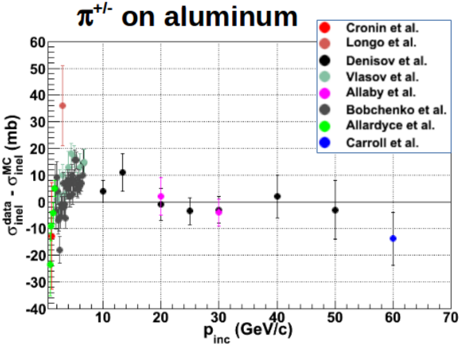


- The MC quasi-elastic component has been subtracted by looking at interactions where no new particles ($\pi's$ or K's) are created (geant4.2.p03 FTFP_BERT).

Data - MC Inelastic Cross Sections

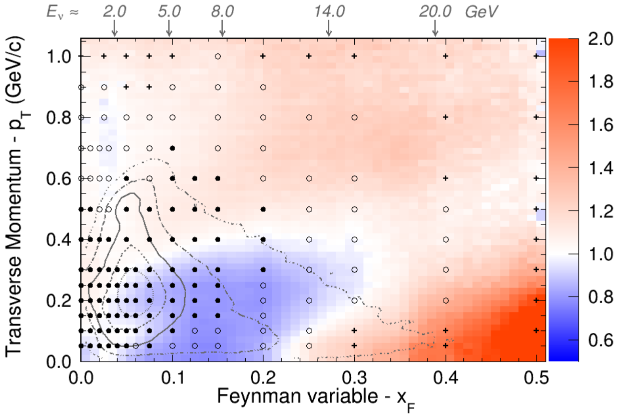
- Total Inelastic Cross Section





NA49 for $pC \to \pi^+ X$

NA49 Data-MC comparison (Closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%)

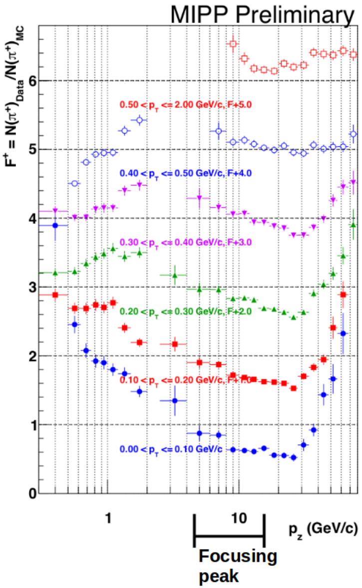


x_F: Feynman-x, $x_F = 2p_L^{CM}/\sqrt{s}$

MIPP NuMI π Yields

- Using MIPP yields reduces the uncertainty associated with the target geometry.
- The yields from target are a convolution of many interactions inside of the target.

J.Paley, M.D. Messier,
R. Raja et Al.
FNAL JETP April 2014,
Phys. Rev. D 90, 032001 (2014)



What is our strategy to calculate the flux?

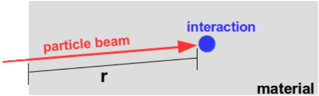
How do We Use Data to Correct the HP Models?

We apply a weight to the ν yield based on its hadronic interaction history

- The cascades that lead to ν's are tabulated at generation: the kinematics and the material of the cascades are saved.
- The correction is applied at the ν event, event by event at analysis time.

Attenuation Corrections

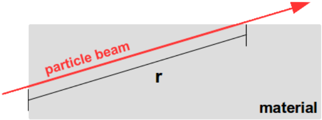
When the particle interacts in a volume



$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$$

N_A: Avogadro Number, ρ: density, A: mass number

When the particle passes through the volume without interacting



$$correction(r) = e^{-r\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$$

Two variables are important here:

- The amount of material $rN_A\rho/A$.
- The σ_{Data} and σ_{MC} disagreement.

Particle Production Correction

For thin target data (NA49 for instance):

$$correction(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$

- The **scale** has been calculated using Fluka and allows us to use NA49 for proton on carbon in p_{inc} in [12,120] GeV.
- The **scale** was checked by comparing with NA61 $pC \to \pi^{\pm}$ at 31 GeV.

For thick target data (MIPP):

$$correction(p_Z, p_T) = \frac{n_{Data}(p_Z, p_T)}{n_{MC}(p_Z, p_T)}$$

f: Invariant differential cross section and n is the particle yield and $f = Ed^3\sigma/dp^3$

What More can We do

Scaling *pC* to other materials

- Looking at data that measure hadronic interactions in different materials (Barton, Skubic, Eichten).
- Finding the uncertainty associated to extend proton on carbon interaction to other materials.

Determining the pion production from neutron carbon interactions using isospin arguments

$$\boxed{\begin{aligned}\sigma(pC \to \pi^+ X) = \sigma(nC \to \pi^- X)\\ \sigma(pC \to \pi^- X) = \sigma(nC \to \pi^+ X)\end{aligned}}$$

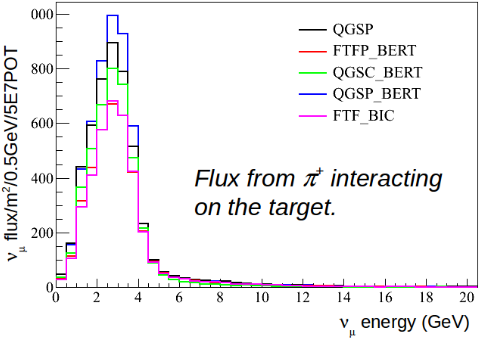
Estimate the K^0 yield using quark counting arguments

$$\boxed{N(K0) = \frac{N(K^+) + 3N(K^-)}{4}}$$

What if Data is not Available?

Option 1:

- Spread between different geant4 models.



Option 2:

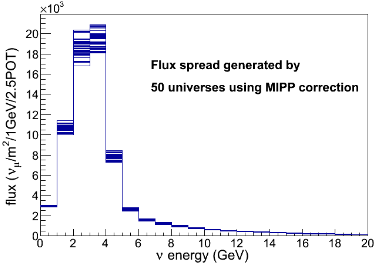
- Our best guess is anchored to data if at all possible, guided by agreement with other datasets.
- We are applying 40% uncertainty in 4 uncorrelated X_F regions per any conbination of projectile and produced particle.

How do we Propagate the Uncertainties?

- 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: flux, detector, cross sections.
- Measurements are repeated in each individual universe and the statistical variations are used to evaluate systematic uncertainties.

We assume highly correlated error bin-to-bin in the HP data that we used

(The figure shows the result of applying MIPP data with $+0.75$ correlation).



Results and More...

A Little Bit of History...

- Historically, we have had two predictions of the NuMI flux: **Generation-0** and **Generation-1** based on:
  - Thin targets for $pC \rightarrow (\pi, K, p)X$.
  - Attenuation of the primary proton beam in the target.
  - Model spread when there is no data to applied.
  - Focusing Uncertainties.
- Previous analyses used:

Flux	Analsis	Reference
Gen-0	ν_μ CCQE	PRL 111 (2013) 022502
	$\bar{\nu}_\mu$ CCQE	PRL 111 (2013) 022501
Gen-1	CC Target Ratios	PRL 112 (2014) 231801
	Coherent π	PRL 113 (2014) 261802
	ν_μ muon+proton	PRD 91 (2015) 071301
	$\bar{\nu}_\mu$ CC π^0	PRB 749 (2015) 130-136

A Little Bit of History...

In 2014, we started working on a new flux prediction "Generation-2" motivated by:

- **Hadron Production:**
  - Thick target data was published by the MIPP experiment using a LE NuMI target (2014).
  - The need to reduce flux uncertainties (by replacing the model spread with data).
  - Understanding of the particle absorption in the beamline volumes.
- **Improvements in the geometry simulation of NuMI:**
  - Accurate target positions.
  - A water layer around the horn inner conductors (and other missing materials).
  - A improved horn geometry model.
- **Sharing our results with all NuMI experiments:**
  - Numi-X efforts to converge with all flux working groups.
  - Unifying flux ntuples for all NuMI experiments (R. Hatcher).

Generation-2

Having thin and thick target data give an opportunity to have two flux predictions:

Thin Target Data

- Use thin target data to correct all interactions.

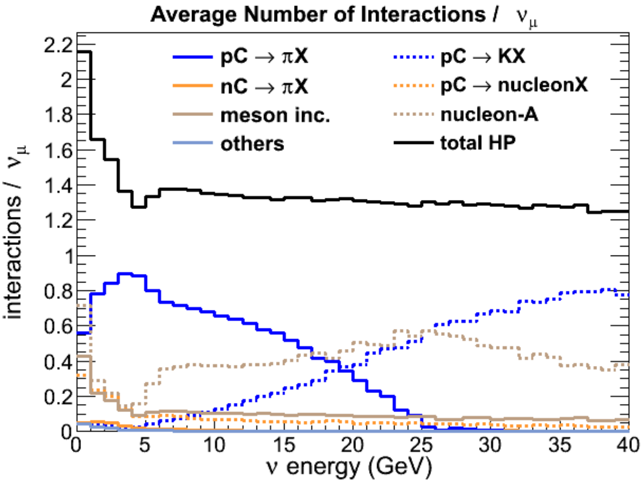
Thick Target Data

- Use MIPP NuMI as primary correction.
- Use thin target data for interactions not covered yet.

