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MINERvA experiment

Fermilab
50 Years of Discovery

Neutrino Flux Prediction for the NuMI Beam

Fermilab 50th Anniversary Symposium and Users Meeting

Leo Aliaga
Fermilab

June 8, 2017

By 1960s….

- The Standard Model was under construction… many remaining unsolved problems in the electroweak sector….

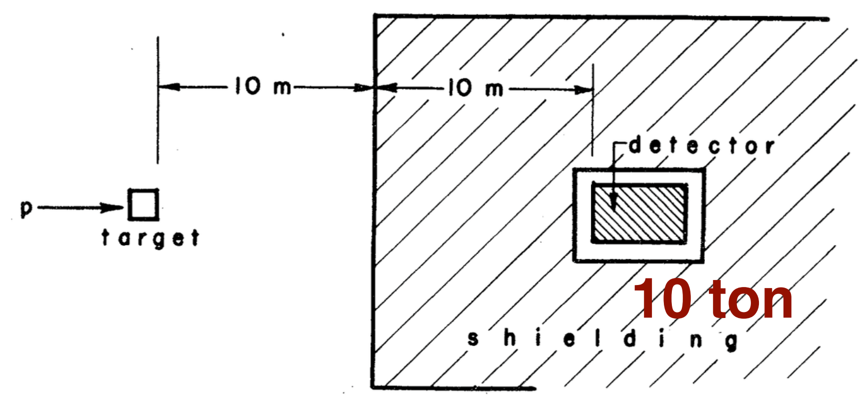
For instance, ***are ν** (emitted in β decays)* ***and ν** (emitted in π -> μ)* ***identical particles?***

Is it possible to use high energy ν's to study weak interactions?

- The concept of the **neutrino beam from accelerators** was proposed independently by Pontecorvo and Schwartz to answer the question…

If we have:

- 5×10^{12} 3 GeV protons/sec, 10 ton detector.
- 10 m decay length, 10 m shielding.
- Detector at 20 m.

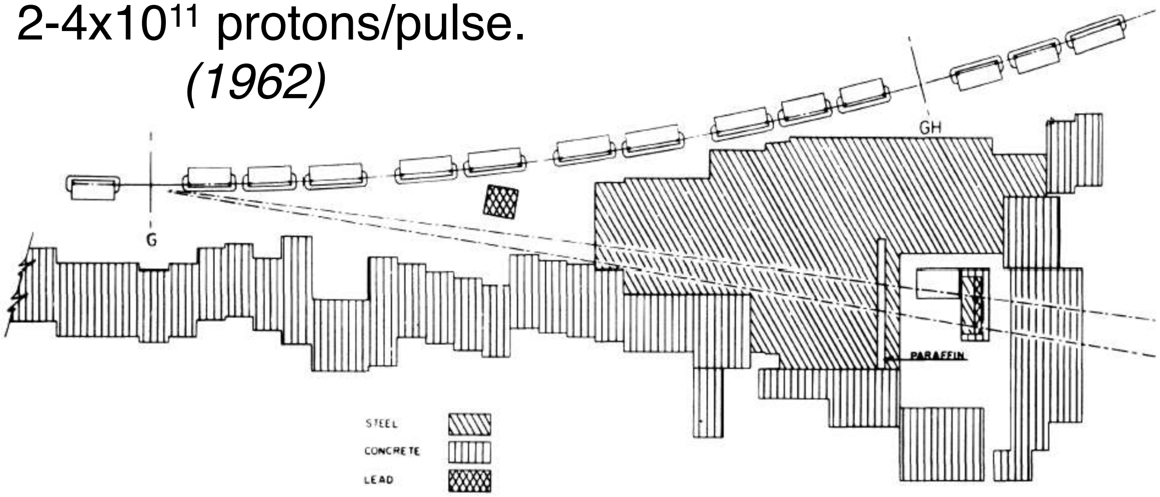


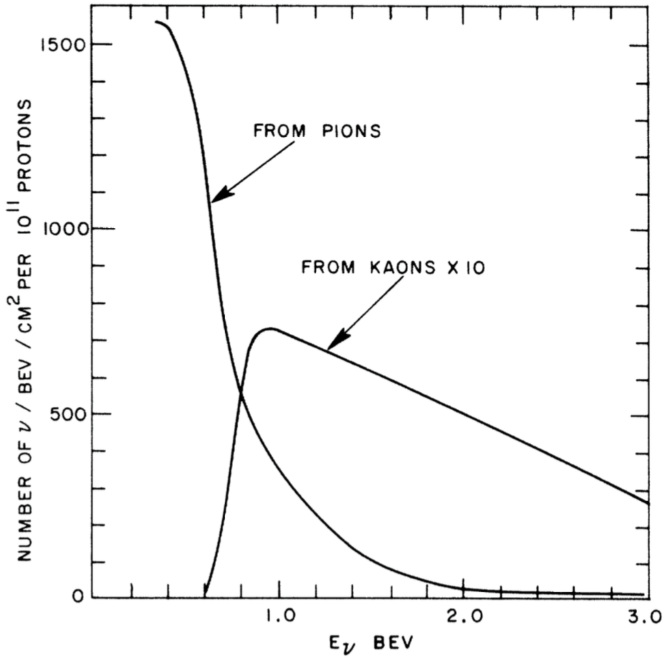
Yes! we get 1 ν per hour.

The First Beam…

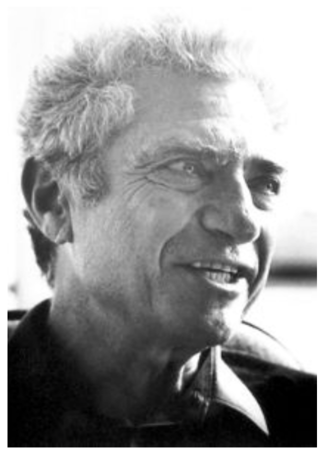
- Brookhaven AGS, 15 GeV protons.
- 2-4x10^{11} protons/pulse.

(1962)





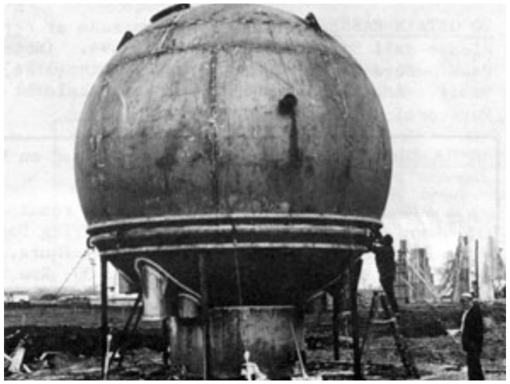




LEDERMAN SCHWARTZ STEINBERGER

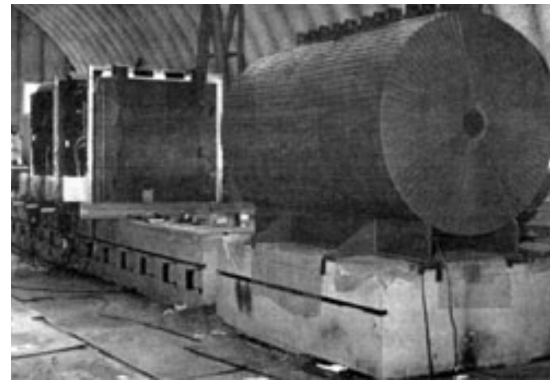
for the neutrino beam method and the demonstration of the doublet structure of leptons through the ***discovery of the muon neutrino*** *(1982)*

Fermilab Took on the Challenge to Investigate Neutrinos



15 FT- BC

The "Wonder Building"



Caltech Detector

I feel that we then will be in business to do experiments on our accelerator*, and I feel that this detection will come in the Caltech-NAL experiment. The Caltech installation excites my envy -* ***their enthusiasm and improvisation gives us a real incentive to provide them with the neutrinos they are waiting for****.*

(User's Meeting 1971)

Fermilab has played a key role in the accelerator neutrino beam.

