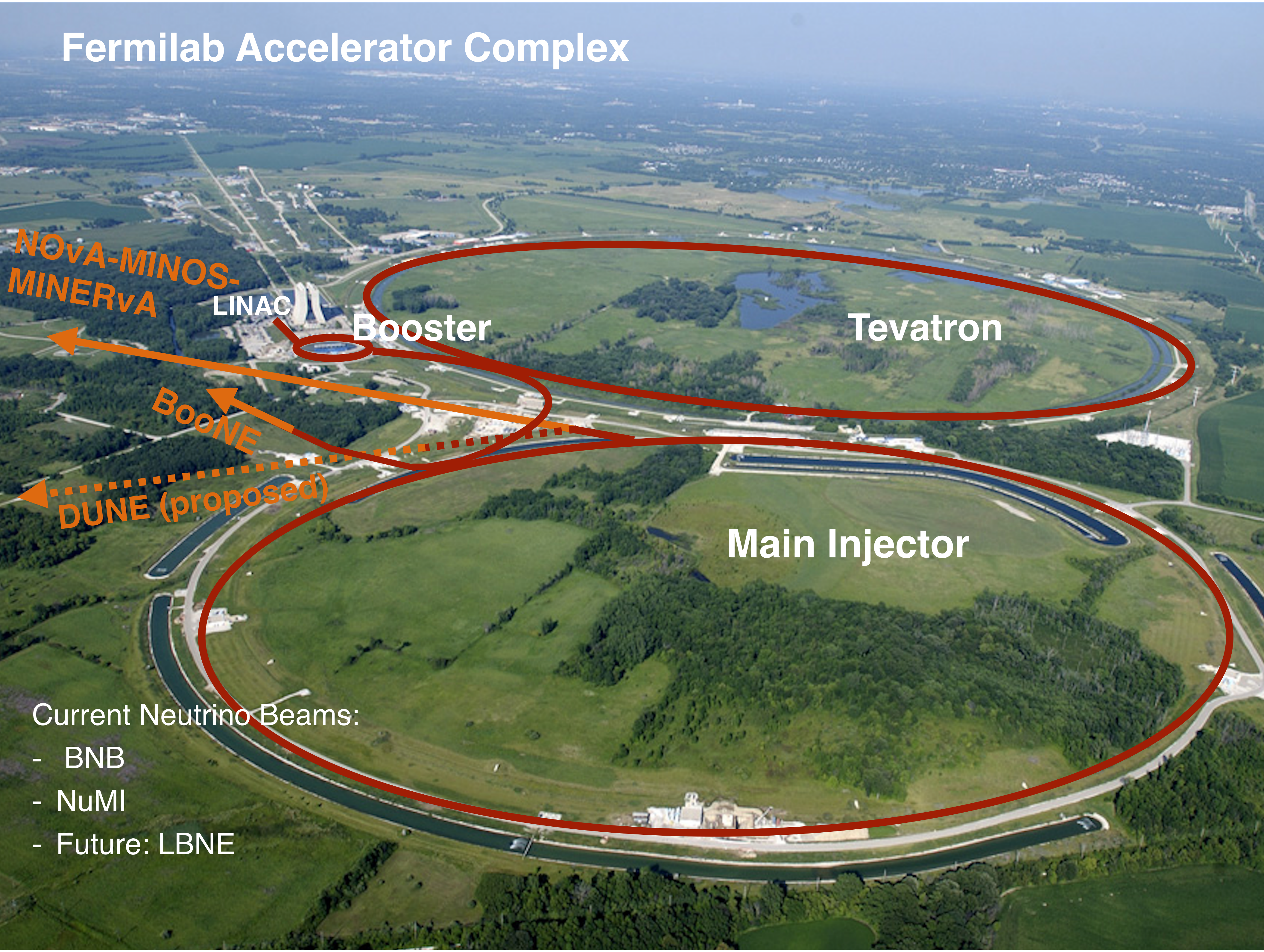
Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

The NuMI Flux Prediction

Leo Aliaga

11th International Workshop on Neutrino-Nucleus Scattering in the Few-GeV Region

June 25-30, 2017, Field Institute, Toronto, Canada


Fermilab Accelerator Complex
NOvA-MINOS-MINERvA
LINAC
Booster
Tevatron
BooNE
DUNE (proposed)
Main Injector
Current Neutrino Beams:
- BNB
- NuMI
- Future: LBNE

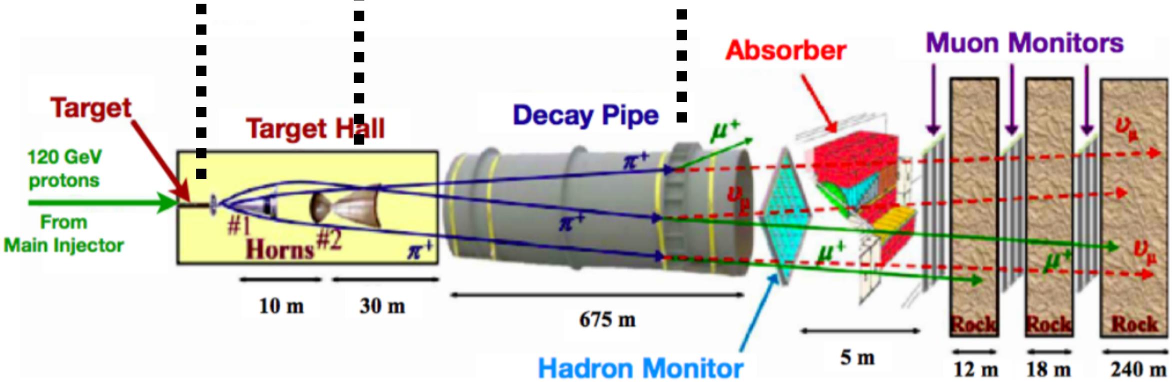
NuMI

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 (note, they can also interact!)



NOvA

MINERvA

MINOS

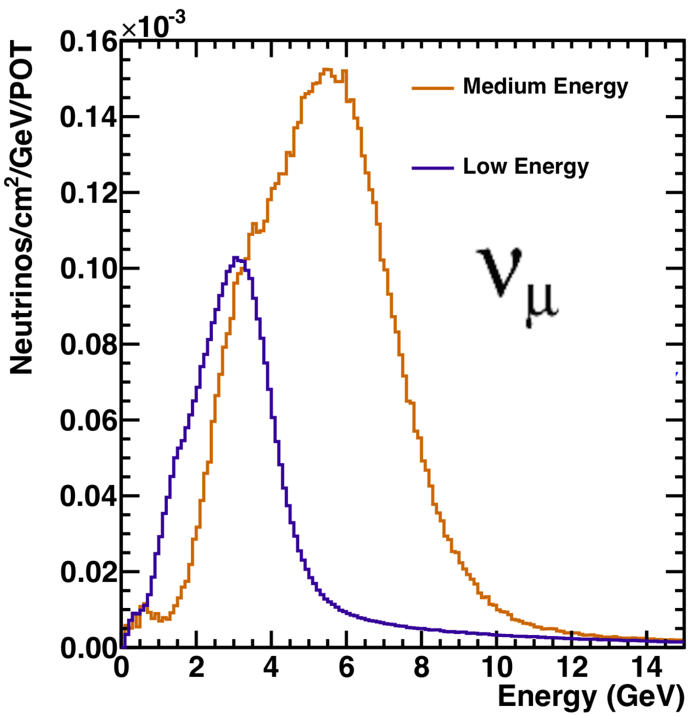
$$\pi^{\pm} \longrightarrow \mu\nu_{\mu}$$

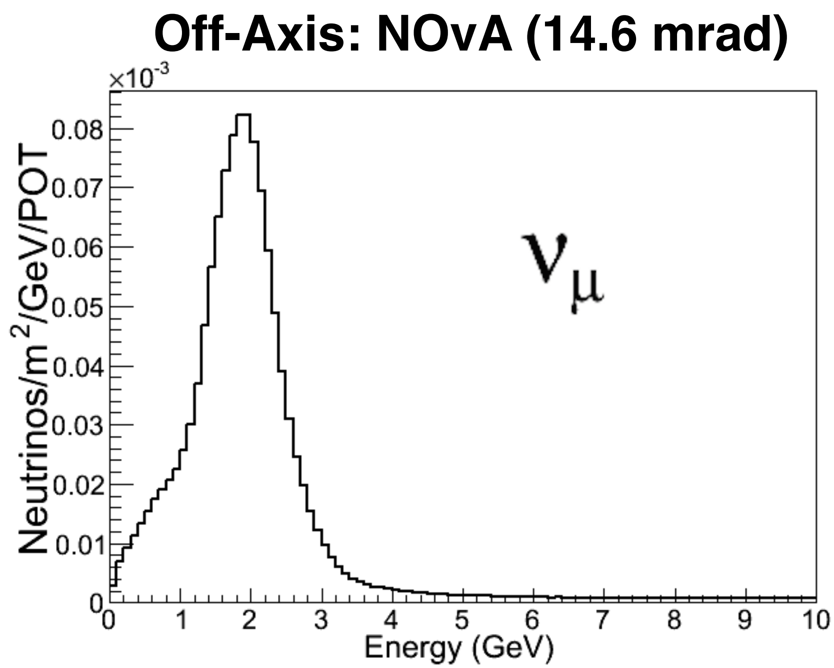
$$K^{\pm} \longrightarrow \mu\nu_{\mu}$$

NuMI (Neutrinos at the Main Injector)

Mode	time	Average Power (kW)	POT
Low Energy (LE)	2005-2012	250	$1.6\text{x}10^{21}$
Medium Energy (ME)	2013-present	400 -> 700	$1.2\ \text{x}10^{21}$

- *ME mode is produced by moving the target position upstream and moving the horn 2 downstream*





*NuMI provides neutrinos for the Fermilab high intensity neutrino studies: **oscillation parameters, cross-sections, search for exotic physics, etc.***

Why is it so Hard to Determine the Flux?

Two Challenges:

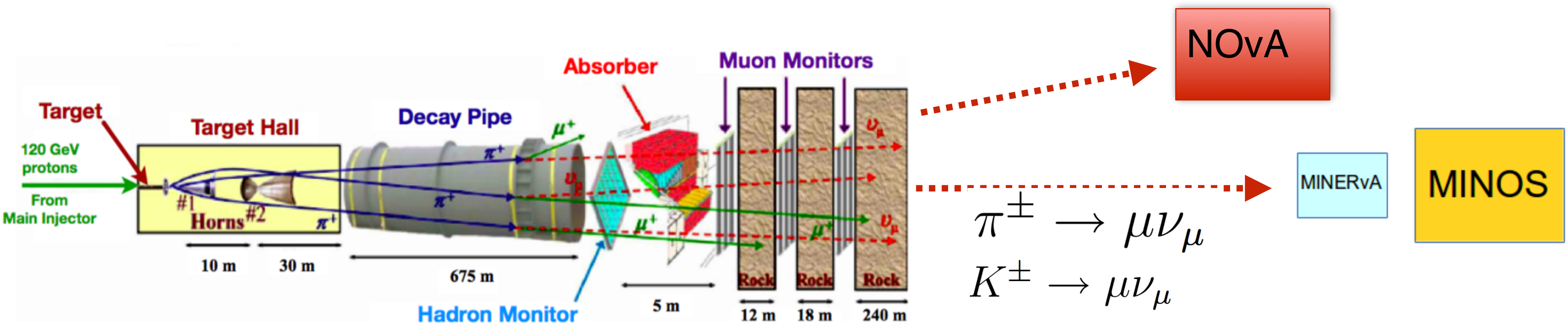
1. **Beam focusing uncertainties** (every mm matters): target longitudinal position, alignment, materials, etc.

Optimized to have small uncertainties around the peak.

2. **Hadron production uncertainties:** big discrepancies between hadronic models.

To have a good a priori flux prediction we need to constrain the hadron production data.

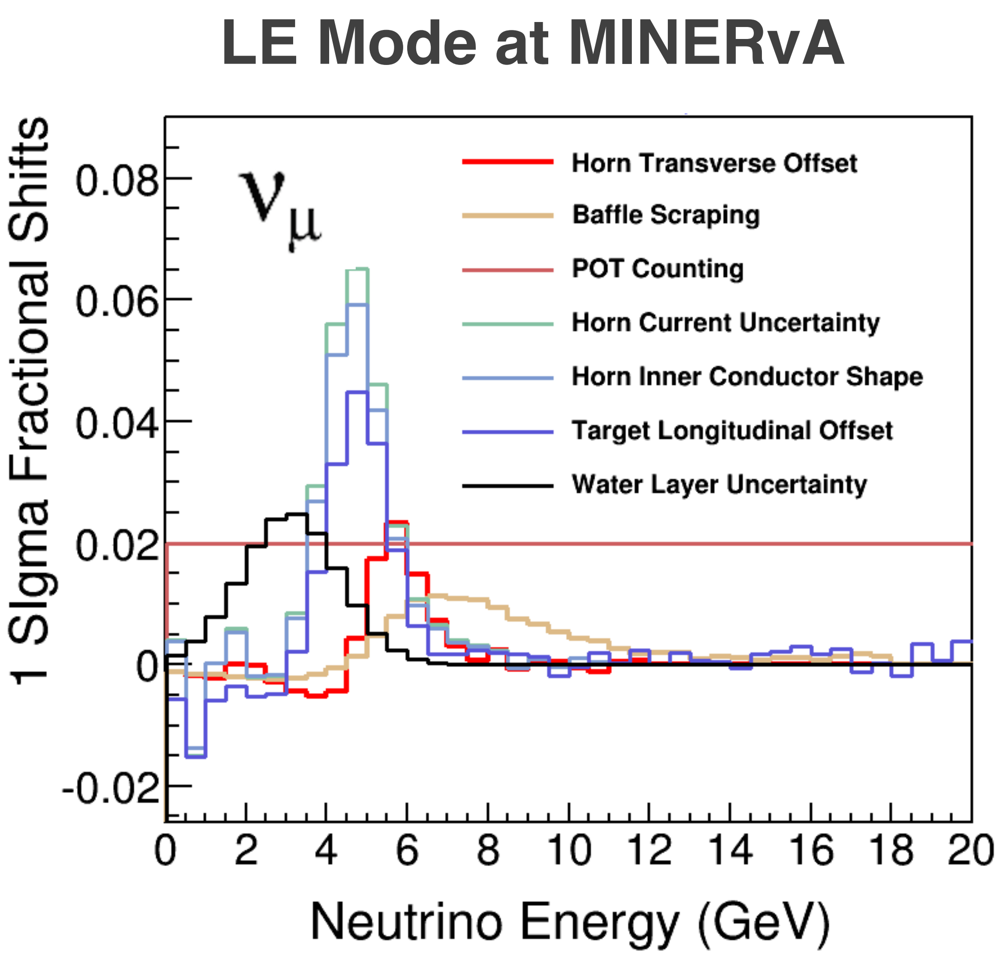
In this talk I will be focused ν_μ signal in the LE mode at MINERvA.

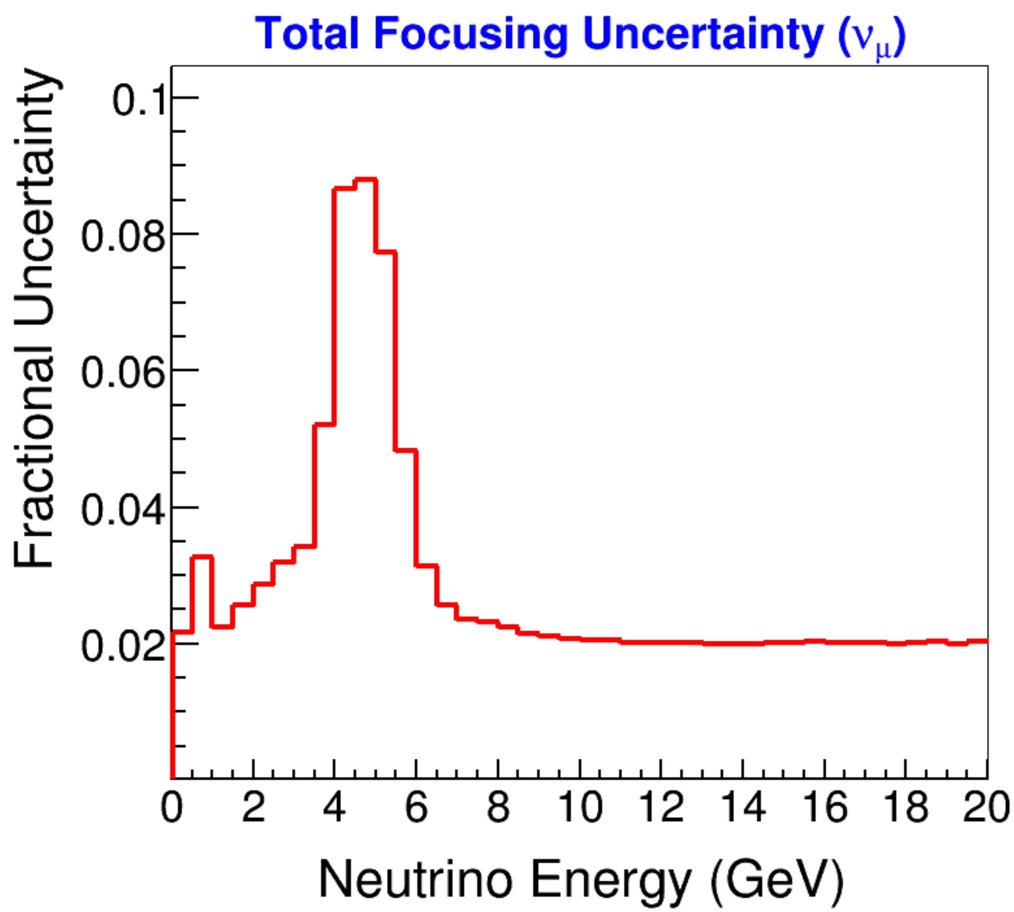


$$\pi^{\pm} \rightarrow \mu\nu_\mu$$
$$K^{\pm} \rightarrow \mu\nu_\mu$$

Focusing Uncertainties

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





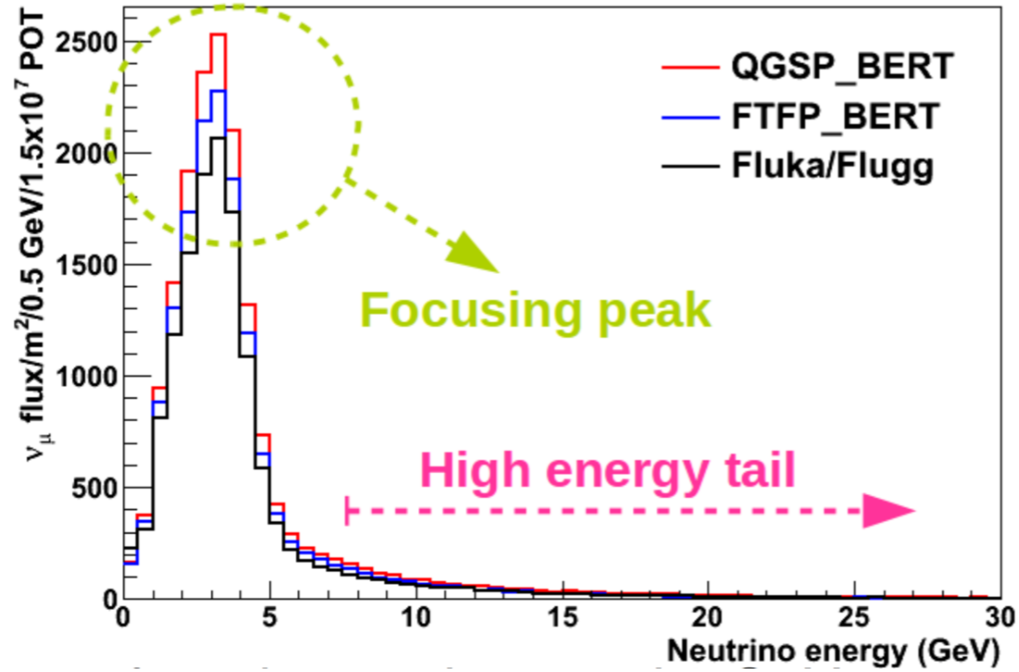
Understanding the Flux

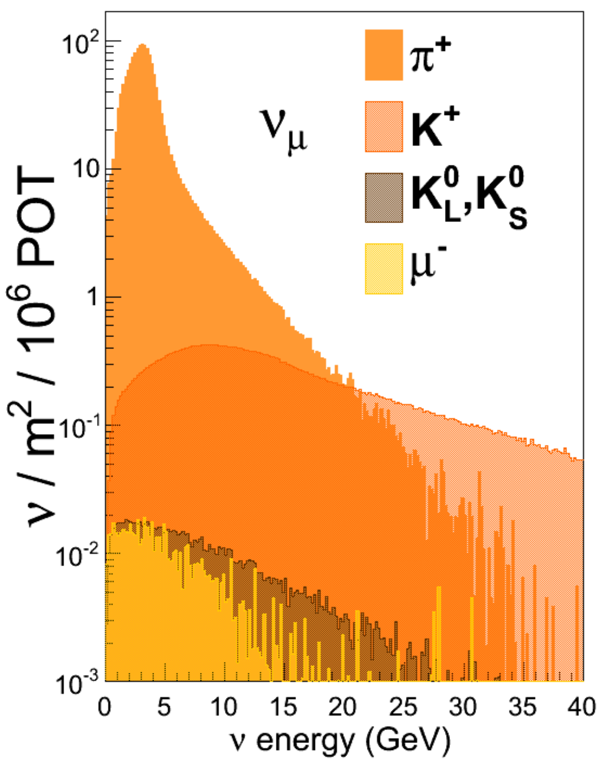
Big discrepancies between flux predictions from hadronic models

Then, we need data to constrain the model

Wide band beam

- Flux spectrum shows a peak at 3 GeV.
- Long energy tail up to 120 GeV.