- Extending the data coverage using theoretical inputs.
- For interactions not covered, apply an educated guess based on data.
- Correct for the effects of the beam attenuation in the NuMI materials.

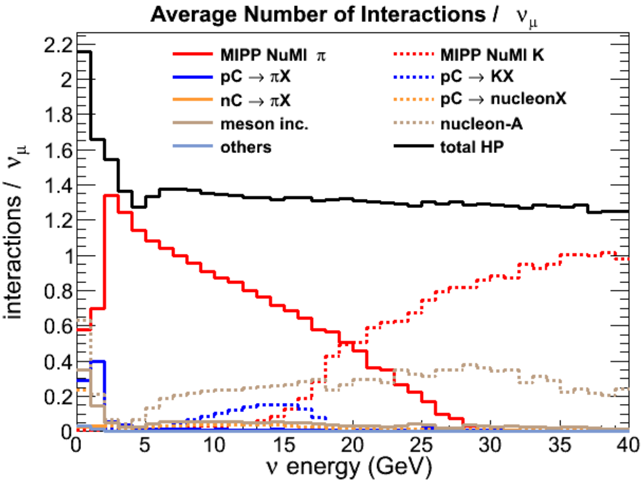
Interactions Covered

Generation-2 thin



Interactions Covered

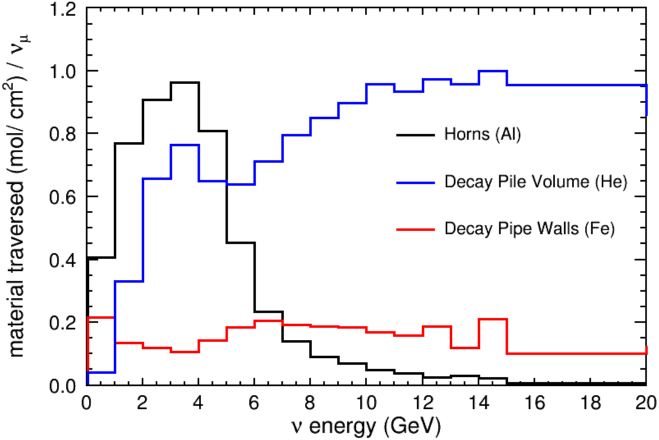
Generation-2 thick



Material Transversed

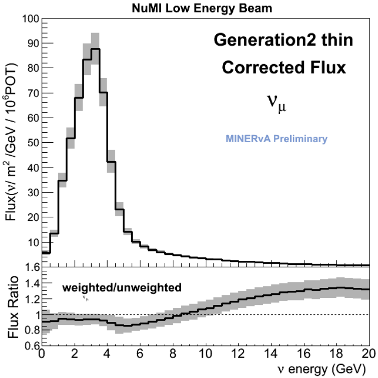
π parent of ν_μ

Reference: $1mol/cm^2 = 10cm$ of Al and $1mol/cm^2 \approx 500m$ of He.

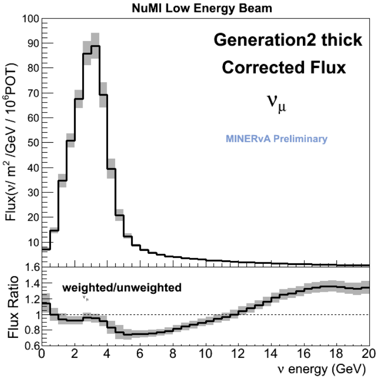


Generation-2 Flux Prediction for MINERvA

Gen2-thin

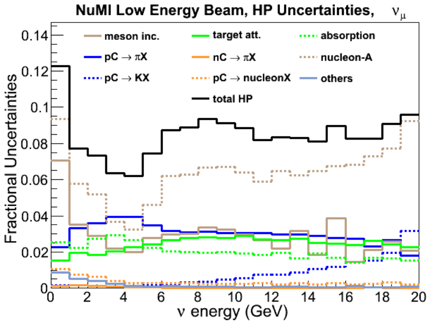


Gen2-thick

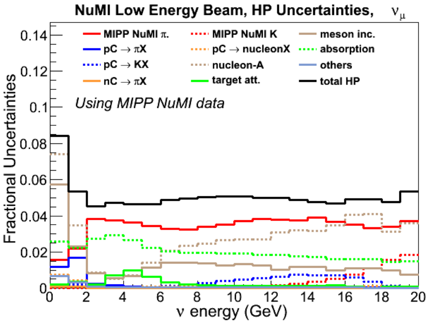


Generation-2 HP Uncertainties

Gen2-thin

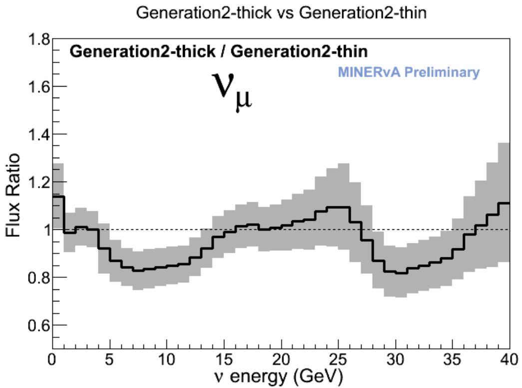


Gen2-thick



Gen2-thin vs Gen2-thick

A comparison between these two predictions shows a significant disagreement.



To decide between two a priori predictions, we compare to an in-situ measurement: **the "Low-nu" technique**.

Low-nu Basics

- Charge-current scattering with lower hadronic recoil energy is a standard candle.
- Differential cross section can be expresed as:

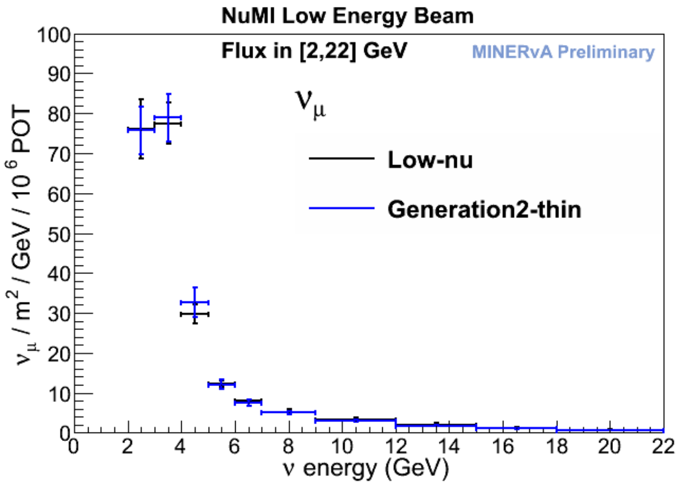
$$\frac{d\sigma}{d\nu} = A(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{E^2})$$

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

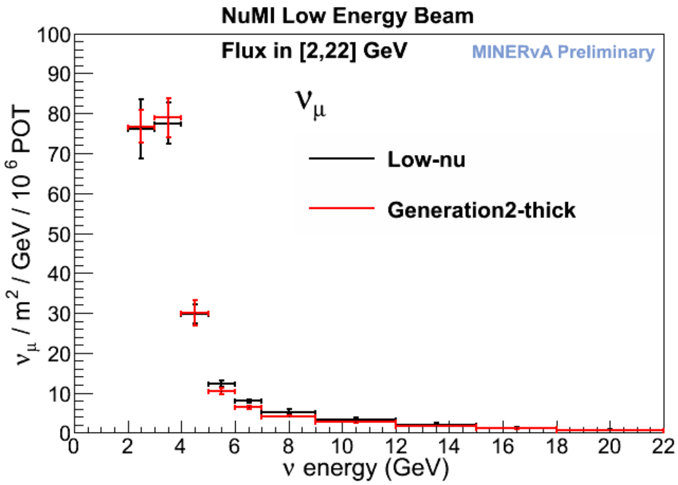
- As $\nu/E \to 0$, $\frac{d\sigma}{d\nu} \to A$, then it gives us the flux shape.
  - For finite ν, we use GENIE to compute corections.
- Normalization tied to external measurements at high energy (NOMAD σ_{tot} on carbon).

