Neutrino Beams and Sources

Fermilab Neutrino University 2017

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July 5, 2017

My Background

- I have made my PhD in the College of William and Mary working in MINERvA experiment.
- My thesis was: “**Neutrino Flux Prediction for the NuMI Beamline**”.
- I am a postdoc in the Scientific Computing Division working at the NOvA experiment.

Neutrino Sources

Natural sources

- Solar.
- Atmospheric.
- Supernova.
- Big bang.
- AGNs.
- Geoneutrinos.
- …

We got them for free, no control over sources.

Artificial sources

- Radioactive sources.
- Reactors.
- Accelerators.
- Beta beams.
- …

Intense sources, we can control timing, sometimes energy,

Outline

- Introduction.

Neutrinos from:

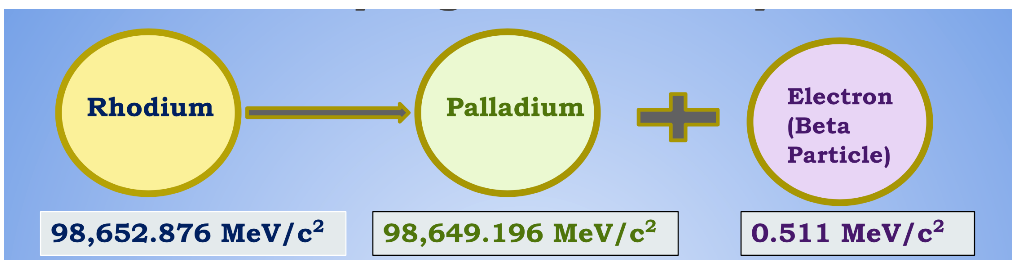
- Reactors
- Sun
- Supernova.
- Atmosphere.
- Accelerators

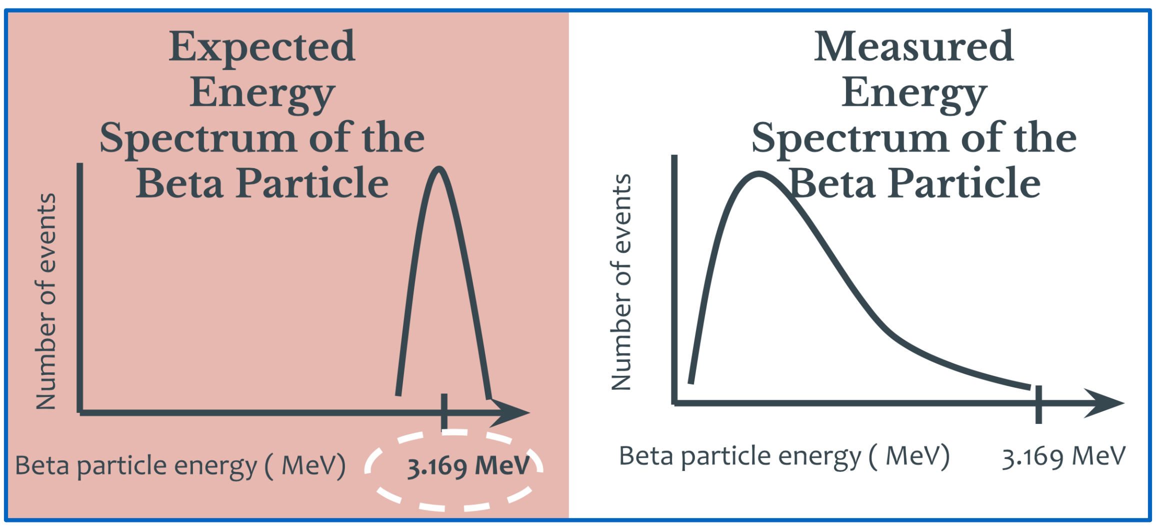
Look at the lecture:"Astrophysical Neutrinos" (John Beacom). July 26.

I will be focused on the conventional neutrino beams.

- How to make a conventional neutrino beam.
- Example: NuMI.

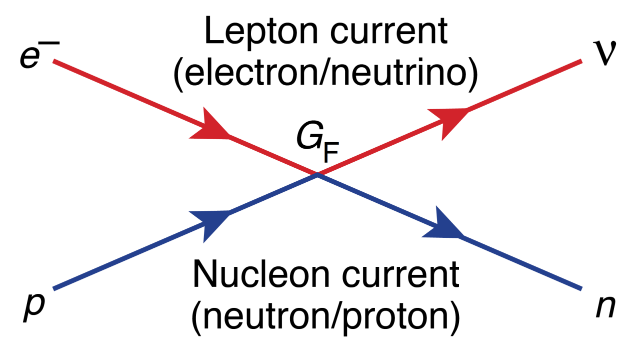
Discovery of Neutrino





- 1914: Observations by J. Chadwick.
- 1930: Pauli introduced the neutrino.
- 1933: Fermi develops the theory of beta decay.

Basic Current-Current Interaction



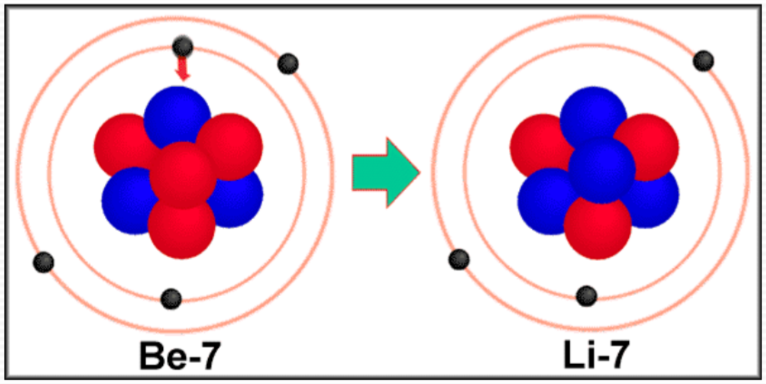
Beta Decay

β-

$$^{A}_{Z}\{P\} \rightarrow {}^{A}_{(Z+1)}\{D\} + e^{-} + \bar{\nu}$$

EC

$$e^{-} + {}^{A}_{Z}\{P\} \rightarrow {}^{A}_{(Z-1)}\{D\} + \nu$$



β+

$$^{A}_{Z}\{P\} \rightarrow {}^{A}_{(Z-1)}\{D\} + e^{+} + \nu$$

Neutrino Cross Section

- 1934: Bethe-Peierls calculate the cross section for neutrino interaction $\sigma_{\nu p} \sim 5x10^{-44}$ cm^2 for neutrinos with energies of a few MeV from a reactor.

- For the corresponding electromagnetic process: $\sigma_{\gamma p} \sim 10^{-25}$ cm^2.

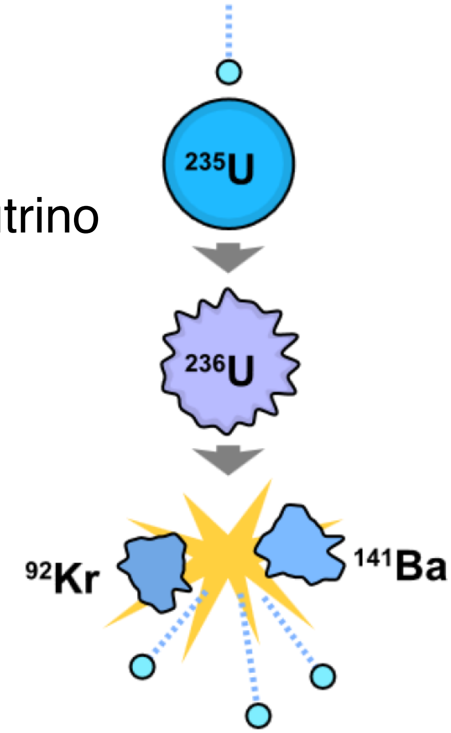
  - Need a light year of steel to stop a neutrino of few MeV.

  - Need 200 Earths to stop a few GeV neutrino.

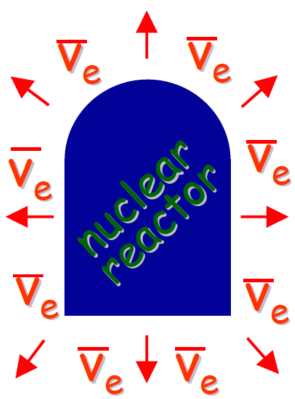
Look at the Neutrino Cross Sections lecture (Gabe Perdue). July 19.

Neutrino from Reactors

Reactor Neutrinos



- This was the first neutrino detection: It was needed an intense neutrino source.
- Reactors: powerful source of antineutrino electrons from beta decays of fission products

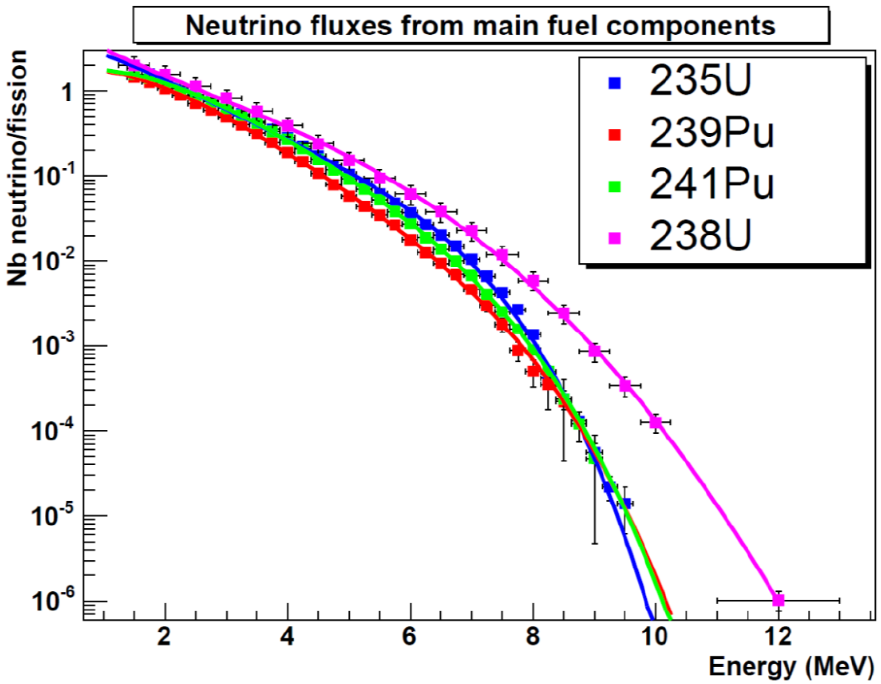


From bound neutron decays:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Reactor Neutrinos

- The spectrum is a sum over beta decays of fragments produced in the thermal neutron induced fission.

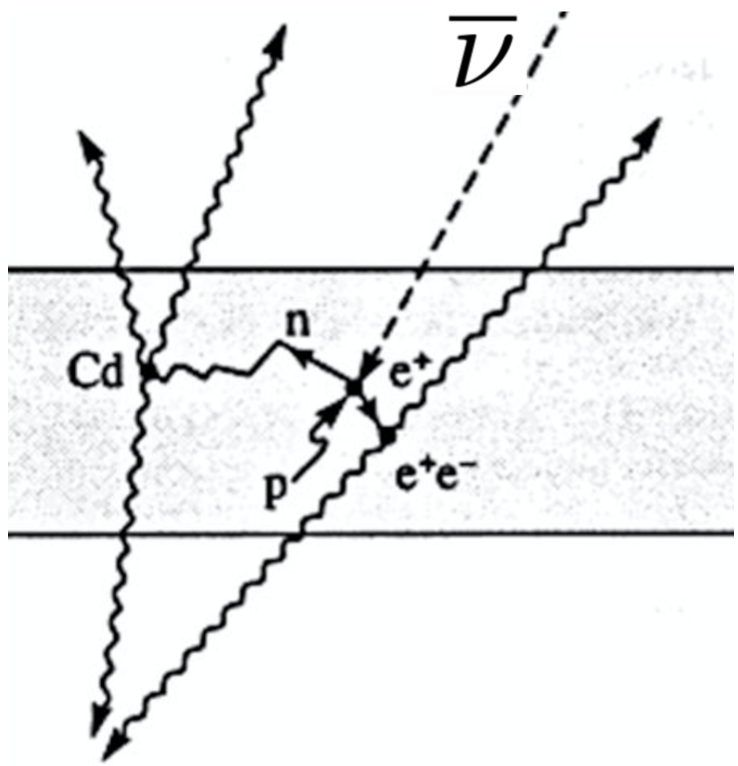


- Large power reactor produces about 6×10^{20} antineutrinos / s.

Project Poltergeist

- A team lead by Clyde L. Cowan and Frederick Reines designed an experiment to detect neutrinos.

- Using neutrinos from nuclear fission interacting with a proton via inverse beta decay.



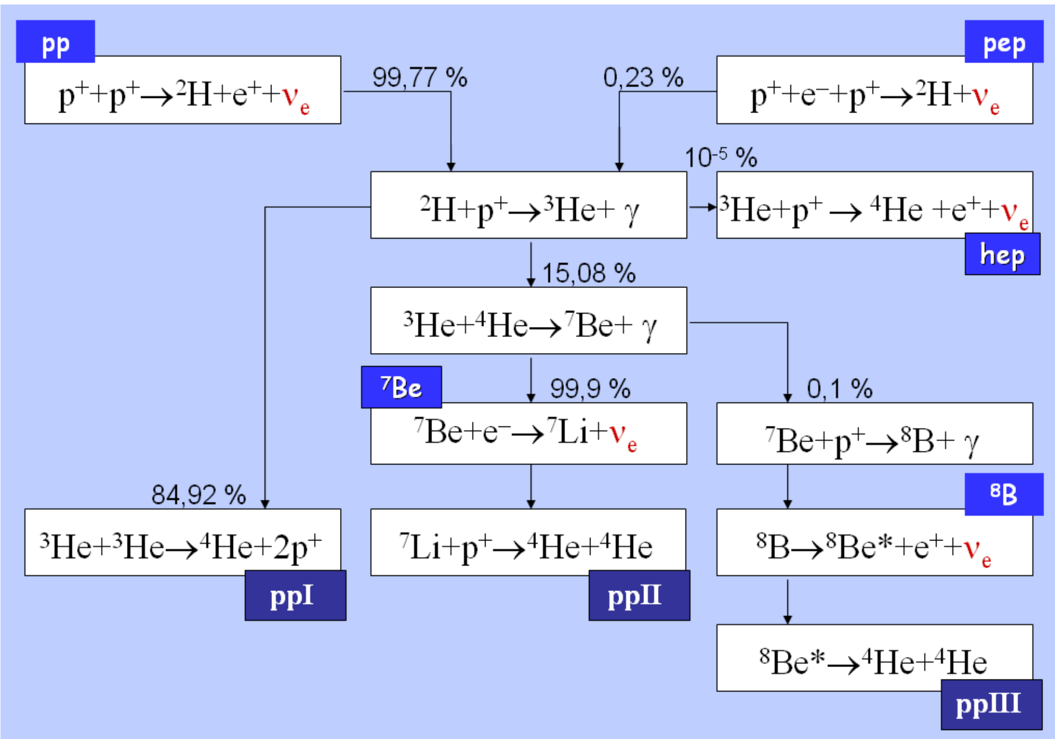
- 1956: Neutrinos are observed at a rate of 0.56 counts per hour.