	Experiment
70s	CITF
	HPWF
	15’ BC
80s and 90s	CCFR
	NuTeV
2000s	MiniBooNE,
	SciBooNE
	MINOS
	MINERvA
	NOvA
	MINOS+
	MicroBooNE
	…..

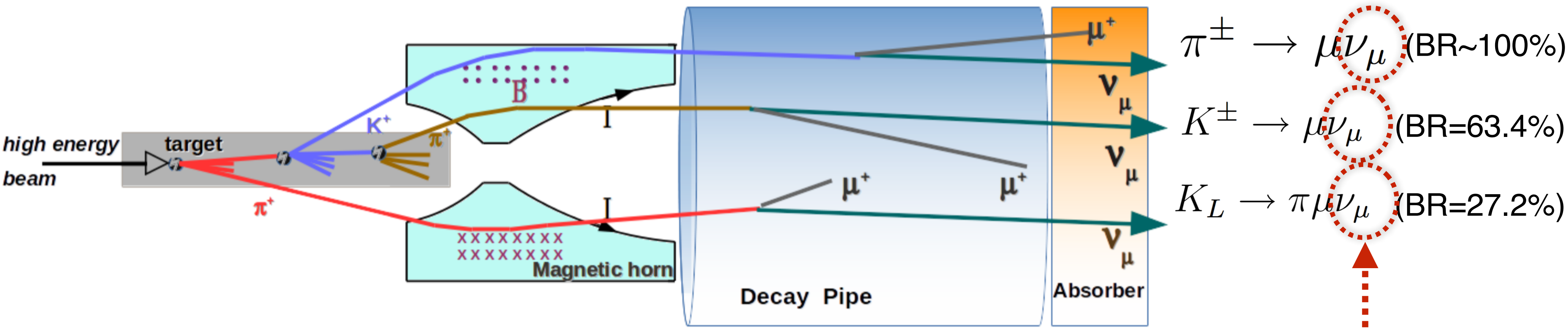
(excluding beam-dump experiments).

dedicated to different physics challenges…

Studying the week neutral current, Weinberg angle, neutrino oscillation parameters …

How to Make a Conventional Neutrino Beam

- Fermilab history on conventional neutrino beams is rich.



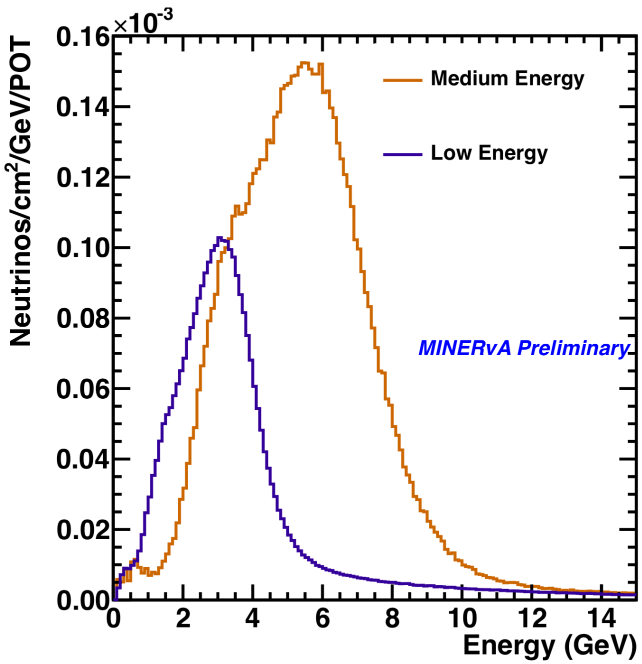
- A very intense proton beam colliding with a target producing π's and K’s.
- A system to focus the π's and K’s (added by van der Meer).
- An extended decay region.
- Absorbers for the remaining hadrons.

My thesis is about the prediction the neutrino flux at NuMI

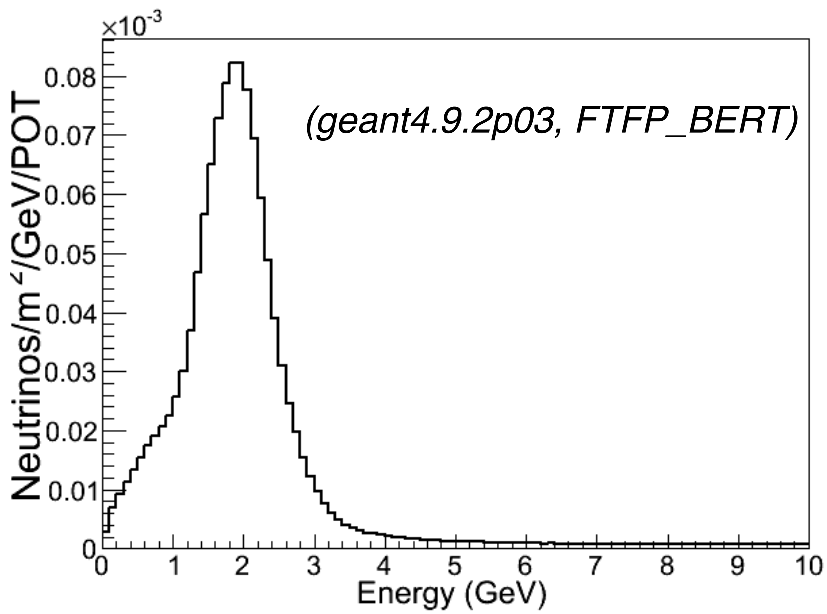
NuMI (Neutrinos at the Main Injector)