More details on January 8, Wine & Cheese by Jeff Nelson

Generation-2 thin and Low-nu Comparison

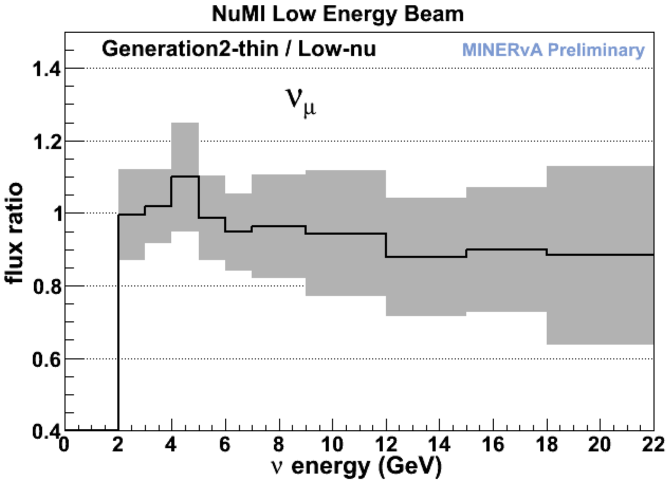


Generation-2 thick and Low-nu Comparison



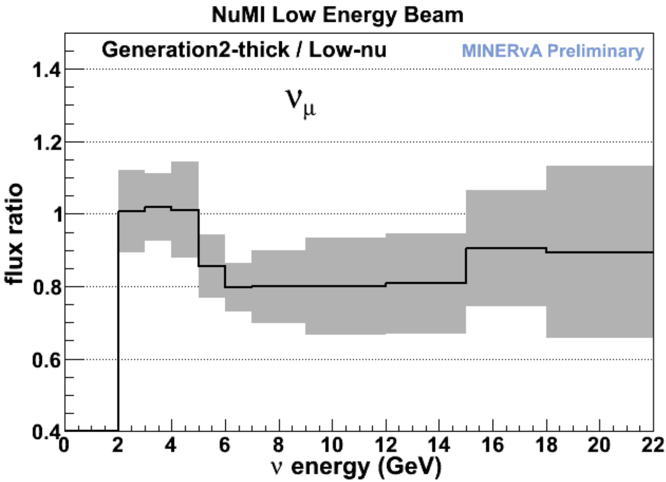
Generation-2 Thin and Low-nu Comparison

We see consistency along the whole neutrino energy range (low-nu flux predicts the flux for >2 GeV)



Generation-2 thick and Low-nu Comparison

We see consistency in the peak but significant disagreement in the $[5, 15] GeV$ regime.

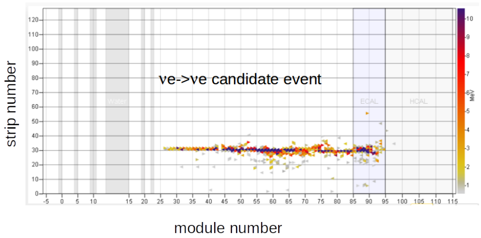


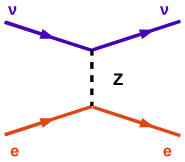
Conclusions of the A Priori Flux Comparison

- Based on the agreement of Gen-2 thin and low-nu, we decided to use Gen-2 thin for our next round of analysis.
- Gen-2 thick offers the prospect of significantly smaller errors: this validate the technique of measuring thick target data.
- Gen-2 thin can be applied directly to the Medium Energy Flux.
- Atop of the a priori flux, we apply an additional constraint of the flux with $\nu - e$ **scattering** measurements.

ν-e Scattering

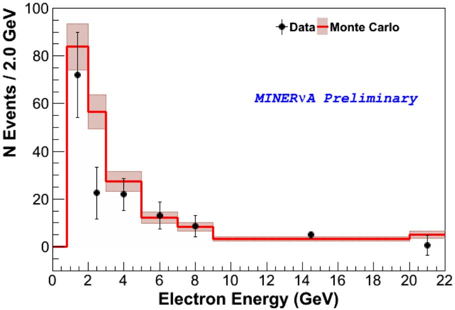
- Neutrino scattering on electrons is a standard candle:
  - Standard electroweak theory predicts it precisely.
  - Signal is a single electron moving in beam direction.
  - The cross section for this process is smaller than the cross section on the nucleus scattering by a factor of 2000.
  - Statistically limited.
- By improving the flux normalization uncertainties, this reduces the uncertainties on our absolute cross-section measurements.





ν-e Scattering

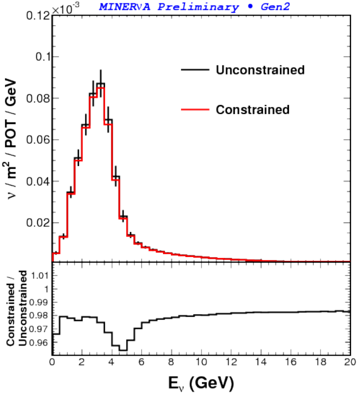
- $123 \pm 17.0(stats) \pm 9.1(sys)$ events founded in MINERvA (J.Park, FNAL JETP Dec 2013)
- Observed ν-e scattering events give a constraint on the flux: we can use it to weight up or down the more likely or unlikely universes.



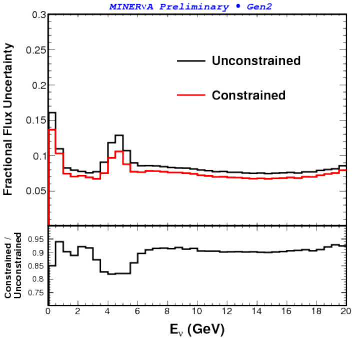
ν-e Scattering Constraint on Generation-2 Thin

Effect on ν_μ:

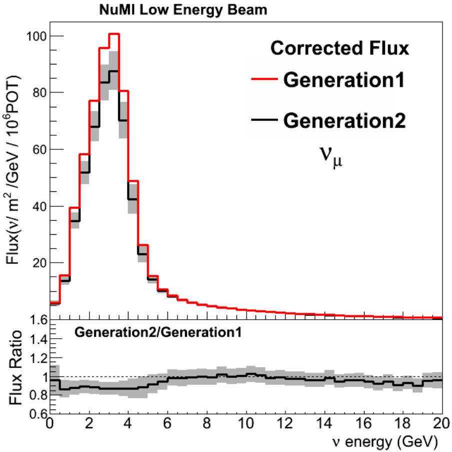
Flux changing after $\nu - e$ constraint



Fractional Error changing after $\nu - e$ constraint



Updating MINERvA Results



Integrated flux ratios in $[1.5, 10]GeV$ for $\frac{Gen2-thin}{Gen1}$:

ν_μ	0.887
$\bar{\nu}_\mu$	0.888

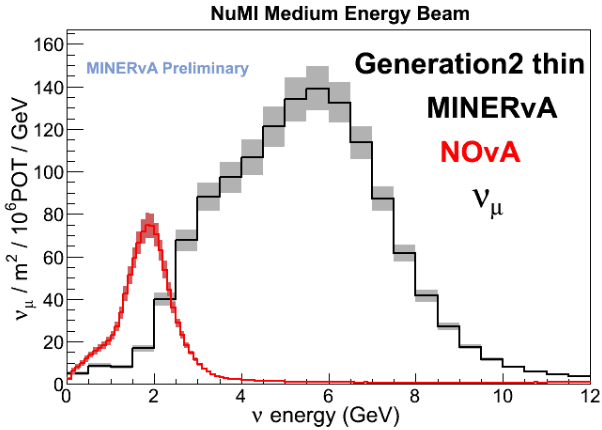
ME and Extension to Other Detectors

ME and Extension to Other Detectors

- All techniques presented here can be used to predict a a priori flux for any conventional neutrino beam.
- For NuMI, we developed a computational tool called "PPFX" (Package to Predict the Flux) open and free.
- PPFX can be used direclty to calculate the flux at any position in the NuMI beamline.
- I will show preliminary plots of the flux passing through the center of the front face of MINERvA and NOvA Near Detector.