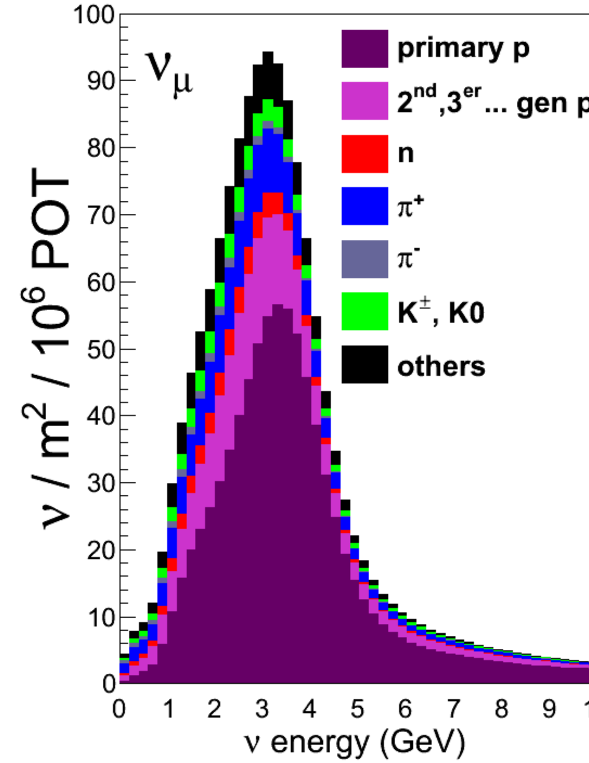




Neutrino ancestry

parents **grandparents**

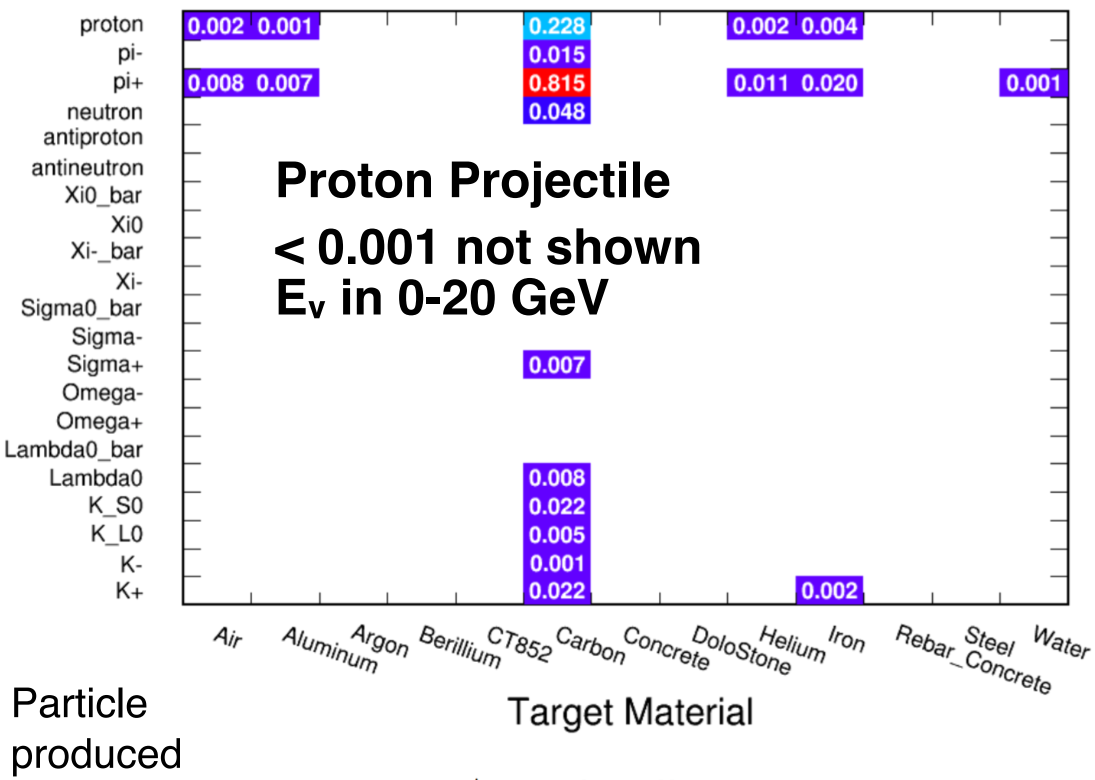
LE Mode at MINERvA



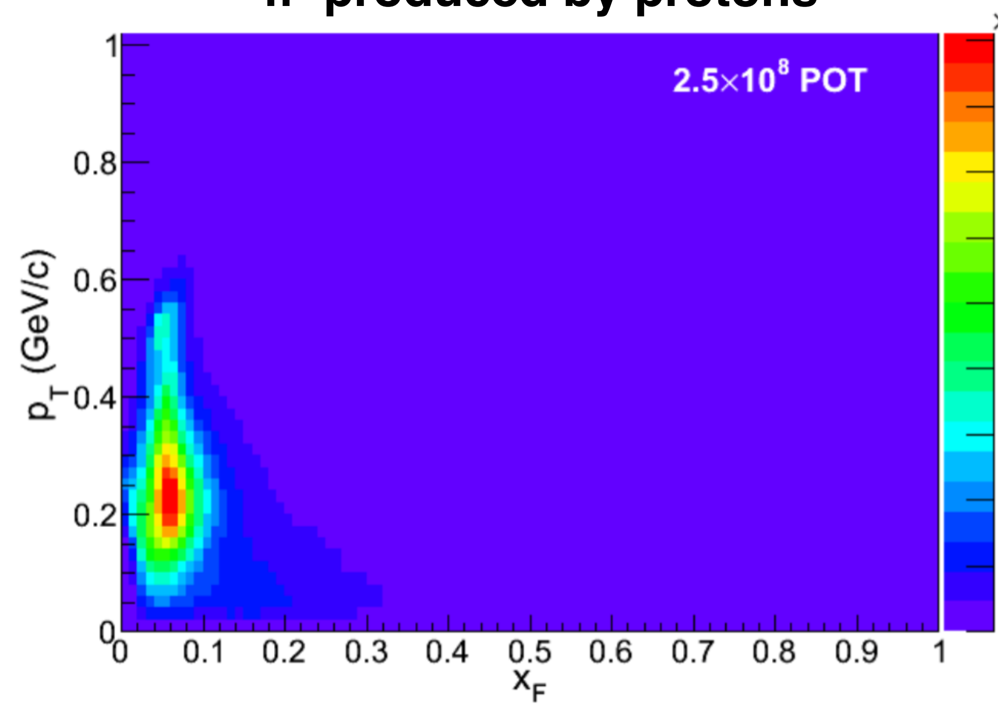
Understanding the Flux

LE Mode at MINERvA

<interaction>/ν_μ



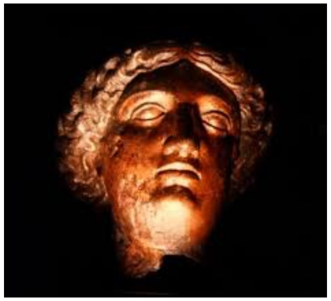
π^+ produced by protons



$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

π^+ projectile:

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



MINERvA Strategy for Predicting the Flux

1. Calculate an a-priori flux

- ***Accounting for every optical modeling uncertainty.***
- ***Correcting the hadron production in the beam line to constrain to external hadron production data.***

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.***

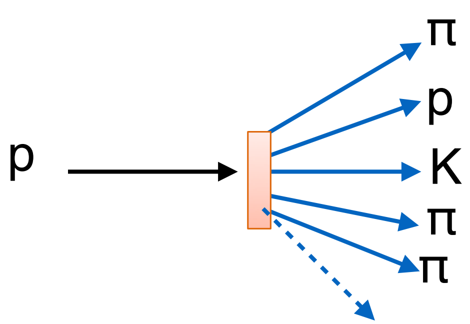
3. Package to Predict the FluX

- ***Develop every tool in such a way they can be used by any experiment at NuMI (PPFX).***

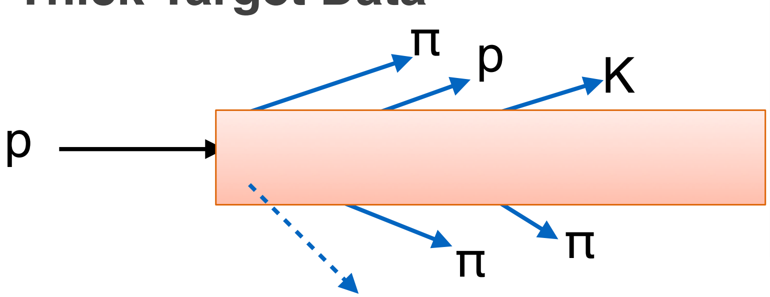
External Data? What Sort of Data is Available?

- Hadron production data at the relevant energies for NuMI (references in the backup slides):

Thin Target Data



Thick Target Data



- Inelastic/absorption
  - 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 $p_Z > 20GeV/c$.
- MIPP: proton on a spare NuMI target at 120 GeV:
  - $\pi^{\pm}$ up to 80 GeV/c.
  - K/π for $p_Z > 20GeV/c$.

Checking the consistency with the low-nu measurement, we decided to use a prediction based only on thin target corrections (backup).

How do We Use the Data to Correct the Models?

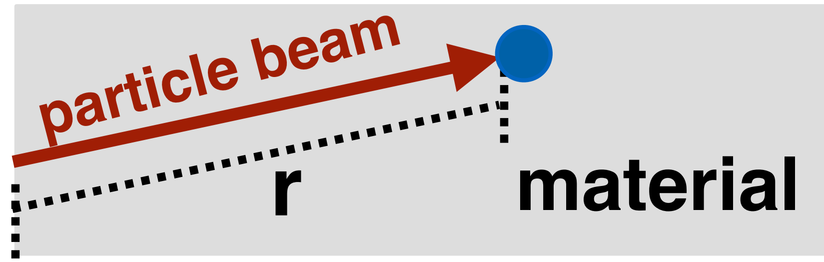
We apply a weight to the neutrino yield based on the its hadronic interaction history.

- The cascades that lead to a neutrino are tabulated at generation: kinematics of the interactions and the amount of material traversed by every particle.
- The correction is applied event by event at analysis time:
- Two corrections are applied (data/MC):

    1. Beam attenuation.

    2. Hadron production.

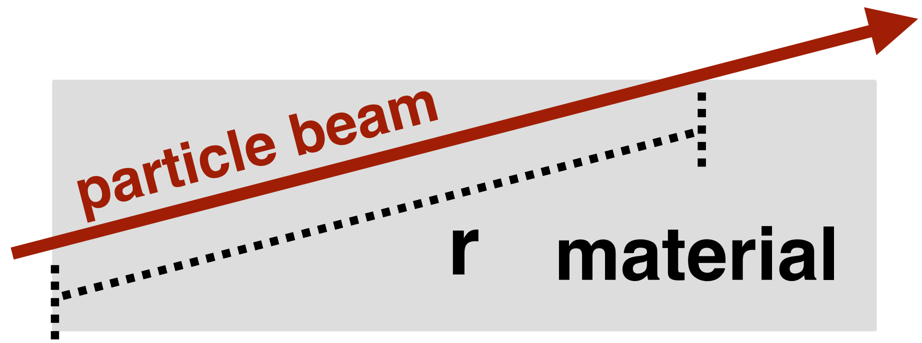
1. Beam Attenuation



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

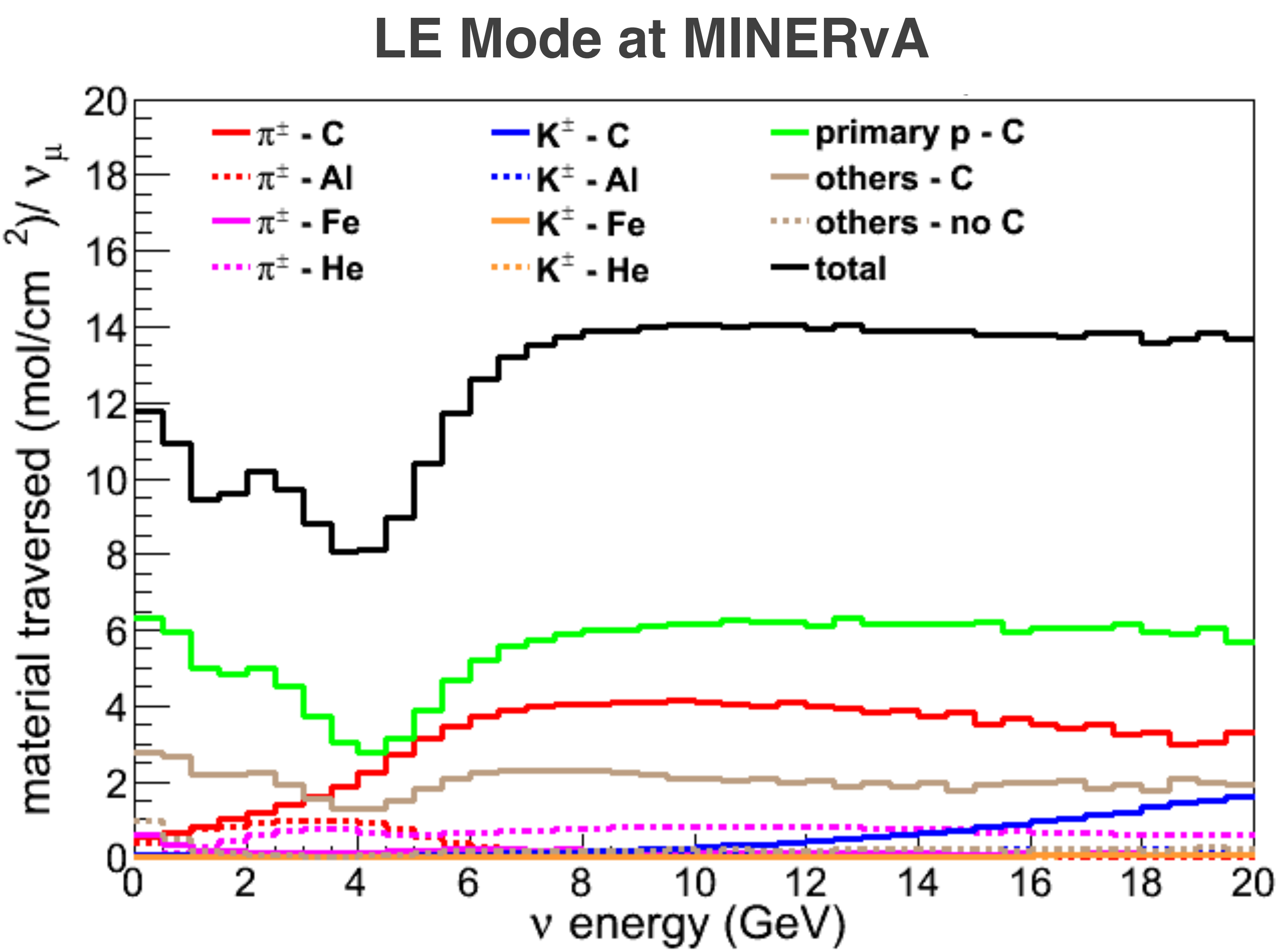
$$correction(r) = e^{-r\frac{N_A\rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

Two variables are important here:

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

Amount of Material Traversed

- Muon neutrino parent:



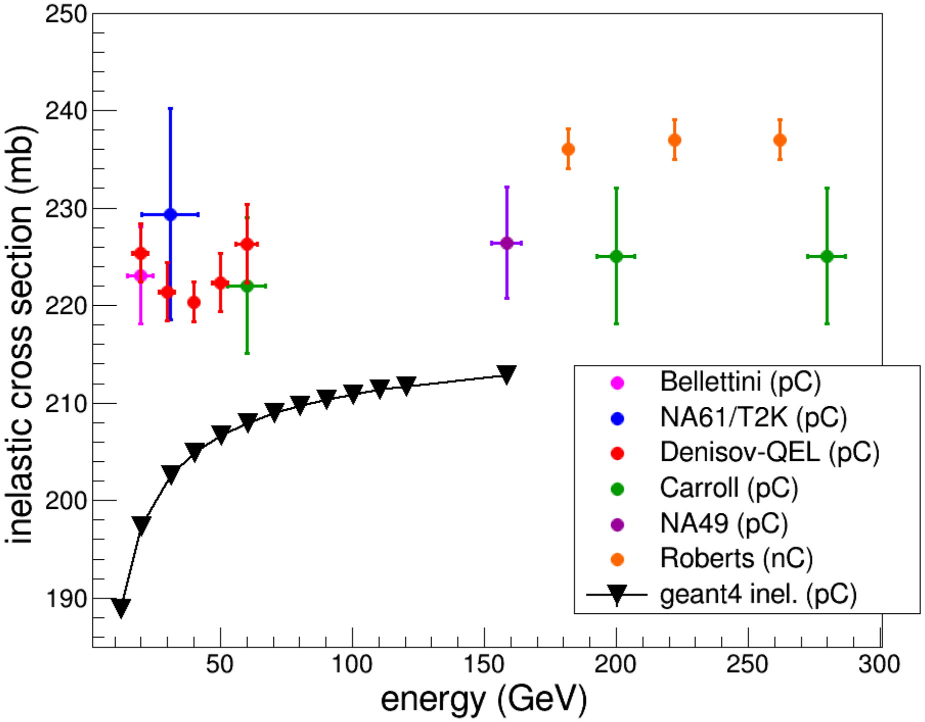
References:

- ***C: 6 mol/cm² ≈ 40 cm***
- ***Al: 1 mol/cm² ≈ 10 cm***
- ***He: 1 mol/cm² ≈ 500 m***

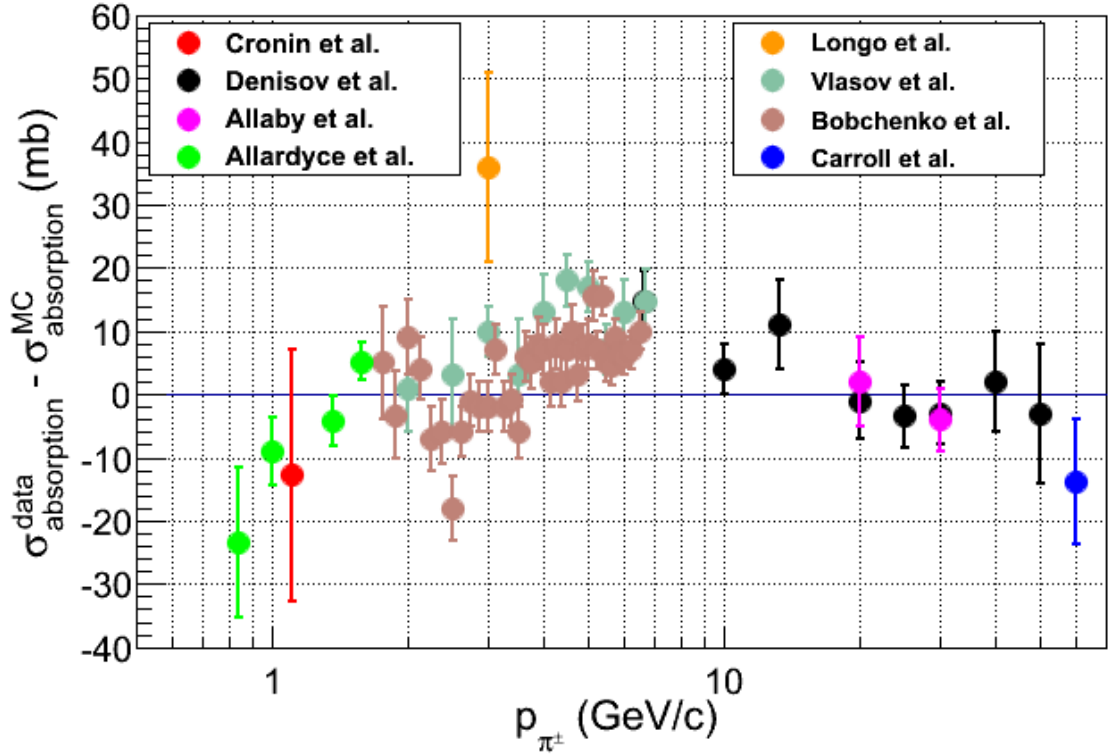
Data - MC Comparison

- Inelastic cross section
- Absorption cross section

Proton on Carbon



Pion on Aluminum



Reference (Geant4):

$\sigma_{absorption}$ = 243.2 mbar

Reference (Geant4):

$\sigma_{absorption}$ = 344 mbar

$$\sigma_{total} = \sigma_{elastic} + \underbrace{\sigma_{inelastic} + \sigma_{quasi-elastic}}_{\sigma_{absorption}}$$

2. Hadron Production

For thin target (NA49 for instance):

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

*(**$f=Ed^3\sigma/dp^3$**: invariant production cross section)*

- The **scale** allows us to use NA49 for proton on carbon in 12-120 GeV (calculated with FLUKA).
- It was checked by comparing with NA61 at 31 GeV (negligible difference).