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

On-Axis: MINERvA and MINOS



Off-Axis: NOvA



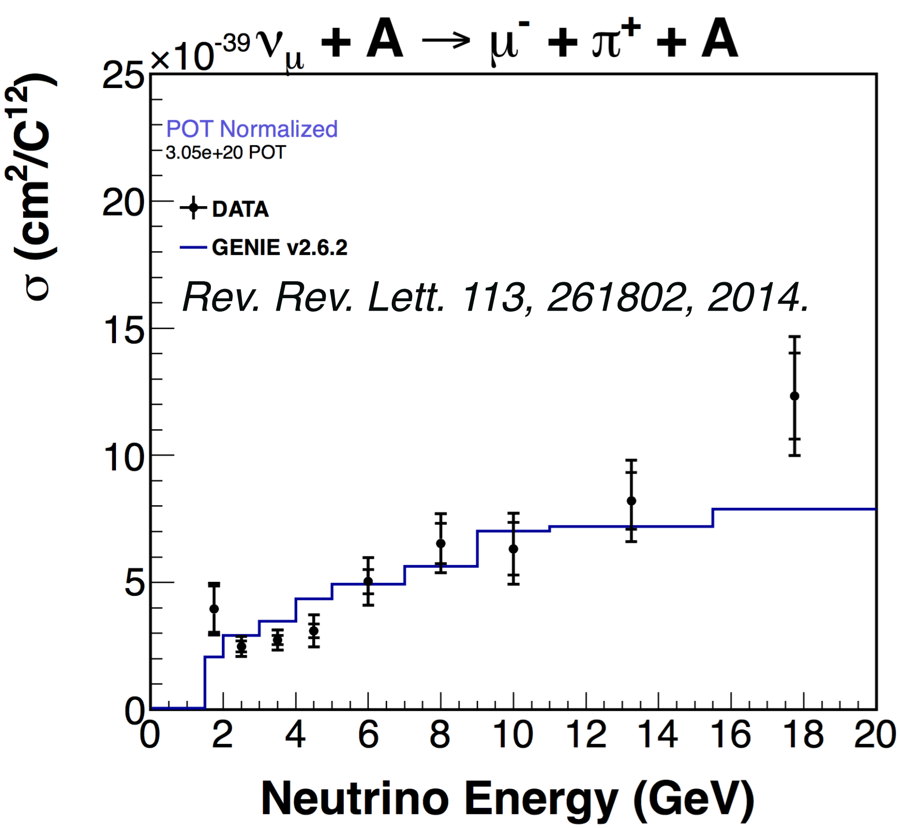
NuMI provides neutrinos for the Fermilab high intensity neutrino studies: ***oscillation parameters, cross-sections, search for exotic physics, etc.***

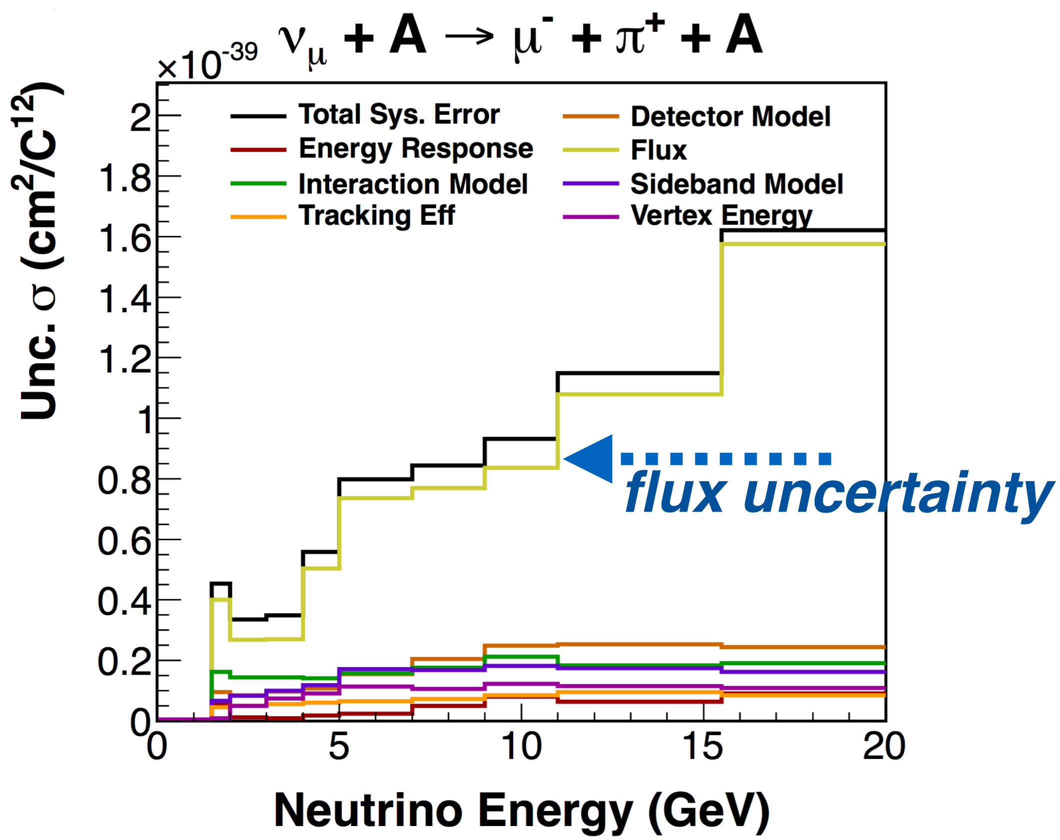
Why is the Flux Important?

$$\sigma(E) = \frac{N(E)}{\phi(E) \times T}$$

Example: MINERvA coherent charged pion production

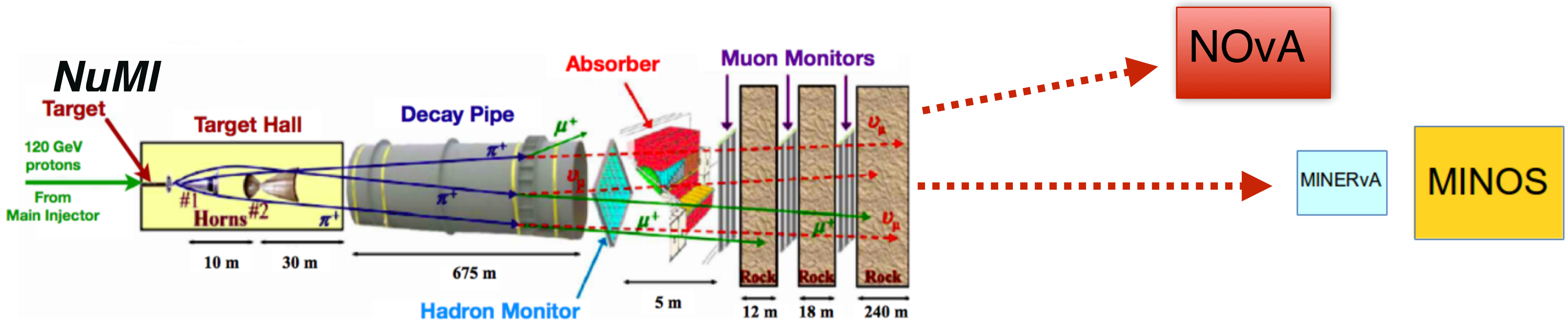
- The systematic uncertainties are dominated by the uncertainty in the flux.





- Flux systematics in oscillation experiments are sub-dominant.