Neutrino from the Sun, Supernovae and the Atmosphere

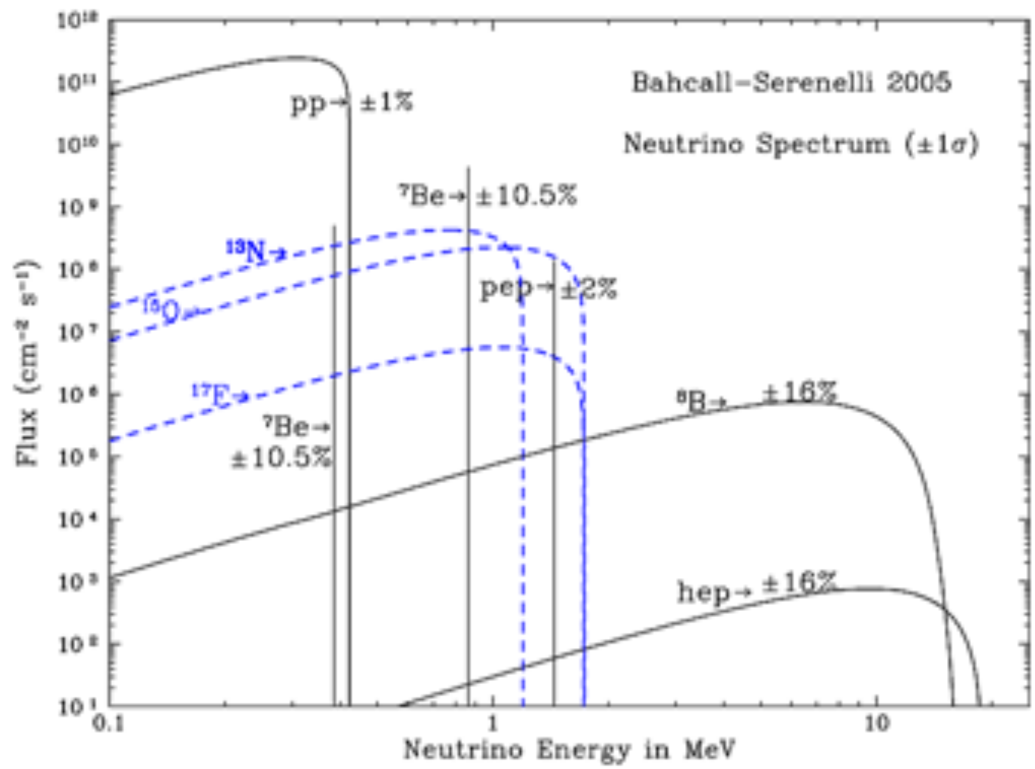
Solar Neutrinos

- The Sun emits light from the nuclear fusions that produces a lot of energy.

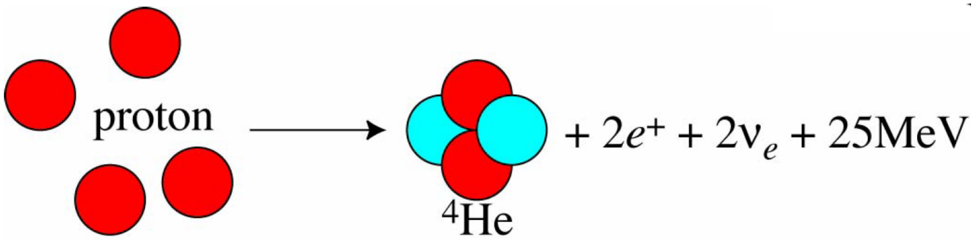
Reaction chain

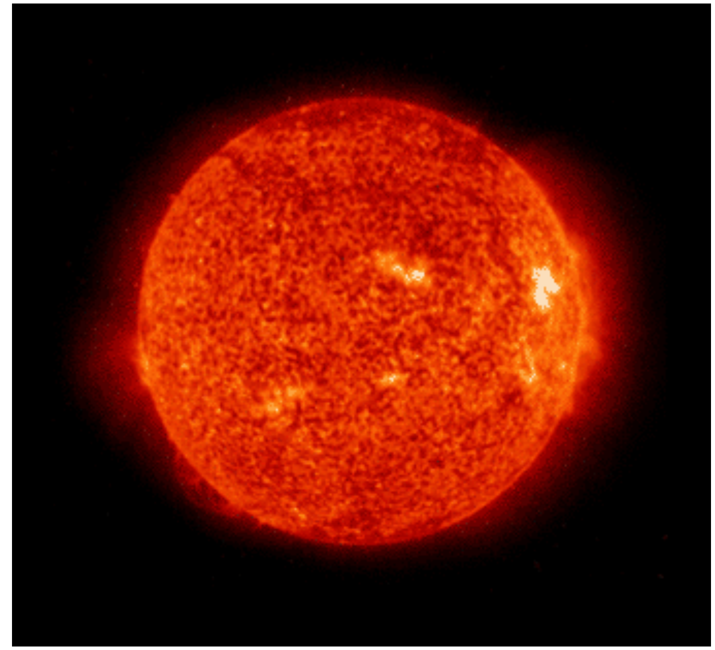


Neutrino Flux



Solar Neutrinos





- Sun luminosity: $L_{Sun} = 3.846 \times 10^{26}$ W.
- AU: distance Sun-Earth.
- $\phi_\nu = (2L_{Sun}/25\ \text{MeV}) / (4\pi\,[1\ \text{AU}]^2) = 7 \times 10^{10}$ / sec/ cm^2

Supernova Neutrinos

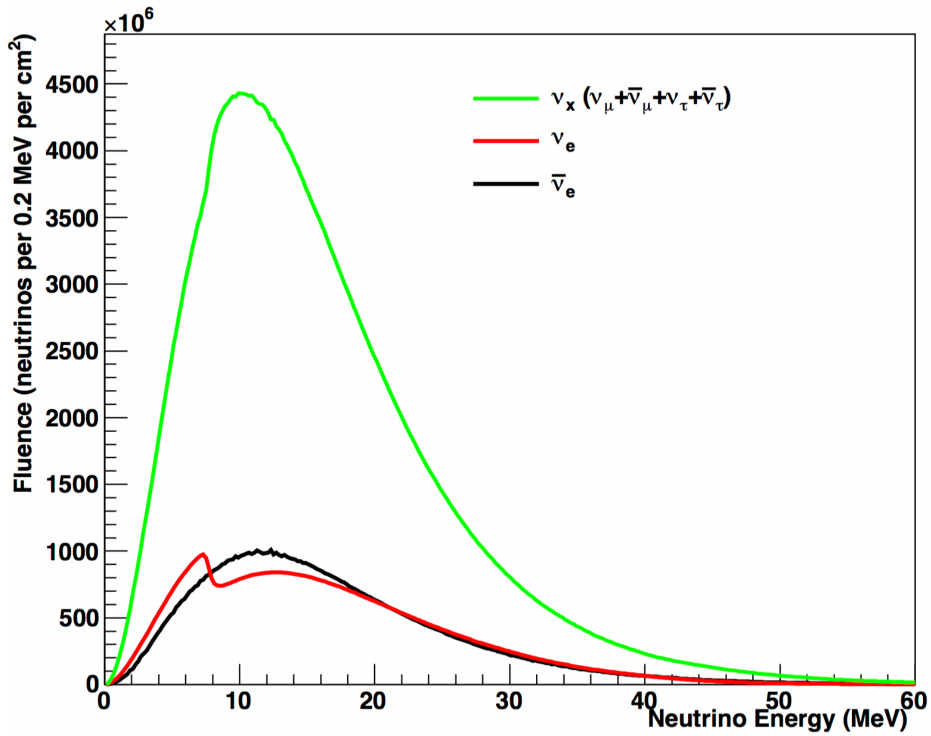
Type II

- Massive stars when gravitational pressure wins against pressure from fission reactions.
  - Iron reaches its maximum binding energy.
  - Inward collapse until the central density reaches the nuclear density.

$$e^- + p \rightarrow \nu_e + n$$

- A bounce causes an explosion.
  - An outward shock wave is produced.
  - Cooling through neutrino emission

$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_e + \bar{\nu}_e$$
$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_\mu + \bar{\nu}_\mu$$
$$e^+ + e^- \rightarrow Z^0 \rightarrow \nu_\tau + \bar{\nu}_\tau$$

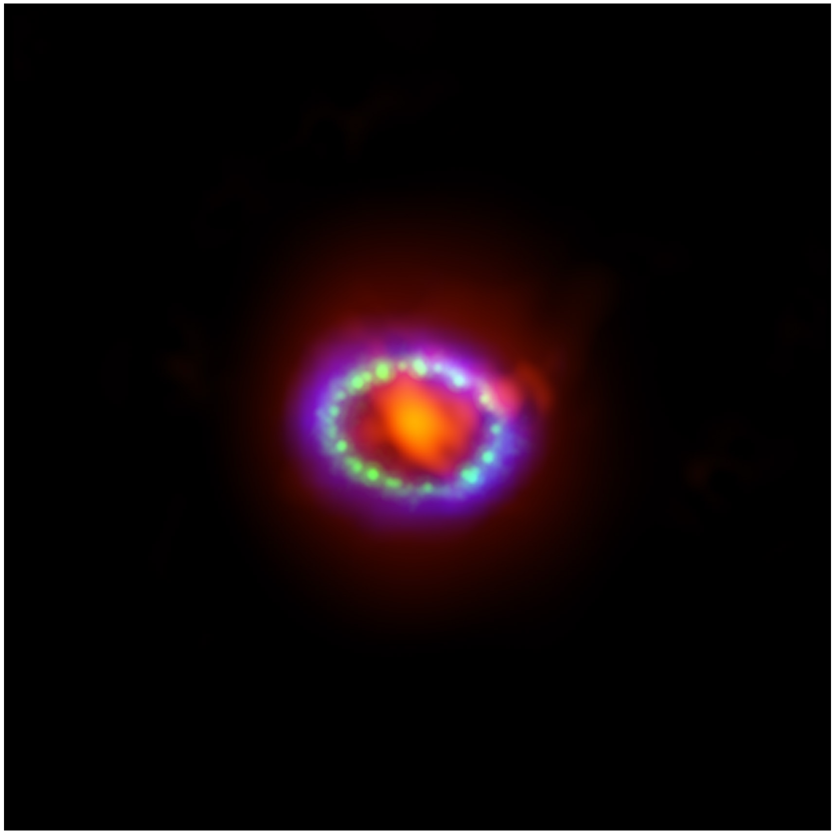


K. Scholberg.10.1146/**annurev-nucl-102711-095006**

~ 99% of the ~10^{53} erg of the Supernova released energy is carried by neutrinos.

SN 1987 A

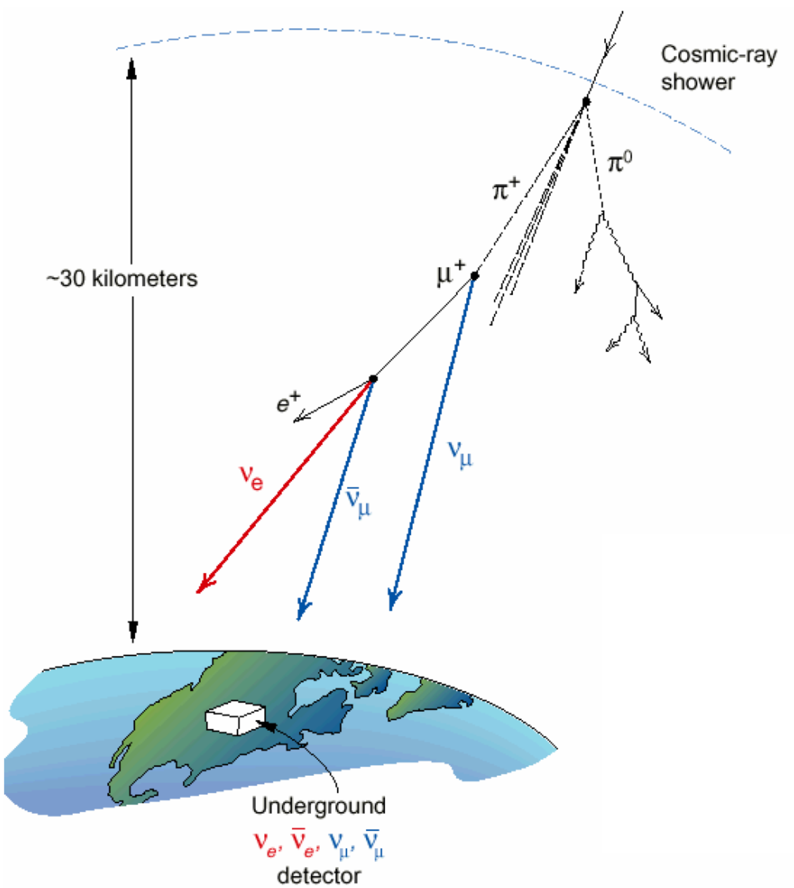
- Observed in the Large Magellanic Cloud, two hours before its visible energy.
- Observed in 3 neutrino detectors: Kamiokande II (12 neutrinos), IMB and Baksan.



- Several detectors currently running are sensitive to a core-collapse supernova neutrino signal in the Milky Way.
- It can provide an early warning and trigger for detectors.
- **NOvA** is part of the SNEWS.

Atmospheric Neutrinos

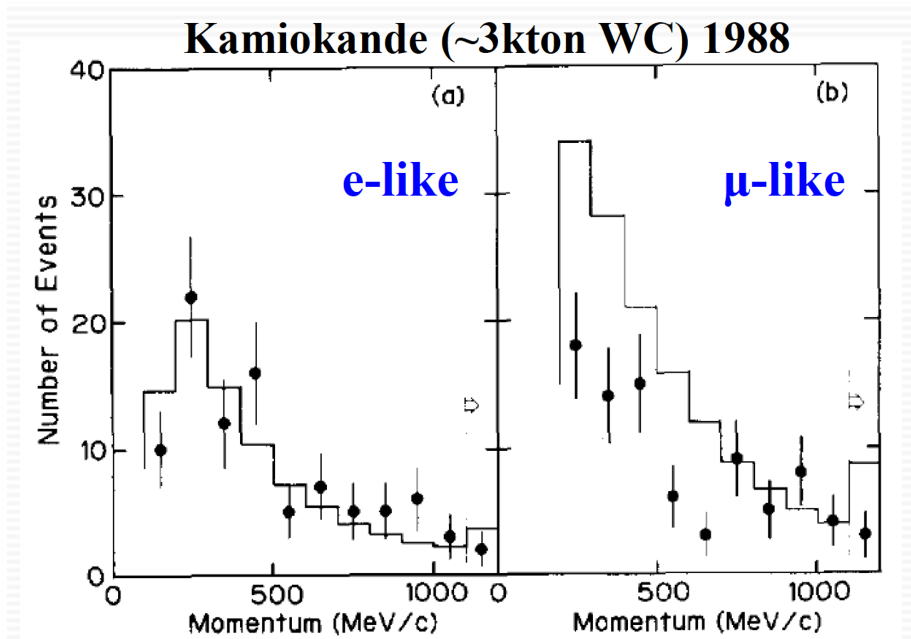
- Cosmic rays (mostly protons) interact in the upper atmosphere creating hadronic showers (mostly pions).