Example: NA49 Data/MC comparison (closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).

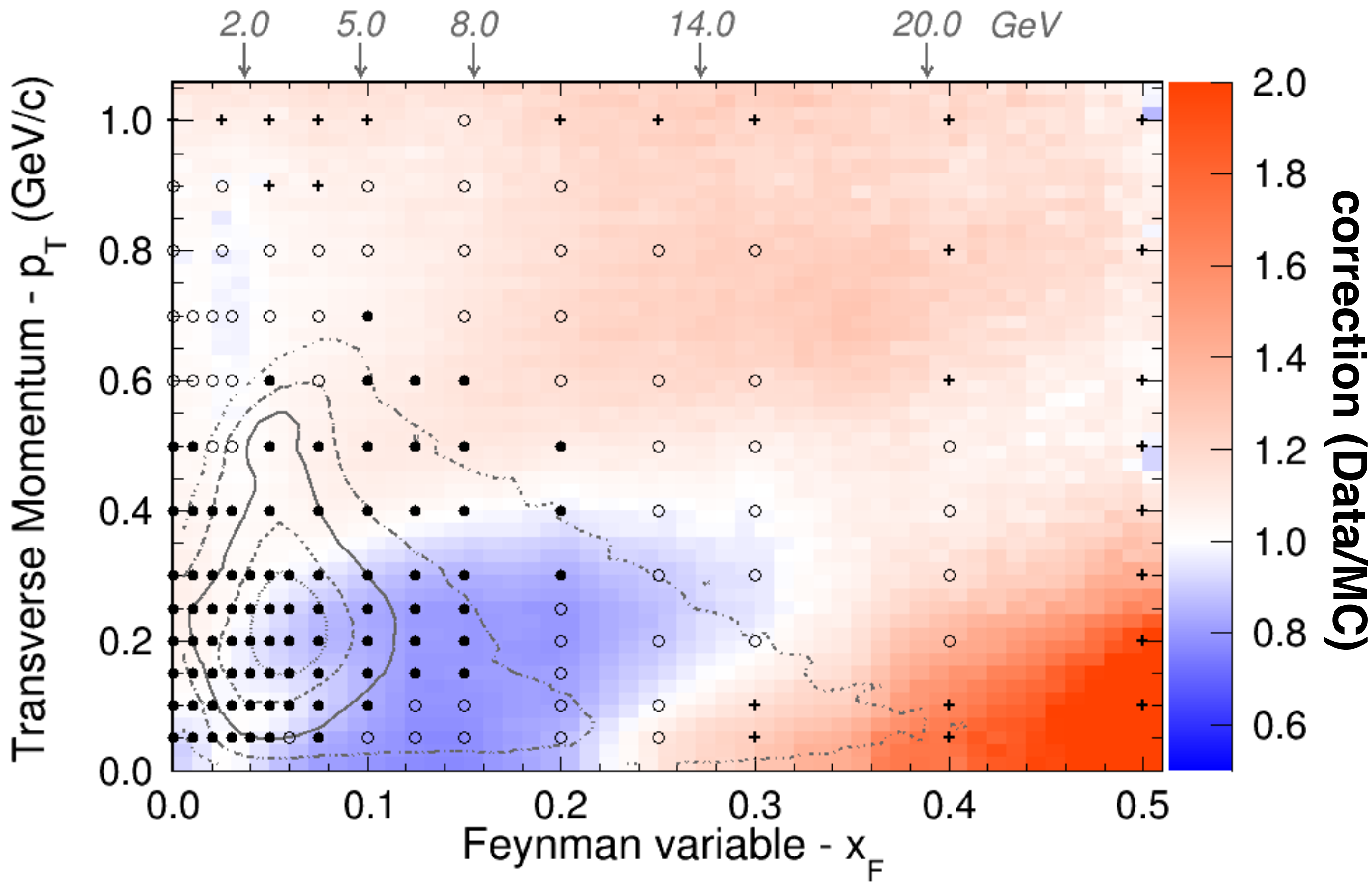
LE Mode On-Axis

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

- Systematics are highly correlated bin-to-bin.
- Systematics and statistical errors are considered uncorrelated each other.

$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

$pC \rightarrow \pi^+ X$



Systematic uncertainties = 3.8% (added in quadrature).

If There is not Direct Data

Extending the data coverage

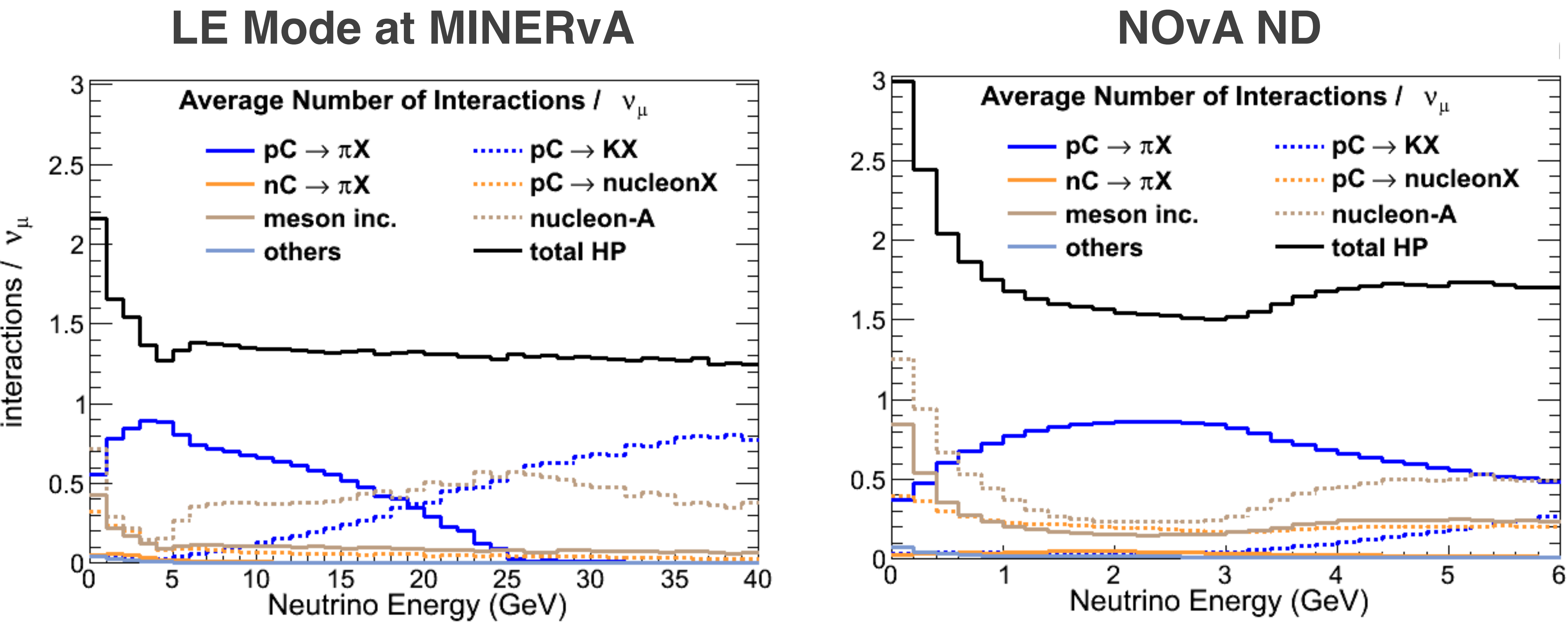
- Constrain pA interactions with pC adding an additional uncertainty found by comparing A dependence of Barton, Skubic and Eichten.

- Use theoretical guidance (isospin arguments, quark counting arguments, etc.)

What if data is not available?

- Guided by the agreement with other datasets: processes categorized by projectile and produced particle. 40% error assigned in 4 x_F bins.

Average Number of Interactions



- π, K and nucleons productions from pC based on data.
- nucleon-A (quasi-elastics, extension from carbon to other materials, production outside data coverage, etc).
- We assume large uncertainty for meson incident.

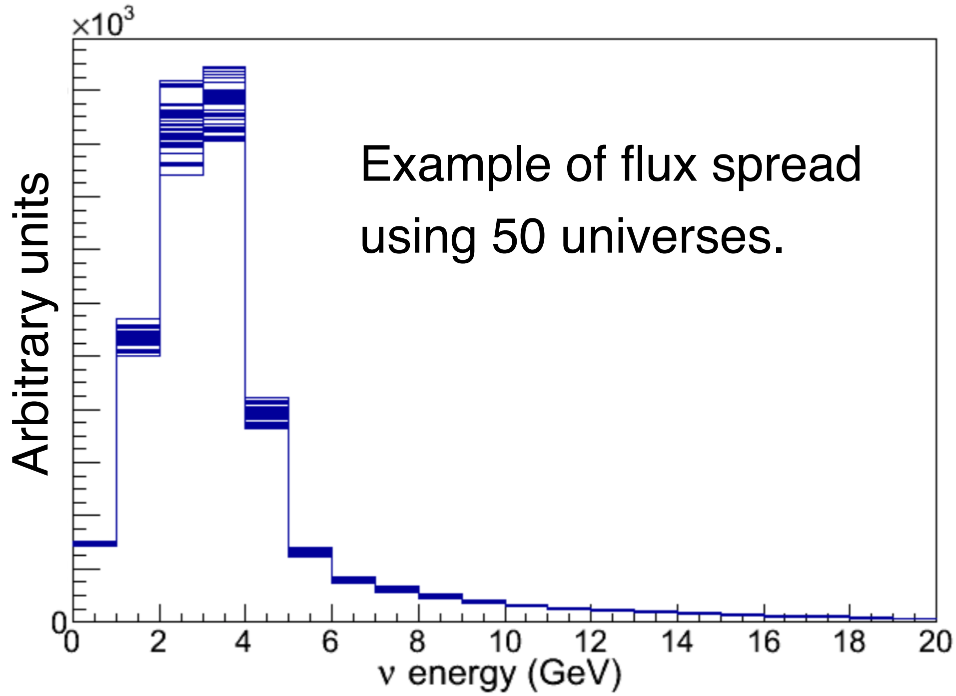
Uncertainties

- The systematics is evaluated by using the **“multi-universe” technique** where each datapoint is a parameter.

- In each universe, each parameter has a value by random sampling from a multi-dimensional Gaussian distribution centered on the default parameter values with covariances to account for the uncertainties and correlations.

- The corrections are propagated to the final neutrino.

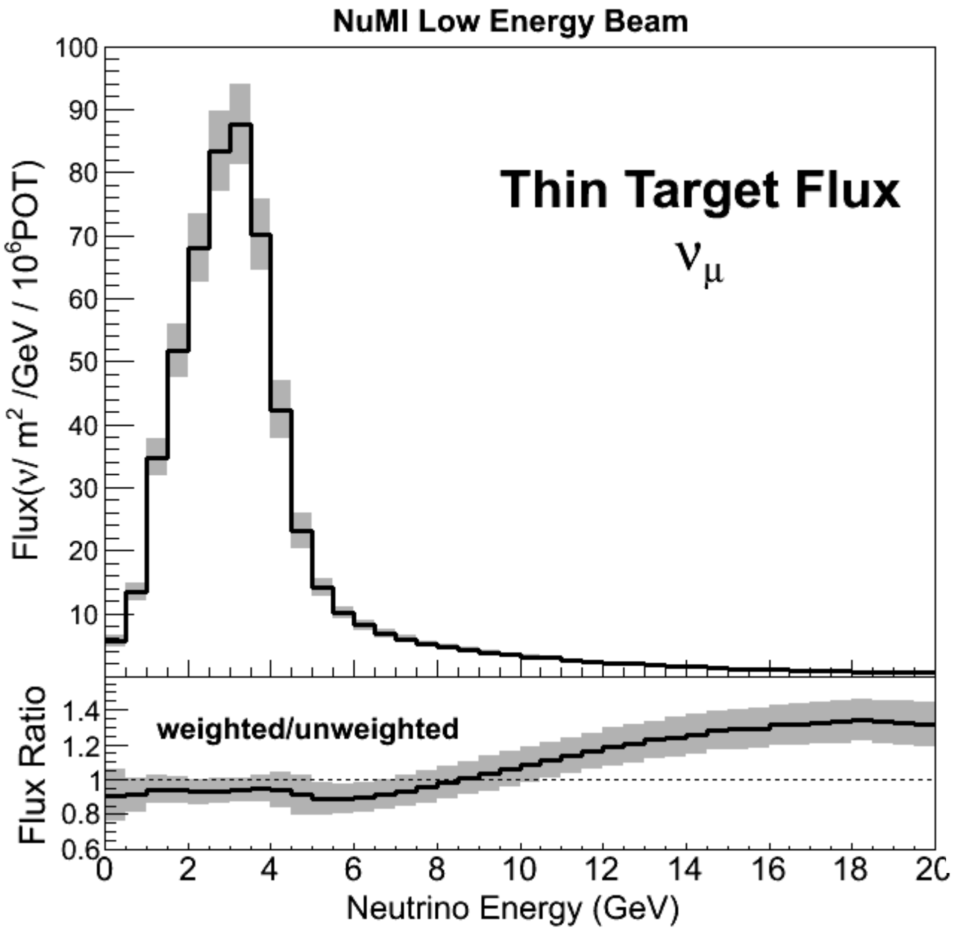
- The resulting flux predictions are used to compute the variance in each neutrino energy bin and the covariance between bins.

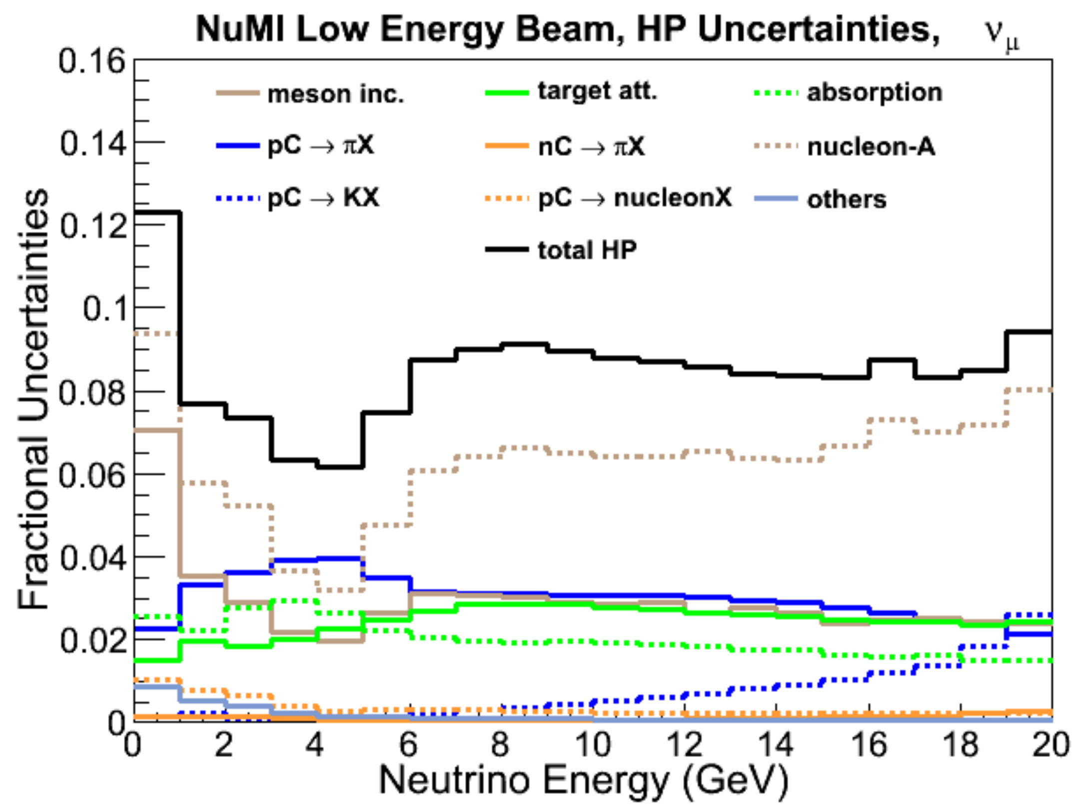


Example of flux spread using 50 universes.