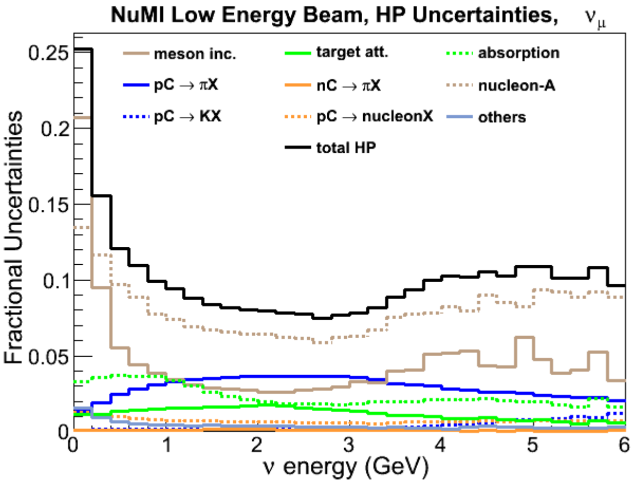
MINERvA and NOvA

Just HP errors are shown



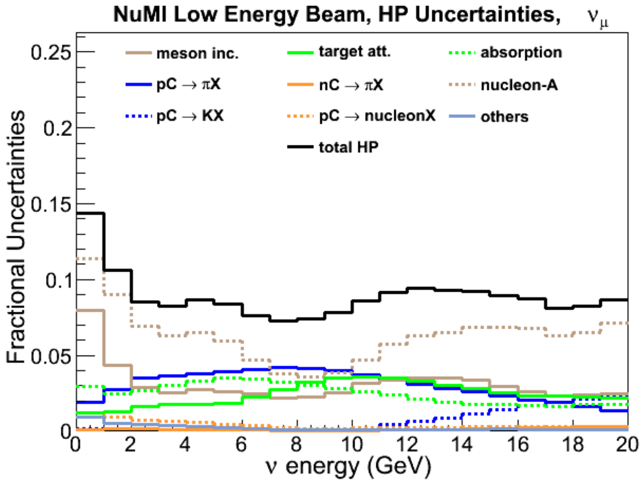
HP Fractional Errors

NOvA

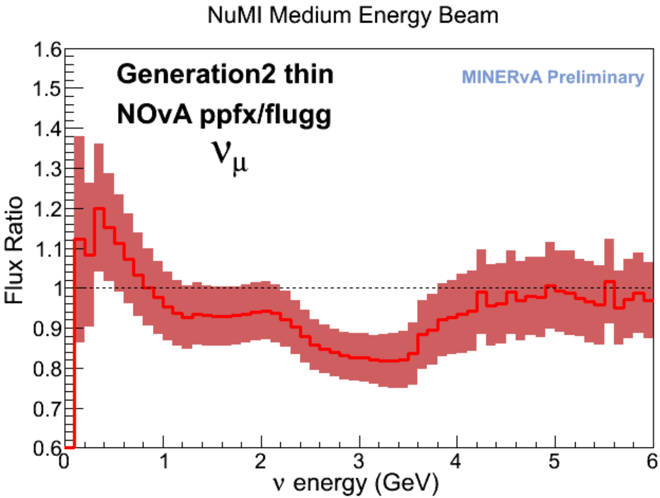


HP Fractional Errors

MINERvA



NOvA Comparison with Flugg



Thanks to Alex Radovic to provide us NOvA oficial flux histograms.

Conclusions

- For MINERvA and other experiments it is crucial to have a precise measurement of the flux with small uncertainties.
- We have shown a new computation of the NuMI flux with reduced uncertainties and improved error budget accounting.
- Our work indicates where additional data is needed in order to further reduce uncertainties for NuMI and LBNF.
  - The program of measurements proposed by USNA61 is extremely important.

Conclusions

- The procedure and the computational tools will be available for all experiments that see NuMI ν's.
- Paper in preparation. It will be released in January 2016.

Backup Slides

6 Joint Experimental-Theoretical Seminars in 2015:

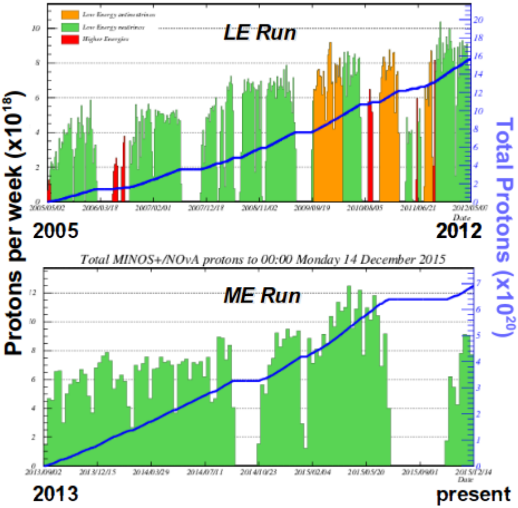
- **Trung Le, Rutgers University.** *Antineutrino Production of Neutral Pions in MINERvA. Jan9.*
- **Joel Mousseau, U. of Florida.** *First Search for EMC Effect and Shadowing in Neutrino Scattering at MINERvA.May8.*
- **Carrie McGivern U. of Pittsburgh.** *Charged Current Pion Production as Seen by Muons at MINERvA. June 26.*
- **Jeremy Wolcott U. of Rochester** *Electron Neutrino Quasi-Elastic Scattering and Observation of Neutral-Current Diffractive-like Process at MINERvA. September 18.*
- **Phil Rodrigues U. of Rochester** *Identification of multinucleon effects in neutrino-carbon interactions at MINERvA. December 11.*
- **Leo Aliaga, William and Mary** *Flux Results from MINERvA. December 18.*

The Main Injector Beam

120 GeV protons from FNAL Main Injector

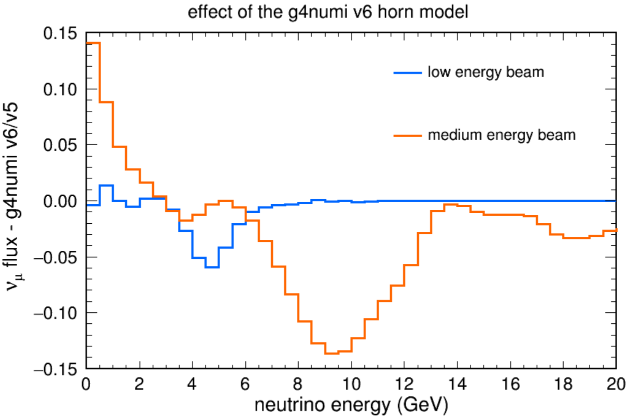
	LE	ME
Frequency	1 spill/2.2 s	1 spill/1.3 s
Spill length	10 μs	10 μs
Typical Intensity	$\approx$ 3E13 POT/spill	$\approx$ 3E13 POT/spill
Beam Power	$\approx$ 250 kW	$\approx$ 400 kW

Low and Medium Energy Runs



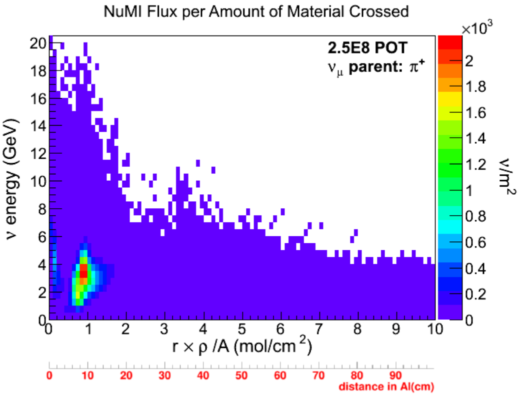
Geometric Effects in the Horn Simulation

Effect of the new horn model



The Distance Traveled By the Hadron ν Parents

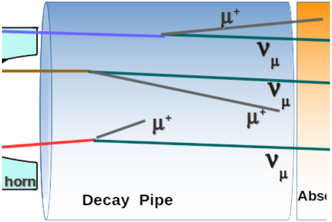
π^+ neutrino parents passing through the horns inner conductors.



The horn inner conductor is long and thin:

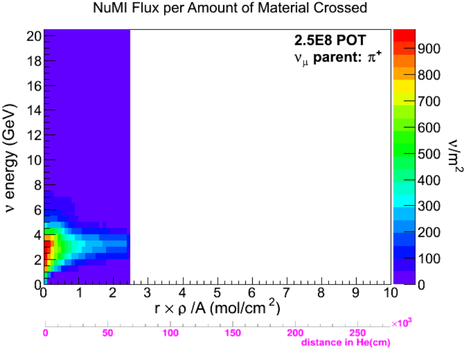
- Calculations indicate that the horn material reduces the flux by 40%.

The Distance Traveled By the Hadron ν Parents



- Long pipe (675 m) filled with He gas.
- Studies show the He effect:
  - 10% reduction in focusing peak.
  - 5% increase in the tail.

π^+ neutrino parent passing through the decay pipe.