- Roughly 2:1 muon neutrinos to electron neutrinos expected:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Events found in Kamiokande:



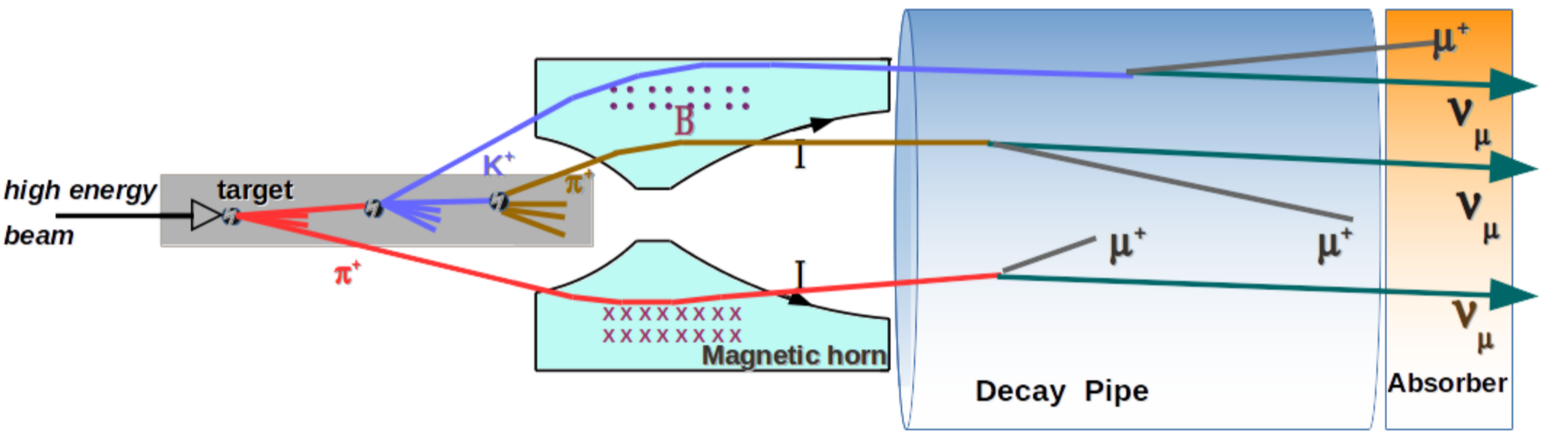
Why?

Neutrino from Accelerators

Conventional Neutrino Beams

How to Make a Conventional Neutrino Beam

- Very similar to neutrinos created in the atmosphere



$\pi^{\pm} \longrightarrow \mu\nu_{\mu}$ (BR~100%)

$K^{\pm} \longrightarrow \mu\nu_{\mu}$ (BR=63.4%)

$K_L \longrightarrow \pi\mu\nu_{\mu}$ (BR=27.2%)

- 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.

Almost a pure muon neutrino beam

By 1960s….

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

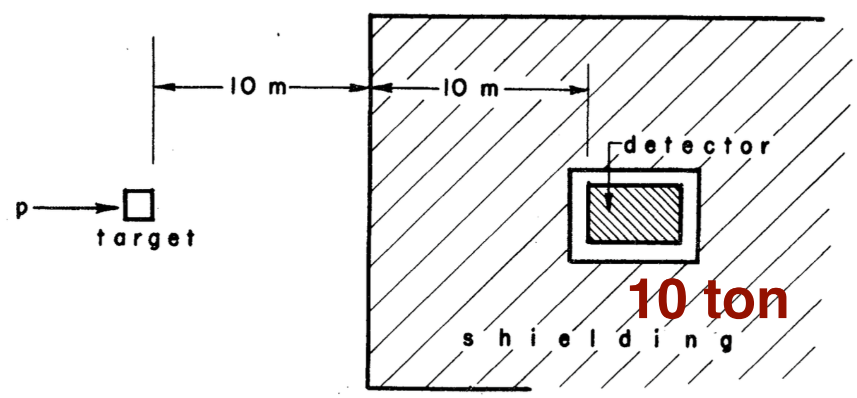
For instance, ***are ν*** *(emitted in β decays)* ***and ν*** *(emitted in π -> μ)* ***identical particles?***

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…

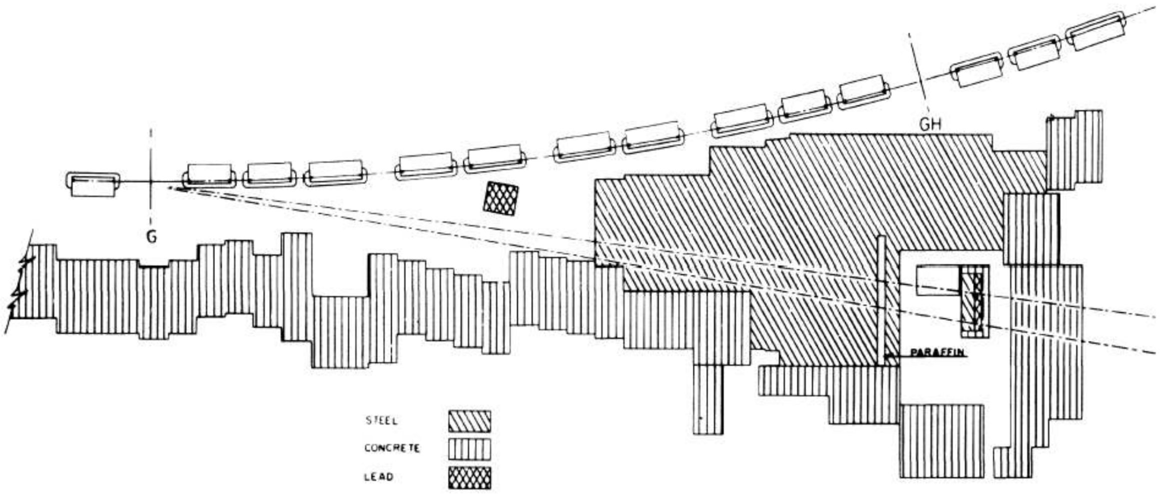
If we have:

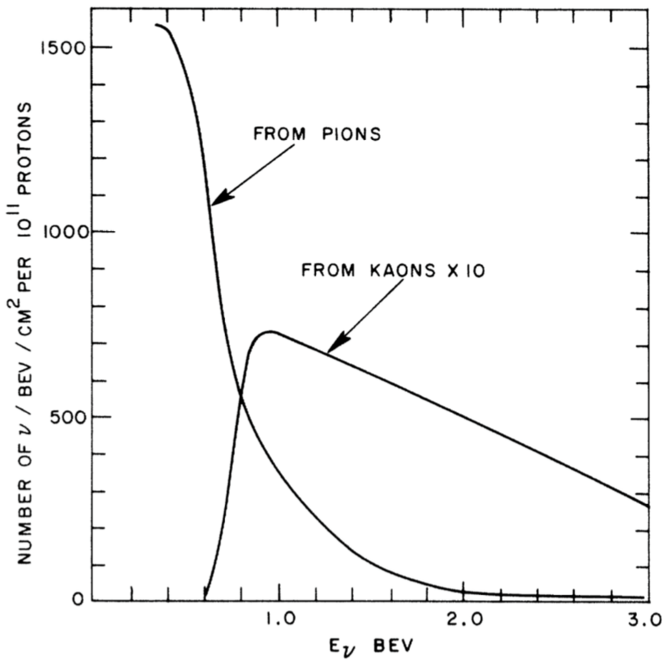
- 5×10^{12} 3 GeV protons/sec, 10 ton detector.
- 10 m decay length, 10 m shielding.
- Detector at 20 m.

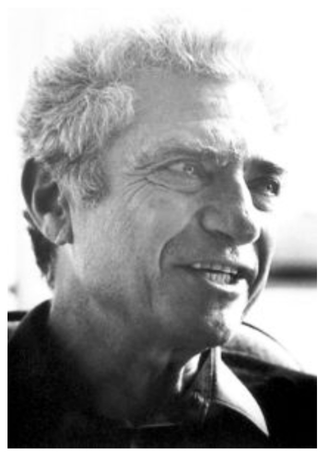


Yes! we get 1 ν per hour.

The First Beam…





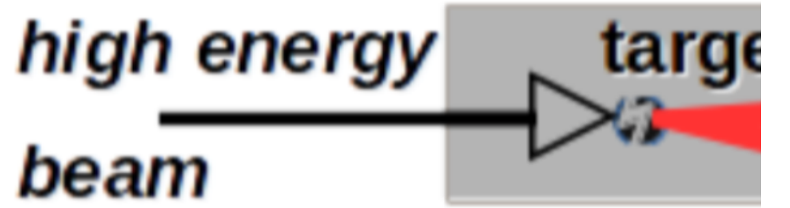


LEDERMAN SCHWARTZ STEINBERGER

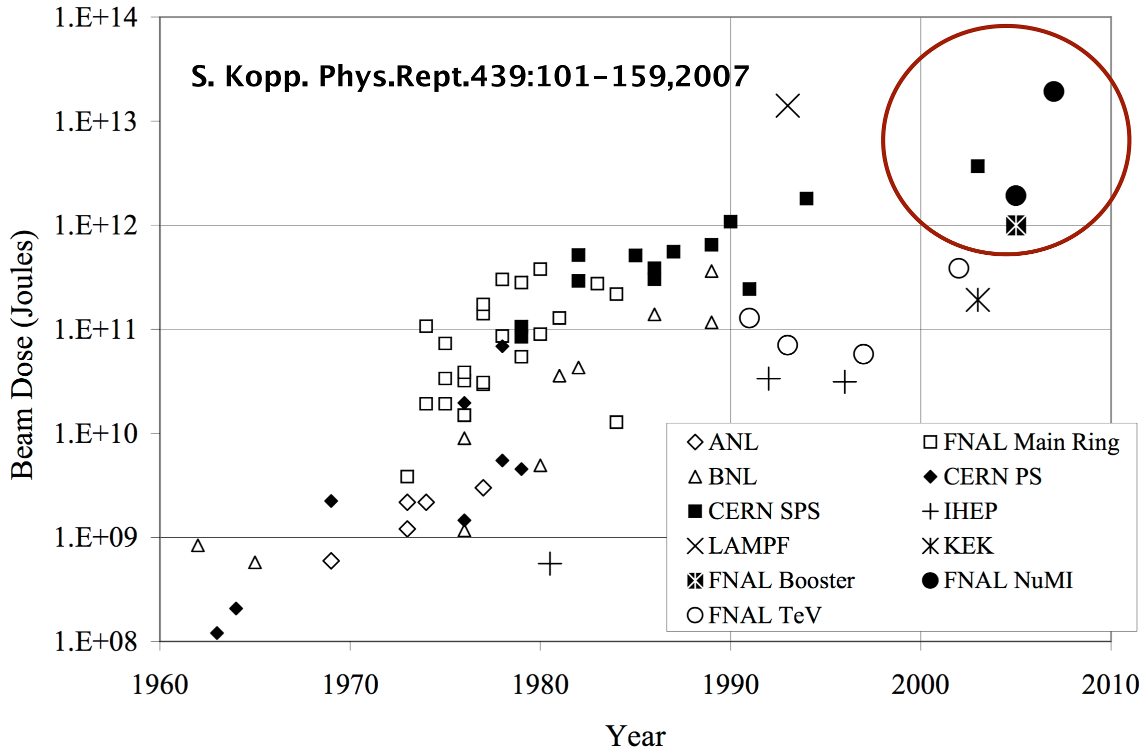
*for the neutrino beam method and the demonstration of the doublet structure of leptons through the **discovery of the muon neutrino** (1982)*

How to Make a Conventional Neutrino Beam

Protons on target:

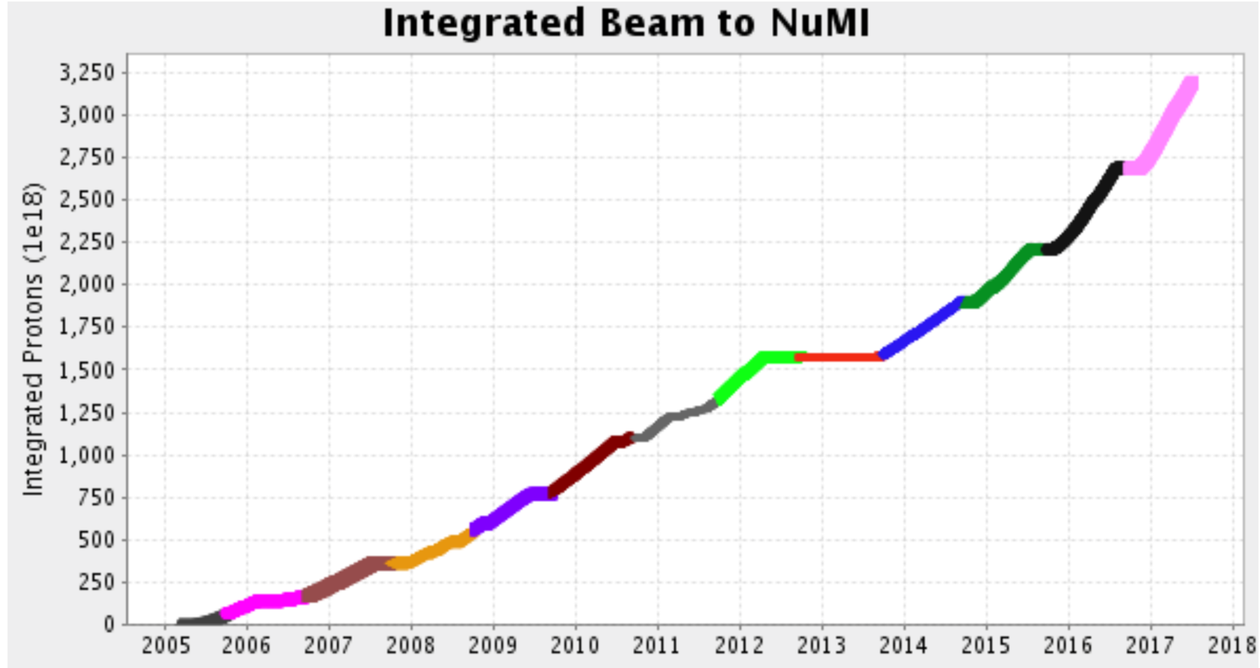


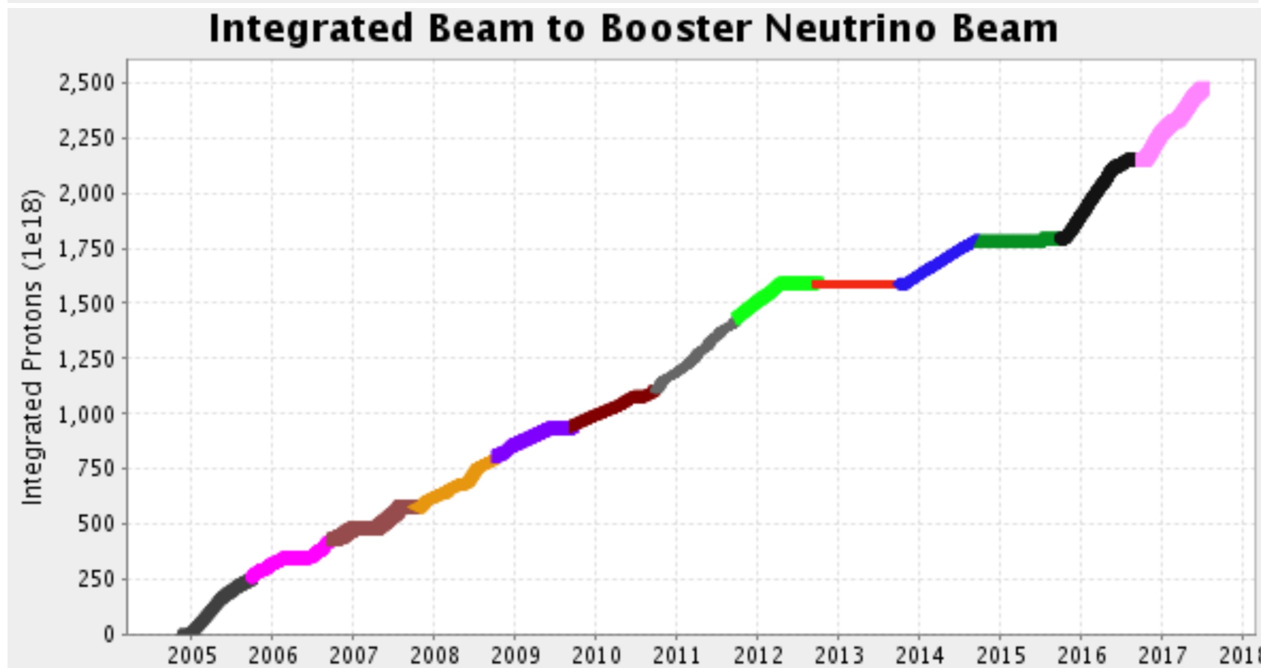
- Higher proton energy -> higher pion energy -> higher neutrino energy
- More particles on target -> more pions -> more neutrinos.



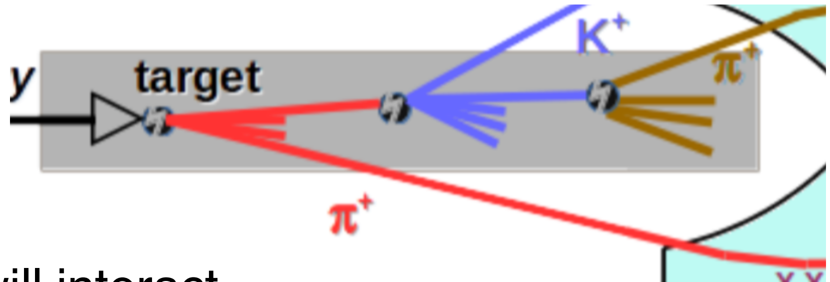
The history continued after 2006.

Protons on target at Fermilab:





How to Make a Conventional Neutrino Beam

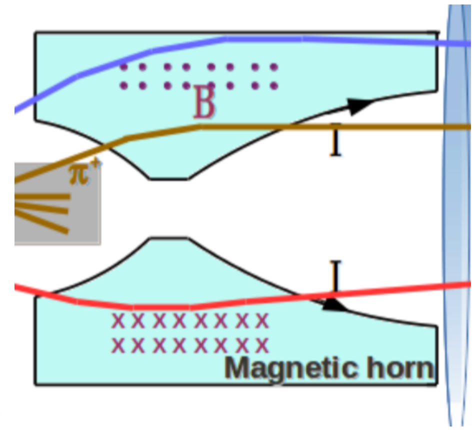


Target:

- Longer the target, higher probability the protons will interact.
- Longer the target, more produced particles will scatter.
- But, more protons interact, hotter the target will get.
- Target N times wider that the +-σ of proton beam size.

	Material	Shape	Length (cm)	Size (mm)
SBN	Be	cylinder	71	10
MINOS	Graphite	ruler	96	6.4 x 15
NOvA	Graphite	ruler	120	7.4 x 63
T2K	Graphite	cylinder	90	12-15

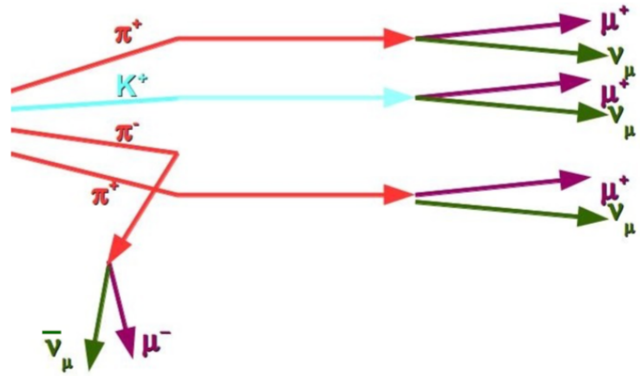
How to Make a Conventional Neutrino Beam



Horns:

Want to focus as many particles as possible and cancel as much background:

- Make π(K) decay parallel to the beam direction.
- Deflect unwanted particles.



- Pions diverge from the target with a typical angle:

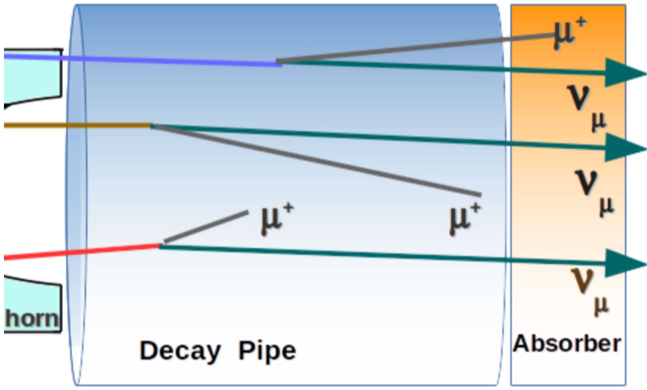
$$\theta_\pi \approx p_T/p_\pi \approx \langle p_T \rangle/p = 280\text{MeV}/p_\pi = 2/\gamma$$

- Neutrinos from pion decay ~ 1/ γ .

Important to correct

- Parabolic shape horn inner conductor makes the horn behaves as a lens (p_T proportional to the distance to the axis), with a focal length proportional to the pion momentum.

How to Make a Conventional Neutrino Beam



Decay pipe:

- Length and wide of the decay pipes depends on what pion energy you want to focus.
- Longer decay regions, more muon decays (more electron neutrinos)
- Evacuated decay regions is better… less beam absorption. More dangerous? Instead using He or air.

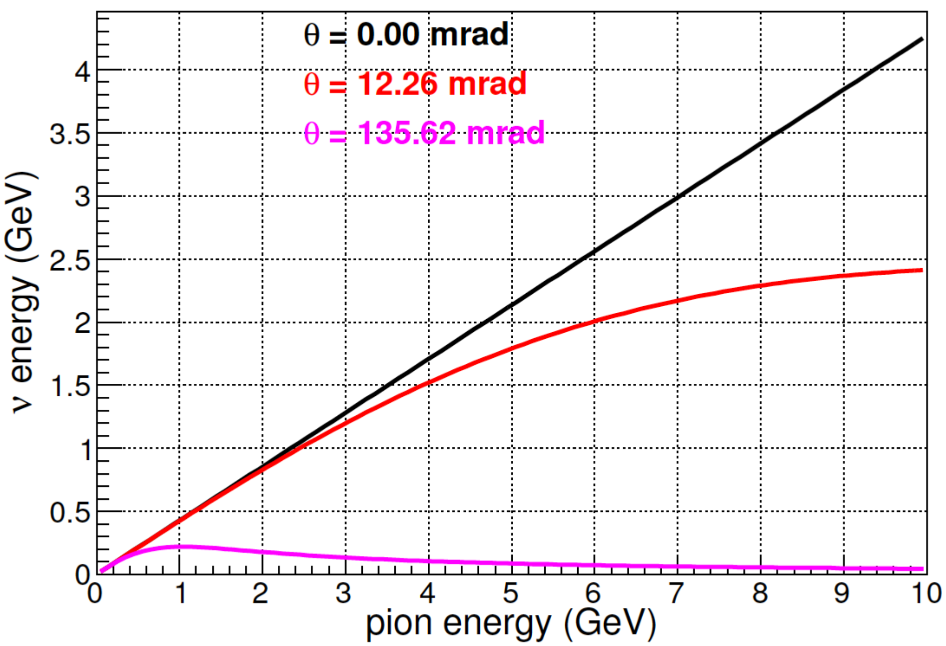
	Length (m)
SBN	50
MINOS / NOvA	675
T2K	130

How to Make a Conventional Neutrino Beam

Neutrino decay:

- Main decay to neutrino mode for neutrino beam:

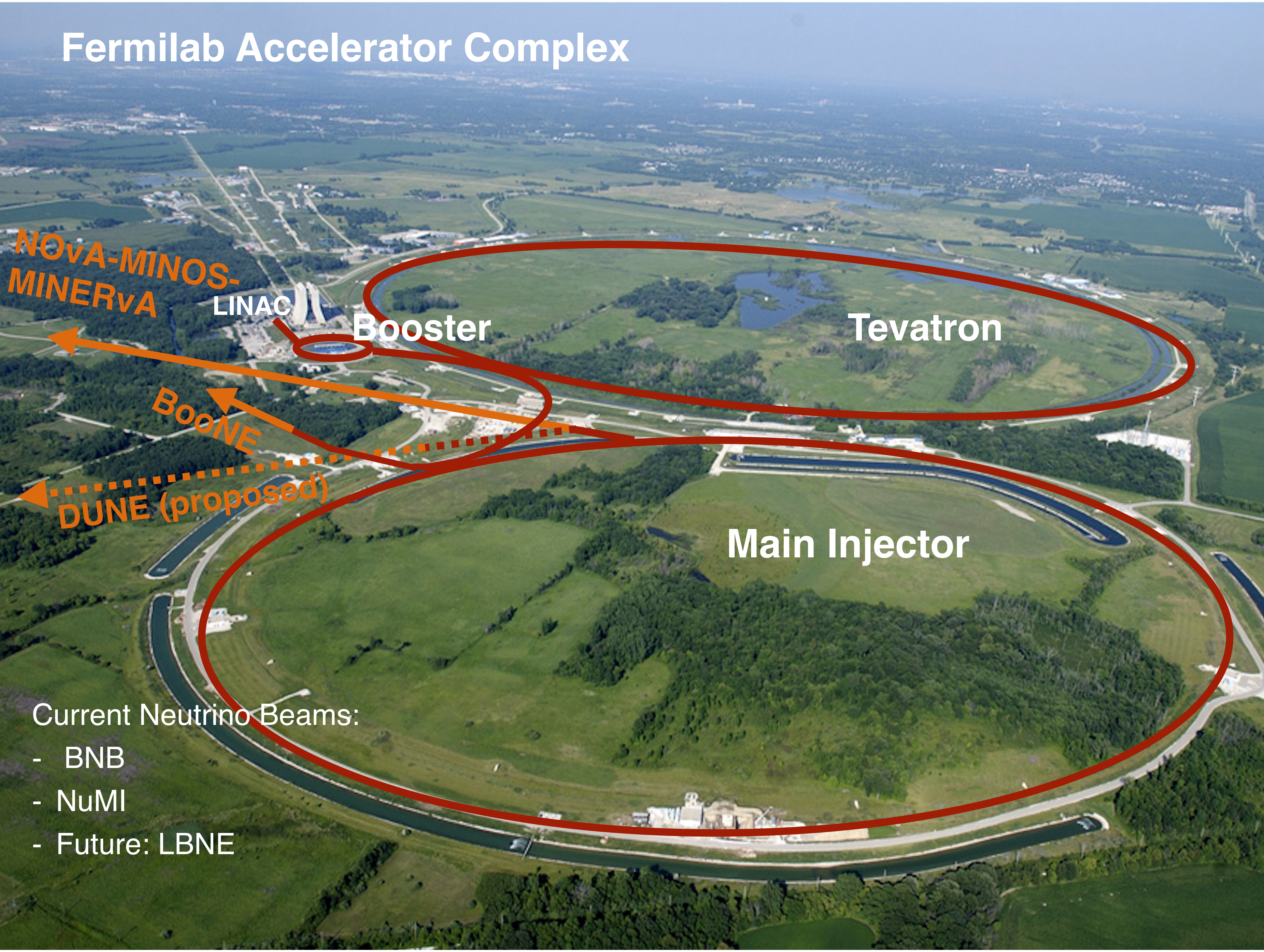
Decay	Chanel	Branching ratio (%)
1	$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	99.9877
2	$\pi^{\pm} \to e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	0.0123
3	$K^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	63.55
4	$K^{\pm} \to \pi^{0} + e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	5.07
5	$K^{\pm} \to \pi^{0} + \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	3.353
6	$K^{0}_{L} \to \pi^{\pm} + e^{\mp} + \nu_{e}$	40.55
7	$K^{0}_{L} \to \pi^{\pm} + \mu^{\mp} + \nu_{\mu}$	27.04
8	$\mu^{\pm} \to e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$	100.0



- From 2 pion body decay:

$$E_{\nu} \approx \frac{(1 - \frac{m_{\mu}^{2}}{M^{2}})E_{\pi(K)}}{1 + \gamma^{2}\tan^{2}\theta_{\nu}}$$

- dP/dΩ ??