A Priori Flux Results for LE MINERvA

- MINERvA published the flux prediction for LE NuMI beam based on thin target data correction

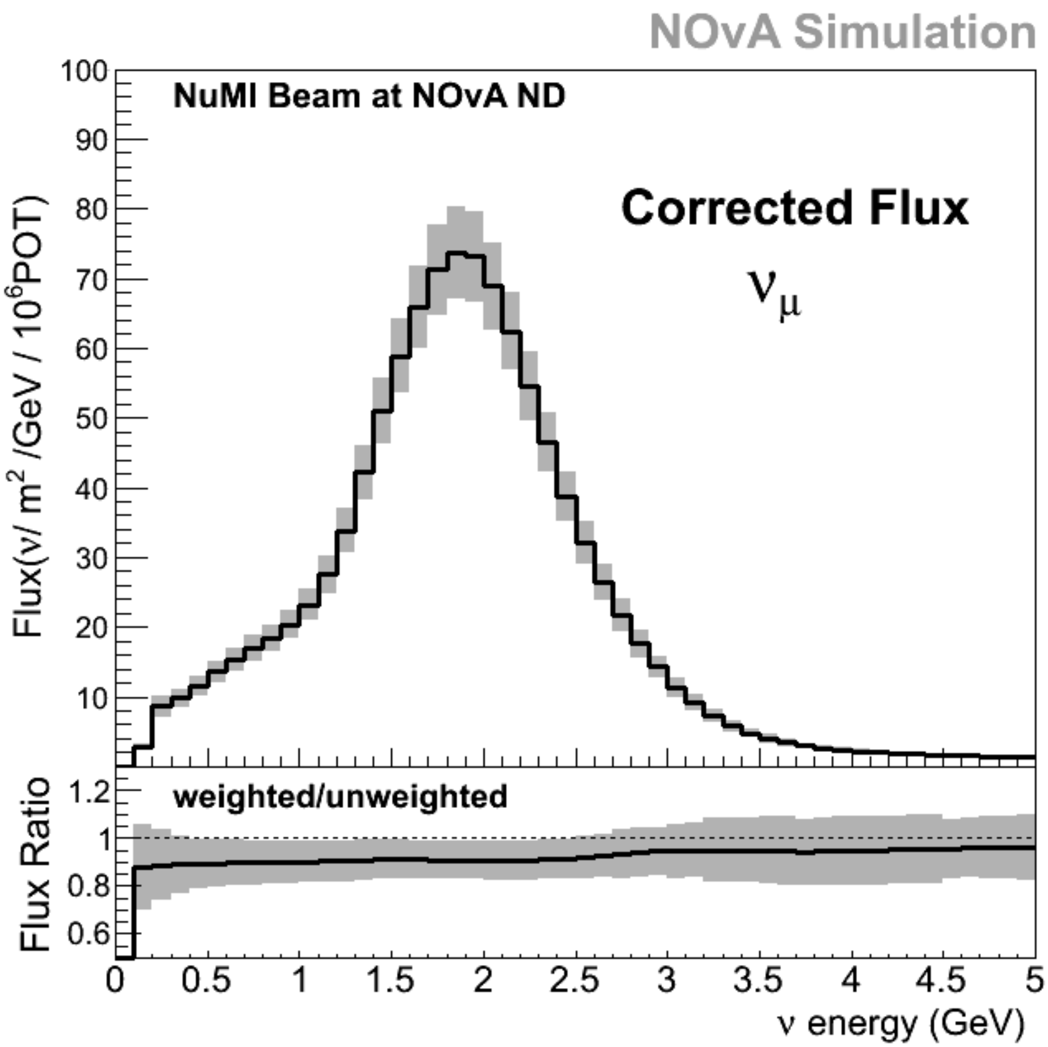


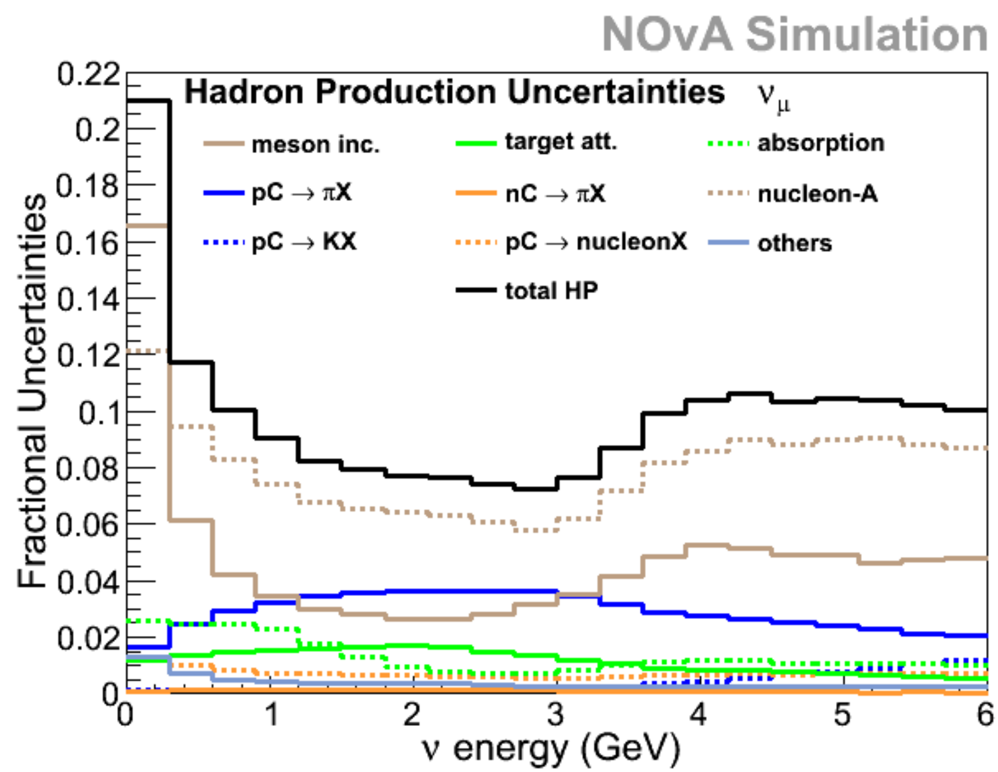


Phys. Rev. D 94, 092005 (2016)

A Priori Flux Results for NOvA Near Detector

- A fully implemented a priori flux prediction in NOvA





Conclusions 1

- For MINERvA and other experiments it is crucial to have a precise measurement of the flux with small uncertainties.

- This work has made a new computation of the NuMI flux with reduced uncertainties and improved error budget accounting.

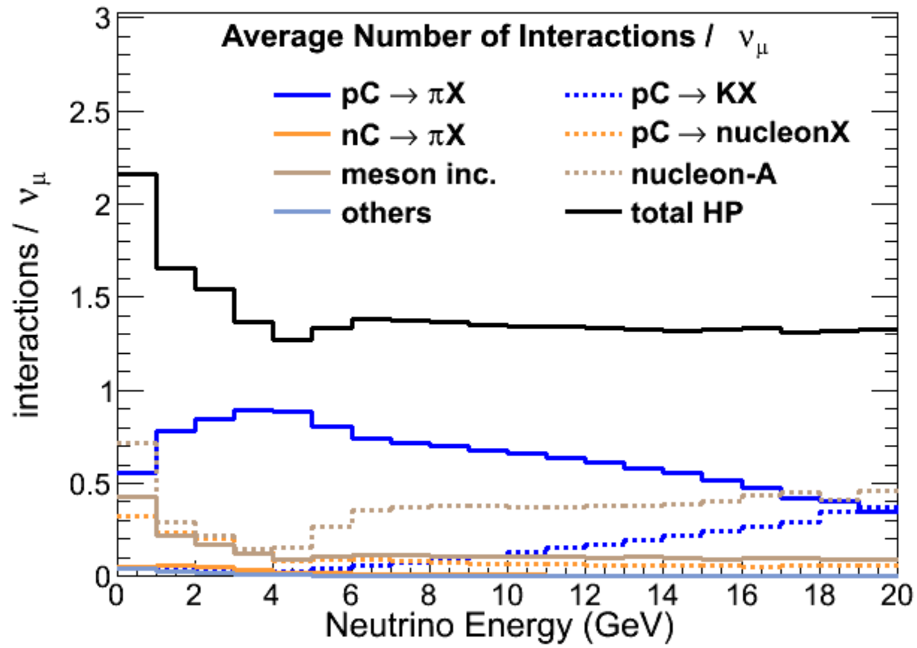
Conclusions 2

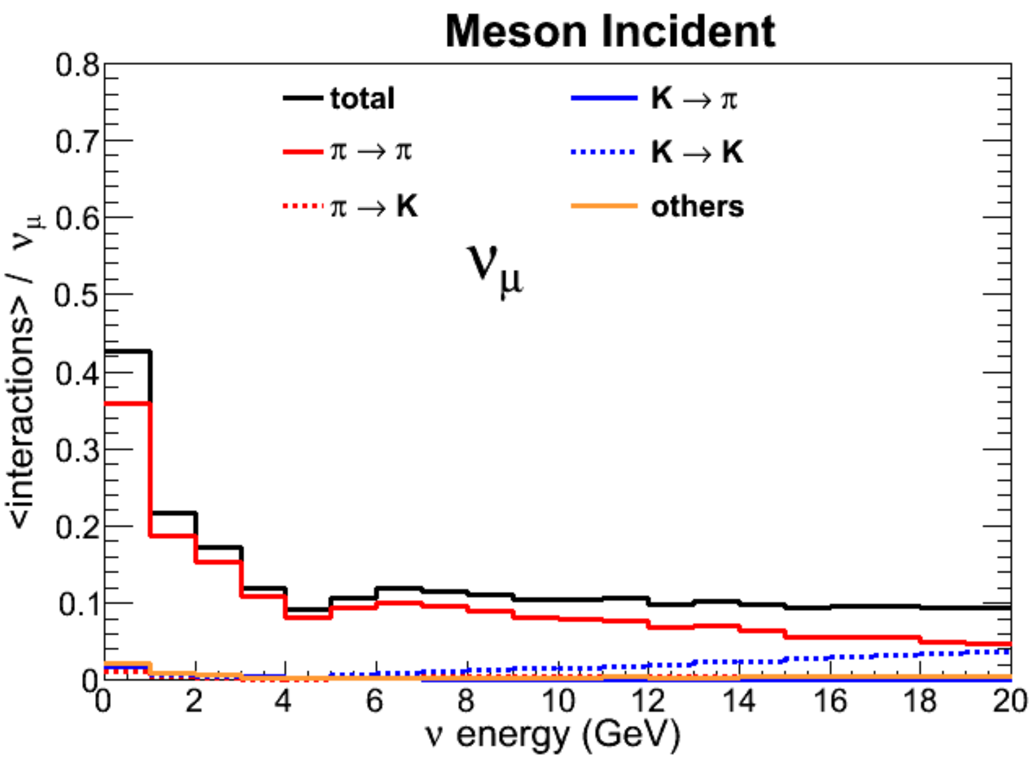
- We developed a computational tool called **"PPFX"** open and free with our techniques that can be used to predict the *a priori* flux for NuMI.
  - Currently, it is also used by NOvA.
- It can be extended to other conventional neutrino beams.
  - It has adapted for DUNE and it is being used by the ND systematics.

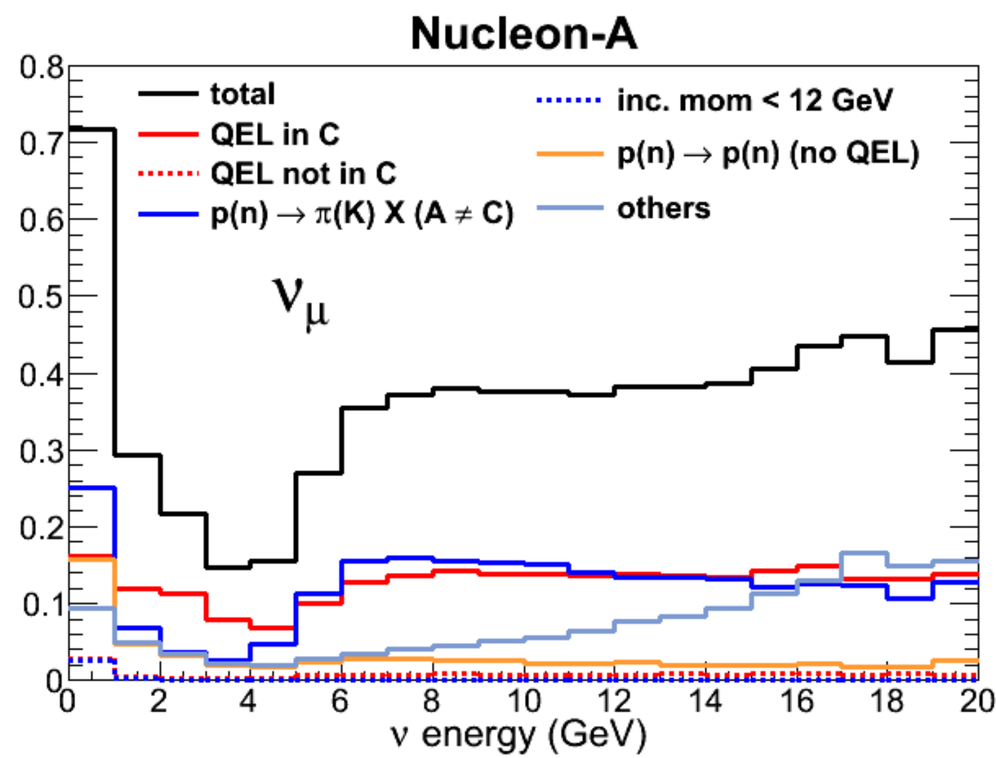
https://cdcvs.fnal.gov/redmine/projects/ppfx

Conclusions 3

- This work also indicates where additional data is needed
  - π -> π at 30 GeV.
  - proton quasi-elastic cross section.
  - pX->π (K)X (A not C).







backup

External Data References

- Thin Target Data:
  - Barton et Al *[Phys. Rev. D 27, 2580 (1983)]*
  - 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]* **FERMILAB-THESIS-2007-76**
    - 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]*

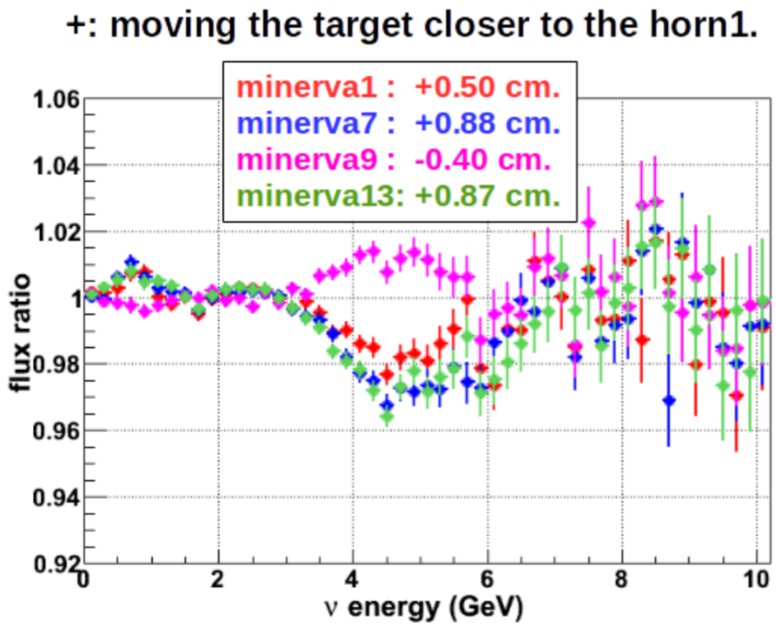
External Data References

- Thick Target Data:
  - Pion production in a spare NuMI Target. Jon Paley et Al (MIPP Collaboration) ***[Phys. Rev. D 90, 032001 (2014)]***
  - Pion / Kaon ratios on a spare NuMI Target. Sharon Seun's thesis

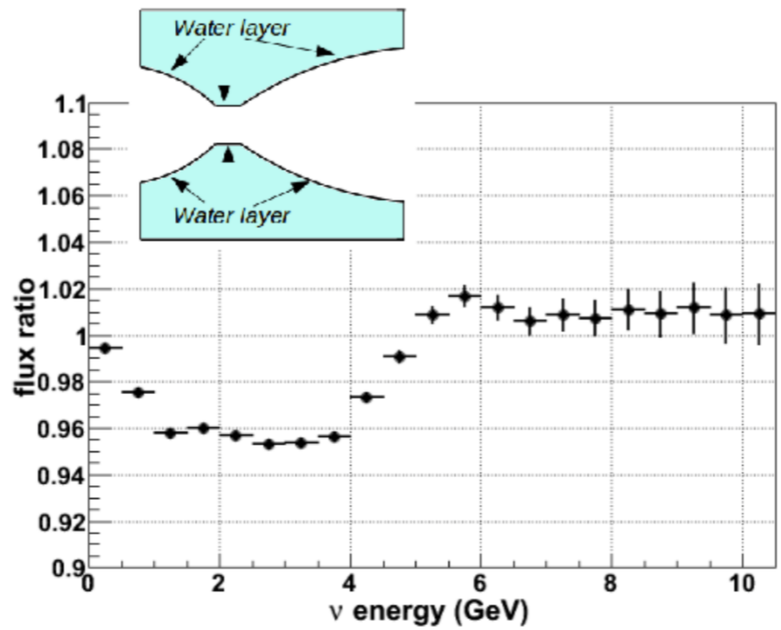
Geometrical Effects on the Beam

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

The relative distance target - horn:



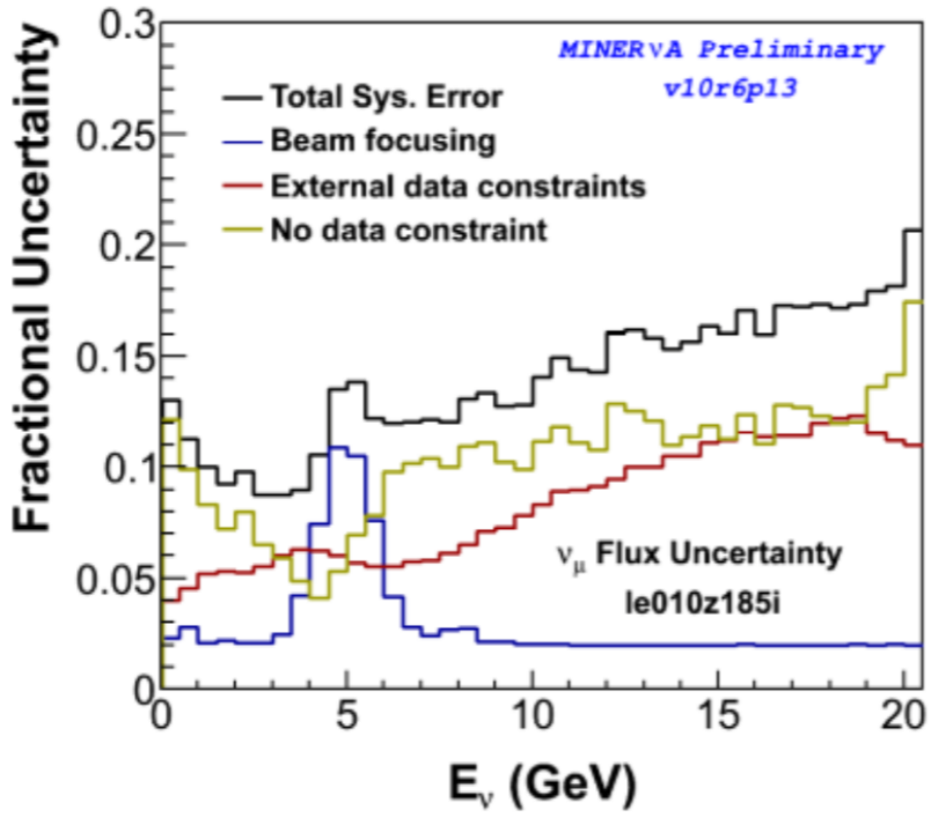
1 mm cooling water layer around the horn inner conductor:



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

Fractional Uncertainties Before PPFX

Fractional Uncertainty



(L. Fields)

Example: NA49 Data/MC comparison **(closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).**

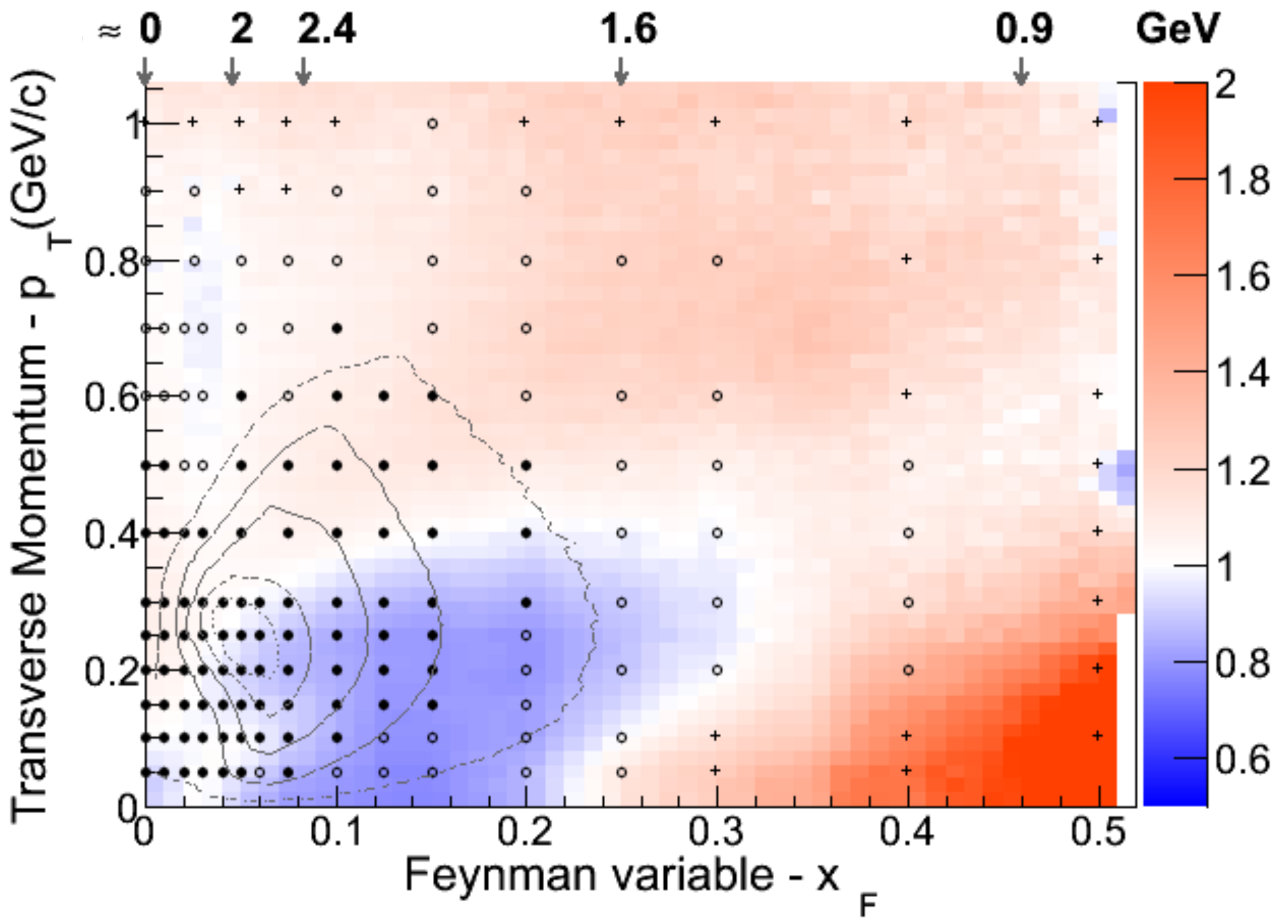
At NOvA

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

- Systematics are highly correlated bin-to-bin.
- Systematics and statistical errors are considered uncorrelated each other.