Thin Target Data References

- NA49 pC @ 158 GeV
  - $\pi^{\pm}$ 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<0.9 [*Eur.Phys.J. C73 (2013) 2364]*

  } some p_T dependence
- MIPP pC @120 GeV *[A. Lebedev Ph.D. thesis]*
  - K/π ratio + NA49 extends kaon coverage to xF<0.5
- Weights applied for 12 < $p_{incident}$ <120 GeV.
  - Data cross-section scaled using FLUKA *[www.fluka.org]*
  - Checked by comparing to NA61 pC → $\pi^{\pm}$ X at 31 GeV/c *[Phys.Rev. C84 (2011)034604]*

ppfx

PPFX: Package to Predict the Flux

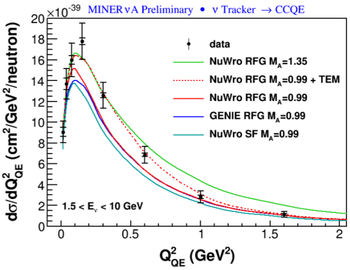
- Experiment independent NuMI reweighting package.
- Applying all relevant data and remove model spread.
- Handle correlated uncertainties.
- Account for the attenuation of particles passing through NuMI materials.
- Use "many universes" technique for the uncertainty propagation.
- This is an external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

PPFX is able to calculate the HP corrected NuMI flux for any detector

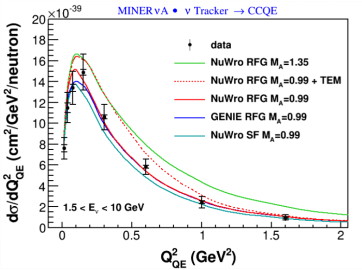
Impact of the New Flux on CCQE Results

Muon Neutrino

New results (using Gen2-thin)



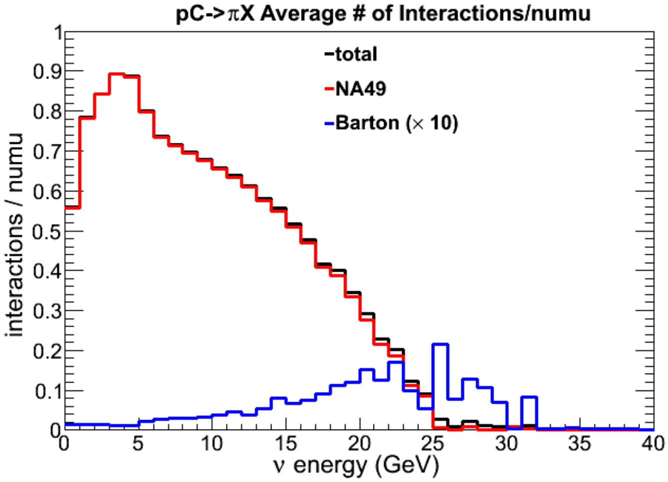
2013 Paper (using Gen0)



Thin Target Data Pion Production Correction

- We use thin target data taken by NA49 to correct their measured yield per incident proton for $x_F < 0.5$.
- The NA49 data were taken at 158 GeV and we correct the Feynman scaling applying weights for proton energies 12-120 GeV, using FLUKA to correct for the residual energy dependence.
- This prescription was checked by scaling NA49 pion production data at 158 GeV to NA61 data taken at 31 GeV.
- We use Barton for $x_F > 0.5$.
- We assume +1.0 bin-to-bin correlation for the systematic errors.

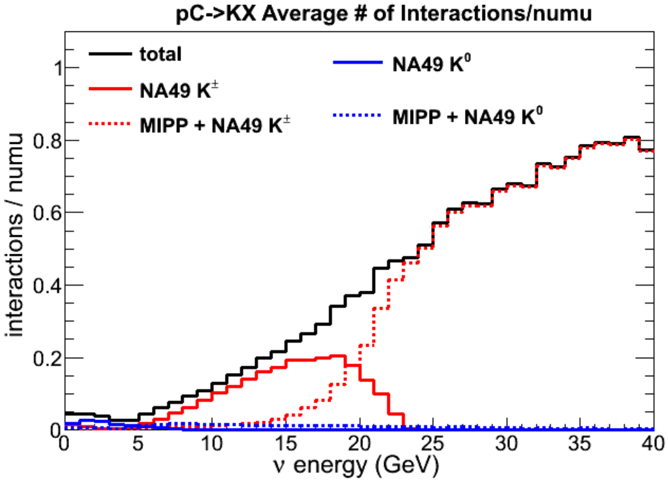
Thin Target Data Pion Production Correction



Thin Target Data Kaon Production Correction

- We use G. Tinti Thesis resuls based on NA49 to correct their measured yield per incident proton for $x_F < 0.2$.
- We combine NA49 pion yields with the π/K ratios from MIPP, Andre Lebedev thesis for $0.2 < x_F < 0.5$
- As in thin target data pion-C Correction, we orrect the Feynman scaling applying weights for proton energies 12-120 GeV, using FLUKA to correct for the residual energy dependence.
- We do not assume any correlation bin-to-bin for the systematic errors of the MIPP ratio.

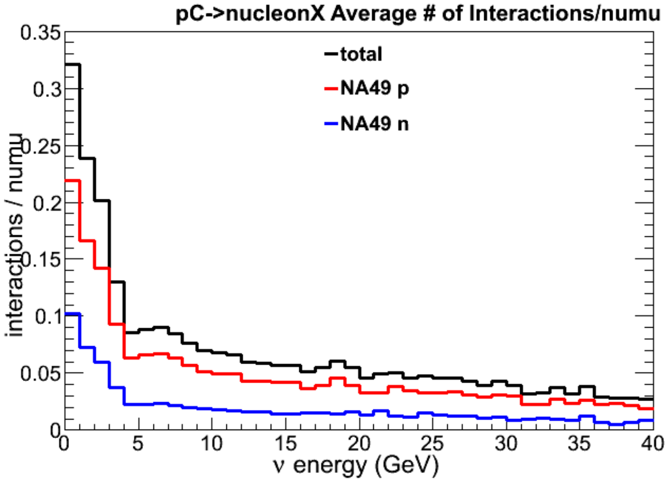
Thin Target Data Kaon Production Correction



Thin Target Data Nucleon Production Correction

- We use thin target data taken by NA49 to correct their measured yield per incident proton for $x_F < 0.95$.
- As in thin target data pion-C Correction, we orrect the Feynman scaling applying weights for proton energies 12-120 GeV, using FLUKA to correct for the residual energy dependence.
- We assume +1.0 bin-to-bin correlation for the systematic errors.

Thin Target Data Nucleon Production Correction



Thin Target Data Pion Production form Neutron - Carbon Interactions Correction

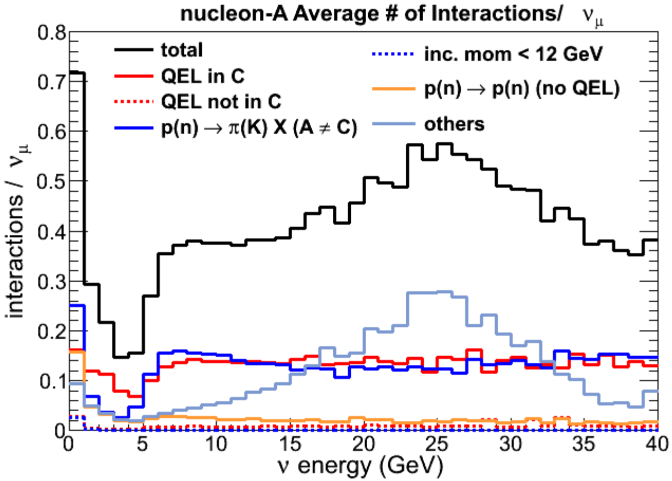
- Using isoscalar symmetry of nucleons interacting in deuteron, we treat $pC \to \pi^+ X$ as $nC \to \pi^- X$ and viceversa.

Thin Target Nucleon Interaction Correction

There are two categories:

- Nucleon interactions on nuclei that are not carbon. We extend the coverage of NA49 to other materials than carbon.
- For all nucleon interactions that are not covered by any dataset we apply 40% unceratinty in 4 x_F uncorrelated regions from $[0, 1]$.

Thin Target Nucleon Interaction Correction

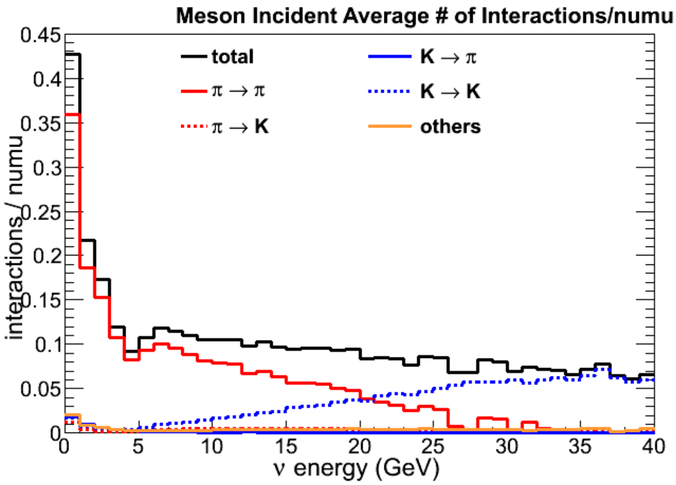


Thin Target Meson Incident Correction

There are two categories:

- There is little applicable data on interactions in which mesons are the projectile.
- We apply 40% unceratinty in 4 x_F uncorrelated regions from $[0, 1]$.