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…

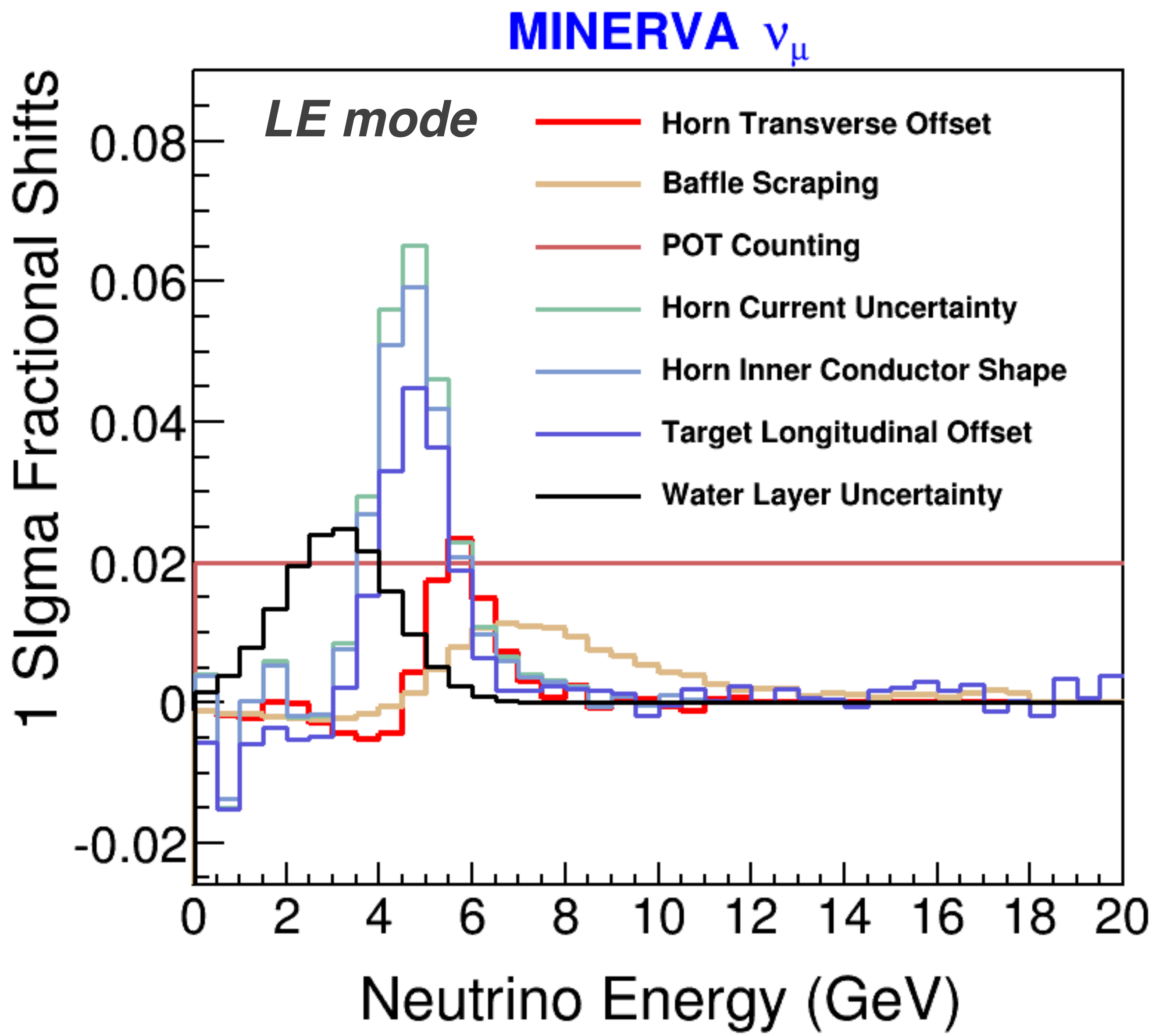
2. **Hadron production uncertainties:** big discrepancies between hadronic models.

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.

Focusing Uncertainties

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



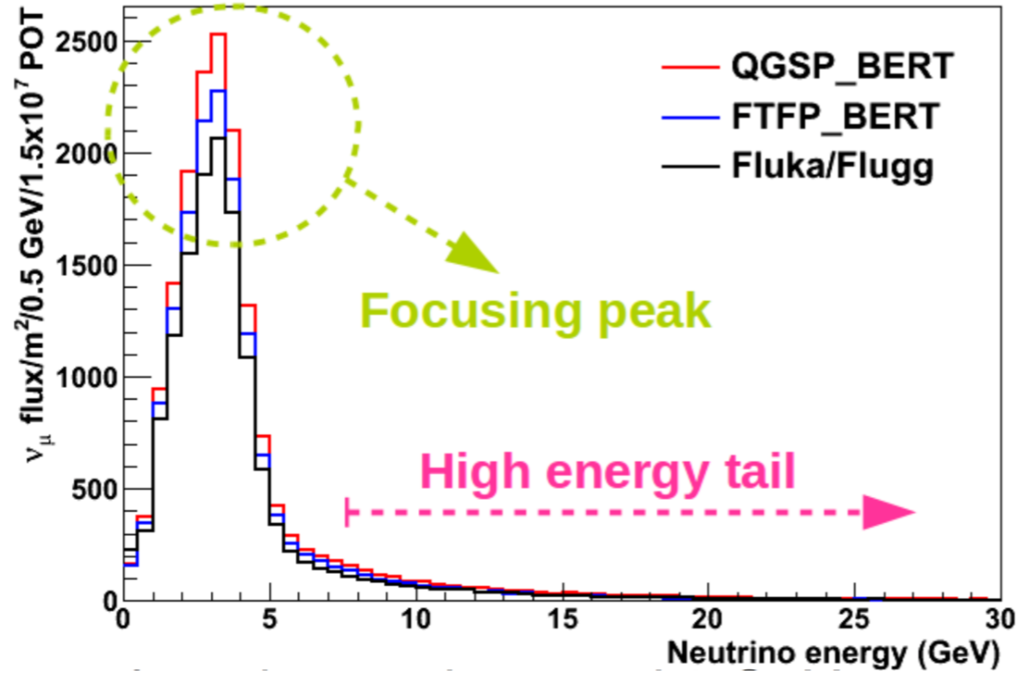
Understanding the Flux

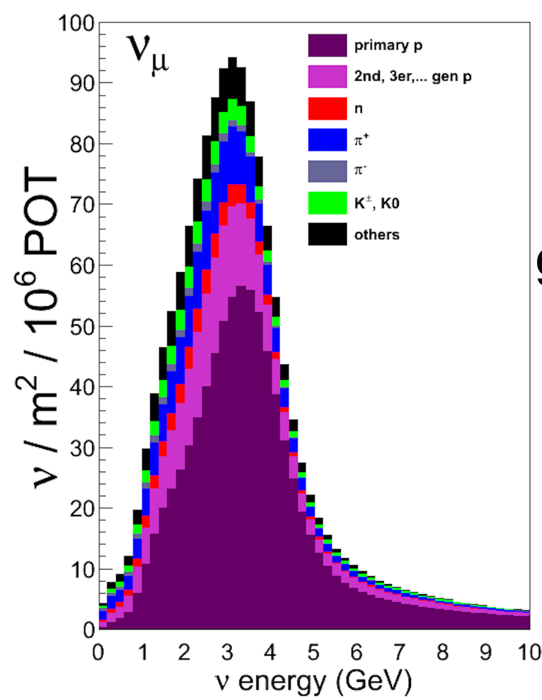
Big discrepancies between flux predictions from hadronic models

Then, we need data to constrain the model

Wide broad band flux

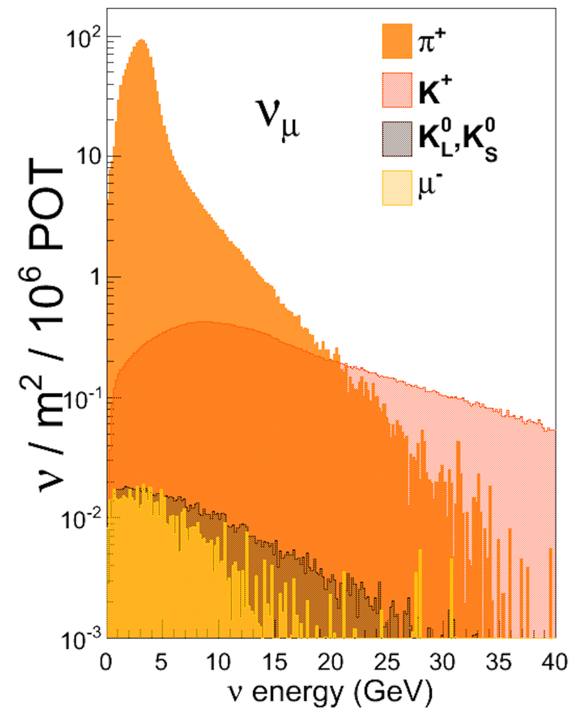
- Flux spectrum shows a peak at 3 GeV.
- Long energy tail up to 120 GeV.