$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

$pC \rightarrow \pi^+ X$



systematic uncertainties = 3.8% (added in quadrature).

General Strategy for Predicting the Flux

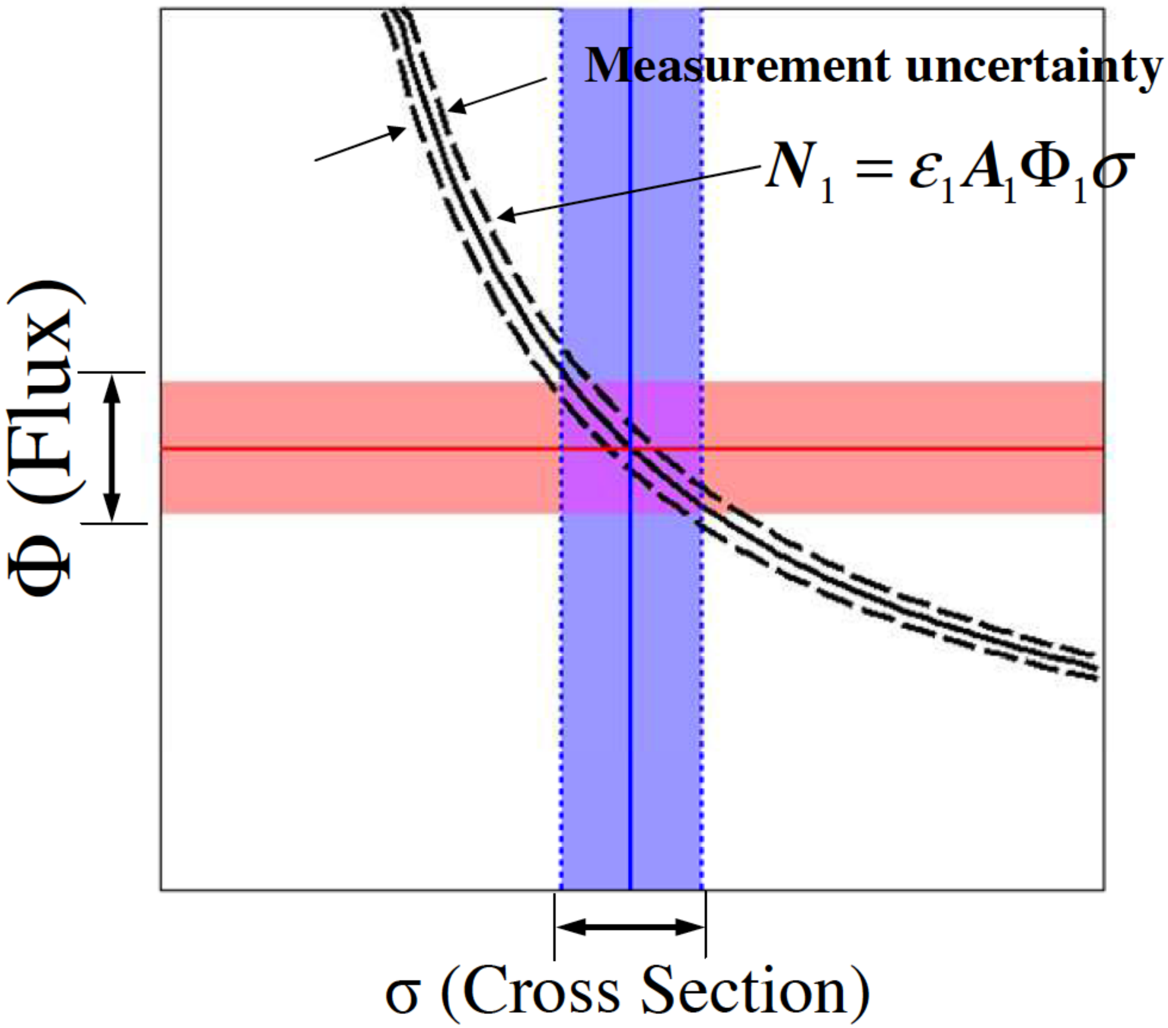
1. Calculate an a-priori flux

- ***Optical Model:*** *accounting for every uncertainty.*
- ***Hadron Production:***
  - To rely on the MC model
  - To constrain to external data.

2. Use in-situ measurements

- ***Multi-parametric Beam Fit:*** *using data measured in the detector from different beam configurations.*
- ***Low-nu method:*** *low recoil event rates is a flux shape measurement.*
- ***Neutrino - electron events:*** *gives a flux normalization.*
- ***…***

Flux and Cross Section are Anti-correlated



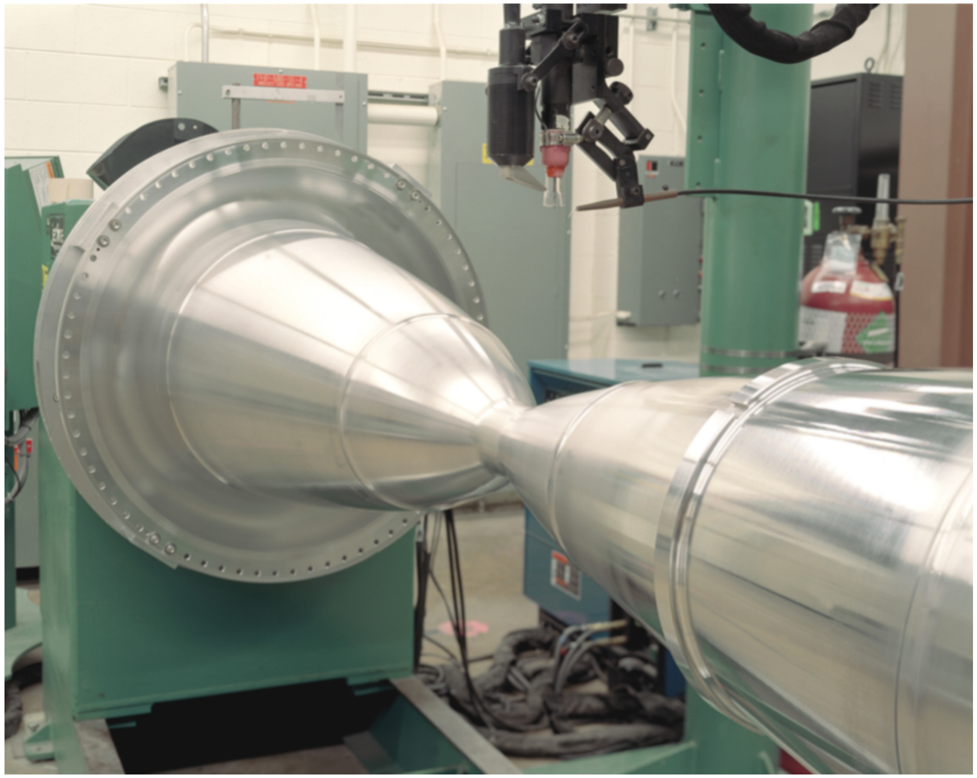
More on NuMI

The NuMI Targets

- Rectangular graphite rod.
- Segmented in fins + beam position monitors.
- Cooled by water in pipes, and enclosed in He container

	LE	ME
Cross sectional view	6.4 x 15 mm^2	7.4 x 63 mm^2
Segment lengths	20 mm	24 mm
Fins	47	48
Total length	960 mm (~2 λ)	1200 mm (~2.5 λ)

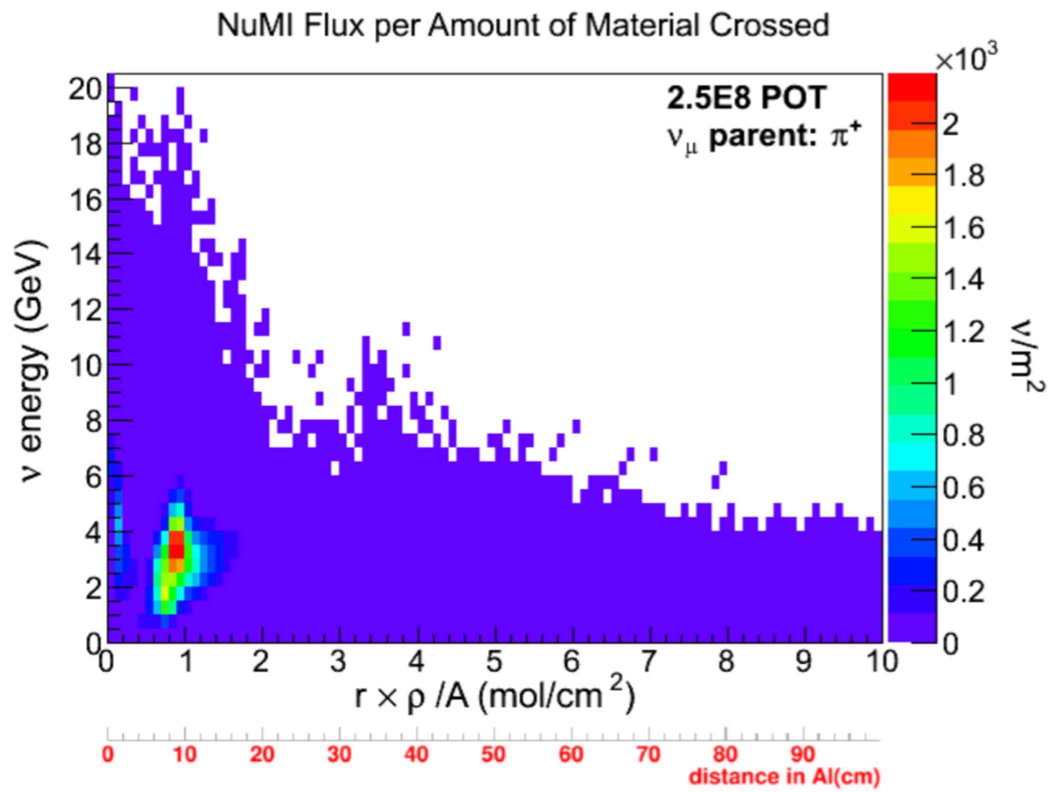
The NuMI Focusing



- A ~200 kA current is pulsed through two aluminum horns to create a toroidal magnetic field.
- Inner conductor is 2-4 mm
- Every charged particle traveling by the horns feel a p_T kick.

The Distance Traveled By the Hadron ν Parents

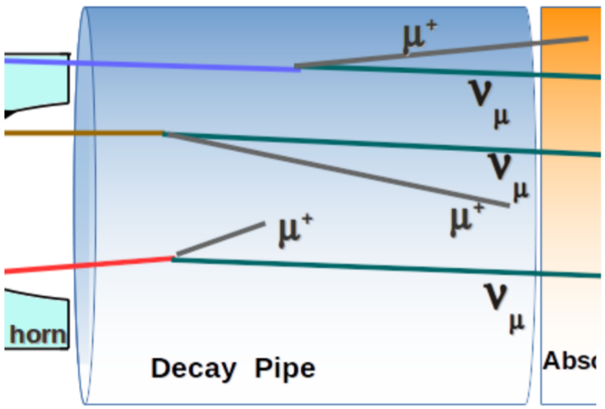
π^+ neutrino parents passing through the horns inner conductors.



The horn inner conductor is long and thin:

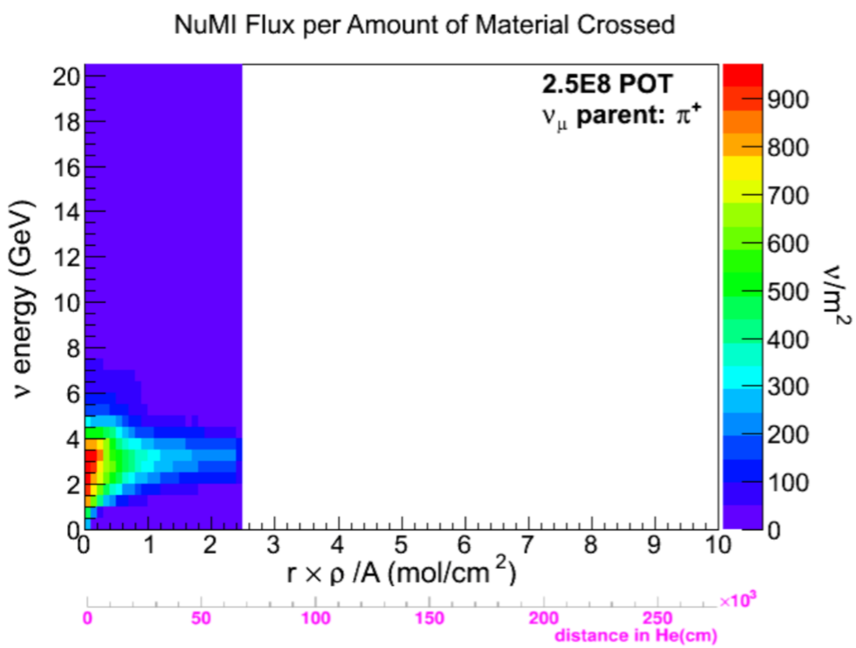
- Calculations indicate that the horn material reduces the flux by 40%.

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.



Thick Target Flux

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

Gen2-thin

- Use thin target data to correct all interactions.

Gen2-thick

- 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.

Example: MIPP NuMI Data/MC comparison (closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).

LE Mode On-Axis

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

- Systematics are highly correlated bin-to-bin.
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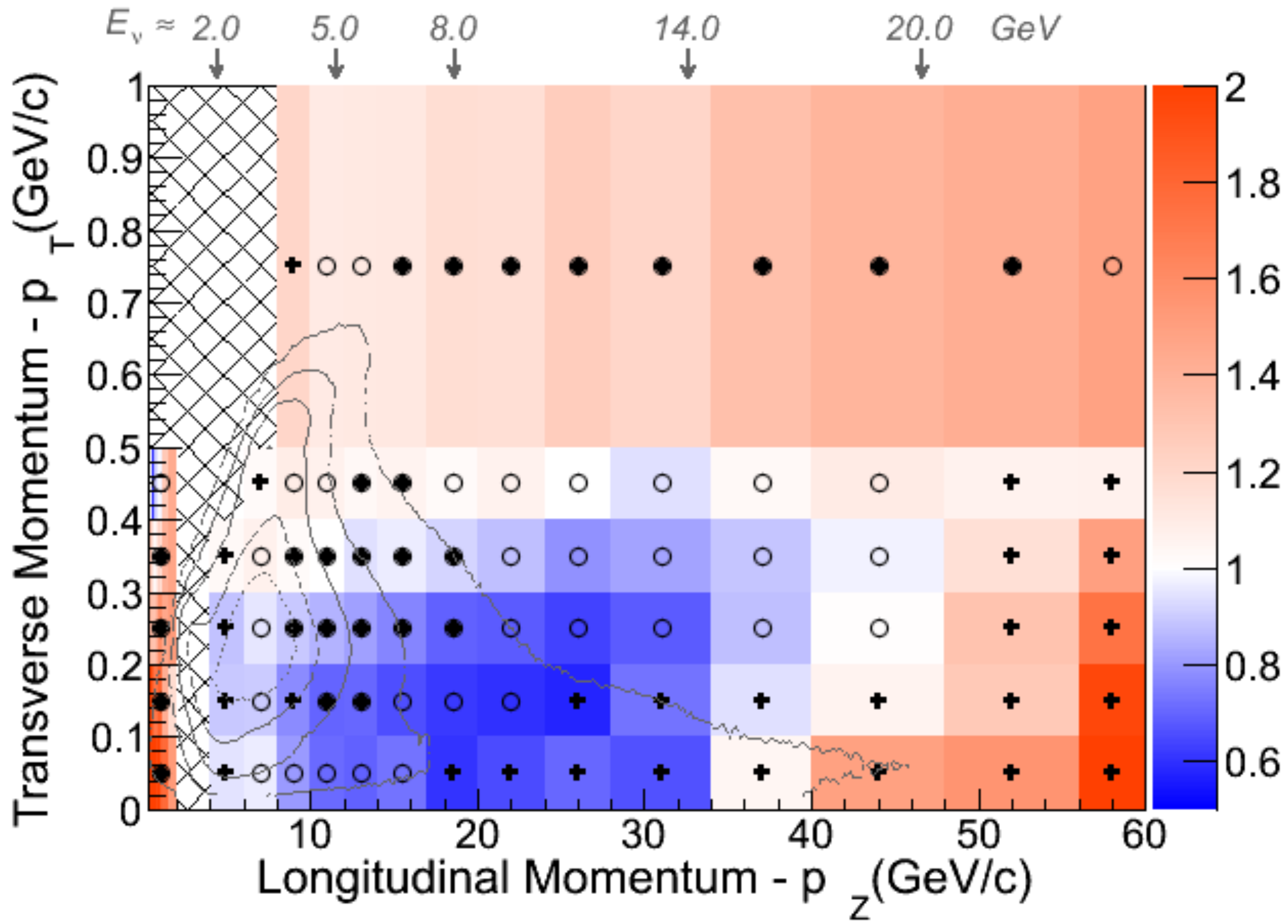
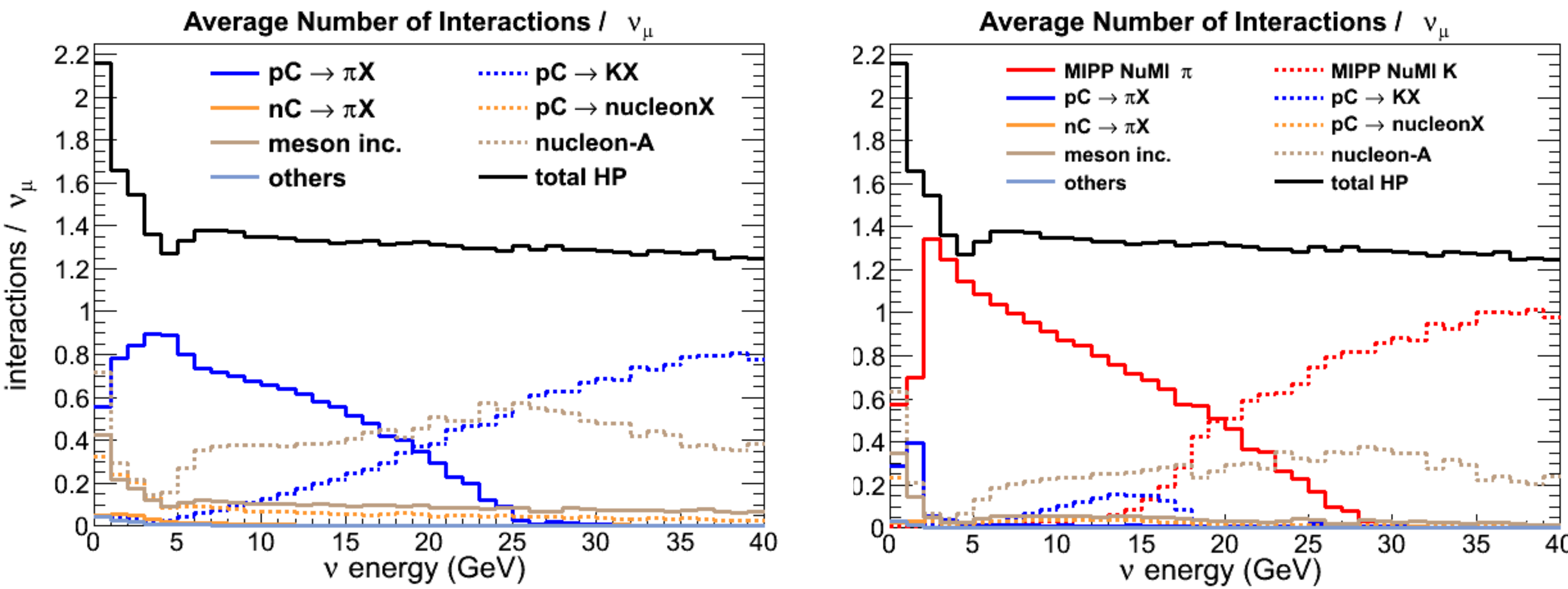
pNuMI -> π^+X



systematic uncertainties = 3.8% (added in quadrature).