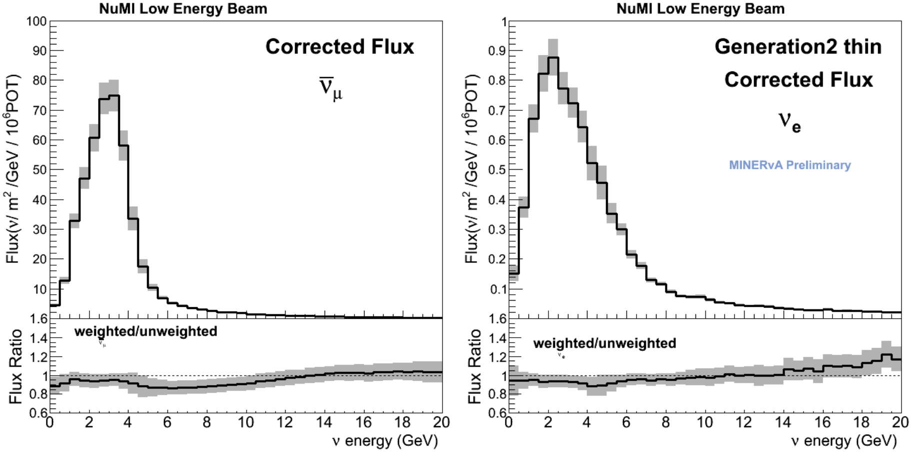
Meson Incident in Geneation-2 thin



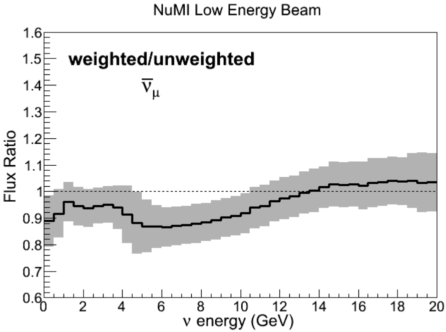
Target and Other Materials Attenuation Correction

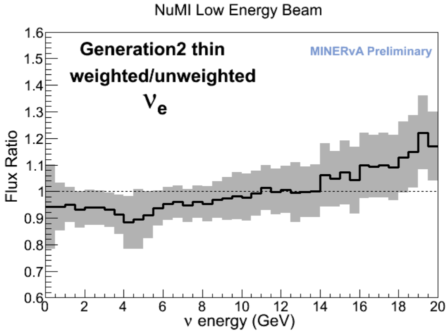
- We attempt to correct the attenuation for the particles the pass through the target (C), the inner conductors of the magnetic horns (Al), the decay pipe volume (He) and the decay pipe walls (Fe).
- We applied this correction when interacts in the target and when the particle leaves.

Generation-2 thin MINERvA $\bar{\nu}_\mu$ and ν_e

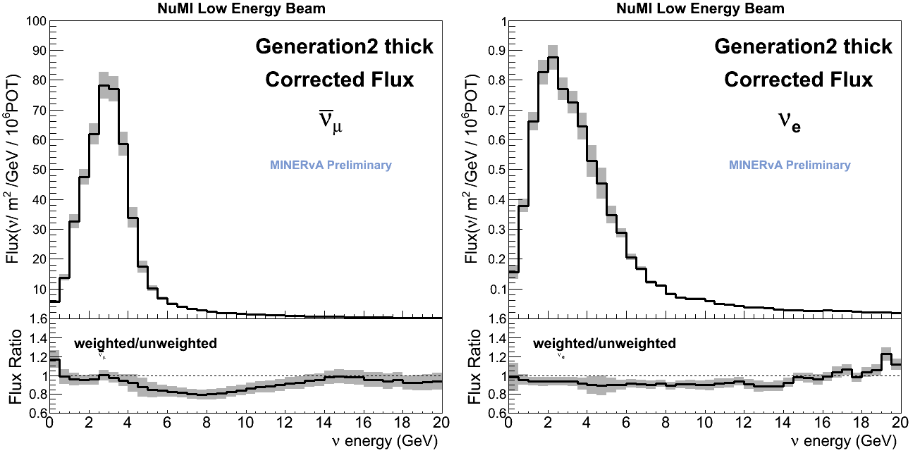


Generation-2 thin MINERvA $\bar{\nu}_\mu$ and ν_e

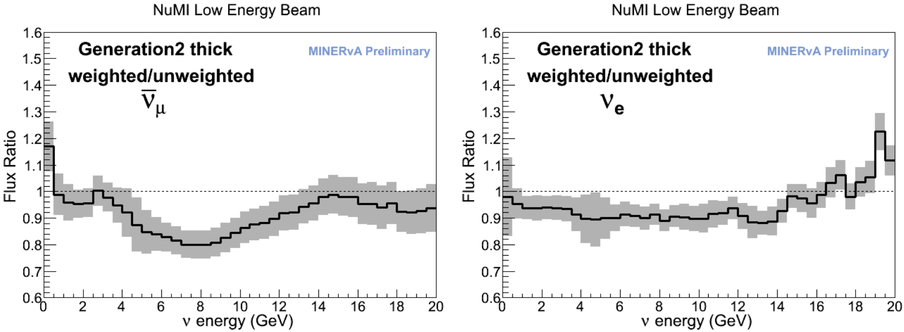




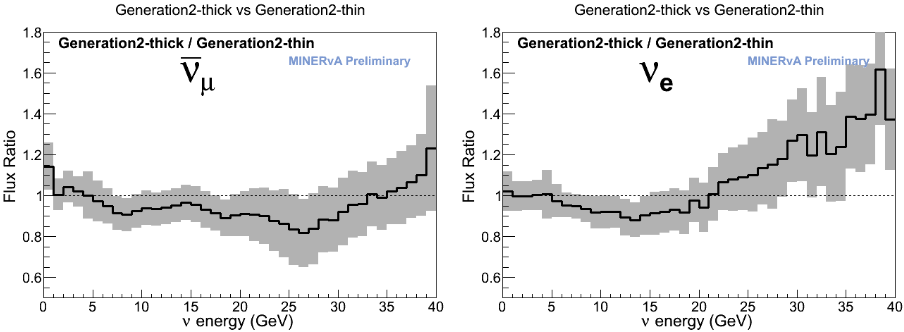
Generation-2 thick MINERvA $\bar{\nu}_\mu$ and ν_e



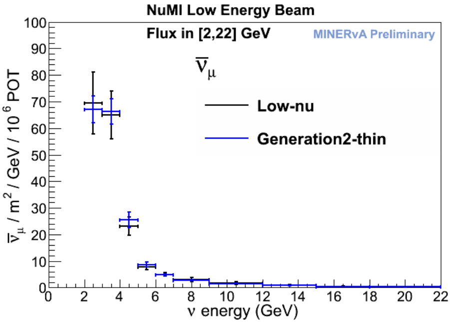
Generation-2 thick MINERvA $\bar{\nu}_\mu$ and ν_e

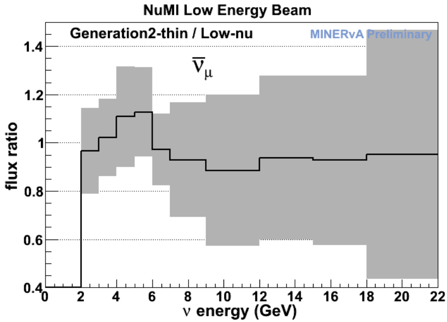


Gen-2 thick/Gen-2 thin MINERvA $\bar{\nu}_\mu$ and ν_e

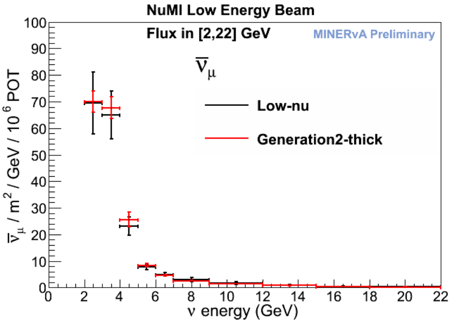


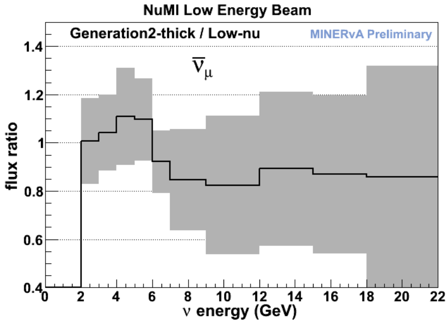
Gen-2 thin vs. Low-nu for $\bar{\nu}_\mu$