Neutrino ancestry

grandparents **parents**



MINERvA Strategy

1. Calculate an a-priori flux

- *Accounting for every optical modeling uncertainty.*
- *Correcting the hadron production in the beam line (main source of uncertainty): 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.*

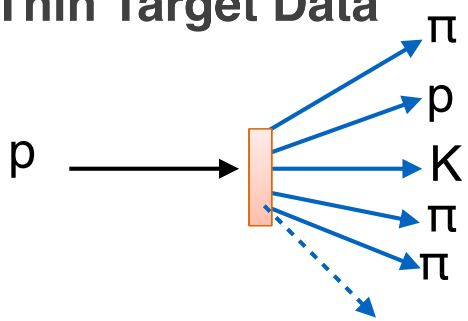
3. Package to Predict the FluX

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

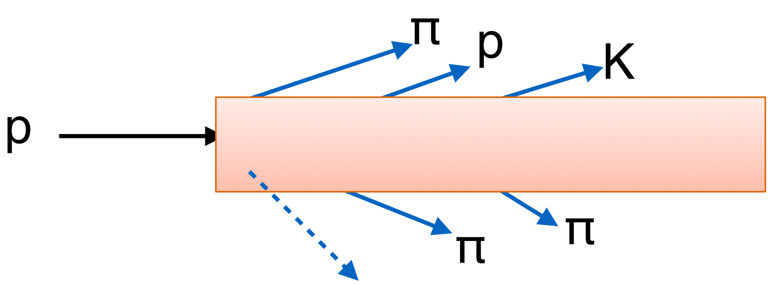
What Sort of Data is Available?

- Many hadron production data is available at the relevant energies for NuMI.

Thin Target Data



Thick Target Data



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

A Priori Corrections

First, we tabulate the hadronic cascade at generation and store all kinematic information… then, we apply a correction event by event:

Attenuation of the particles beams

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

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

Hadron production cross-sections scaled to the NuMI energies

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

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

Uncertainties

- Correlations between dataset inputs are taking into account and propagated to calculate the flux systematics.

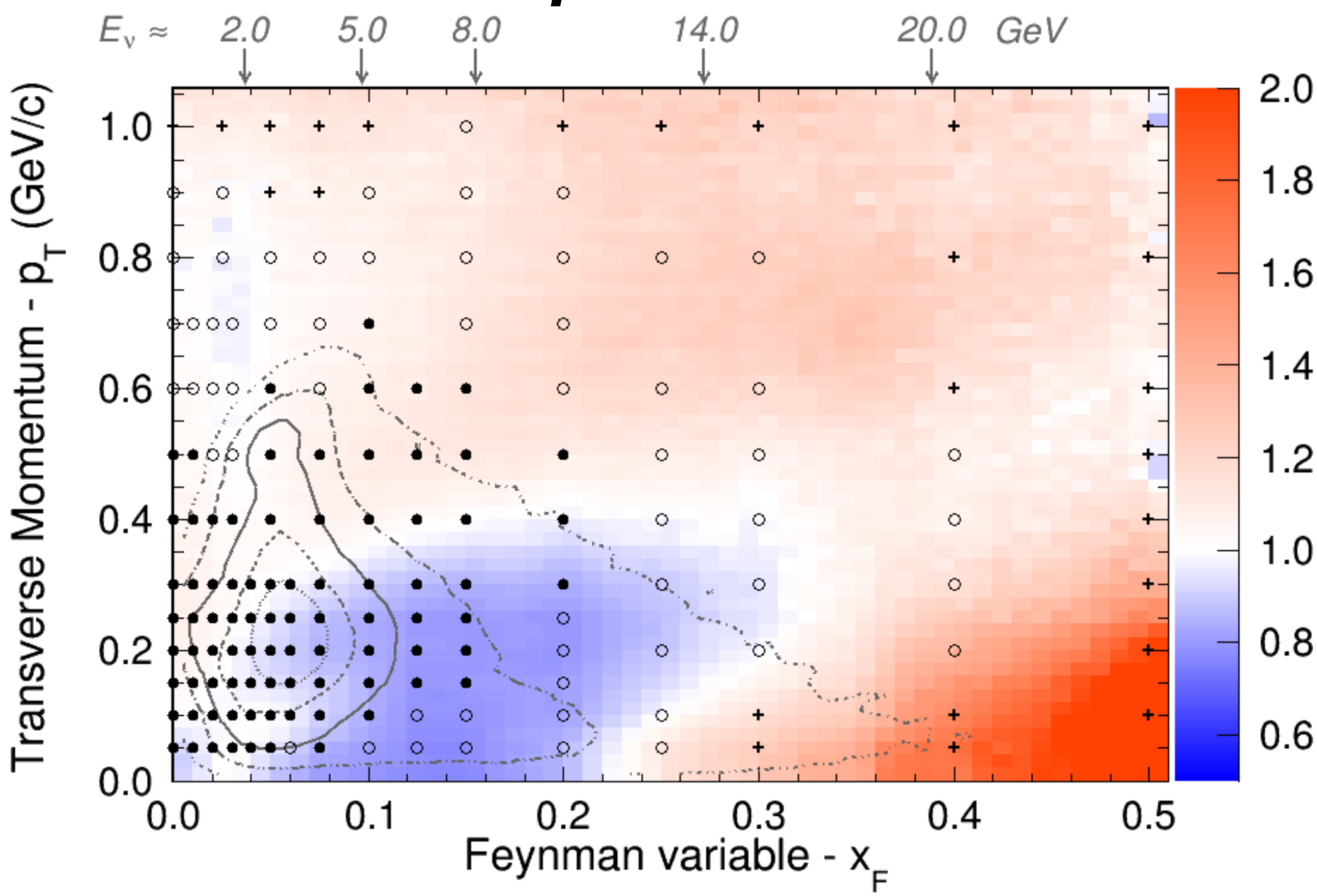
Example: NA49 Data/MC comparison **(closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).**

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.

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

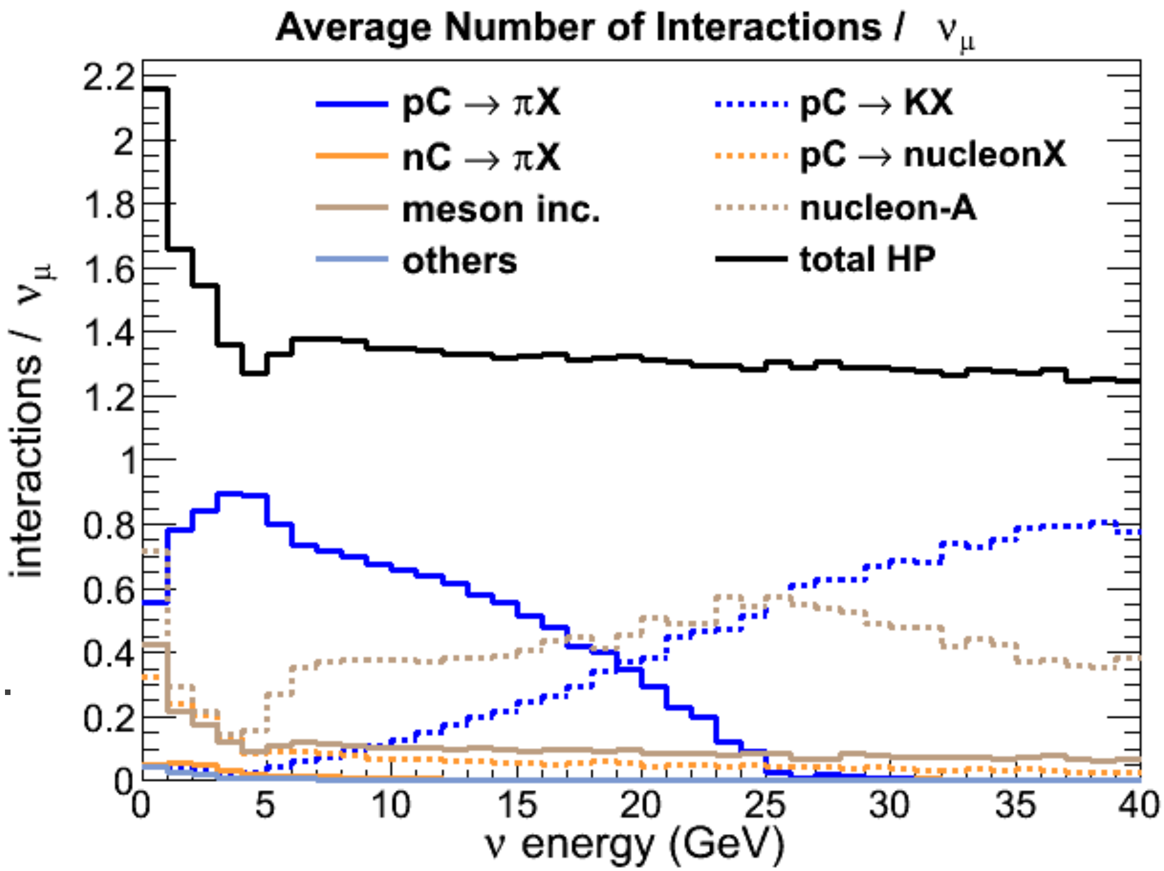
$pC \rightarrow \pi^+ X$



systematic uncertainties = 3.8% (added in quadrature).

Interactions Covered

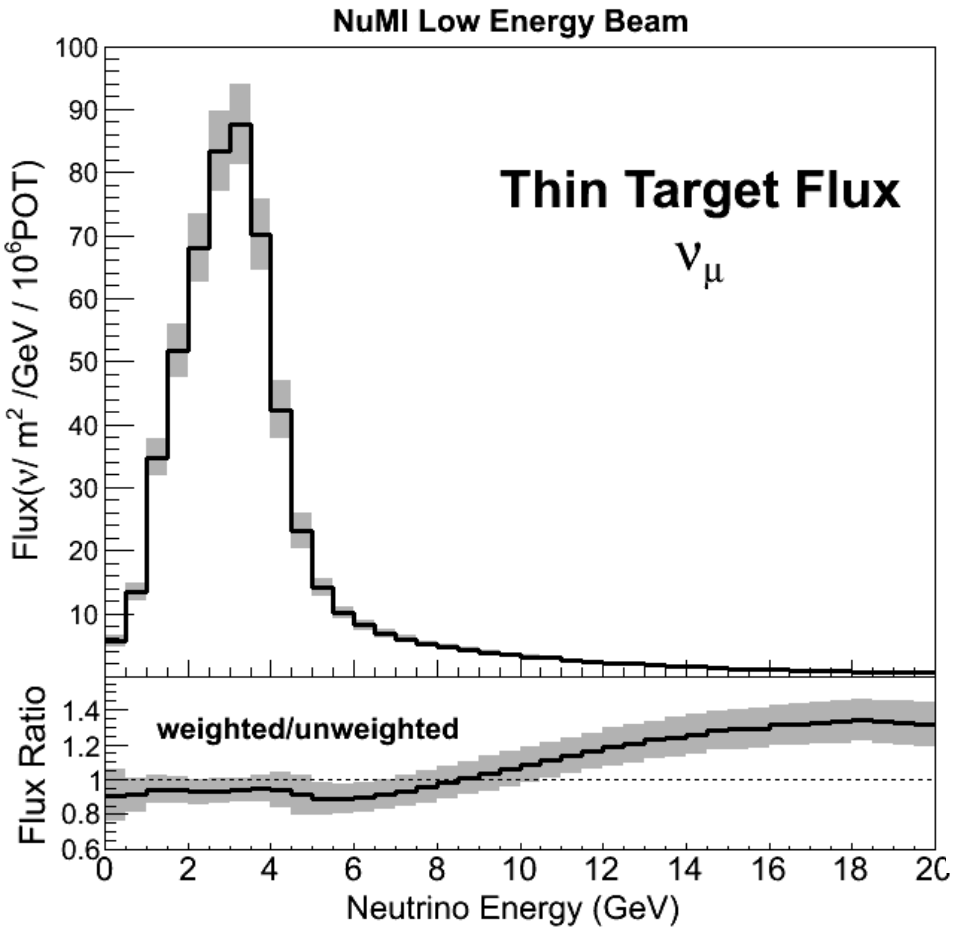
- π, K and nucleons productions based on data.
- Assuming large uncertainty for meson incident.
- Nucleon-A (quasi-elastics, extension from carbon to other materials, production outside data coverage, etc).

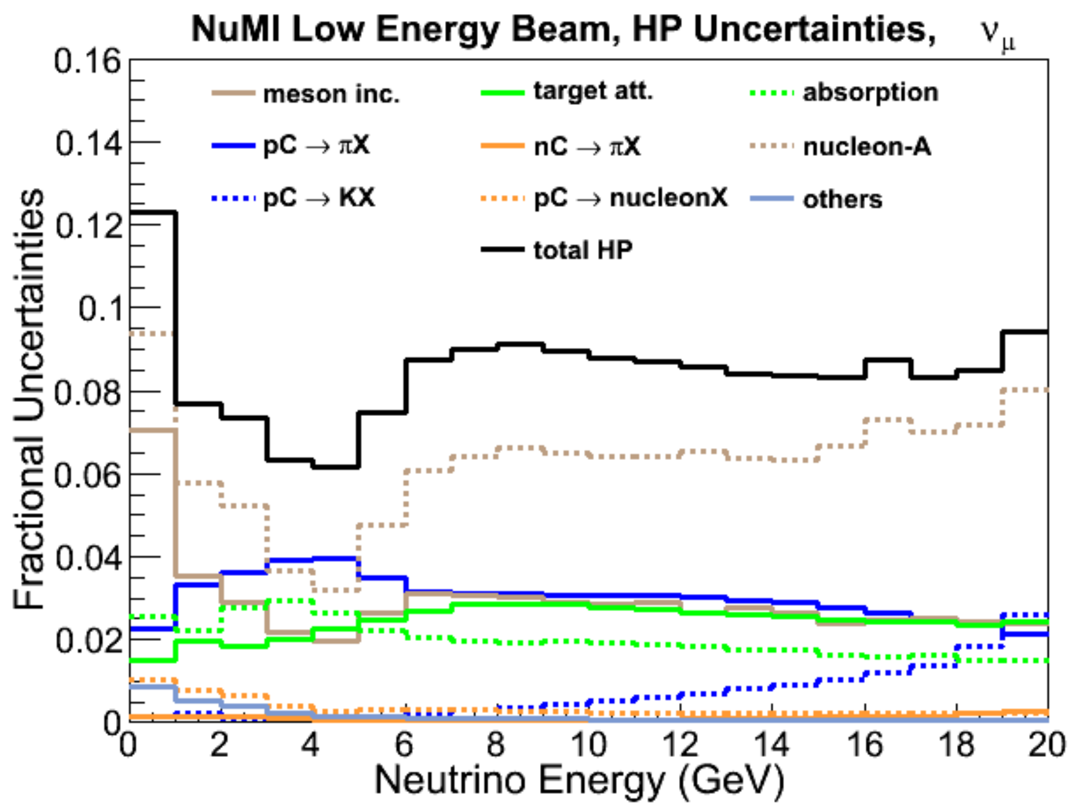


Checking the consistency with our in-situ measurements, we decided to use a prediction based only on thin target corrections.

Results

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





Conclusions

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

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

- 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 and can be extended to any conventional neutrino beam.
  - Currently, it is used by NOvA and DUNE flux systematics.

- Our work indicates where additional hadron production data is needed in order to further reduce uncertainties.

I would like to thank

My thesis advisor Mike Kordosky as well as Tricia Vahle and Jeff Nelson.

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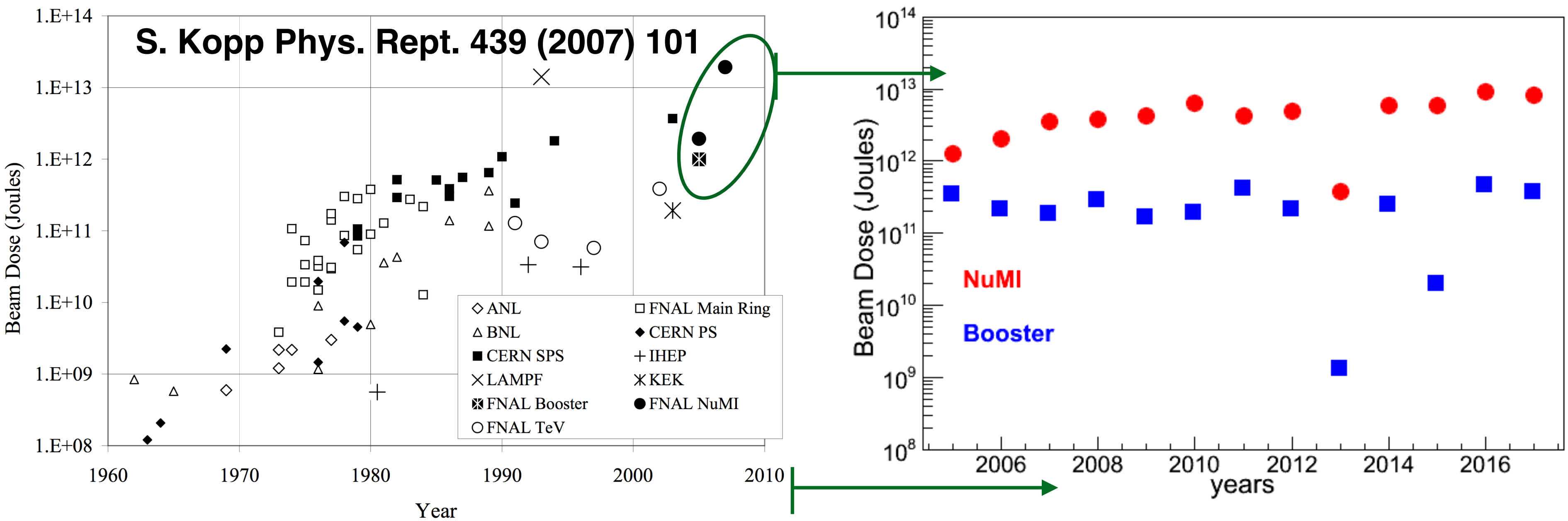
The MINERvA Collaboration

W&M

backup

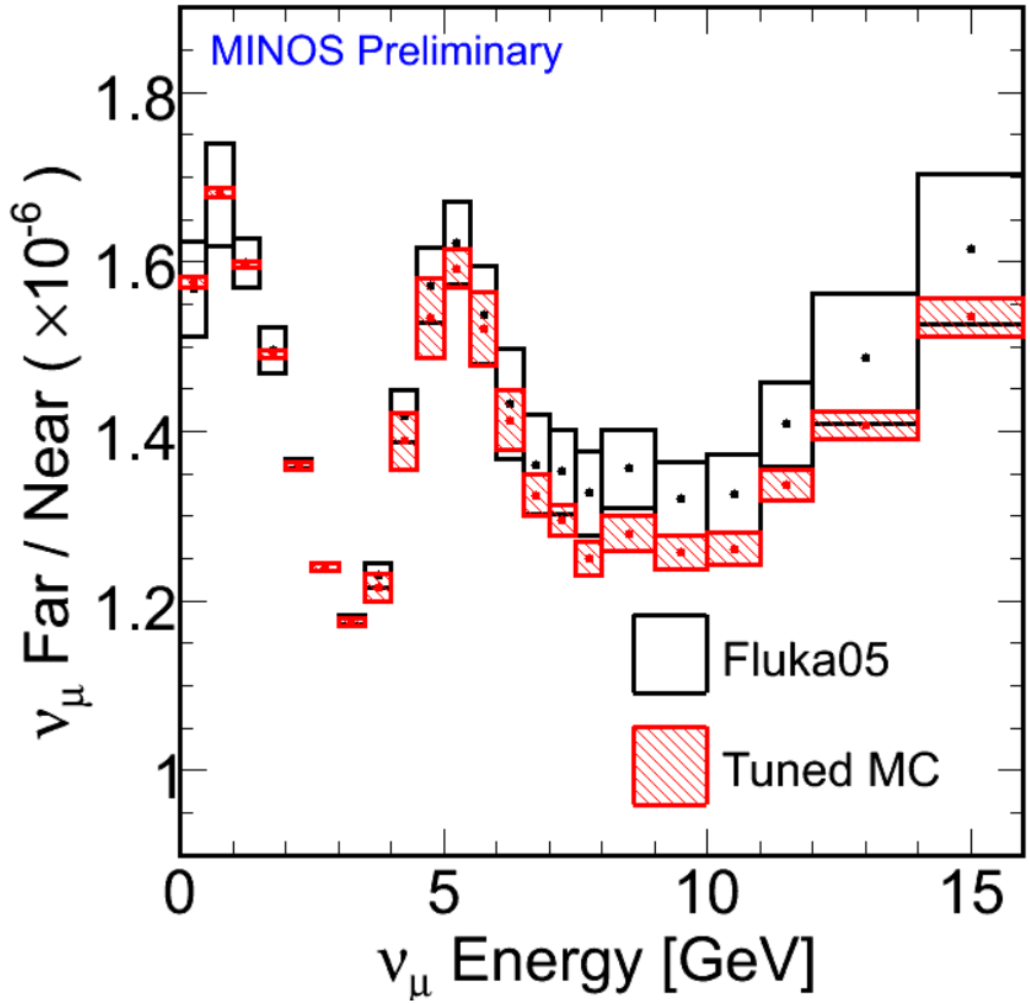
Fermilab has played a key role in the accelerator neutrino beam.



- **Precisely, my thesis work was about the determination of the NuMI neutrino flux:**
    - work in the context of MINERvA cross-section analysis.
    - but… to be used by any detectors at Fermilab that sees NuMI neutrinos.

Why is the Flux Important?

Example: MINOS F/N flux ratio



- Flux partially cancels in the near and far detector.
- F/N can depend of the hadronic model used in the simulation.

Fermilab has played a key role in the accelerator neutrino beam.

Particle Data Group Chin. Phys. C, 40, 100001 (2016)

	Main Ring (Fermilab)							Booster (Fermilab)	Main Injector (Fermilab)	
Date	1975	1975	1974	1979	1976	1991	1998	2002	2005	2016
Proton Kinetic Energy (GeV)	300,400	300,400	300	400	350	800	800	8	120	120
Protons per Cycle (10^{12})	10	10	10	10	13	10	12	4.5	37	43 (49)
Cycle Time (s)	-	-	-	-	-	60	60	0.2	2	1.333
Beam Power (kW)	-	-	-	-	-	20	25	29	350	580 (700)
Target	-	-	-	-	-	-	BeO	Be	Graphite	Graphite
Target Length (cm)	-	-	-	-	-	-	31	71	95	120
Secondary Focussing	bare target	quad trip., SSBT	dichromatic NBB	2-horn WBB	1-horn WBB	quad trip.	SSQT WBB	1-horn WBB	2-horn WBB	2-horn off-axis
Decay Pipe Length (m)	350	350	400	400	400	400	400	50	675	675
$\langle E_\nu \rangle$ (GeV)	40	$50,180^\dagger$	$50,180^\dagger$	25	100	90,260	70,180	1	$3\text{-}20^\ddagger$	2
Experiments	HPWF	CITF, HPWF	CITF, HPWF, 15' BC	15' BC	HPWF 15' BC	15' BC, CCFRR	NuTeV	MiniBooNE, SciBooNE, MicroBooNE	MINOS, MINERνA	NOνA, MINERνA, MINOS+

dedicated to cross-sections

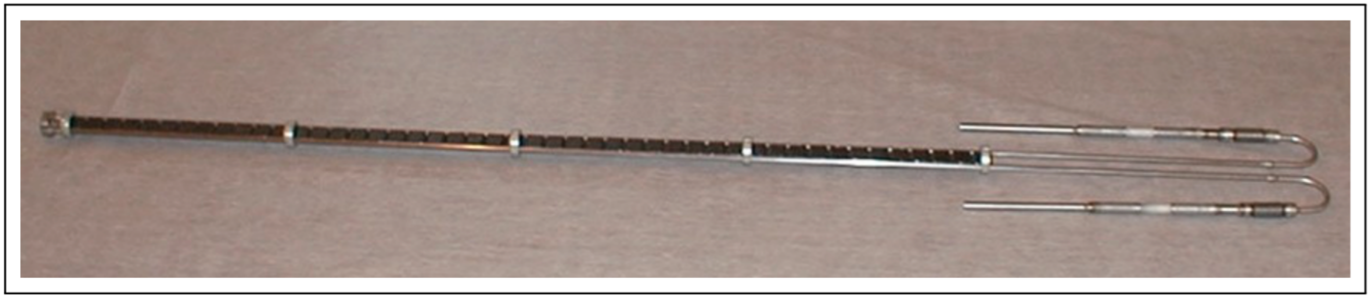
Studying the existence of the week neutral currents

designed to study neutrino oscillation

Looking at $\sin^2\theta_W$

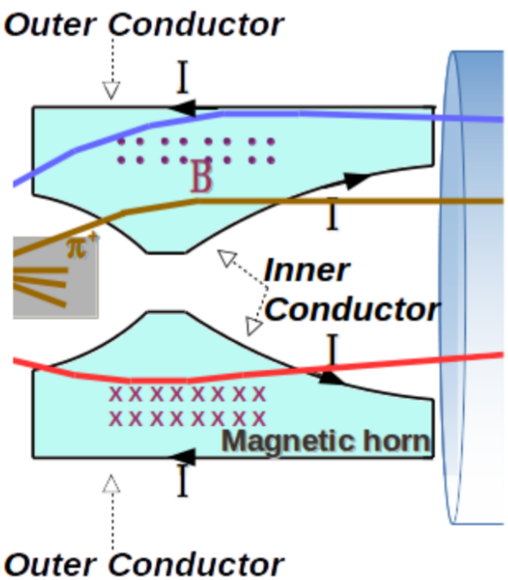
The NuMI Target

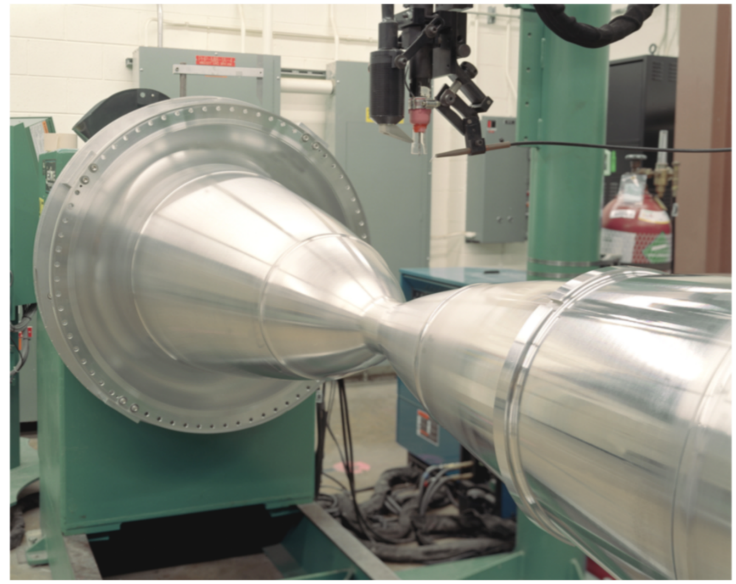
- Rectangular graphite rod.
- Segmented in “fins” + beam position monitors.
- Cooled by water in pipes, and enclosed in helium container



	LE	ME
Cross sectional view	6.4 x 15 mm^2	7.4 x 63 mm^2
Segment lenght	20 mm	24 mm
“Fins”	47	48
Beam position monitors	1	2
Total length	960 mm (~2 λ)	1200 mm (~2.5 λ)

The NuMI Horns





- A ~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 2-4 mm thick.
- Every particle traveling through the horns feels a p_T kick.

Interactions Covered Based on Thick Target Data