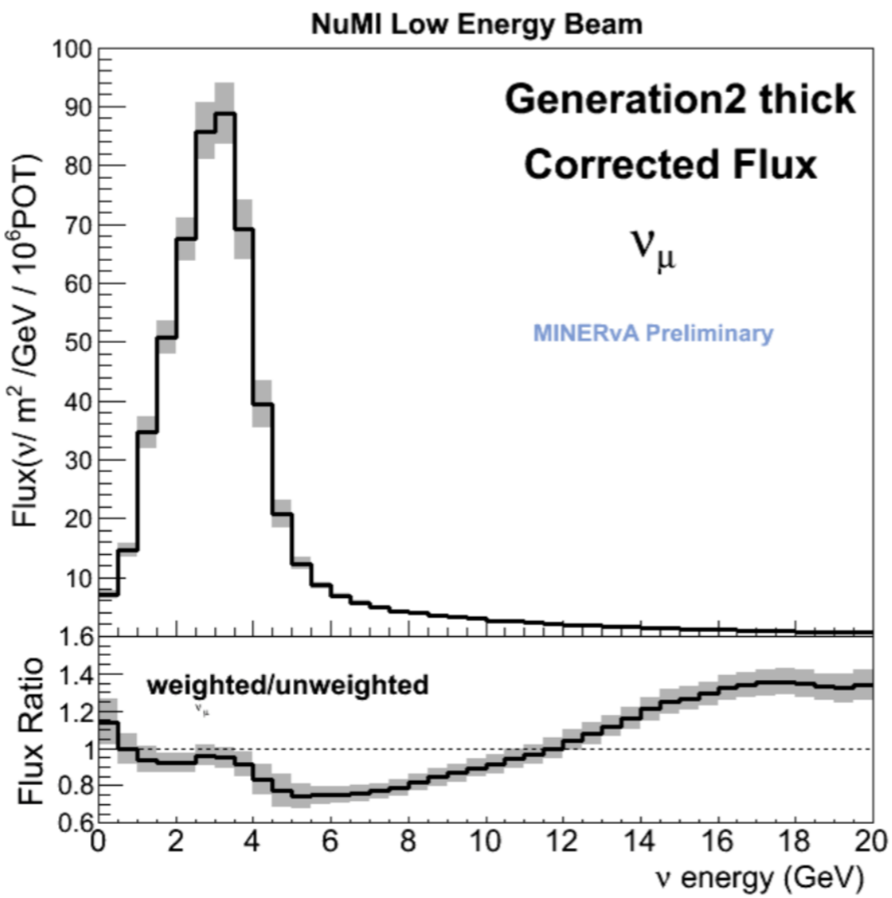
Advantage to use thick target data

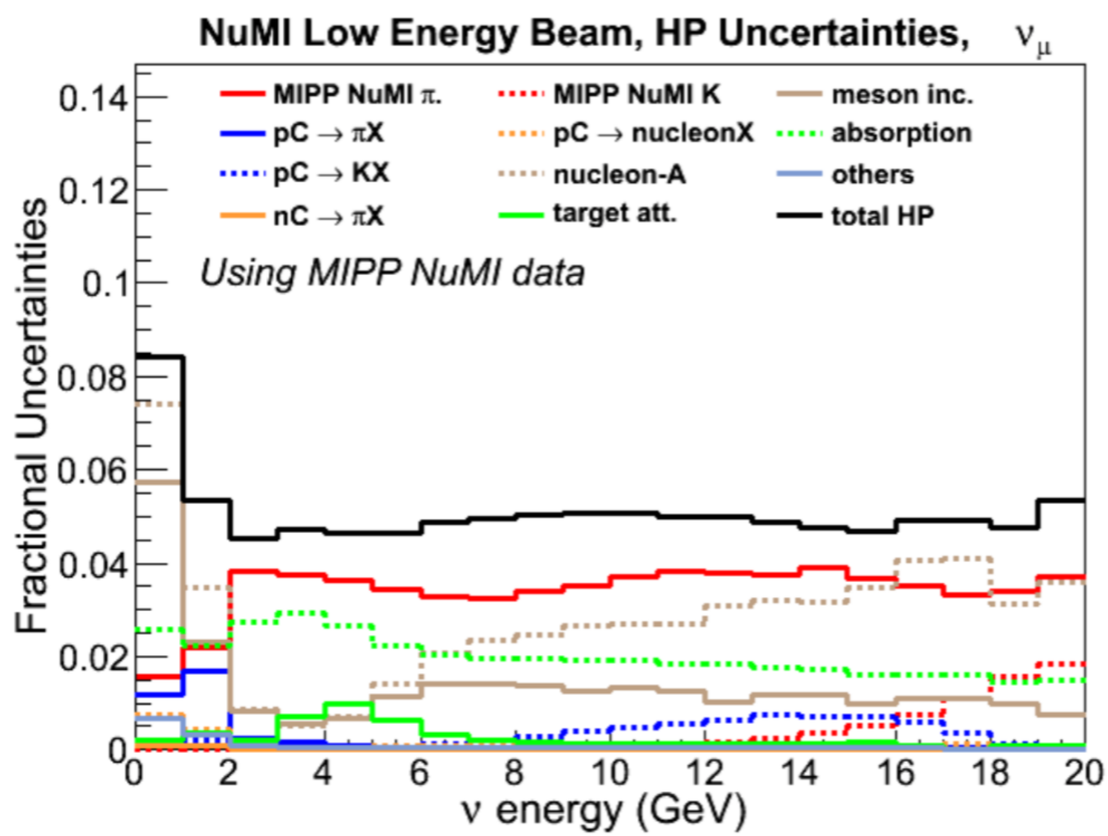


Checking the consistency with our in-situ measurements, we decided to use a prediction based only on thin target corrections.

Thick Target Data Flux

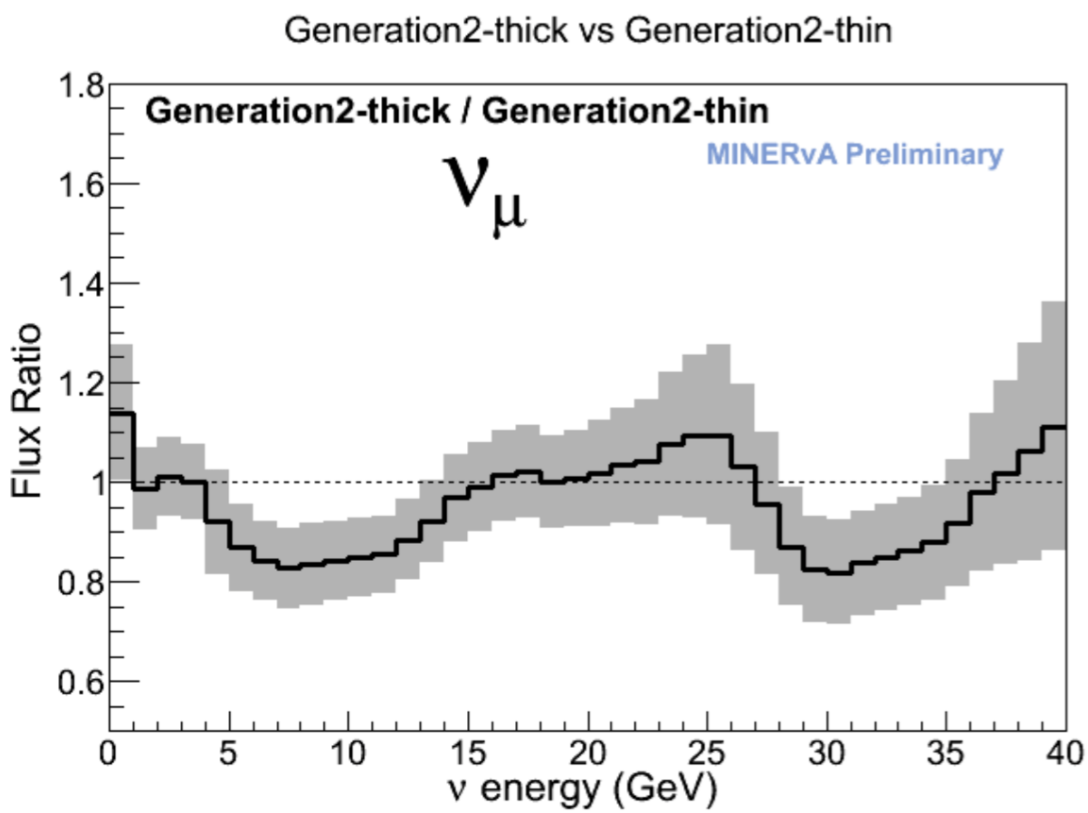
Gen2-thick





Thin - Thick Flux Comparison

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 as a check for thin and thick fluxes

Low-nu Basics

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

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

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

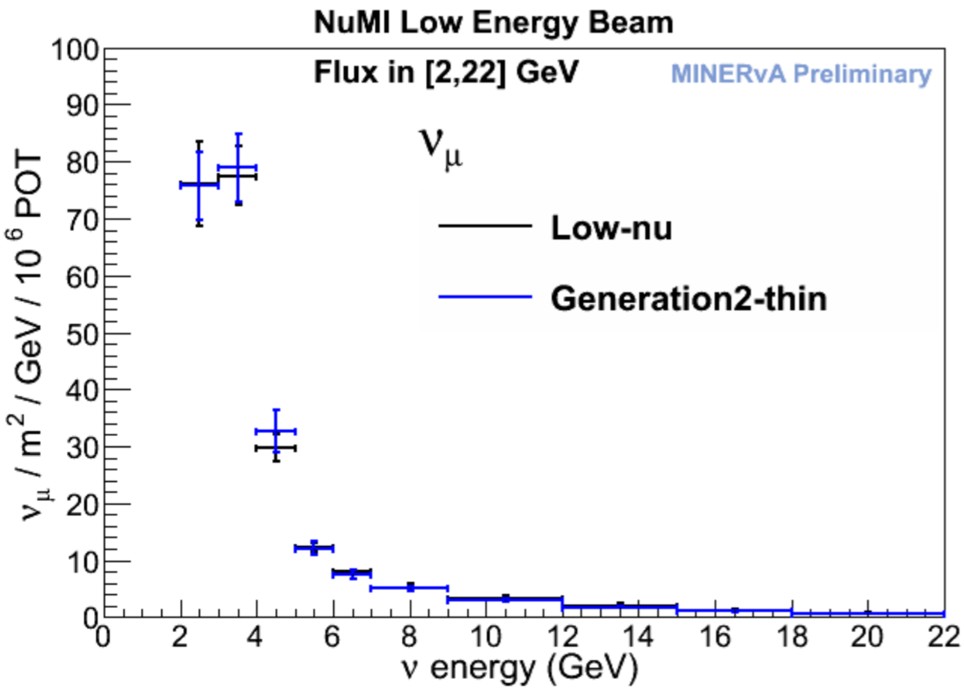
- As $\nu/E \to 0$, $\frac{d\sigma}{d\nu} \to A$, then it gives us the flux shape.
  - For finite ν, we use GENIE to compute corections.
- Normalization tied to external measurements at high energy (NOMAD σ_{tot} on carbon).

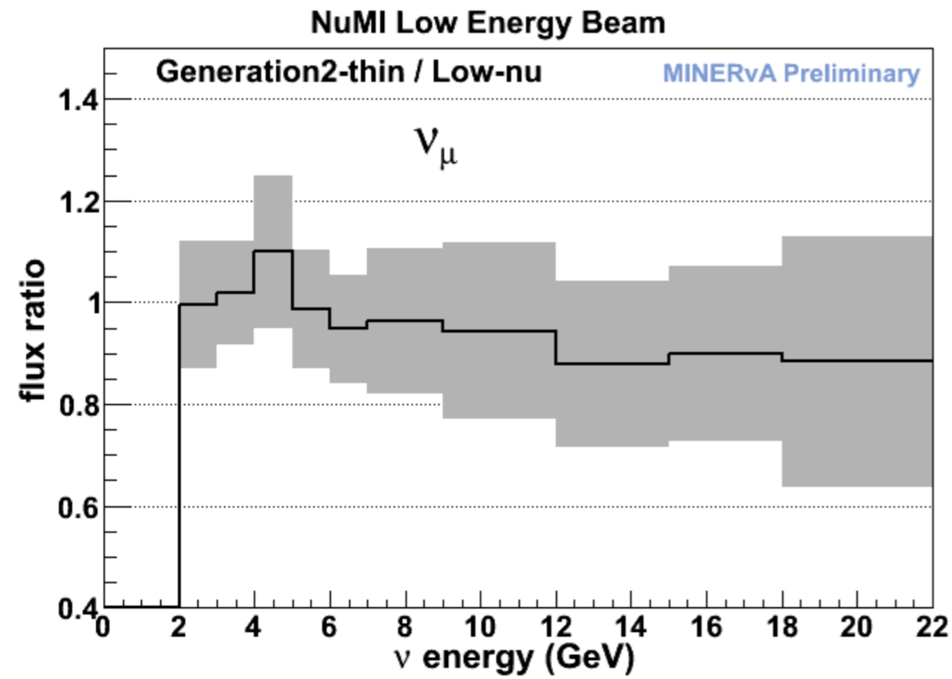
This method was applied by J. Devan to calculate the flux (W&M PhD thesis)

Minerva paper: Phys. Rev. D 94, 112007 (2016)

Thin Target Flux vs Low-nu

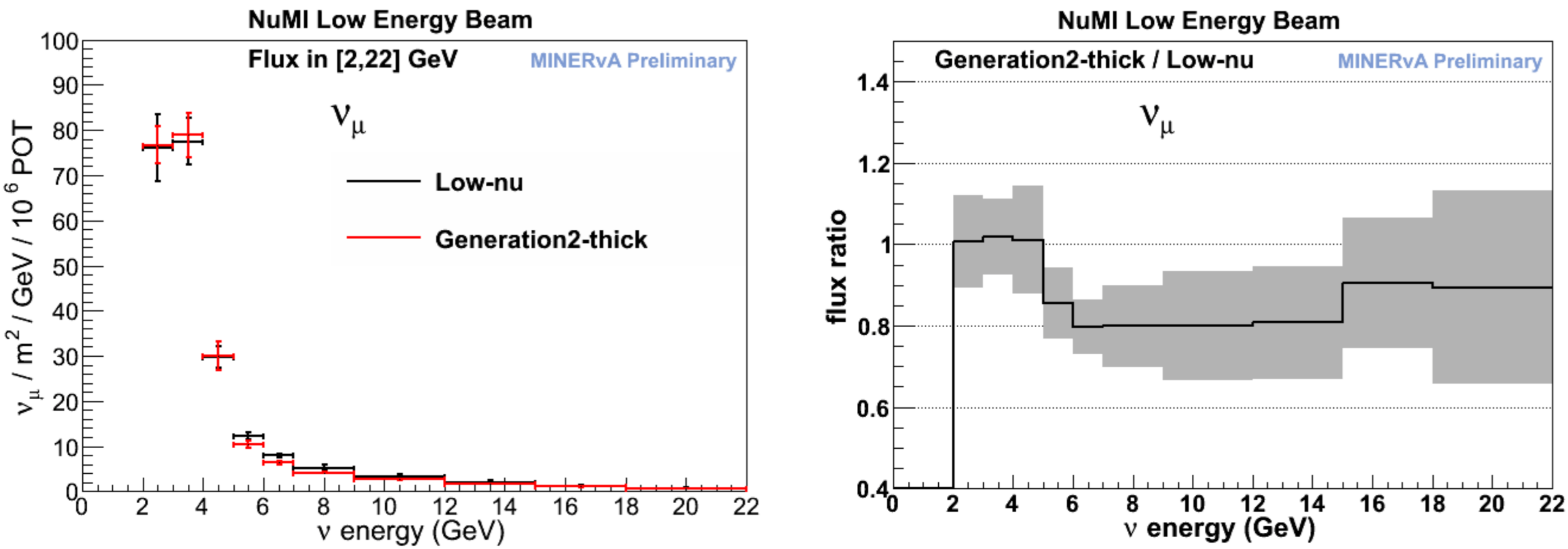
We see consistency along the whole neutrino energy range (low-nu flux predicts the flux for >2 GeV)





Thin Target Flux vs Low-nu

We see consistency in the peak but significant disagreement in the $5 - 15 GeV$ regime.



Conclusions of Gen2 and Low-nu Comparison

- Full covariance comparison **Gen2** - **Low-nu** (2-22 GeV) gives as:

	Low-nu vs Gen2-thin	Low-nu vs Gen2-thick
χ^2	4.8/10	18.6/10

- Based on the agreement of Gen2-thin and low-nu, we recommend to MINERvA to use Gen2-thin for its next round of analysis and update the current MINERvA results.

- Gen2-thick offers the prospect of significantly smaller errors: this validates the technique of measuring thick target data.

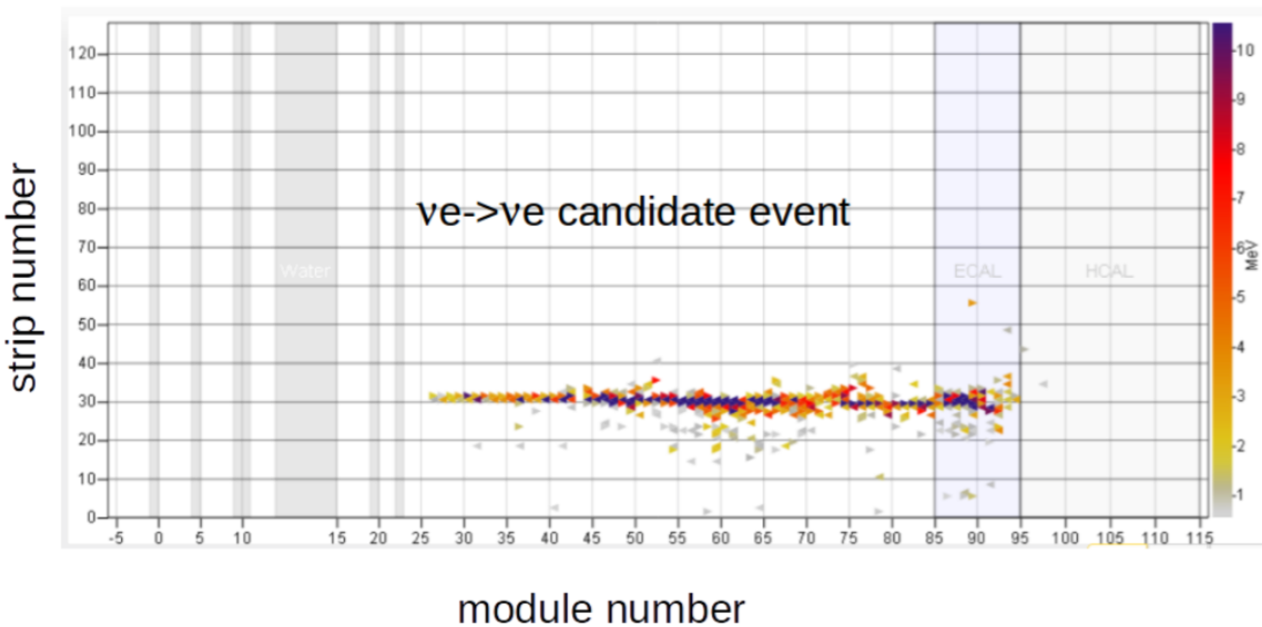
- Gen2-thin can be applied directly to the Medium Energy Flux.

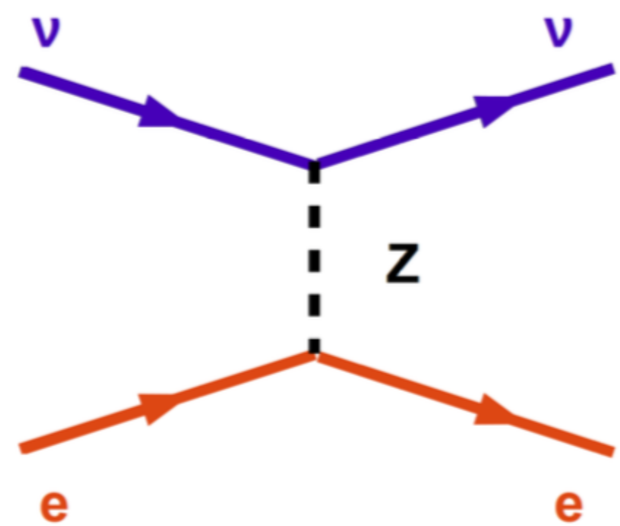
- Atop of the a priori flux, we apply an additional constraint of the flux with $\nu - e$ scattering measurements.

Neutrino on electron scattering for additional constraint

Additional Constraint: neutrino on electron scattering

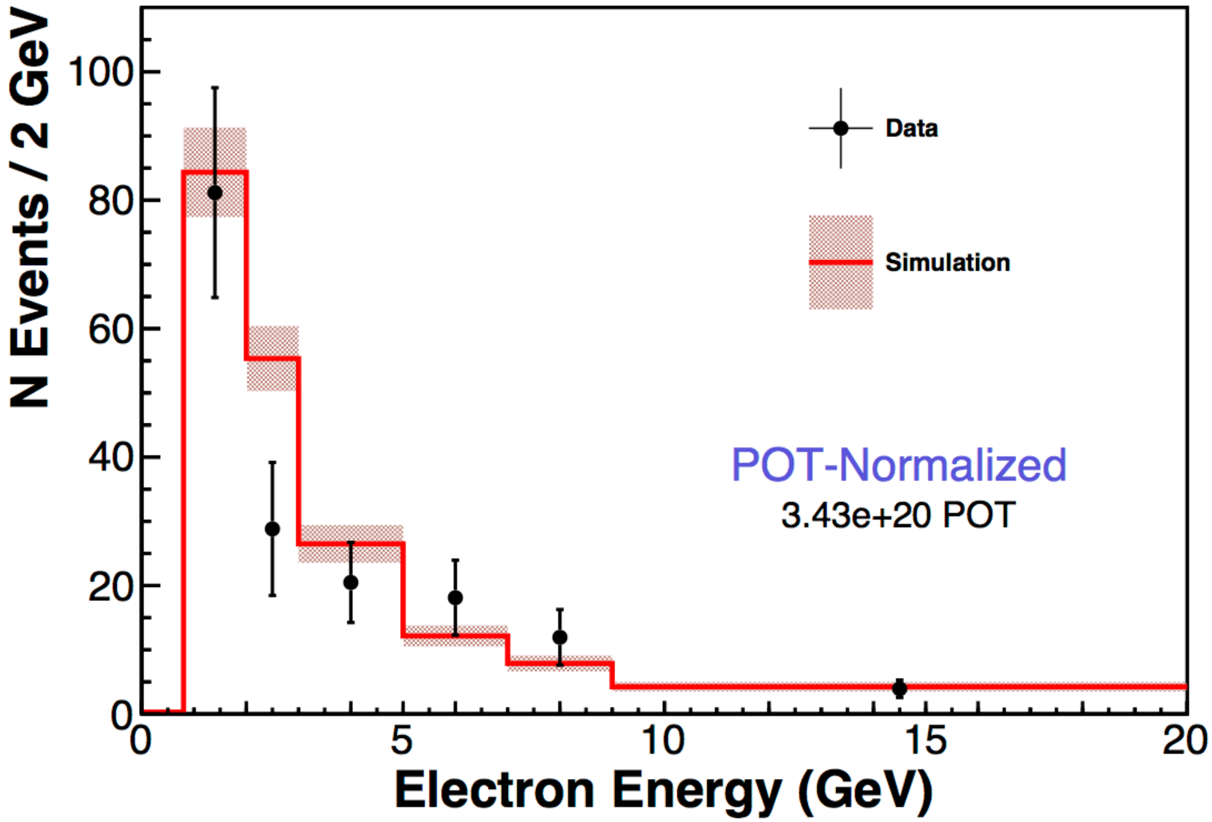
- Neutrino scattering on electrons is a standard candle:
  - Standard electroweak theory predicts it precisely.
  - Signal is a single electron moving in the beam direction.
  - The cross-section for this process is smaller than the cross-section on the nucleus scattering by a factor of 2000.
  - Statistical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





MINERvA Measurements Applied as Constraint

- 123 +- 17.0 (stats) +- 9.1 (sys) events founded in MINERvA.



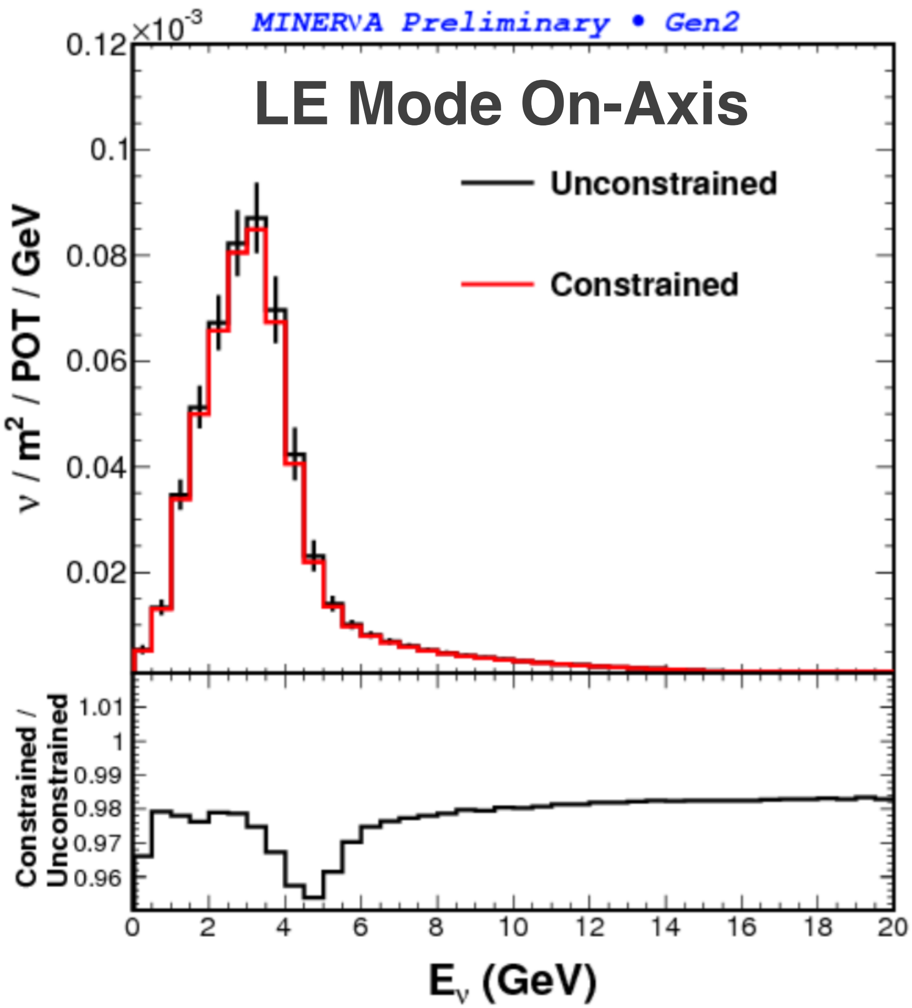
Phys. Rev. D 93, 112007 (2016)

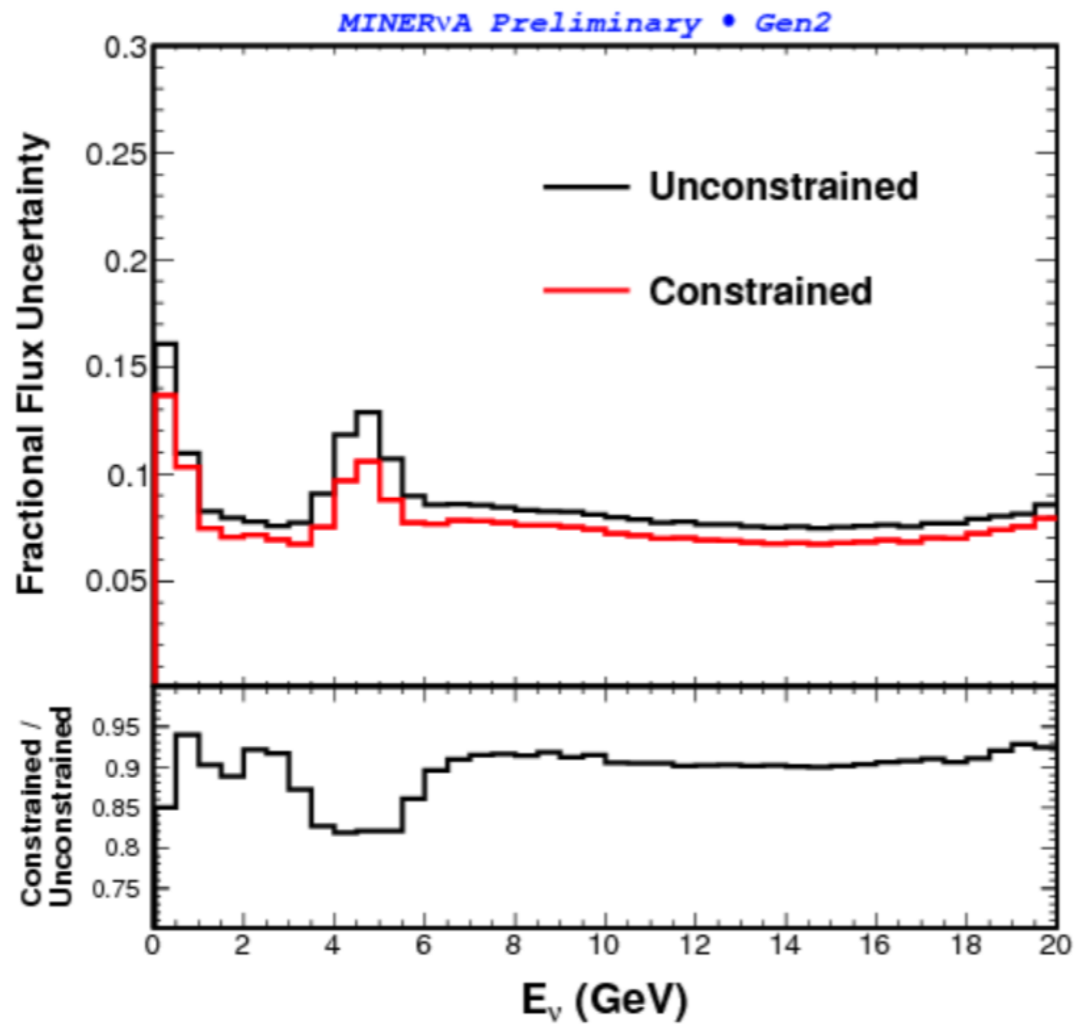
Observed ν-e scattering events give a constraint on the flux: we can use it to weight up or down the more likely or unlikely universes.

Effect on the LE Flux at MINERvA

Change in the central value after the constraint

Change in the fractional error after the constraint



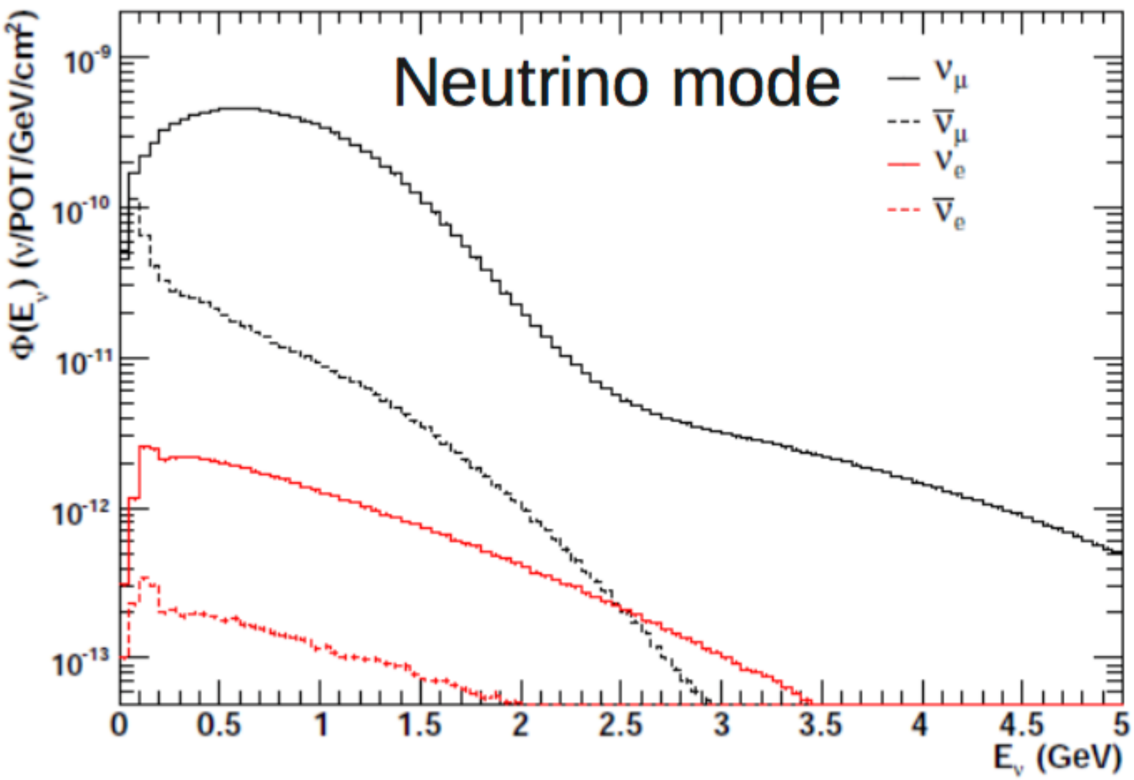


Booster Neutrino Beam

Slides from: **"Booster Neutrino Beam Flux Prediction"**
Zarko Pavlovic
Nuclear Beam and Instrumentation 2014

BNB (Booster Neutrino Beam)

- Running since 2002 to the present.



Experiments

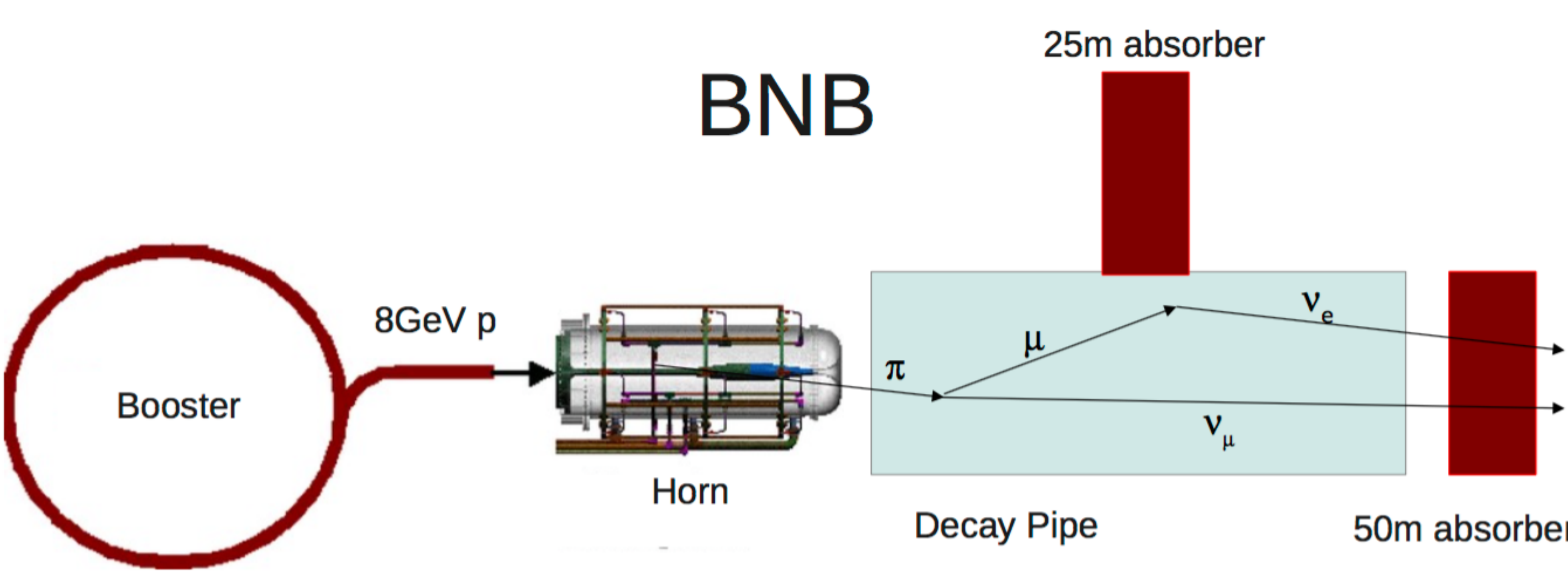
Past/Current

- MiniBooNE
- MicroBooNE
- SciBooNE
- SciBath

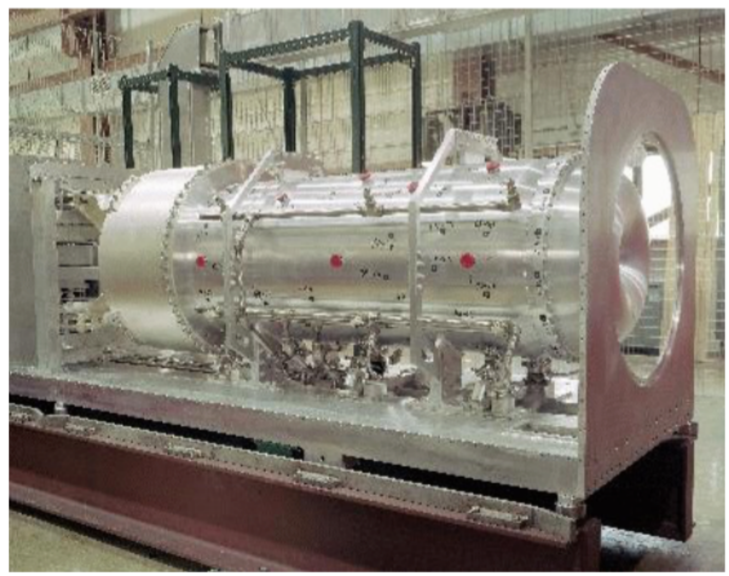
Future

- ICARUS
- LAr1-ND

BNB (Booster Neutrino Beam)



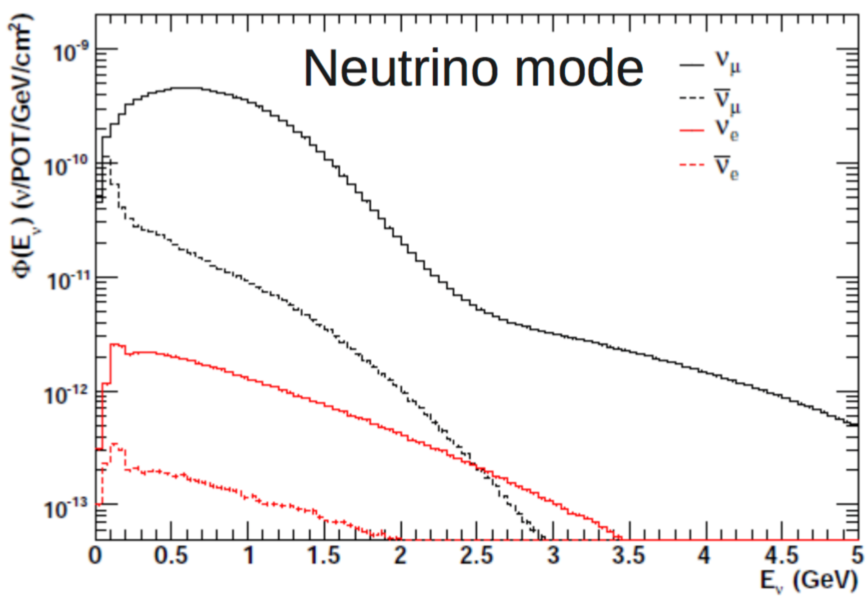
- Proton delivery:
  - 8 GeV protons from Booster
  - Average rate up to 5Hz
  - 4.2e12 PPP
- Horn:
  - Neutrino mode +170kA
  - Antineutrino mode -170kA



BNB (Booster Neutrino Beam)

Neutrino flux prediction

- Geant4 based MC used to predict the flux
- Hadron production cross sections tuned to external data



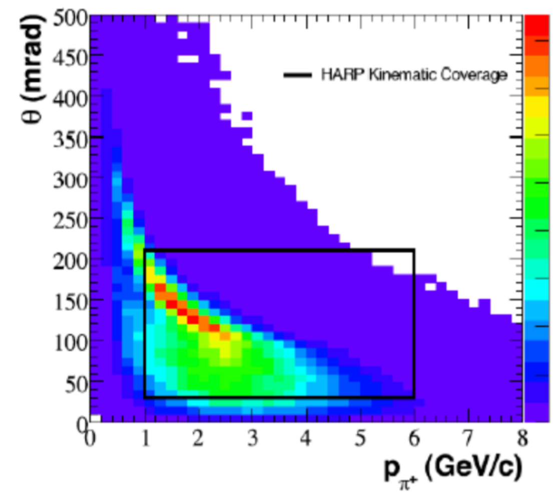
	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/ cm^2/POT)		5.19×10^{-10}		3.26×10^{-11}
Frac. of Total		93.6%		5.86%
Composition	π^+:	96.72%	π^-:	89.74%
	K^+:	2.65%	$\pi^+ \to \mu^+$:	4.54%
	$K^+ \to \pi^+$:	0.26%	K^-:	0.51%
	$K^0 \to \pi^+$:	0.04%	K^0:	0.44%
	K^0:	0.03%	$K^0 \to \pi^-$:	0.24%
	$\pi^- \to \mu^-$:	0.01%	$K^+ \to \mu^+$:	0.06%
	Other:	0.30%	$K^- \to \pi^-$:	0.03%
			Other:	4.43%

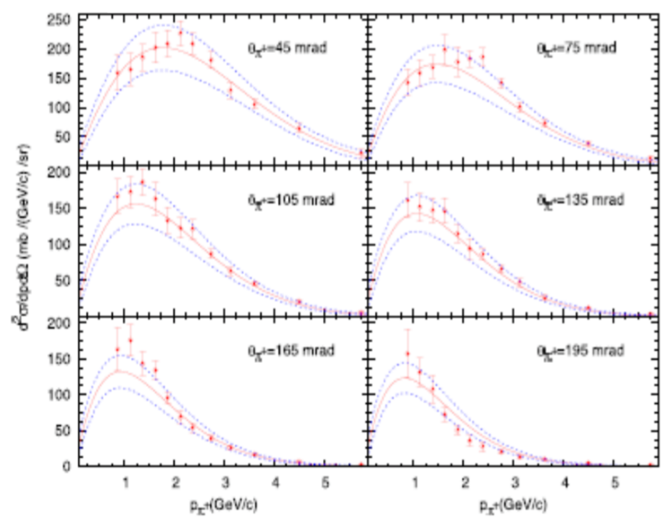
	ν_e		$\overline{\nu}_e$	
Flux (ν/ cm^2/POT)		2.87×10^{-12}		3.00×10^{-13}
Frac. of Total		0.52%		0.05%
Composition	$\pi^+ \to \mu^+$:	51.64%	K^0_L:	70.65%
	K^+:	37.28%	$\pi^- \to \mu^-$	19.33%
	K^0_L:	7.39%	K^-:	4.07%
	π^+:	2.16%	π^-:	1.26%
	$K^+ \to \mu^+$:	0.69%	$K^- \to \mu^-$:	0.07%
	Other:	0.84%	Other:	4.62%

BNB (Booster Neutrino Beam)

Pion production

- Sanford-Wang fits:
  - HARP (thin target)
    - 8.89GeV p on Be target
    - P = 0.75 – 6.5 GeV/c,
      θ = 30 – 210 mrad
  - E910
    - 6.4, 12.3, 17.5 GeV/c
    - P=0.4 – 5.6 GeV/C,
      θ = 18 – 400 mrad
- Fits done both for pi+ and pi-

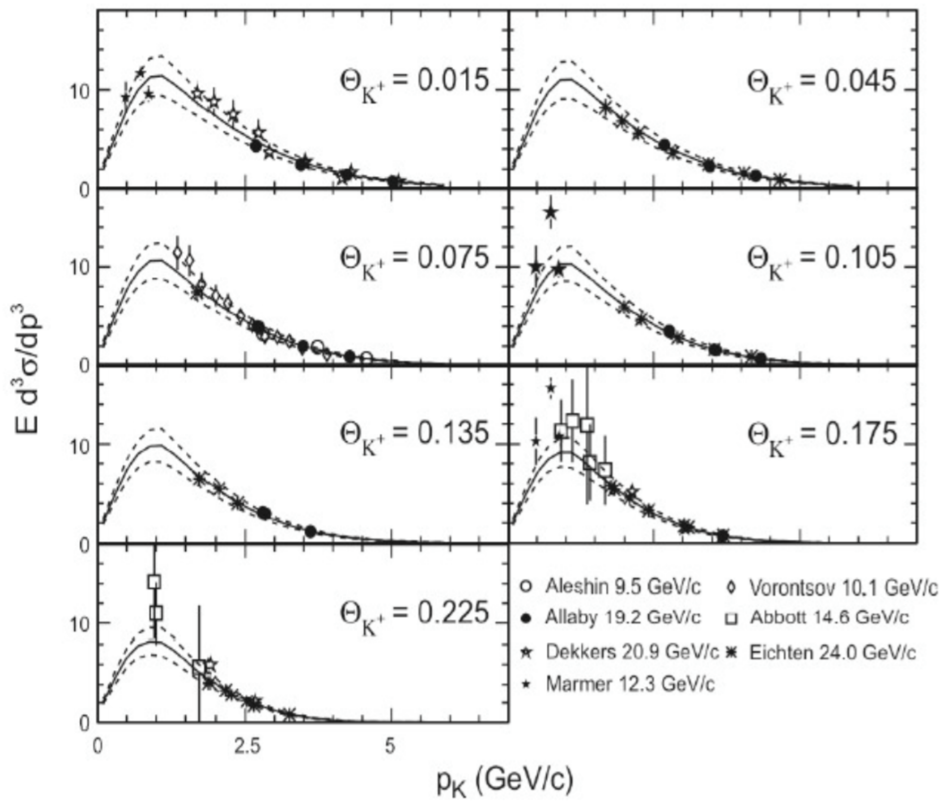




Phys. Rev. D79, 072002 (2009)

Kaon production

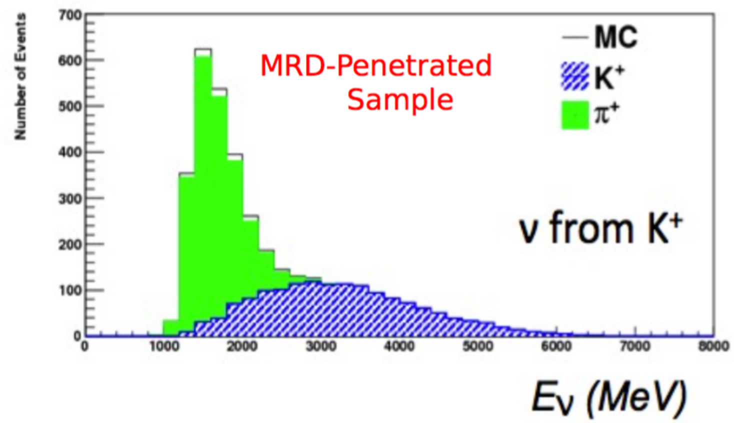
- Feynman scaling based parameterisation used to fit world K+ production data
- Sanford-Wang fits to K0s production data from BNL E910 and KEK Abe et al.

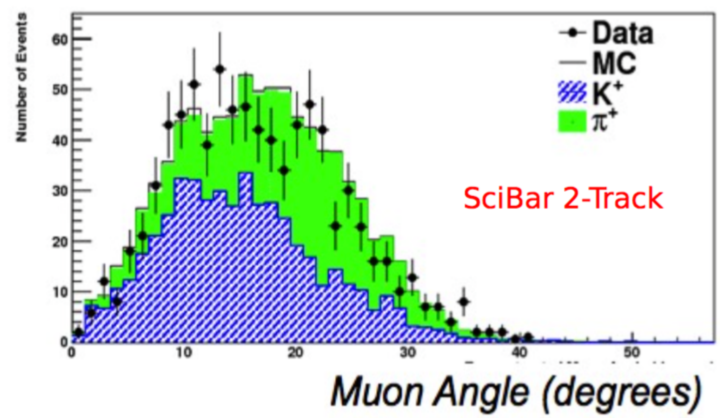


Kaons in BNB

- Kaon production further constrained by SciBooNE measurements
- Found production to be 0.85+-0.12 relative to the global fit to kaons (with 30% error)

Phys.Rev.D84,012009 (2011)



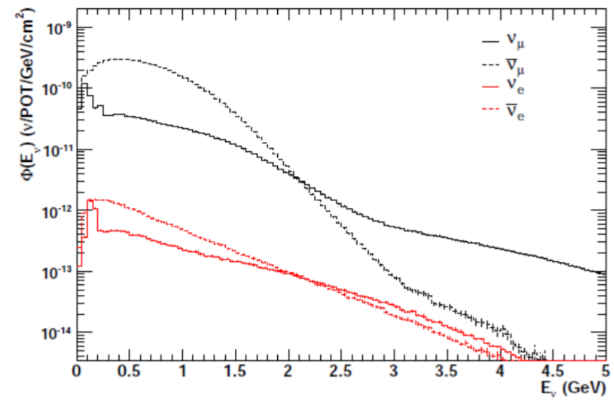


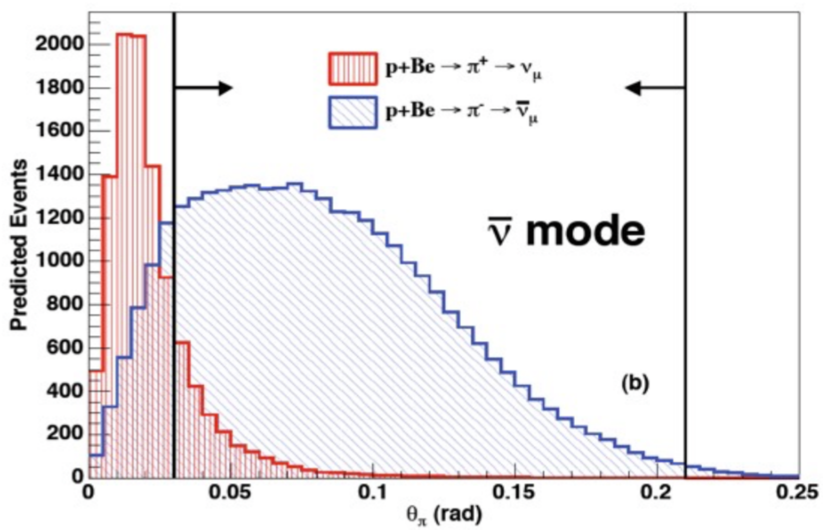
BNB (Booster Neutrino Beam)

Wrong signs

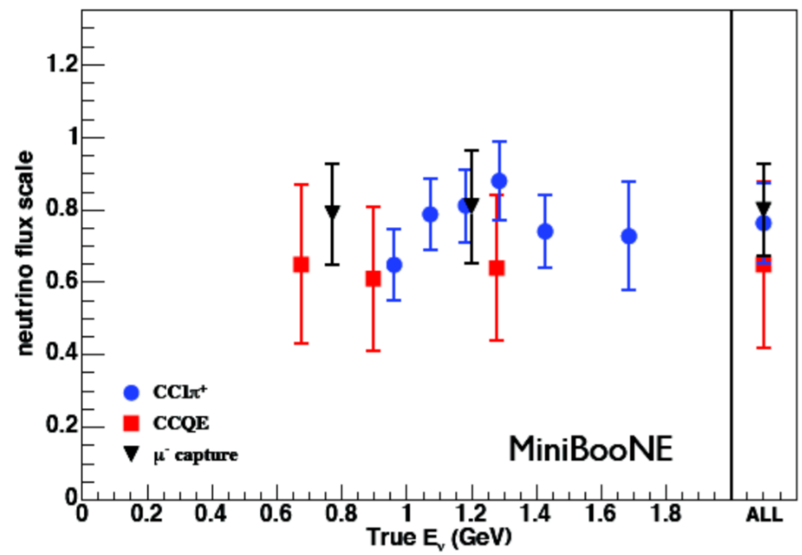
- Significant numu component in antineutrino mode (~16%)
- Not constrained well by HARP/E910
- In-situ measurement in MiniBooNE
  - Numu CCQE angular fit
  - CCπ^+ rate
  - μ^- capture

Antineutrino mode flux





Phys.Rev.D84,072005 (2011)



BNB (Booster Neutrino Beam)

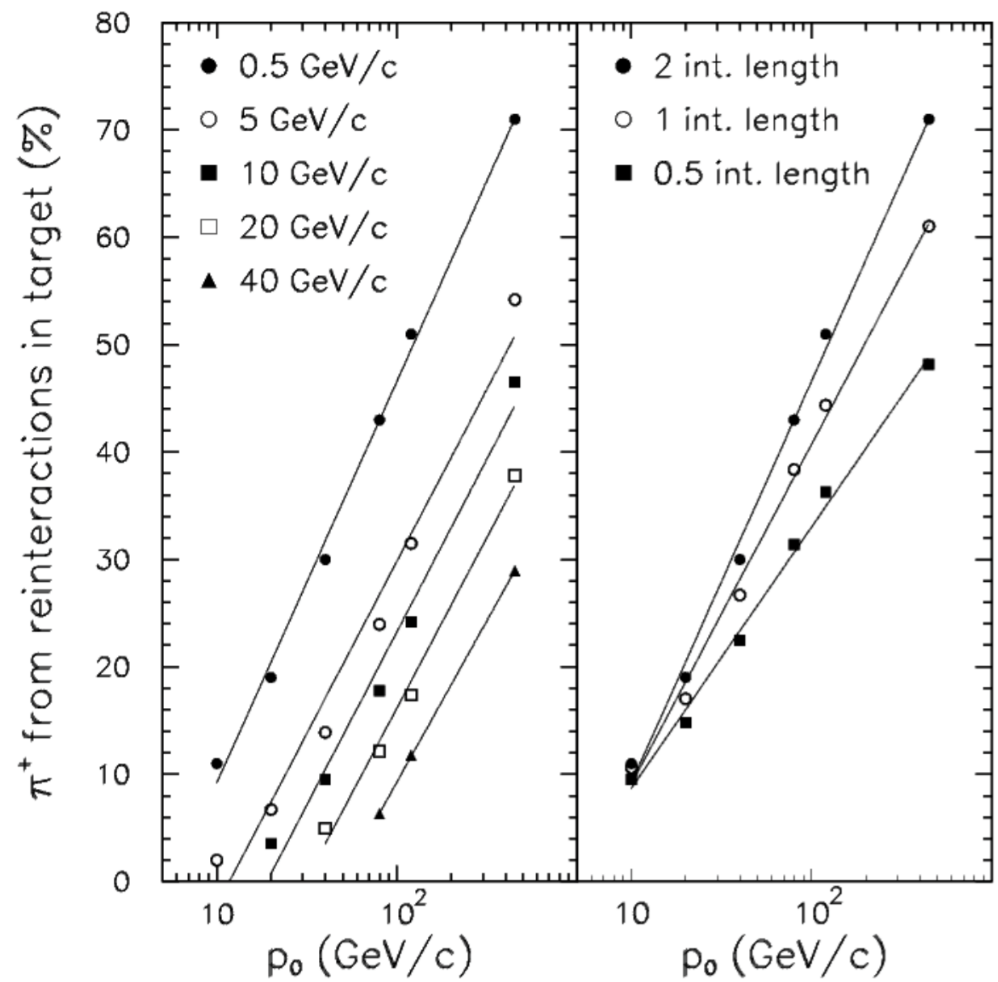
Flux uncertainty

- Propagate uncertainties using many MC worlds to build error matrices that capture correlations between bins of neutrino observables
  - spline fits through HARP data
  - kaon fits
  - Hadron cross sections on Be and Al
  - Horn focusing
  - POT counting
- For numu/numubar CCQE measurement resulting flux uncertainty was at 9-10% level

BNB (Booster Neutrino Beam)

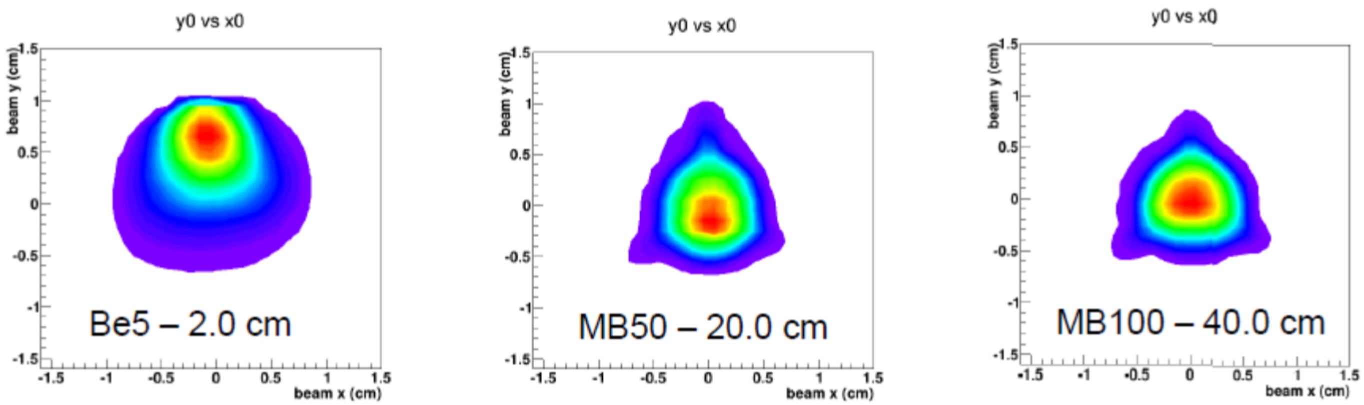
Reinteractions in BNB

- At Booster energies ~90% of pions contributing to neutrino flux from primary p+Be interactions



BNB (Booster Neutrino Beam)

HARP thick target analysis



DATA	Beam radius cut (reduce the edge effect)	P.O.T
MB100	0.4 cm	622791
MB50	0.4 cm	814749
Empty	0.4 cm	475776
Be5	1.0 cm	13070000
Empty	1.0 cm	1990000

Athula Wickremasinghe - NBI Sep 22, 2014 16

Revisiting HARP

- BNB MC correctly models reinteractions – see talk by A. Wickremasinghe at flux workshop (09/22)
  - Extrapolation to thick target agrees at 1% level
- Analysis using alternative (Extended Sanford Wang) parametrisation fitted to HARP only data results in 2% change in neutrino flux
  - Within the expected systematic error