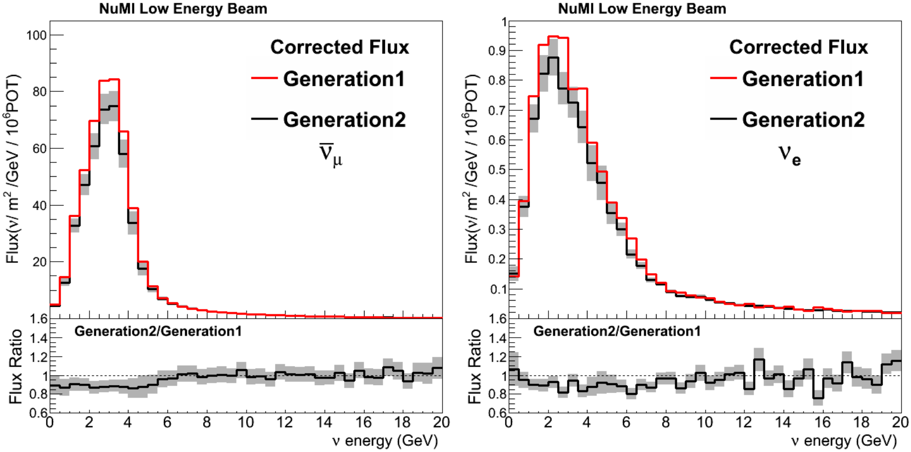


Gen-2 thick vs. Low-nu for $\bar{\nu}_\mu$

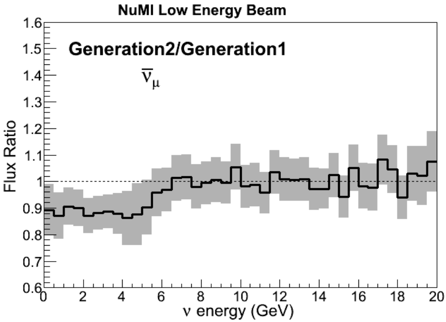


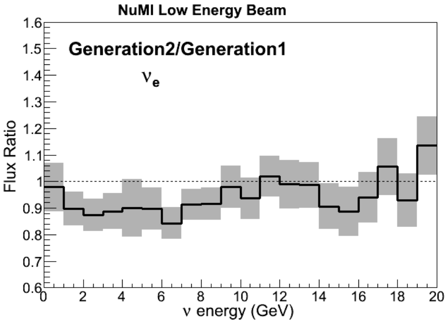


Generation-2 thin vs Gen1 MINERvA $\bar{\nu}_\mu$ and ν_e

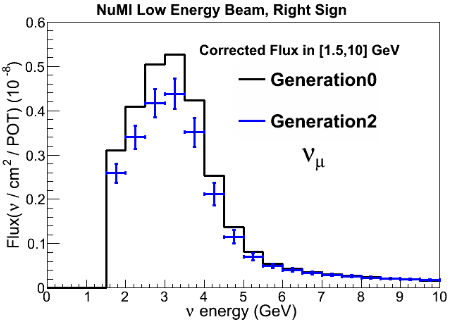


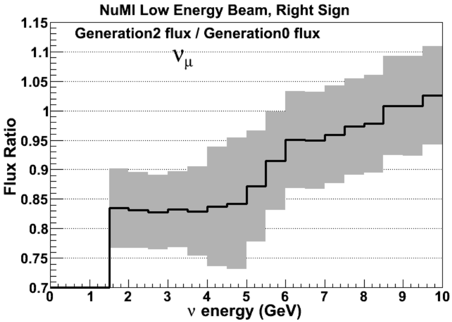
Generation-2 thin vs Gen1 MINERvA $\bar{\nu}_\mu$ and ν_e



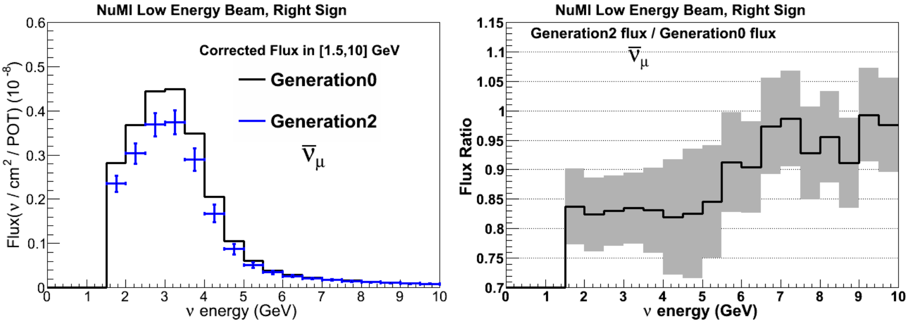


Generation-2 thin vs Gen0 MINERvA ν_μ

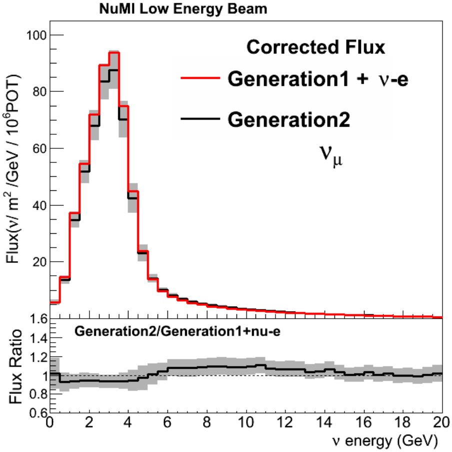


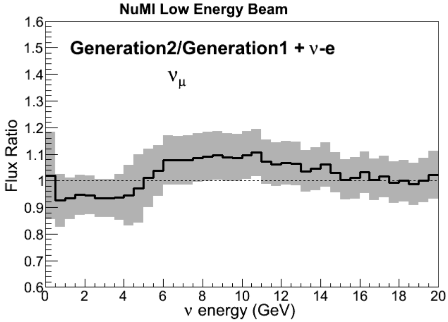


Generation-2 thin vs Gen0 MINERvA $\bar{\nu}_\mu$

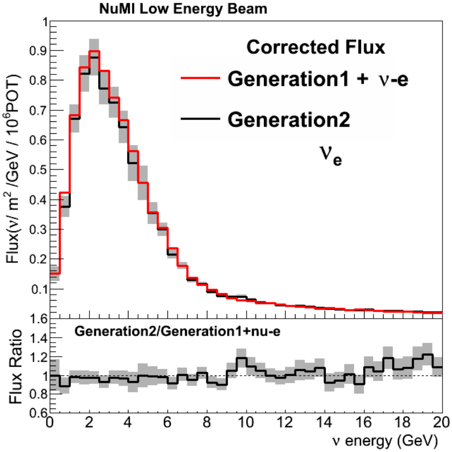


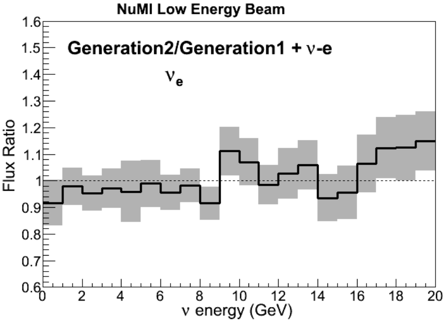
Generation-2 thin vs Gen1+$\nu - e$ for MINERvA ν_μ





Generation-2 thin vs Gen1+$\nu - e$ for MINERvA ν_e





MINERvA ν_μ

Integrated flux ratios:

Gen\range	[1.5, 10] GeV	[0, 10] GeV	[0, 20] GeV	[0, 40] GeV
$\frac{Gen2thin}{Gen0}$	0.846	--	--	--
$\frac{Gen2thin}{Gen1}$	0.887	0.886	0.890	0.891
$\frac{Gen2thin}{Gen1+nu-e}$	0.956	0.954	0.959	0.960

MINERvA $\bar{\nu}_\mu$

Integrated flux ratios

Gen\range	[1.5, 10] GeV	[0, 10] GeV	[0, 20] GeV	[0, 40] GeV
$\frac{Gen2thin}{Gen0}$	0.838	--	--	--
$\frac{Gen2thin}{Gen1}$	0.888	0.889	0.892	0.892
$\frac{Gen2thin}{Gen1+nu-e}$	--	--	--	--

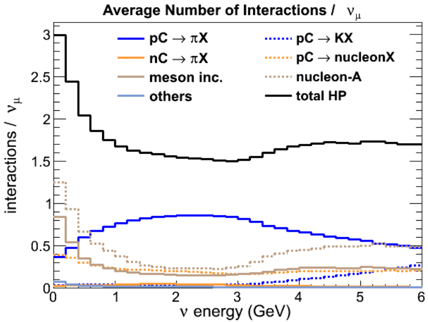
MINERvA ν_e

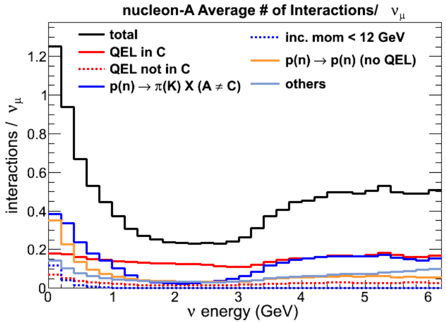
Integrated flux ratios

Gen\range	[1.5, 10] GeV	[0, 10] GeV	[0, 20] GeV	[0, 40] GeV
$\frac{Gen2thin}{Gen0}$	--	--	--	--
$\frac{Gen2thin}{Gen1}$	0.889	0.894	0.900	0.908
$\frac{Gen2thin}{Gen1+nu-e}$	0.970	0.964	0.970	0.980