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

NuMI

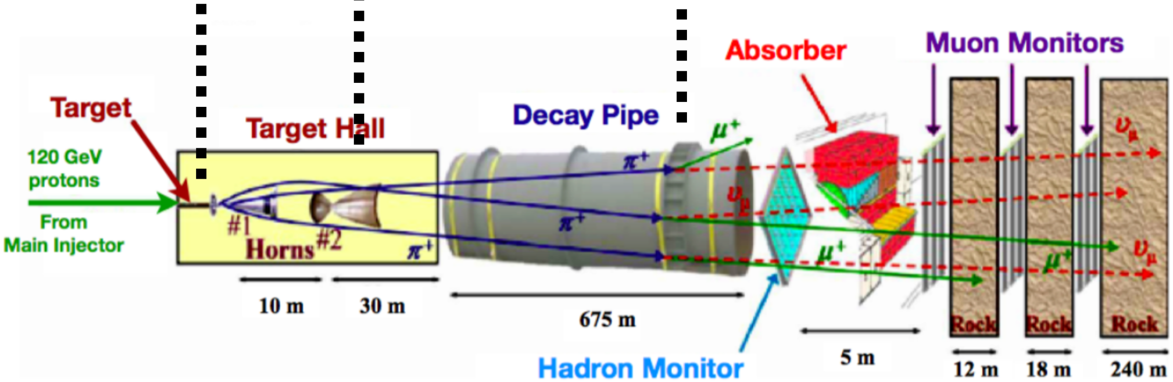
NuMI

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

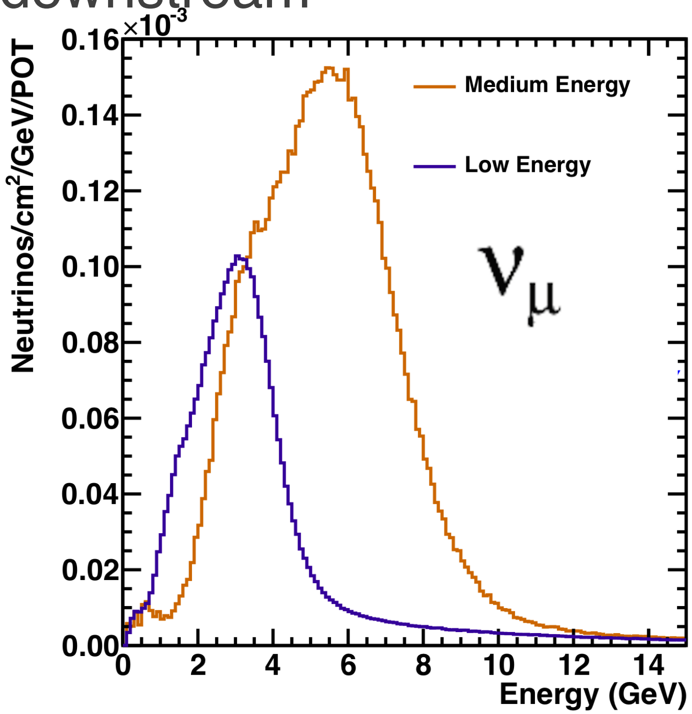
$$\pi^{\pm} \longrightarrow \mu\nu_{\mu}$$

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

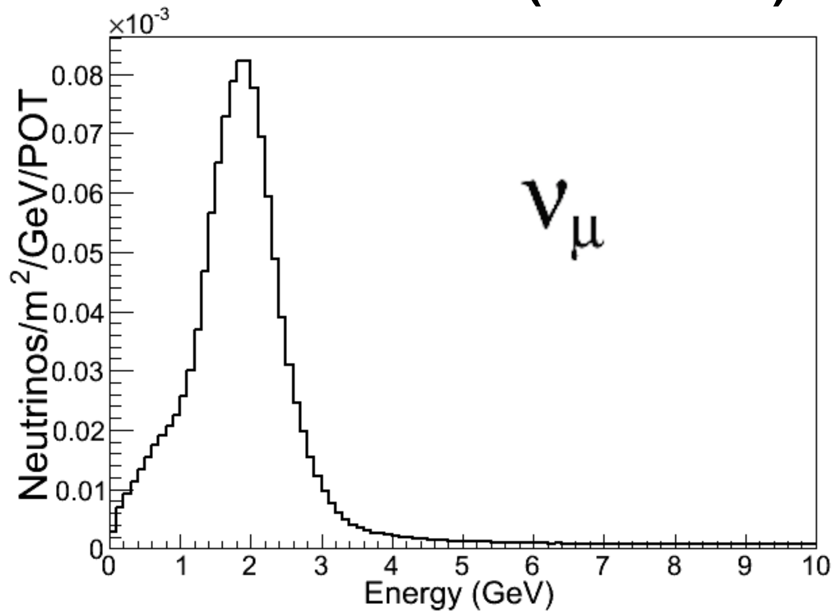
NuMI (Neutrinos at the Main Injector)

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

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



Off-Axis: NOvA (14.6 mrad)



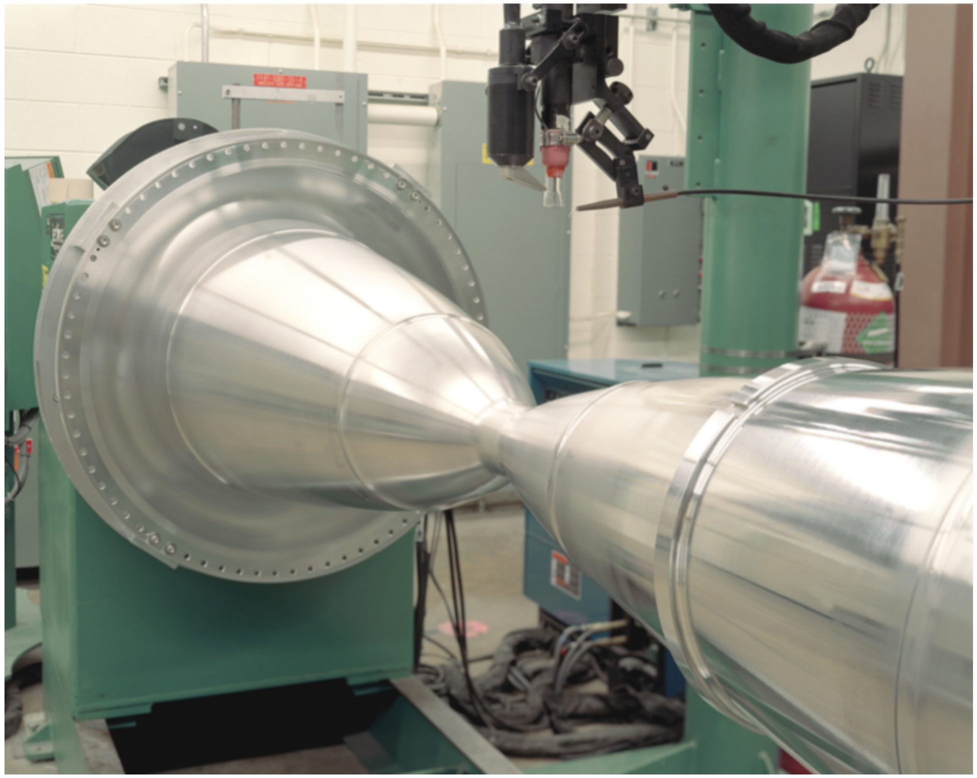
NuMI provides neutrinos for the Fermilab high intensity neutrino studies: oscillation parameters, cross-sections, search for exotic physics, etc.

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

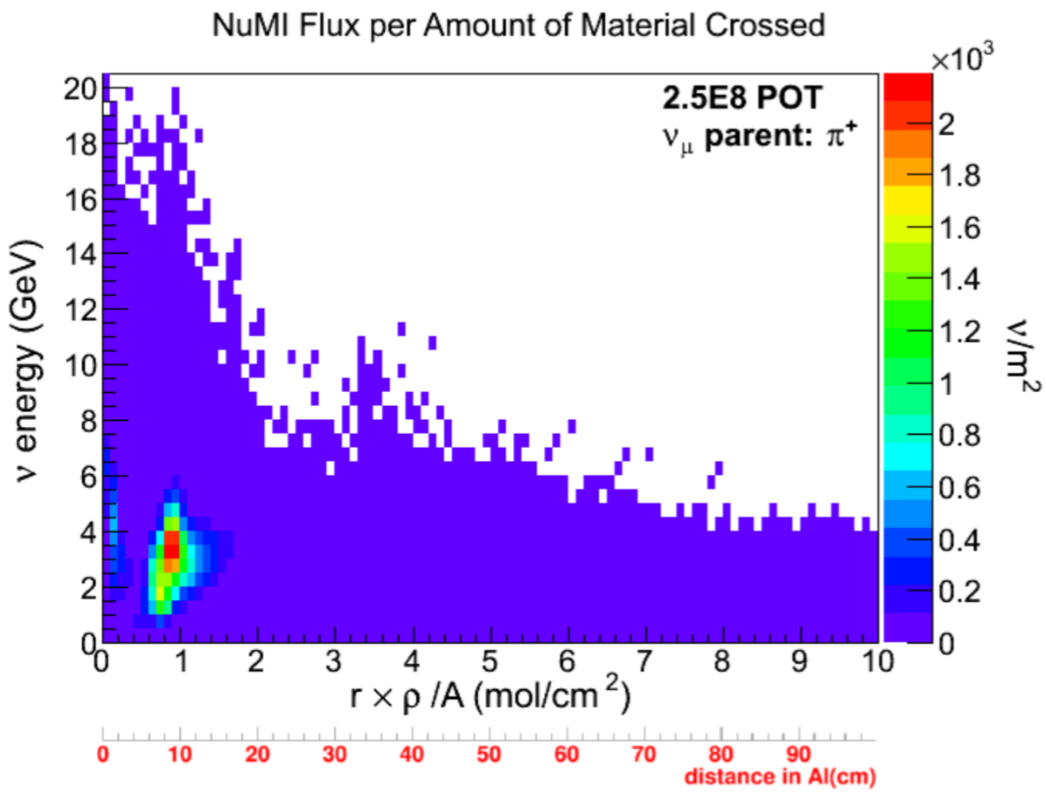


- A ~200 kA current is pulsed through two aluminum horns to create a toroidal magnetic field.
- Inner conductor is 2-4 mm
- Every charged particle traveling by the horns feel a p_T kick.

The Distance Traveled By the Hadron ν Parents

The NuMI Horn 1 Inner Conductor

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

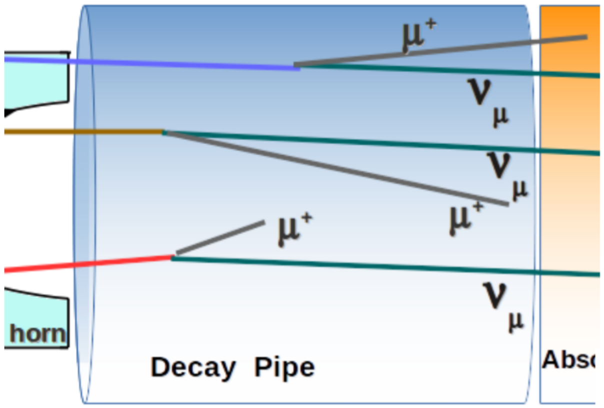


The horn inner conductor is long and thin:

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

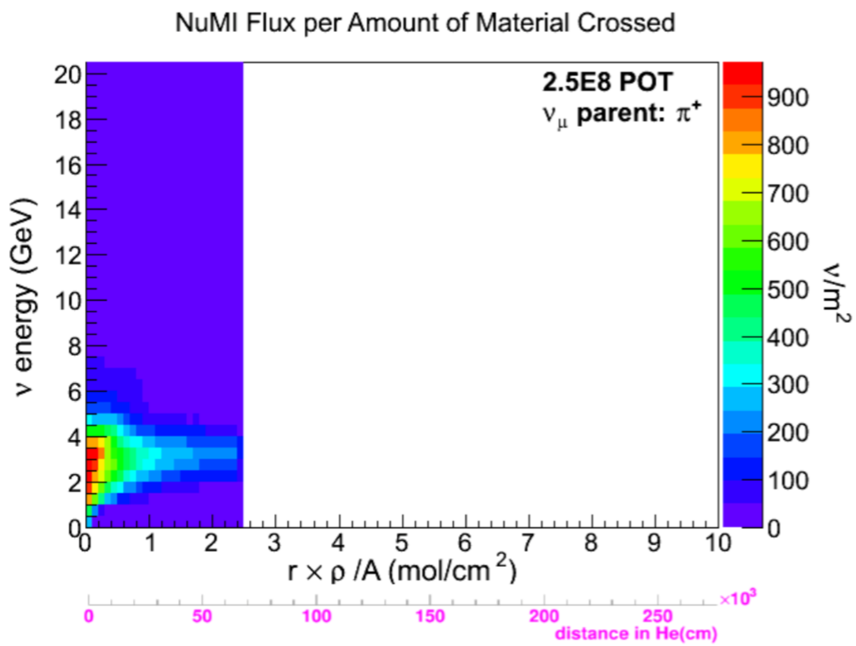
The NuMI Decay Pipe

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.

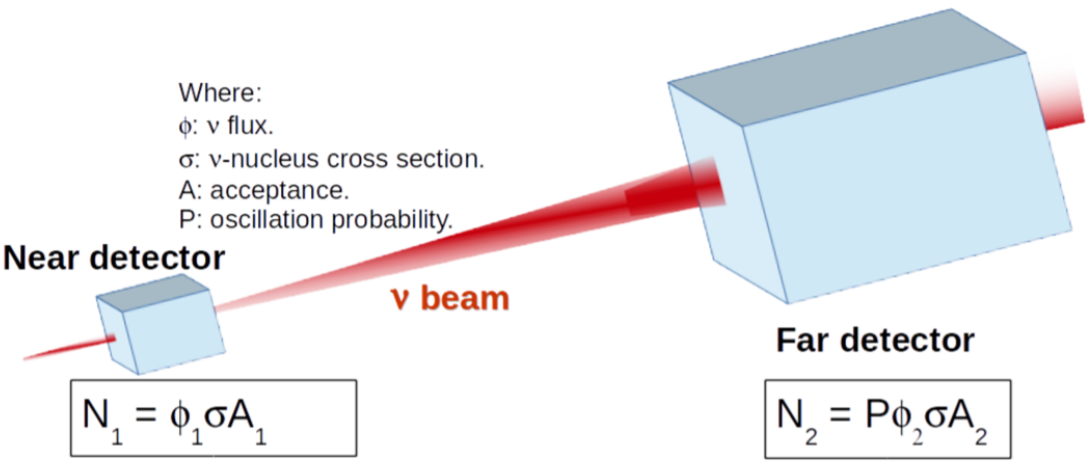
π^+ neutrino parent passing through the decay pipe.



Predicting the Flux: NuMI

Neutrino Oscillation Strategy

Two separated detectors sharing the same ν beam.



The oscillation probability is:

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

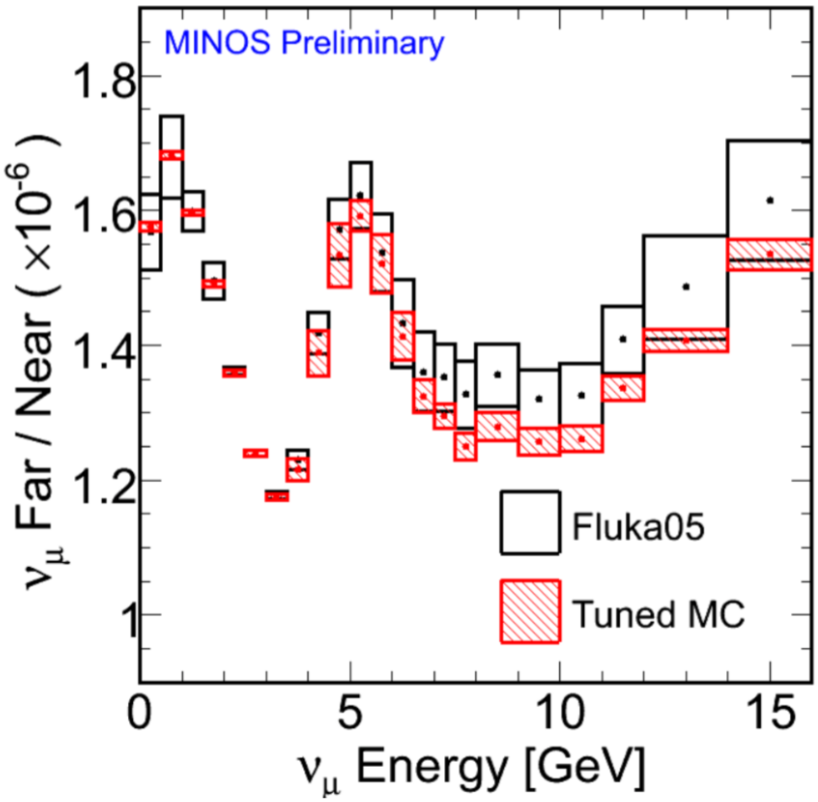
- ϕ just partially cancels.
- If the detectors are different σ does not cancel.

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.



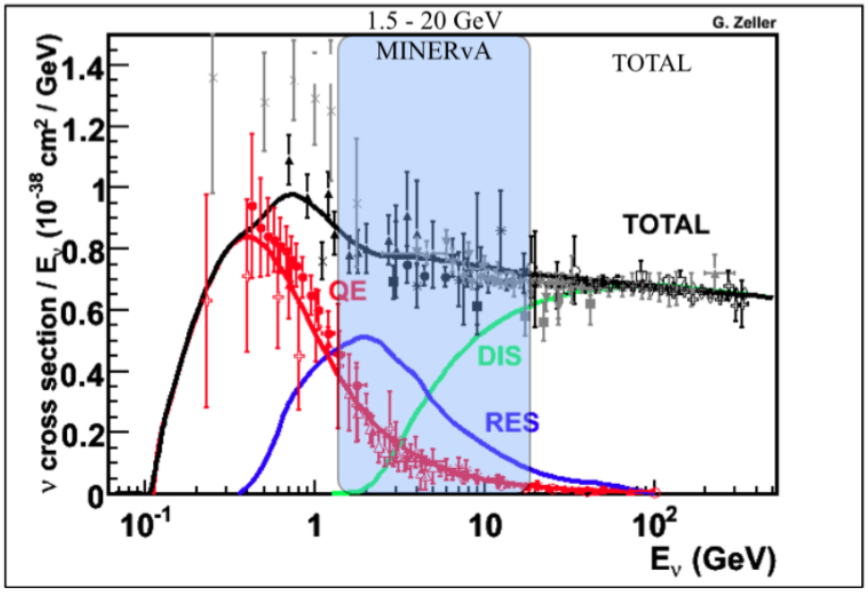
Phys. Rew. D77 (2008) 072002.

Neutrino - Nucleus Cross Sections

- Cross sections between 0.1-20 GeV are not well known, but important in the regime of oscillation experiments.
- Need to understand the effects of the nucleus.

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

Data:



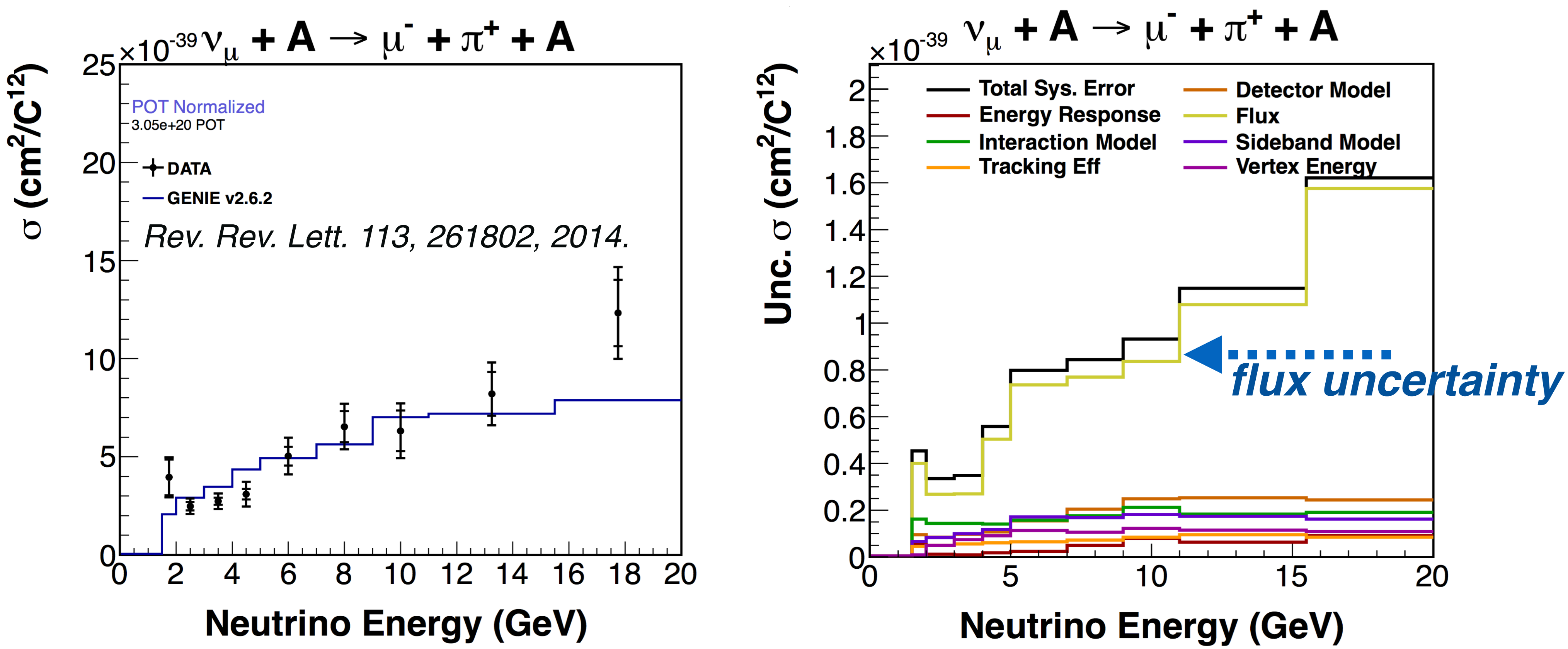
Rev. Mod. Phys. 84, 1307-1341, 2012

Flux Uncertainty

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

- Example: MINERvA coherent charged pion production

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



Why is it so Hard to Determine the Flux?

- Two Challenges:

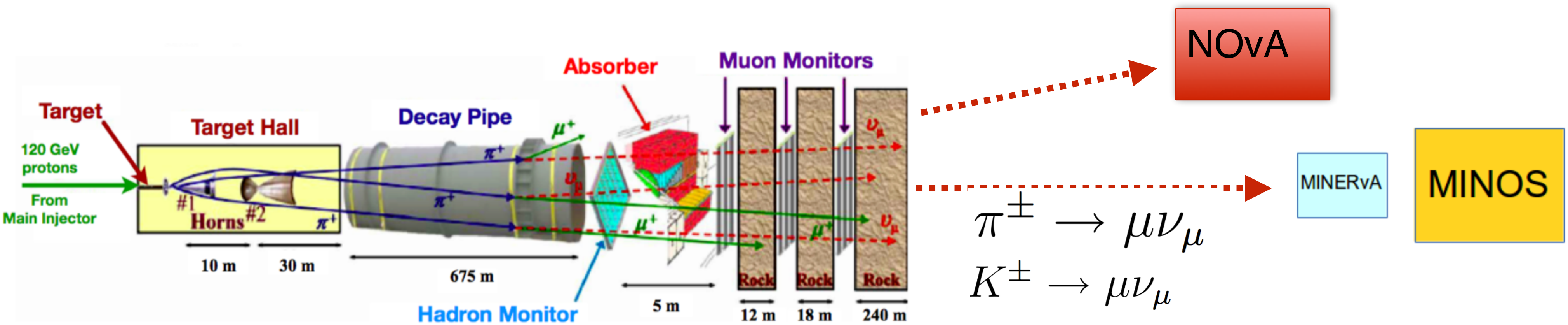
  1. Beam focusing uncertainties (every mm matters): target longitudinal position, alignment, materials, etc.

  → **Optimized to have small uncertainties around the peak.**

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

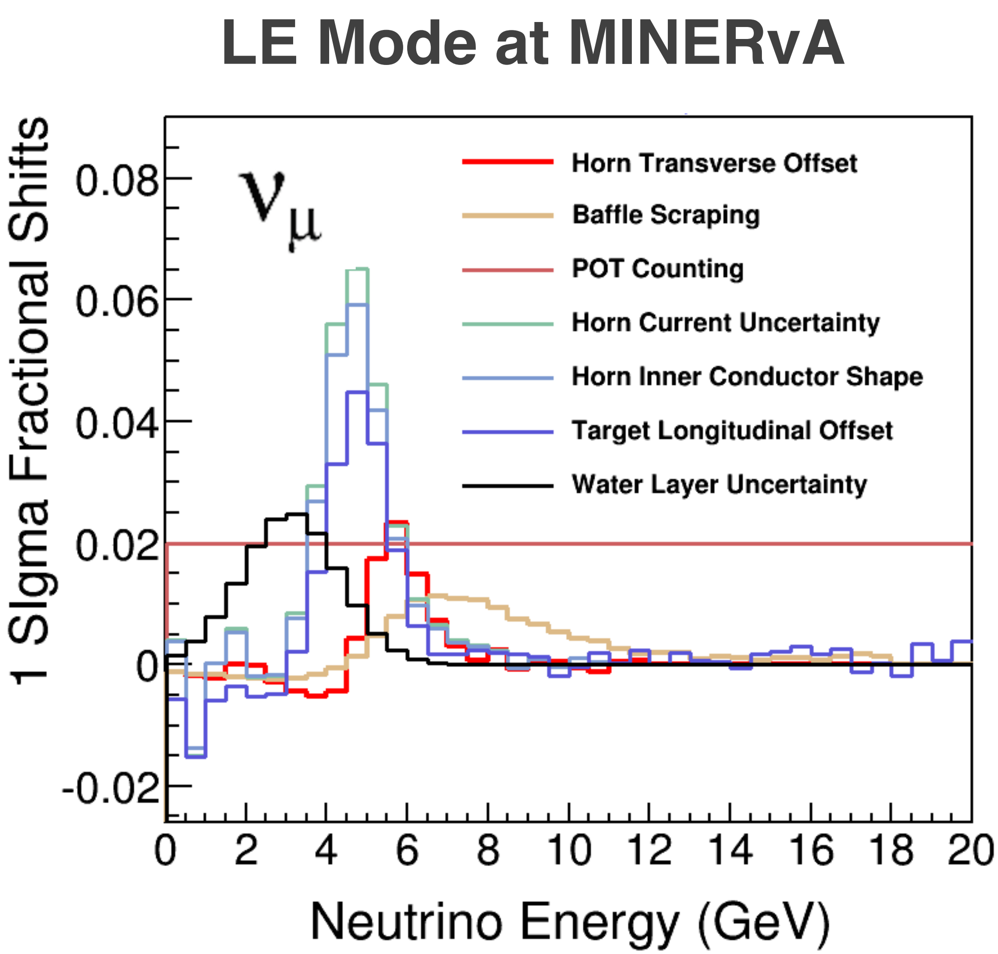
  → **To have a good a priori flux prediction we need to constrain the hadron production data.**

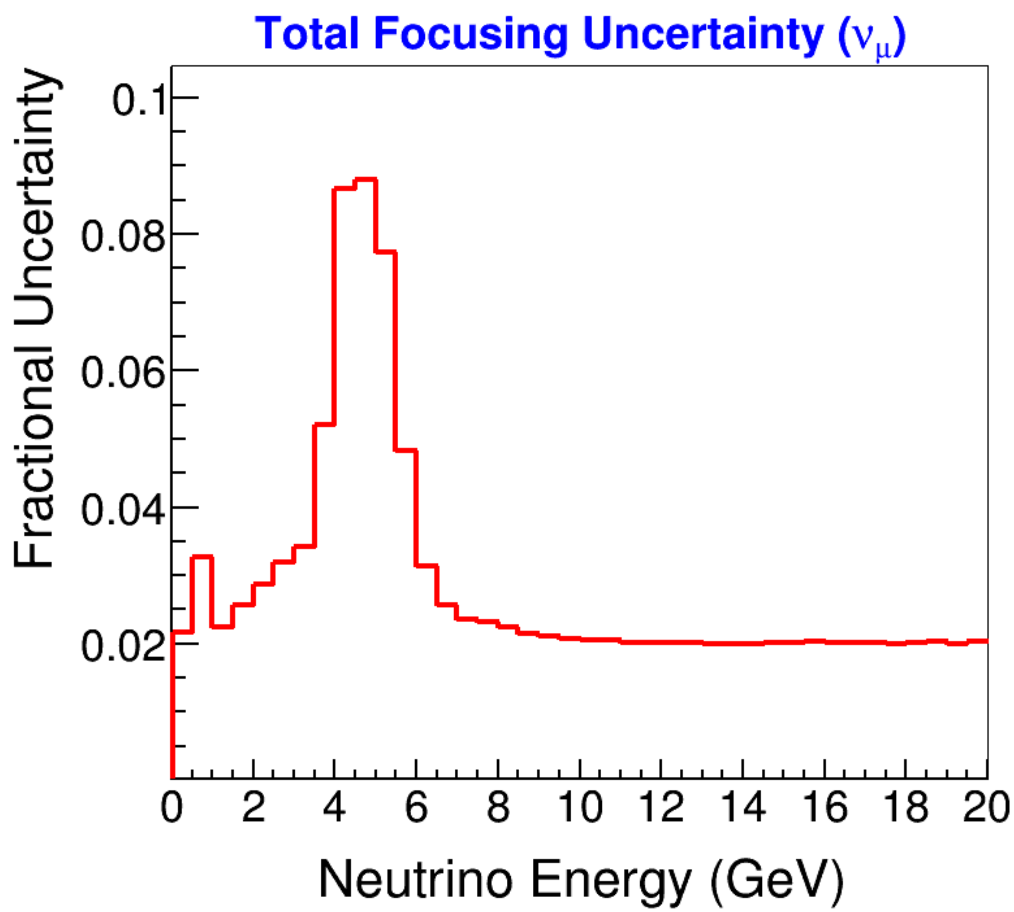
In this talk I will be focused ν_μ signal in the LE mode at MINERvA.



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

Focusing Uncertainties





Hadronic Interactions… we need to use a model

Hadronic processes are traditionally classifed in:

- **Hard processes**. When $Q^2 \to \infty$ ($\geqslant 1GeV^2$), then $\alpha \to 0$ and pQCD can be used.

- **Soft processes**. Low Q^2 ($\sim$ few hunderd MeV)^2, then α too large to apply pQCD.
  - Phenomenological models have been developed.
  - Free parameters determined from the measured data.

The strong force running coupling constant:

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f)ln(\frac{Q^2}{\Lambda^2})}$$

(One loop approximation. $\Lambda \sim 0.2GeV$. n_f: number of quarks flavors.)

The hadronic interactions in the target are non - perturbative QCD.

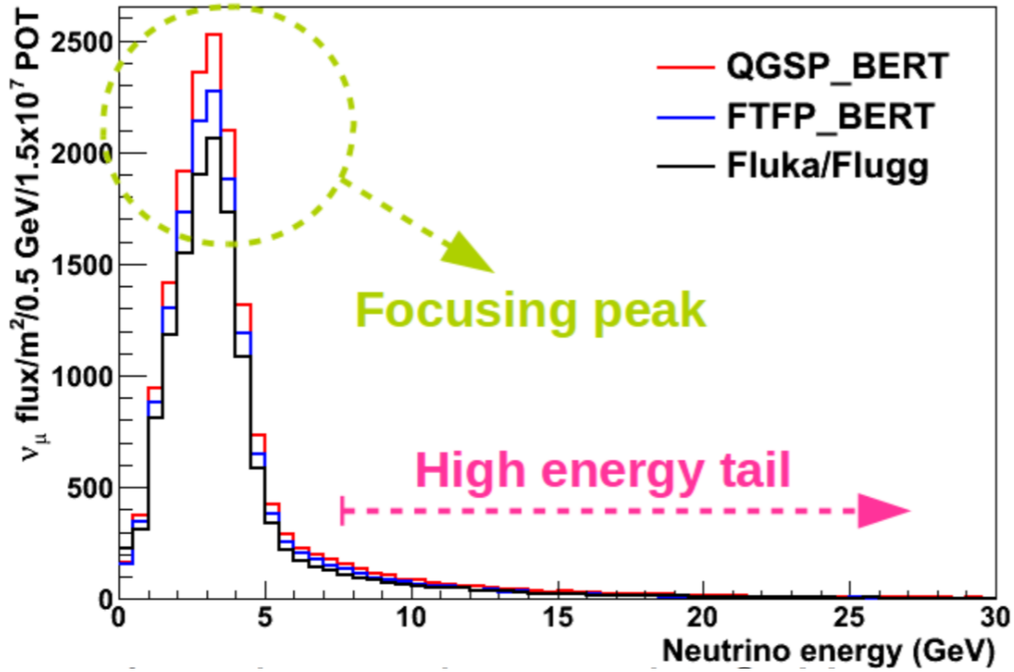
Understanding the Flux

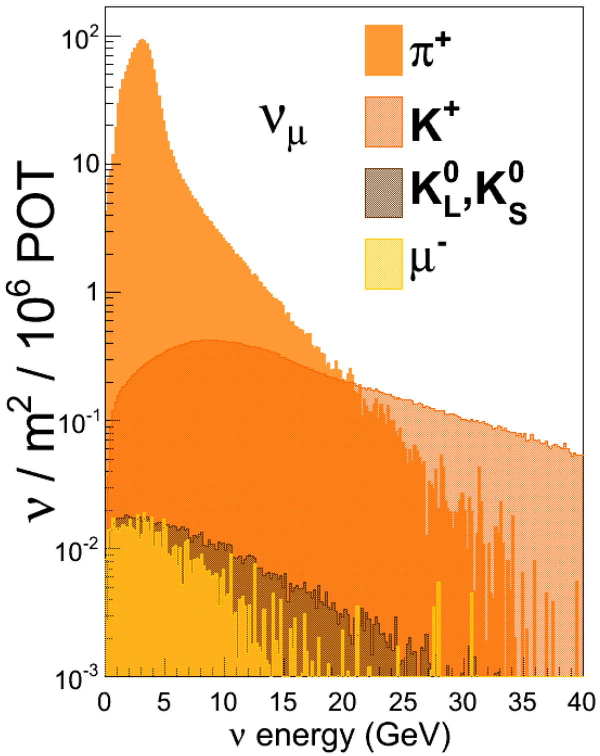
Big discrepancies between flux predictions from hadronic models

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.

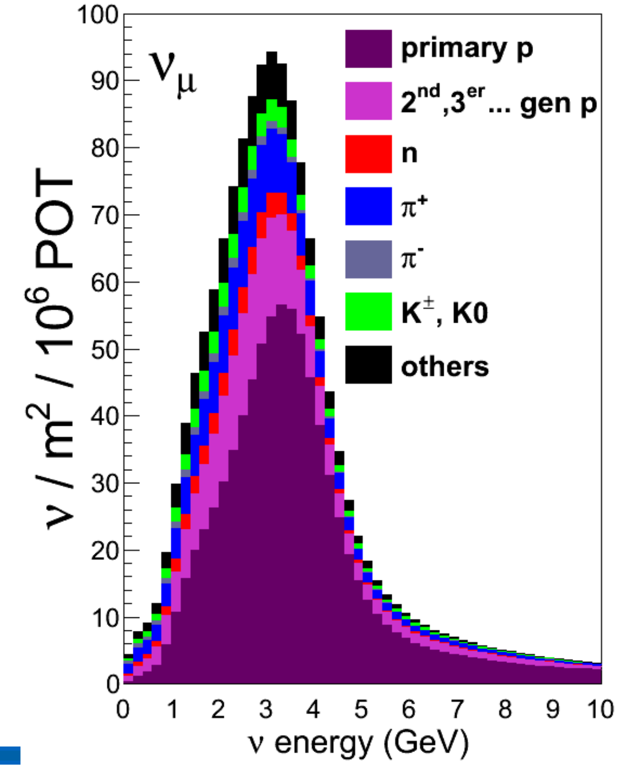




Neutrino ancestry

parents ← → **grandparents**

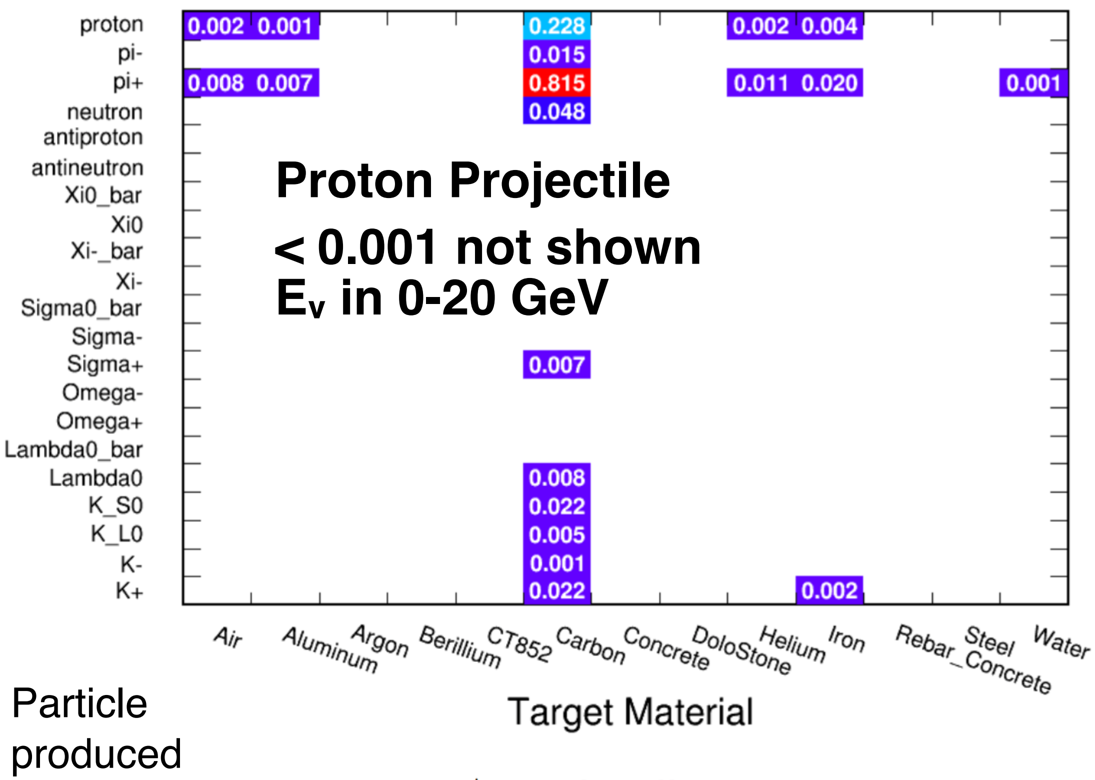
LE Mode at MINERvA



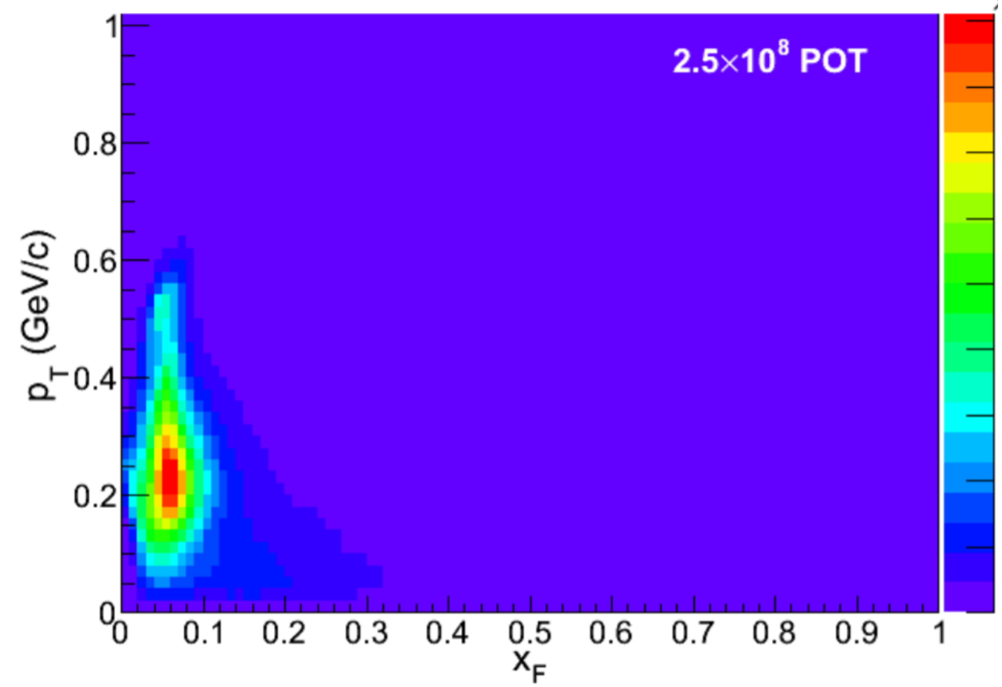
Understanding the Flux

LE Mode at MINERvA ν_μ

<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

HP Uncertainties

There are two sources of the potential HP mismodeling:

- Probability that an interaction happened
  - The amount of material: $rN_A\rho/A$.
  - The σ_{Data} and σ_{MC} disagreement .

Survival probability

$$P(r) = e^{-rN_A\rho\sigma}$$

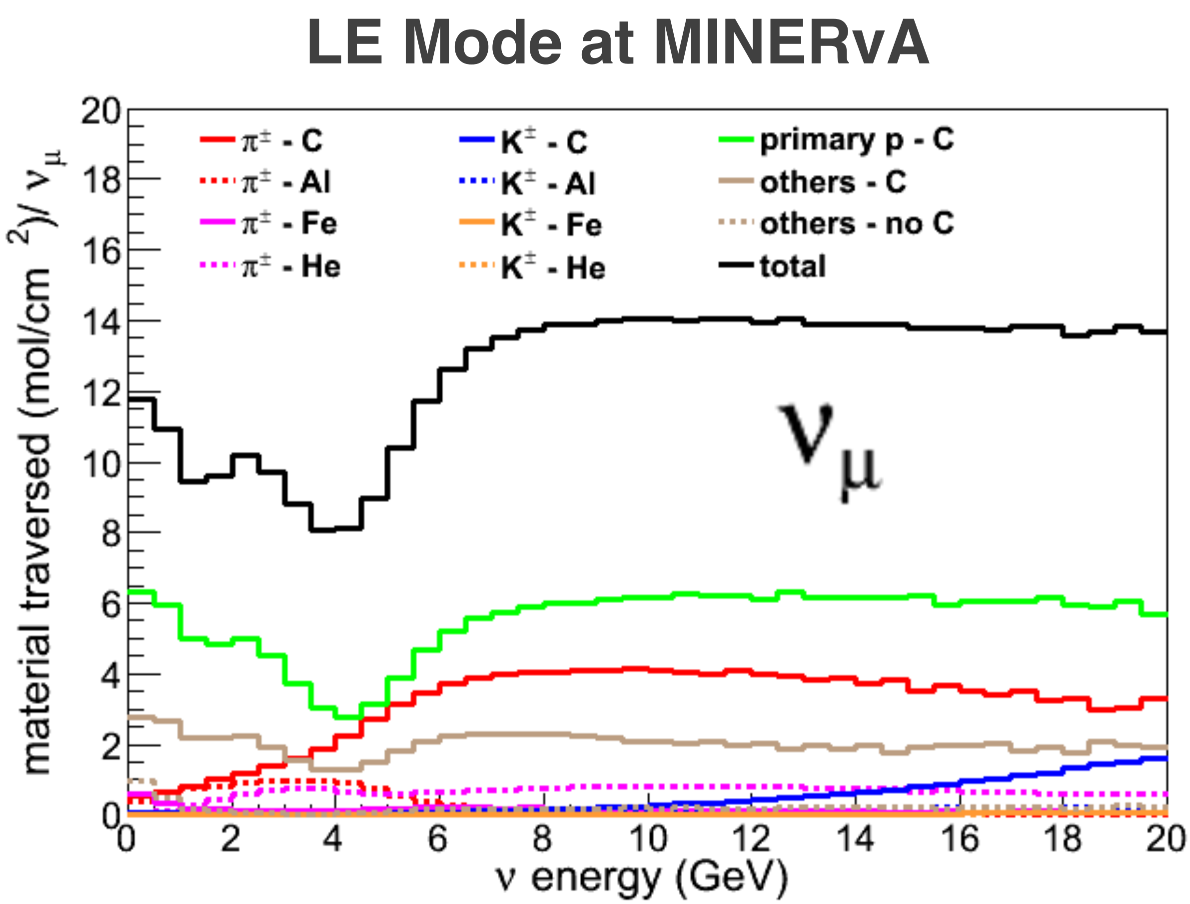
- Given an interactions, having a produced particles in the right kinematic values:

$$f = Ed^3\sigma/dp^3$$

The strategy to handle the HP systematics is to correct the model with external data.

Average amount of material traverse per neutrino

- Muon neutrino parent:



References:

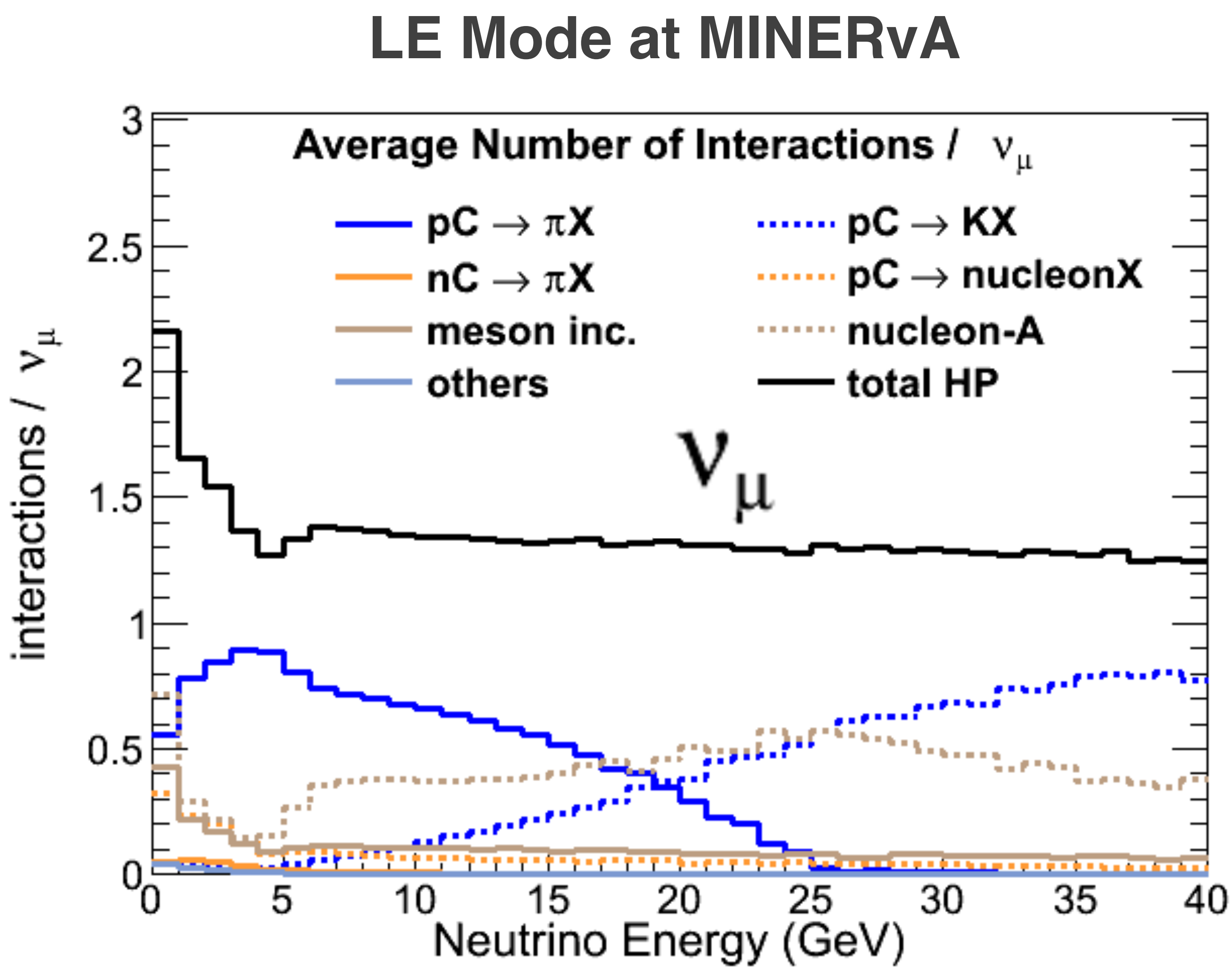
- ***C: 6 mol/cm² ≈ 40 cm***
- ***Al: 1 mol/cm² ≈ 10 cm***
- ***He: 1 mol/cm² ≈ 500 m***

Survival probability: $P(r) = e^{-rN_A\rho\sigma}$

Average Number of Interactions per neutrino

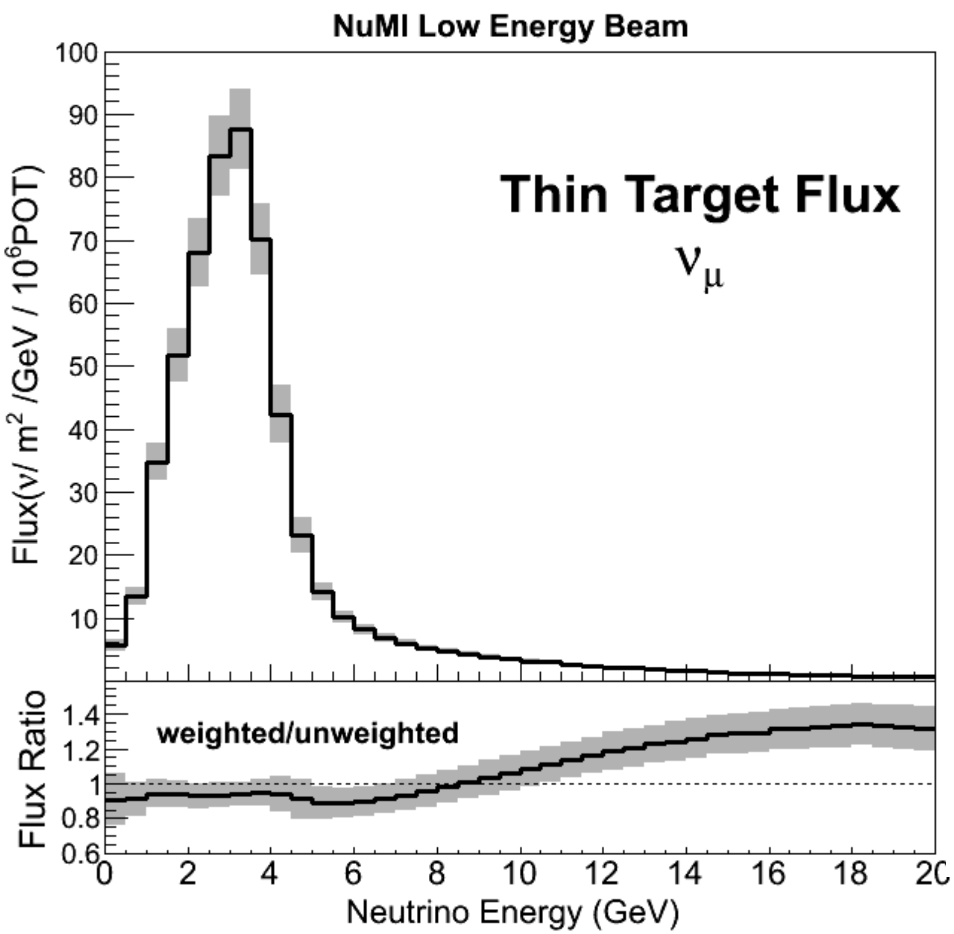
- Differential cross-section:

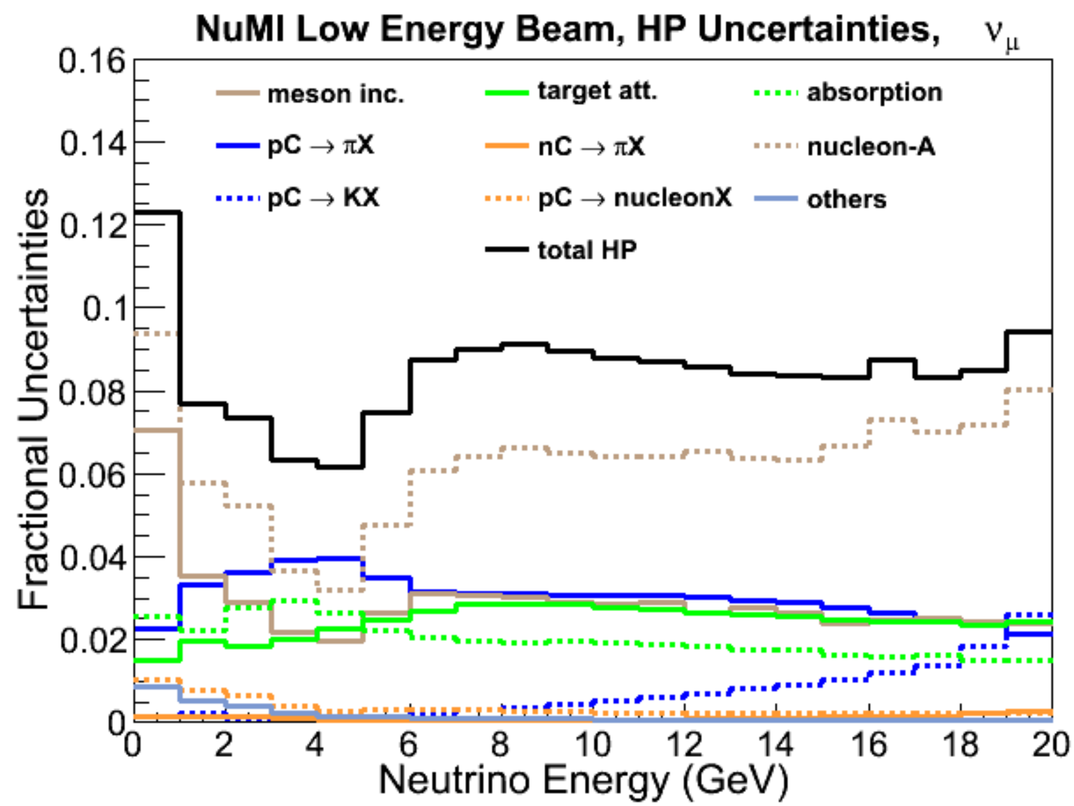
$$f = Ed^3\sigma / dp^3$$



Current knowledge of the NuMI Beam HP Systematics

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





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Conclusions

- Since the discovery of neutrinos, the determination of their parameters has been an area of intense area of study.

- The study of the neutrinos from natural sources has been an interplay between understanding the neutrino behavior and modeling the nature.

- Neutrinos from artificial sources provide a controlled neutrino beam. After some decades, they can allow to enter to a precision era.

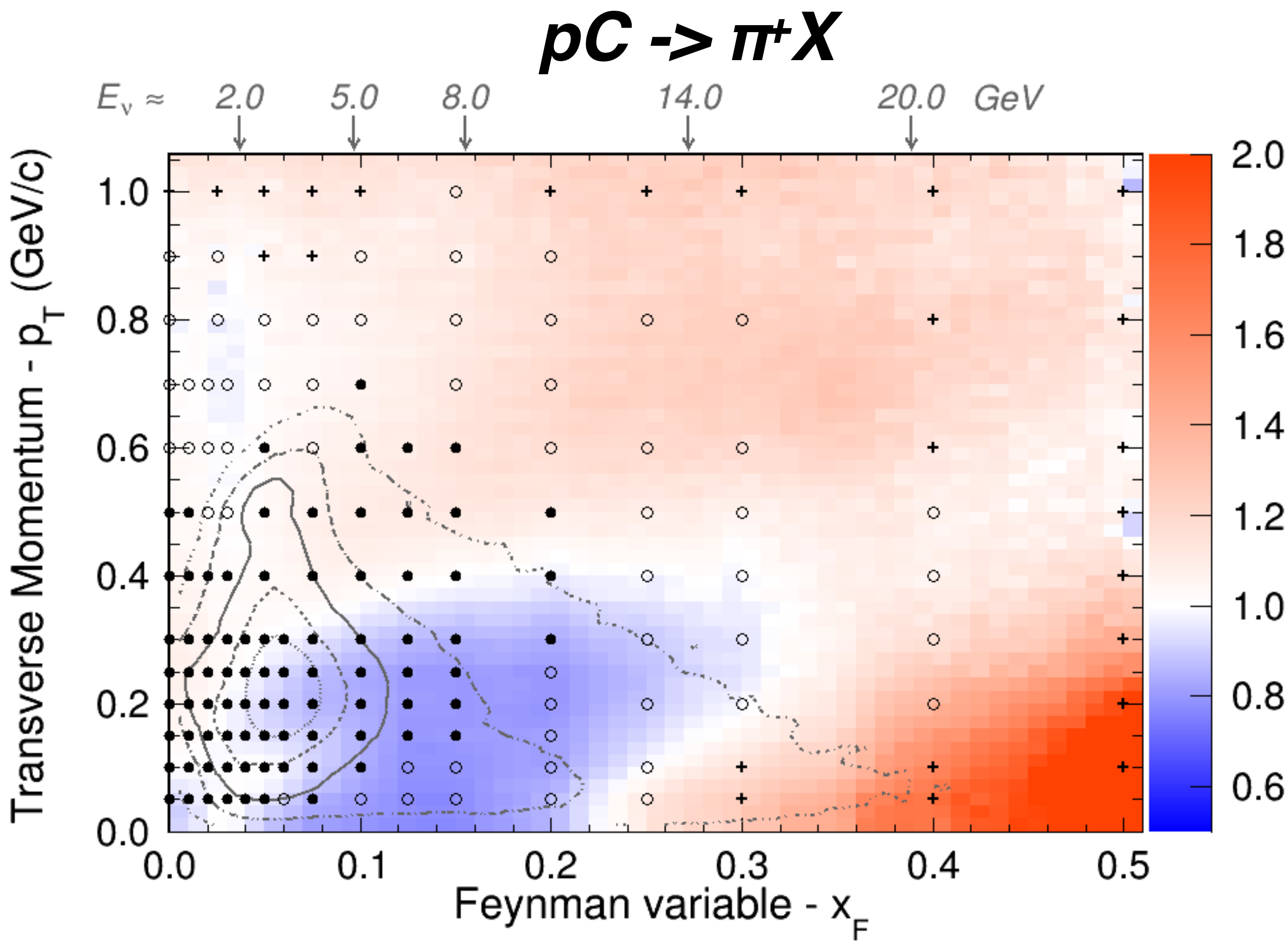
- Fermilab has a key role the current and future neutrino experiments , especially using conventional neutrino beams.

backup

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.



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

systematic uncertainties = 3.8% (added in quadrature).