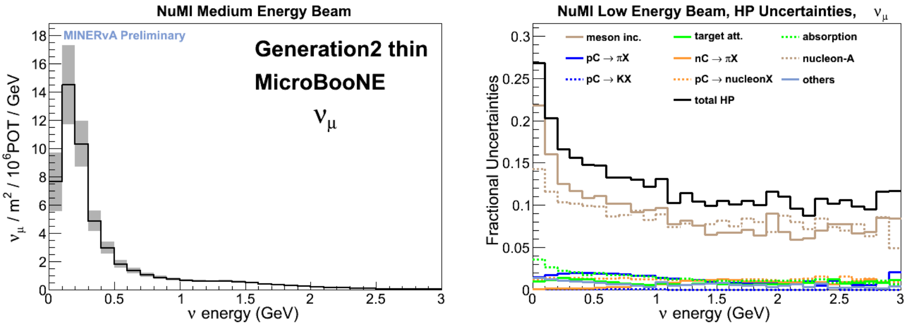
Hadronic Interactions per ν in NOvA

hadronic interactions per neutrino in NOvA





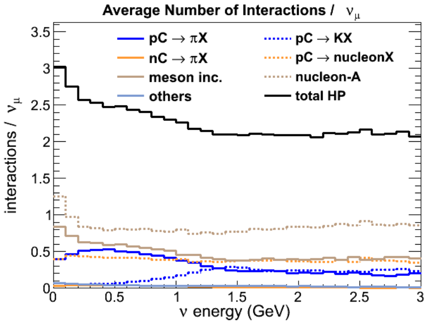
MicroBooNE Flux from NuMI

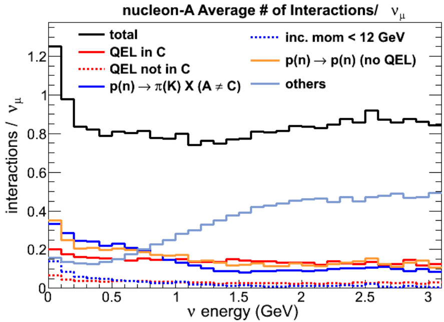


PPFX has not incorporated HARP data. This will reduce "meson inc." uncertainties.

Hadronic Interactions per ν in MicroBooNE

hadronic interactions per neutrino in MicroBooNE



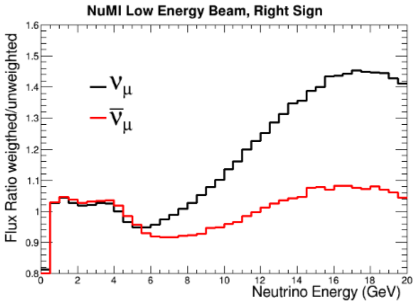


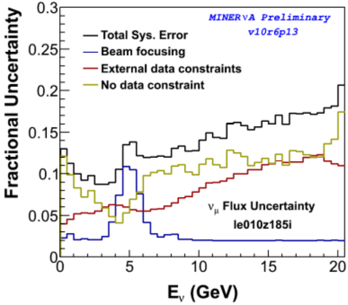
First Version of NuMI Flux Prediction for MINERvA

Flux Generation 1:

Flux HP Correction

Fractional Uncertainty





(L. Fields)

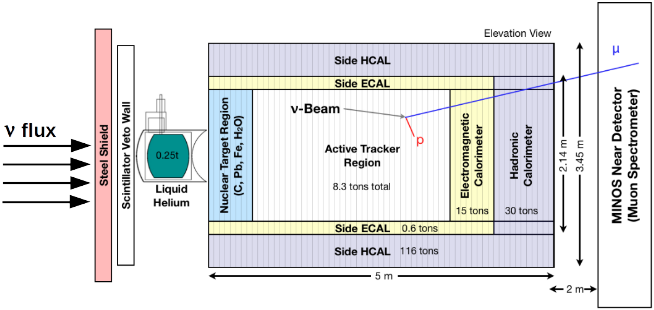
Neutrino oscillation parameter status

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$	$(0.00 - 0.16) \oplus (0.86 - 2.00)$
		$((0.00 - 0.02) \oplus (0.70 - 2.00))$

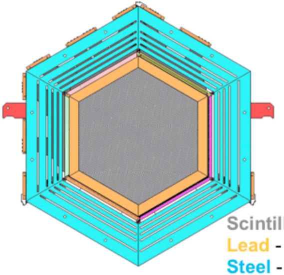
K. Nakamura and S.T. Petcov, (Particle Data Group). Phys. C, 38, 090001 (2014)

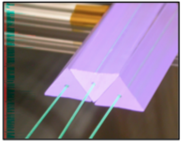
MINERvA Detector

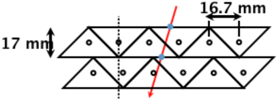
- 120 “modules" perpendicular to the beam direction, containing ∼32k readout channels
- Finely-segmented scintillating central tracking region
- Nuclear targets, plastic (CH), EM and Hadronic calorimeters with additional lead and steel plates
- MINOS near detector doubles as a muon spectometer.



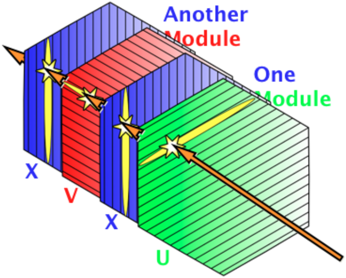
Minerva Detector (In More Detail)



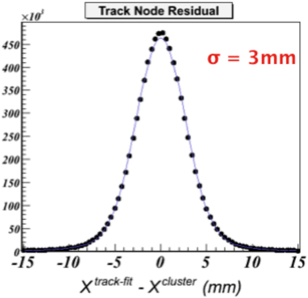




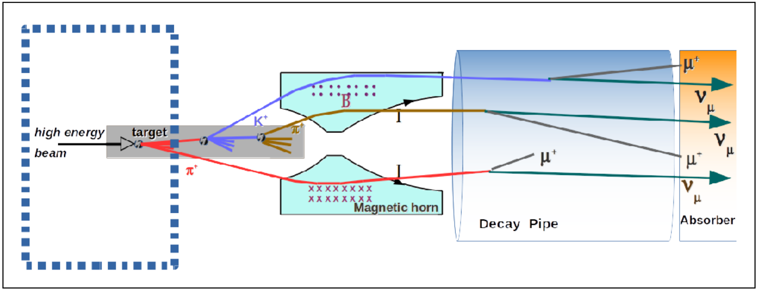
Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry



Charge sharing for improved position resolution (~3 mm) and alignment



The Beam

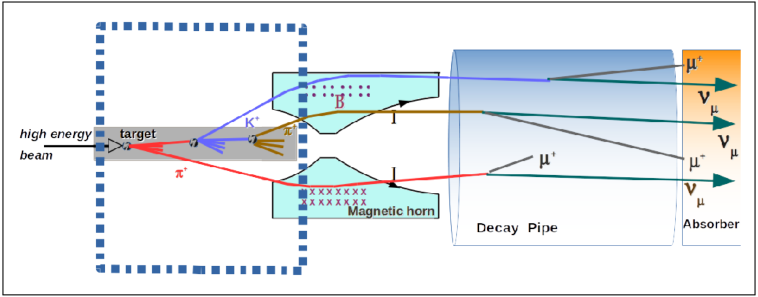


Proton beam from an accelerator

- The higher energy neutrino beam you want, the higher energy protons you have to start with.
- Number of pions produced is roughly a function of "proton power".

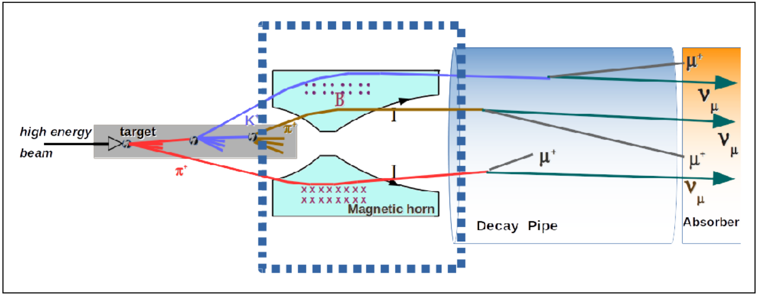
$$P(kW) \propto POT(10^{20}) \times E_p(GeV)/T(10^7 s)$$

The target



- **Intensity:** high beam intensity, more interactions and hotter target... needs cooling.
- **Geometry:** the longer the target, higher probability the protons will interact and more mesons are produced.
- **Material:** low Z, protons interact without losing too much energy.

The focusing



Want to focus as many particles as possible and cancel as much background.... best choice: magnetic proportional the the particle trajectory.

- Cancel p_T of the π and K.
- Deflect unwanted particles.

Inelastic Cross Section pi and K on carbon and aluminum

- MC comparison: