Measurement of Flux Uncertainty in Neutrino Experiments: Present and Future

Deepika Jena

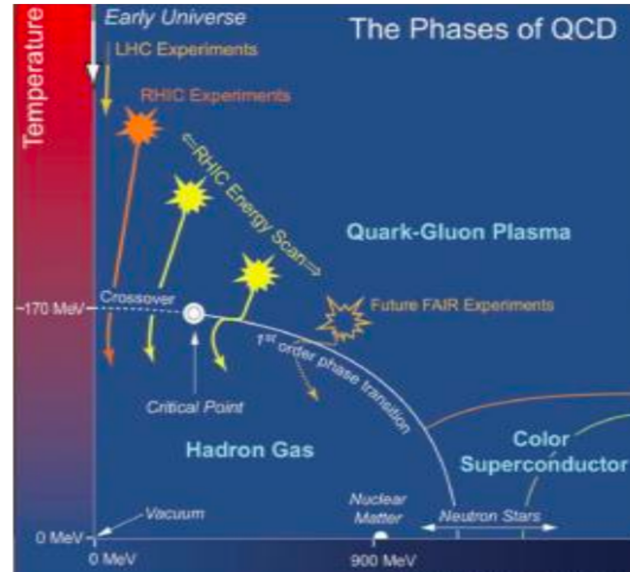
SCD-IF Practice Seminar

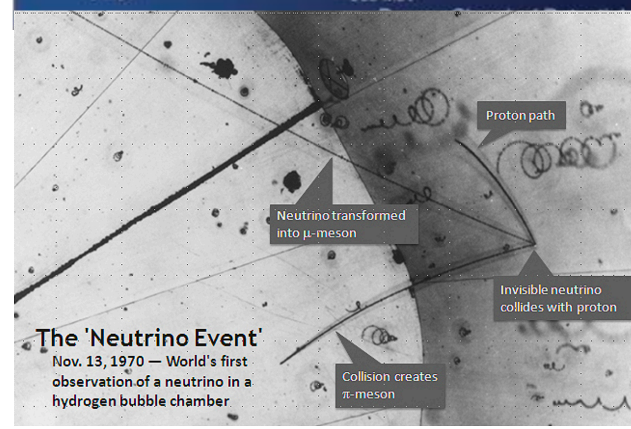
5 May 2020

About me

I started my research career working in ALICE experiment at CERN.
Thesis: Particle Ratio Fluctuations in heavy ion Pb-Pb collisions at 2.76 TeV -> Signature of Quark gluon plasma

Phenomenology work QGP Characterization in ALICE Experiment & Temperature fluctuation in heavy-ion collision.





Neutrino Era

Millions of events -> few events
Collider -> fixed target

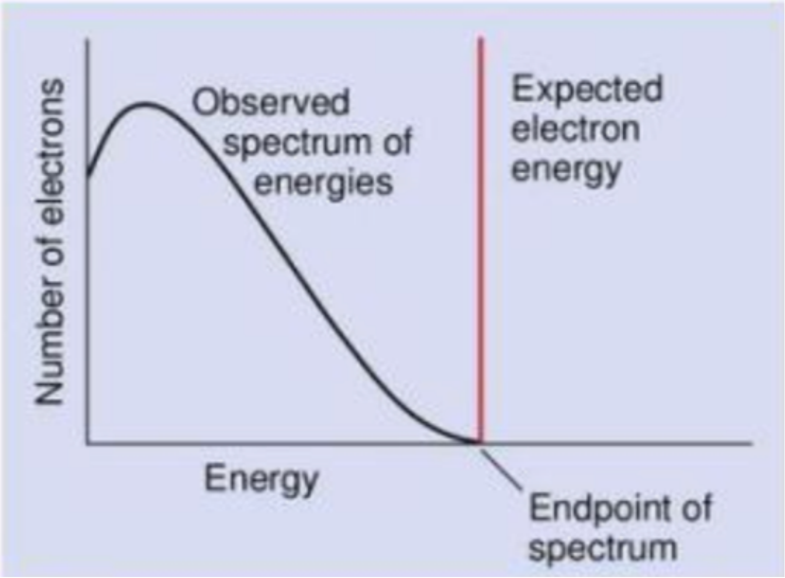
Postdoc
Involvement in DUNE and MINERvA experiment at Fermilab.
Flux and its uncertainties, neutrino-nuclei cross-section analysis

Introduction : Neutrinos

After photon, neutrino is the most abundant particle in the universe.

Pauli in 1930

- Radioactive β decay : $X \rightarrow X' + e^{-} + \bar{\nu}_e$
- Neutral, weakly interacting (rarely interact)
- 3 flavor neutrinos - $\nu_e , \nu_\mu , \nu_\tau$
- Are they really massless ?



Fermilab

Neutrinos are everywhere and forever

After photon, neutrino is the most abundant particle in the universe.

Pauli in 1930

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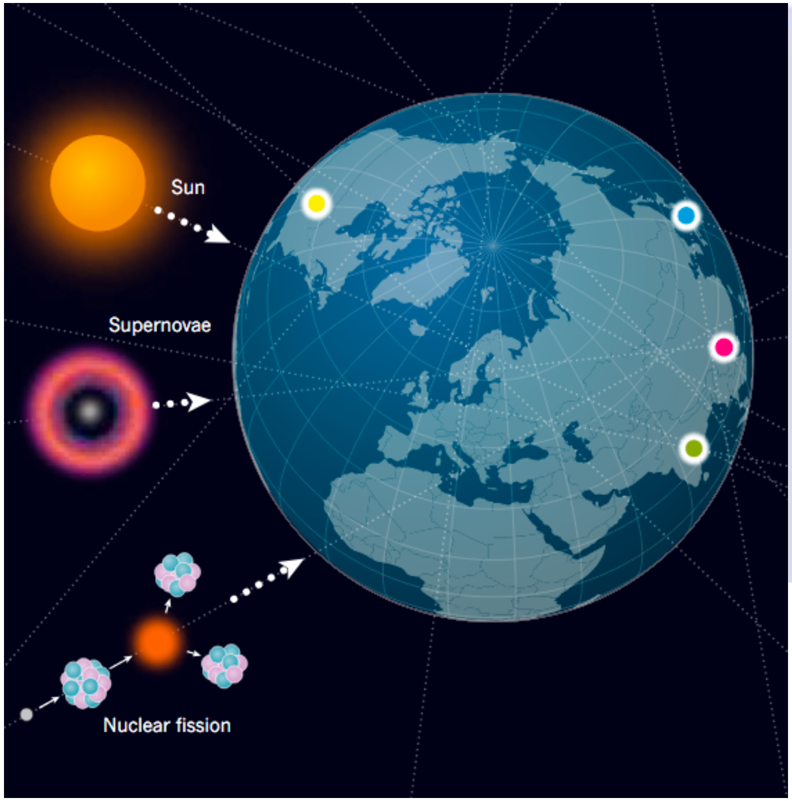

Introduction :Neutrinos

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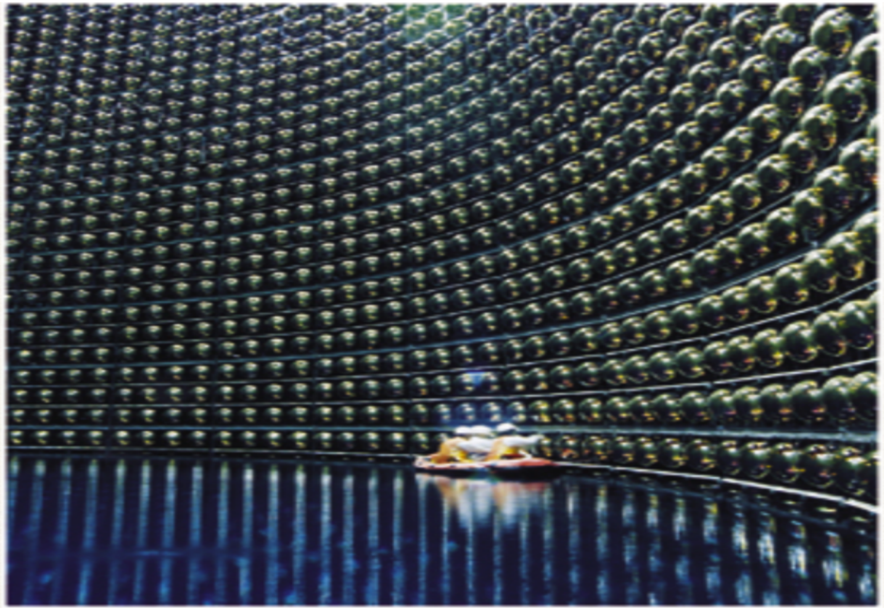

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- Are they really massless ?

The Homestake experiment was the first of many to observe fewer solar neutrinos than expected — "the solar neutrino problem"

Super-K's data indicated that neutrinos oscillate between flavor (ν_e, ν_μ and ν_τ) as they travel through space.

Neutrino Oscillations

Neutrino oscillations means neutrino have mass.
The oscillation is a function of energy and distance travelled.

Every neutrino is a quantum superposition of three mass states, and those states mix in different proportions to make different flavors.

Weak Interaction States — Mixing Matrix — Mass States

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillations

Neutrino oscillations means neutrino have mass

Every neutrino is a quantum superposition of three 'mass states', and those states mix in different proportions to make different flavors.

Many questions arise ?

1. What are parameters of mixing matrix ?
2. What is the value of phase δ_{CP} ?
3. Ordering of mass states ?

Weak Interaction States — Mixing Matrix — Mass States

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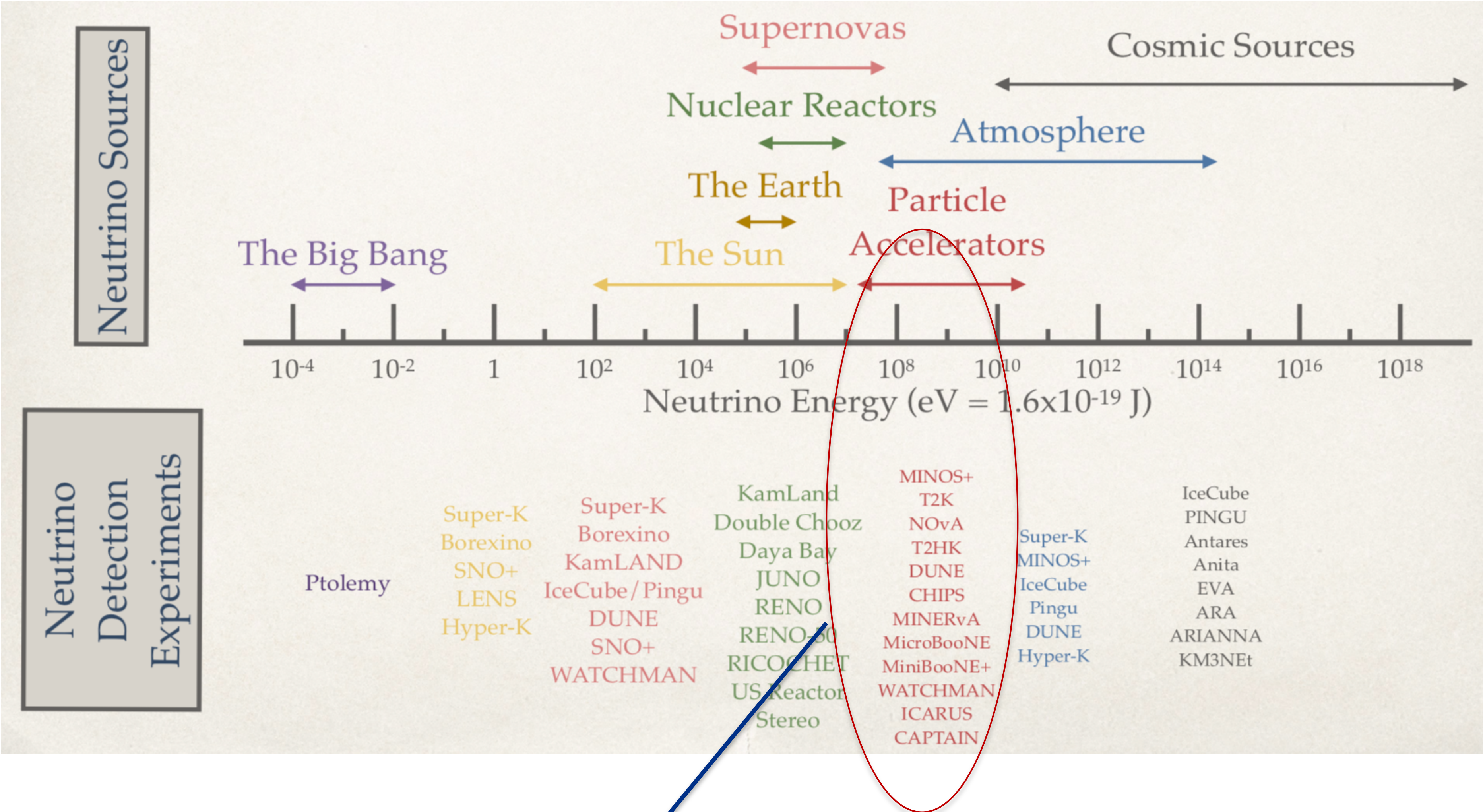
PMNS Matrix (function of three mixing angles (θ_{23} ,θ_{12}, θ_{13}) and CP-violating phase (δ_{CP})

All these questions needs to be answered

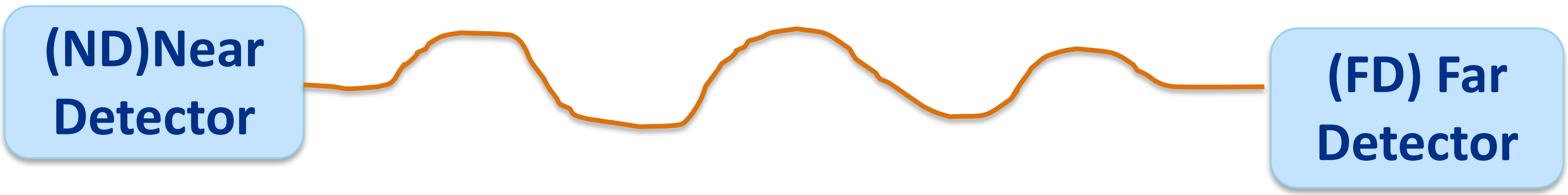
Neutrino Program



In today's talk I'll focus on Accelerator neutrinos

Two detector neutrino oscillation experiment

Build an experiment with a pair of detectors



Experiments will measure rate of neutrino interactions.

Oscillation Probability $P_{\nu_\mu \rightarrow \nu_e}$ is estimated by comparing rate between near to far detector

$$N_{\nu_e}^{FD} = P_{\nu_\mu \rightarrow \nu_e} \times N_{\nu_\mu}^{ND}$$

Rate of neutrino interaction

Observed interaction rate, N, depends on flux, cross sections (σ), and detector acceptance (ε)

$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

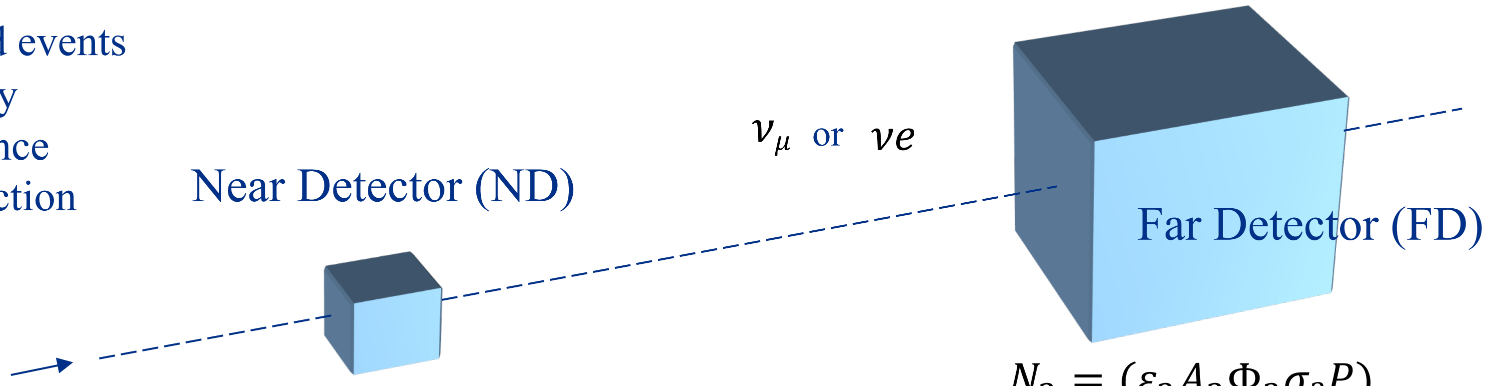
Flux: number of neutrino produced by the accelerator per cm^2, per bin of energy for a given number of protons on target

Cross-section: probability of interation of the neutrinos in the material of the detector

To extract the oscillation parameters, the oscillation probability must be evaluated **as a function of neutrino energy,** since the neutrino beams are not monochromatic

Two detector neutrino oscillation experiment

N: observed events
ε: Efficiency
A: Acceptance
σ: Cross section



ν−beam

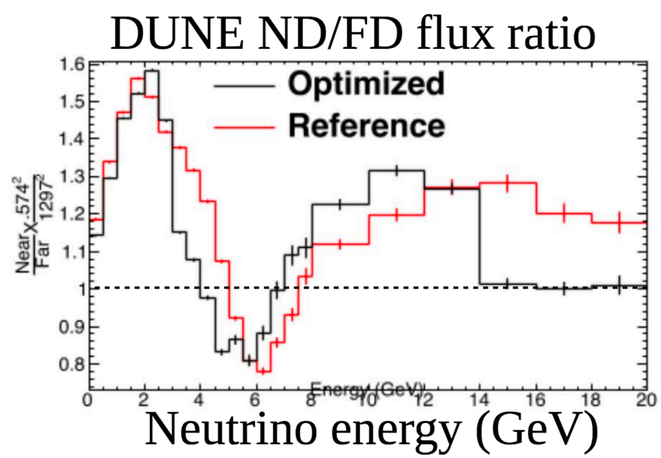
$N_1 = \varepsilon_1 A_1 \Phi_1 \sigma_1$

$N_2 = (\varepsilon_2 A_2 \Phi_2 \sigma_2 P)$

$$P = \left(\frac{N_2}{N_1}\right)\left(\frac{\Phi_1}{\Phi_2}\right)\left(\frac{\boldsymbol{\sigma}_1}{\boldsymbol{\sigma}_2}\right)\left(\frac{\varepsilon_1}{\varepsilon_2}\right)\left(\frac{A_1}{A_2}\right)$$

– Near detector sees distributed source, far detector sees point source.
– Even if the ND and FD were literally identical, the flux differences mean that nothing cancels.
– Independent knowledge of flux and cross sections is very helpful.

One of the key ingredients in neutrino physics is the neutrino flux which has to be known with the maximal precision

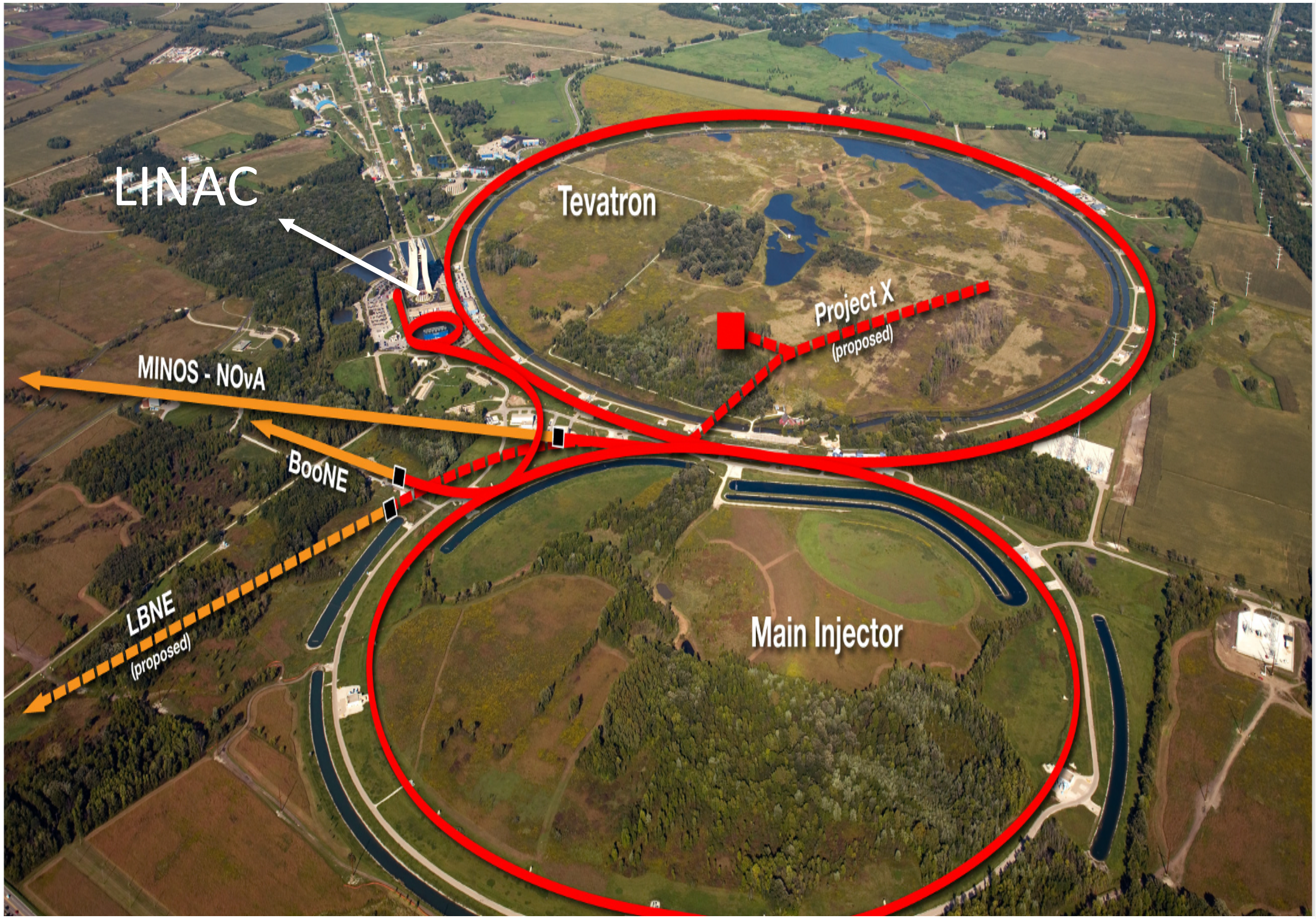


Fermilab

Fermilab – Neutrino program

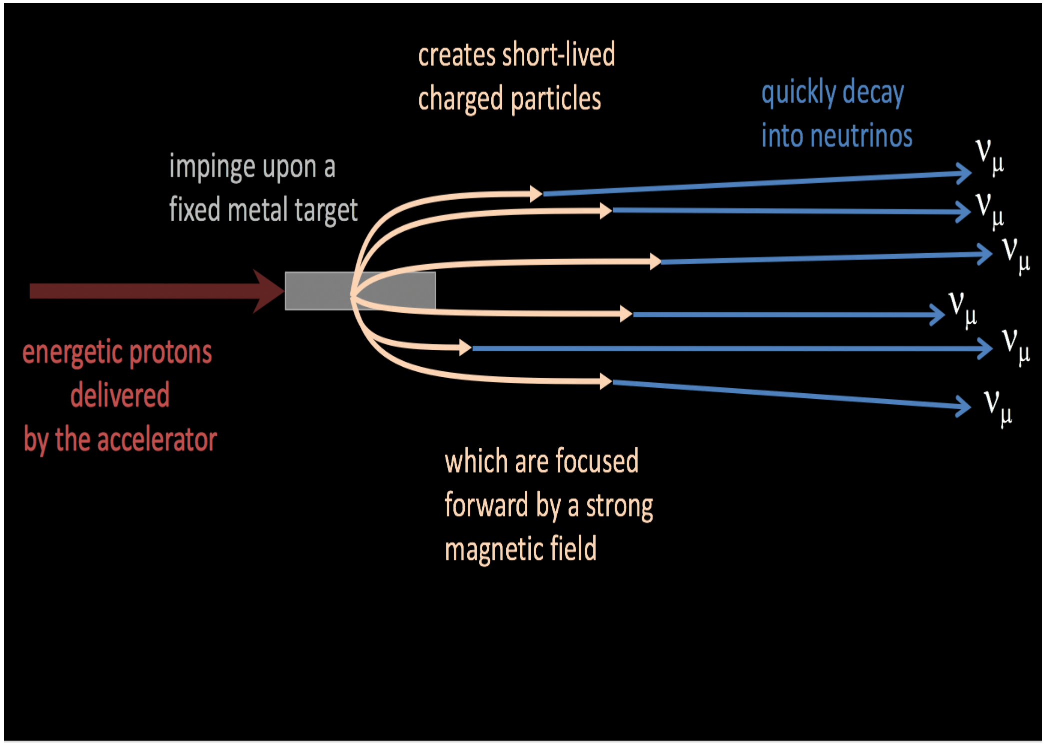
Fermilab produces an intense beam of neutrinos making it an excellent place to pursue neutrino physics

For neutrino oscillation program the accelerator-based neutrino programs will involve producing a neutrino beam with powerful detectors observing it at larger distances.



Neutrino beam

An Intense beam of protons can be used to create an intense beam of neutrinos



Ingredients to build a beamline :

Protons on Target: More particles on target, more pions, more neutrinos.

Target: Longer the target, higher probability to interact.

Horns: Focus as many π^{+-} with the wanted sign and deflect the unwanted sign

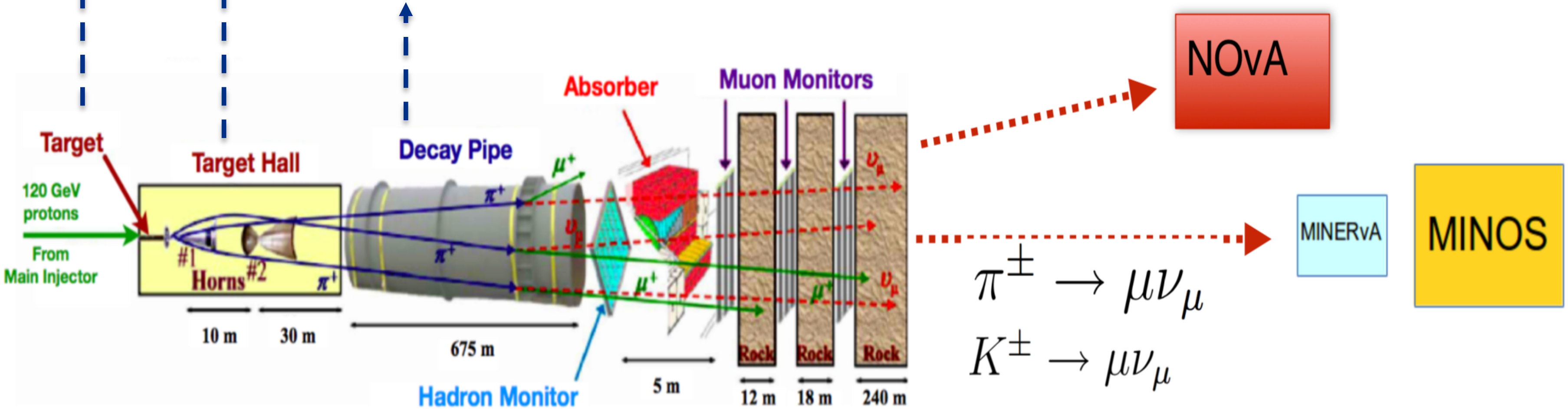
Decay Pipe: Length and wide of the decay pipes depends on what pion energy we want to focus.

NuMI Beamline

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

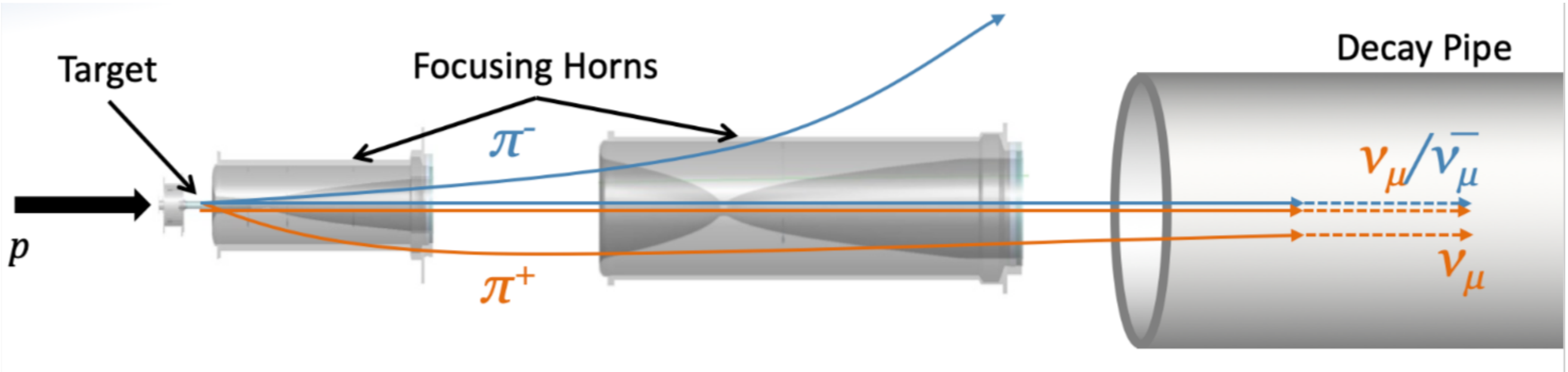


$$\pi^{\pm} \rightarrow \mu\nu_{\mu}$$

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

Many experiments, like NOvA, MINERvA, etc. uses this NuMI beamline to make cross section measurements.

How we predict the flux



Start with basic simulation – G4NuMI

- G4NuMI (based on GEANT4) simulates everything from the primary 120 GeV proton beam to focused mesons that decay to neutrinos. Keeps track of all interaction kinematics, interactions materials, etc.

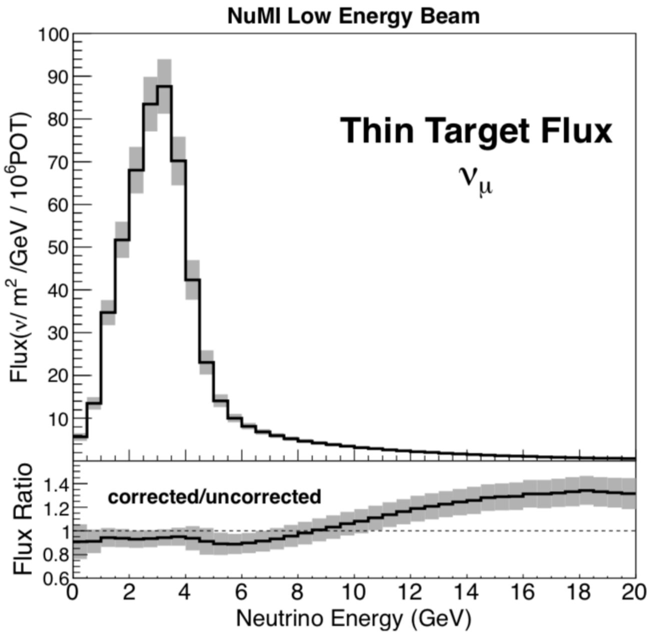
- A variety of models are available in GEANT : QGSP, FTFP; Fluka-based simulations also exist.

Why is it so hard to determine the flux ?

So this prediction comes along with challenge !

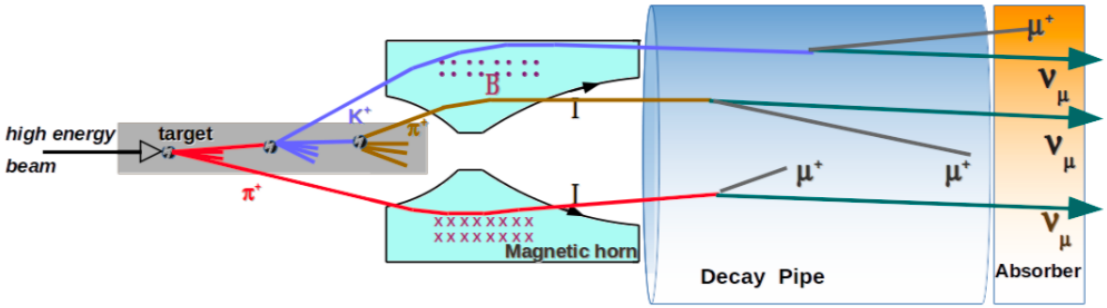
- Simulated flux rely on hadronic models . Big discrepancies between hadronic models. Need external data to constrain the models.

- We mainly focus these changes on our flux prediction modestly in the focusing peak where most of the neutrinos live.



Hadron Production data

The simulations are tuned using external measurement from hadron production data

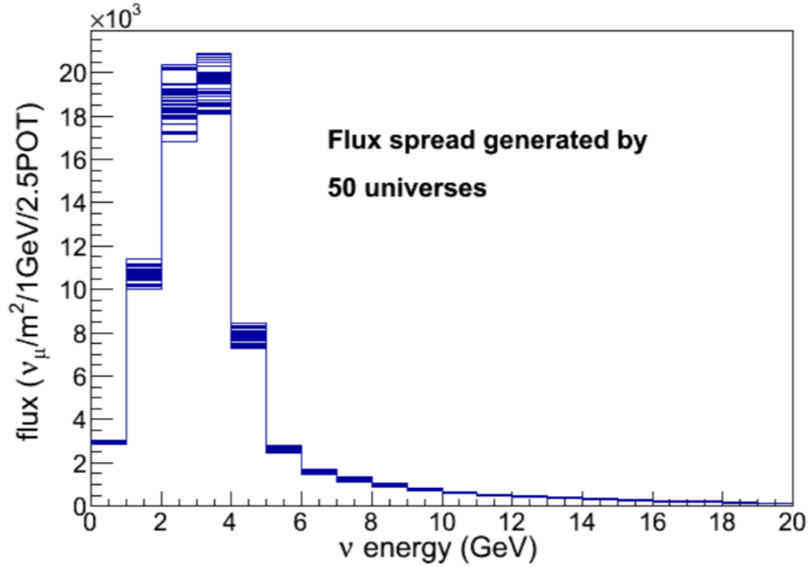


- Tabulate the hadronic cascade at generation with all kinematic information and store in the flux tuples
- MC interactions are weighted to the measured cross section.
- The beam attenuation in target (and other materials) is also corrected.
- Assign and propagate uncertainties.

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

Propagation of Uncertainties:

- Multi-universe Method : creation of a statistical ensembles of individual randomly generated simulations.
- Each universe is generated with measured hadron production cross sections varied within their uncertainties taking into account correlations of parameters.
- Many universes are generated, the rms across all the universes gives us the uncertainty on that simulated value.



Hadron Production Uncertainties

- Hadron production is the main source of flux uncertainties. We use all relevant existing data to constrain the flux to reduce the uncertainties.
- For interactions not covered by data we use a model prediction and apply a large uncertainty chosen based on differences between data and simulations for the interactions that are covered by data.

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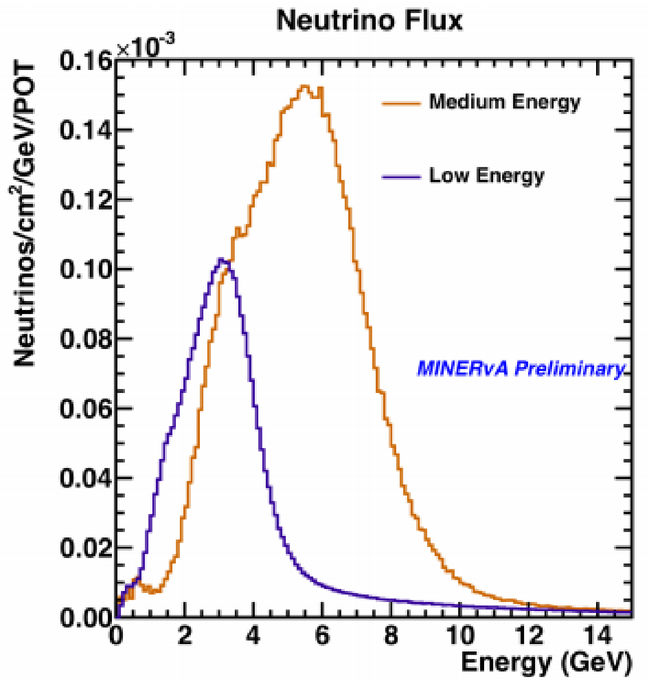
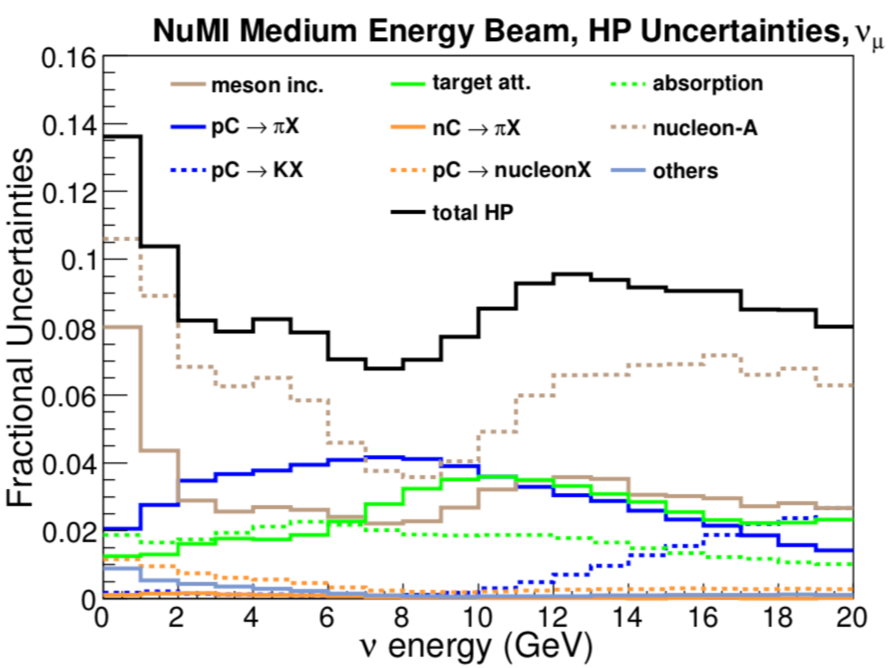
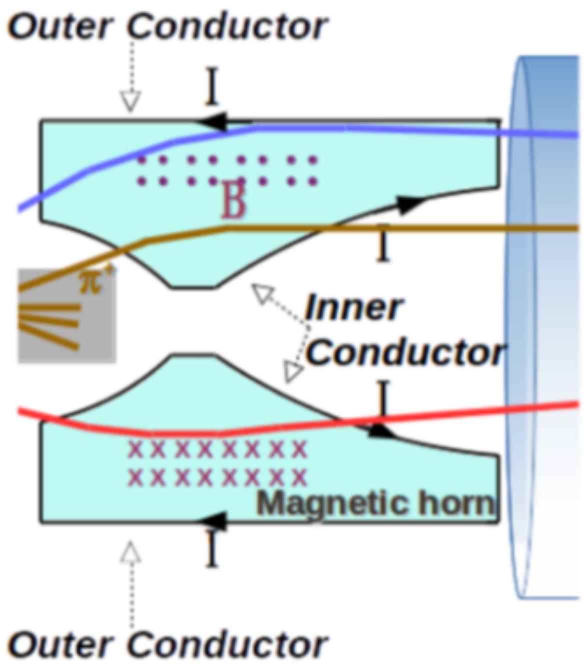


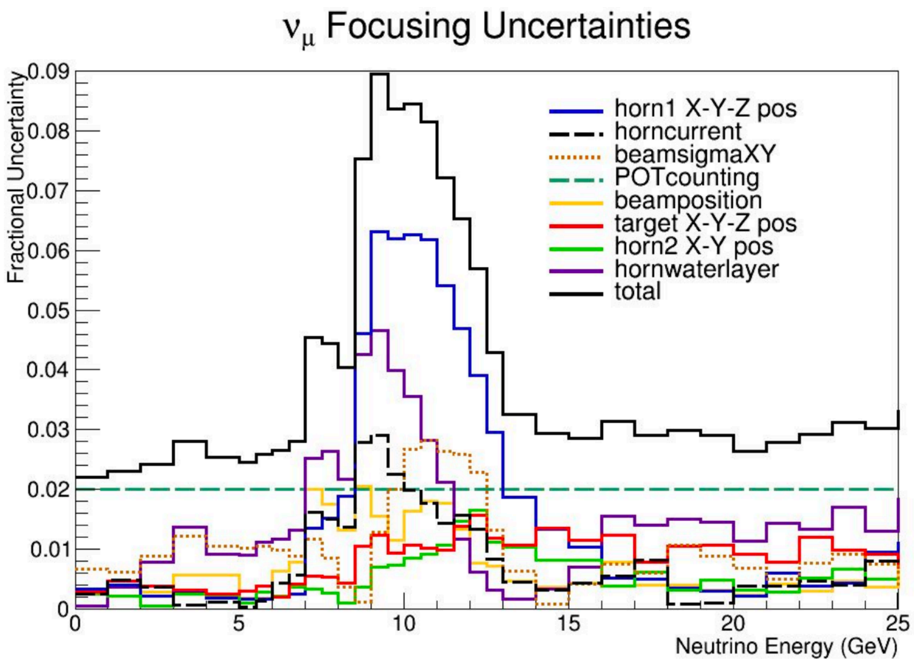


Uncertainties originating from different hadron interactions

Beam Focusing Uncertainties

A large number of geometric details, such as target longitudinal position, horn position etc. can affect the neutrino energy distribution and these details must be precisely known and uncertainties well measured and propagated. Small simulation inaccuracies have a big impact around the focusing peak

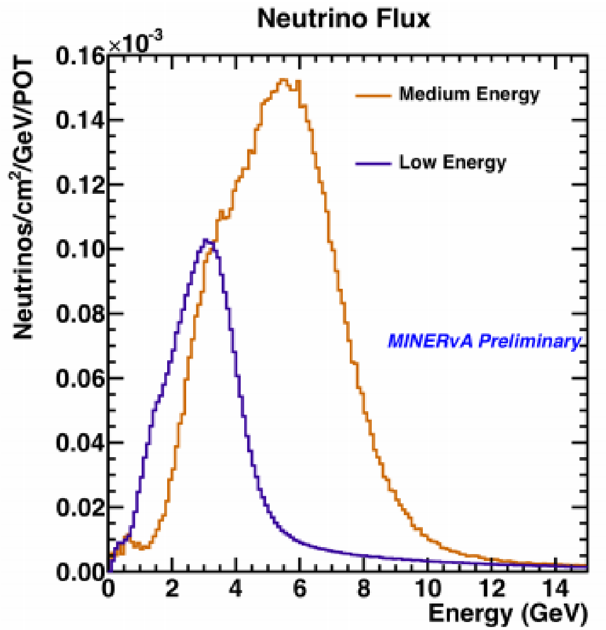


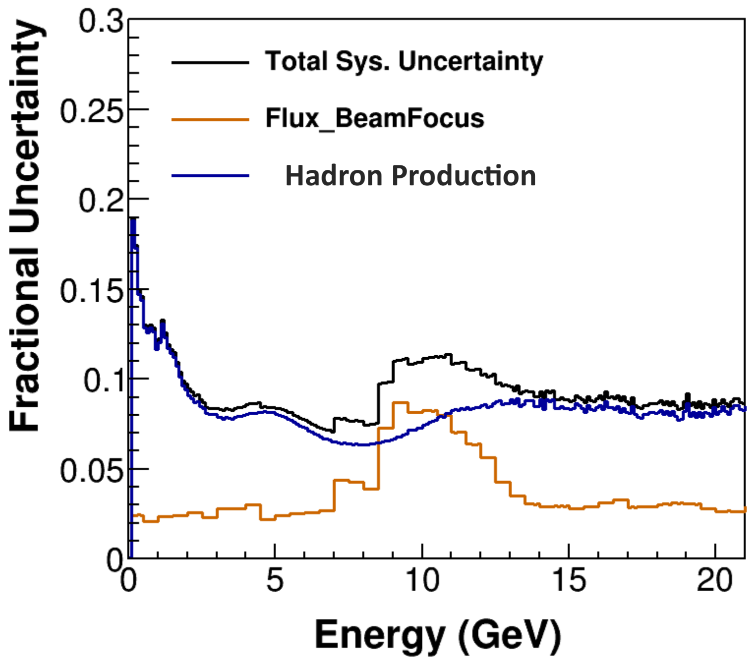


Small in comparison with the hadron production uncertainties

Flux and Flux Uncertainties

- NuMI beamline -> Low and medium energy modes.
- Hadron production uncertainties have dominant contribution to the neutrino flux uncertainty.
- Flux is a limiting systematic for single-detector analysis.
- It is really important to reduce these uncertainties by in-situ measurements.





PPFX (Package to Predict the FluX) : is an external package for MINERvA framework able to calculate the HP corrected NuMI flux for any detector.

MINERvA Strategy for Predicting the Flux

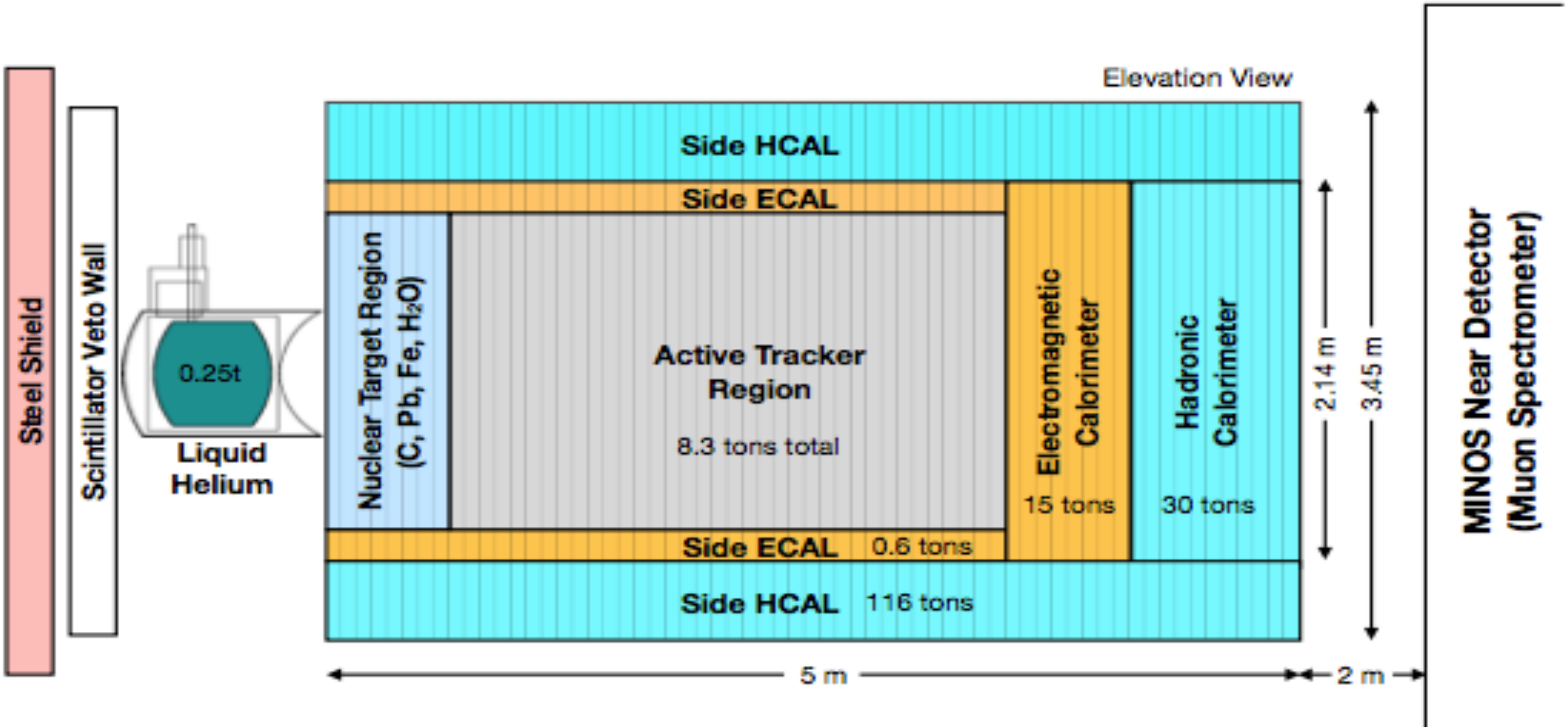
1. Calculate the a-priori flux → G4numi simulates the beam

2. Correct a-priori flux
- Correcting the hadron production in the beam line to constrain with external hadron production data. (PPFX)
- Accounting for focusing and hadron production uncertainty.

3. 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: flux normalization**

Let us discuss about this now

MINERvA (Main INjector ExpeRiment for ν- A)



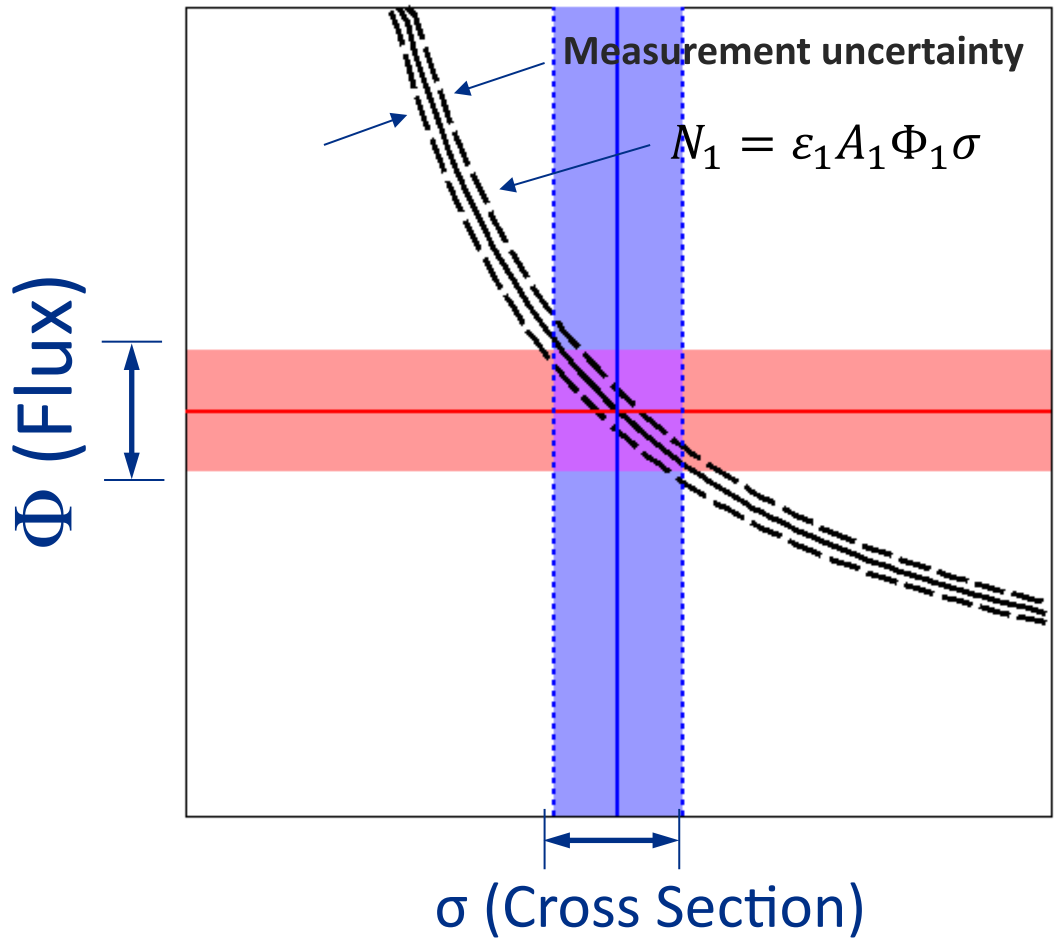
- MINERvA: a dedicated on-axis neutrino-nucleus scattering experiment running at Fermilab in the NuMI (Neutrinos at the Main Injector) beamline.
- Consists of a core of scintillator strips surrounded by ECAL and HCAL.
- Several nuclear targets (C, Fe, Pb, water and He) in the same beam line to take simultaneous measurements.

Neutrino Flux and Cross-section

MINERvA

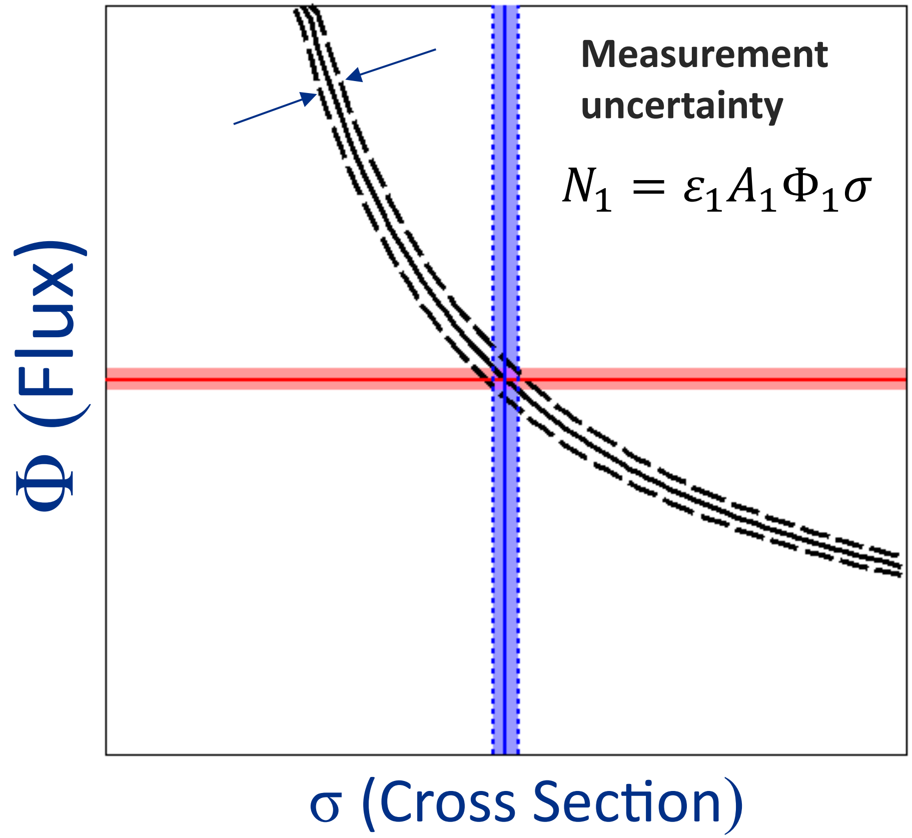
$$\sigma = \frac{N}{\varepsilon A \Phi}$$

Flux uncertainty goes into cross-section uncertainty

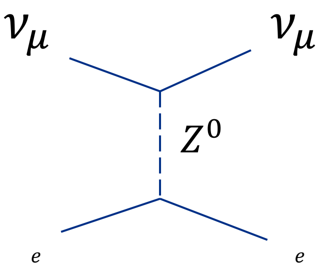


Neutrino-electron Scattering: Standard Candle

- The cross section for neutrino-electron scattering is well understood by standard electroweak scattering theory.
- Discrepancies between data and Monte Carlo predictions will be due to mis-modeling of the flux distribution.
- The final-state distribution of electron energies can be used to constrain the overall normalization.



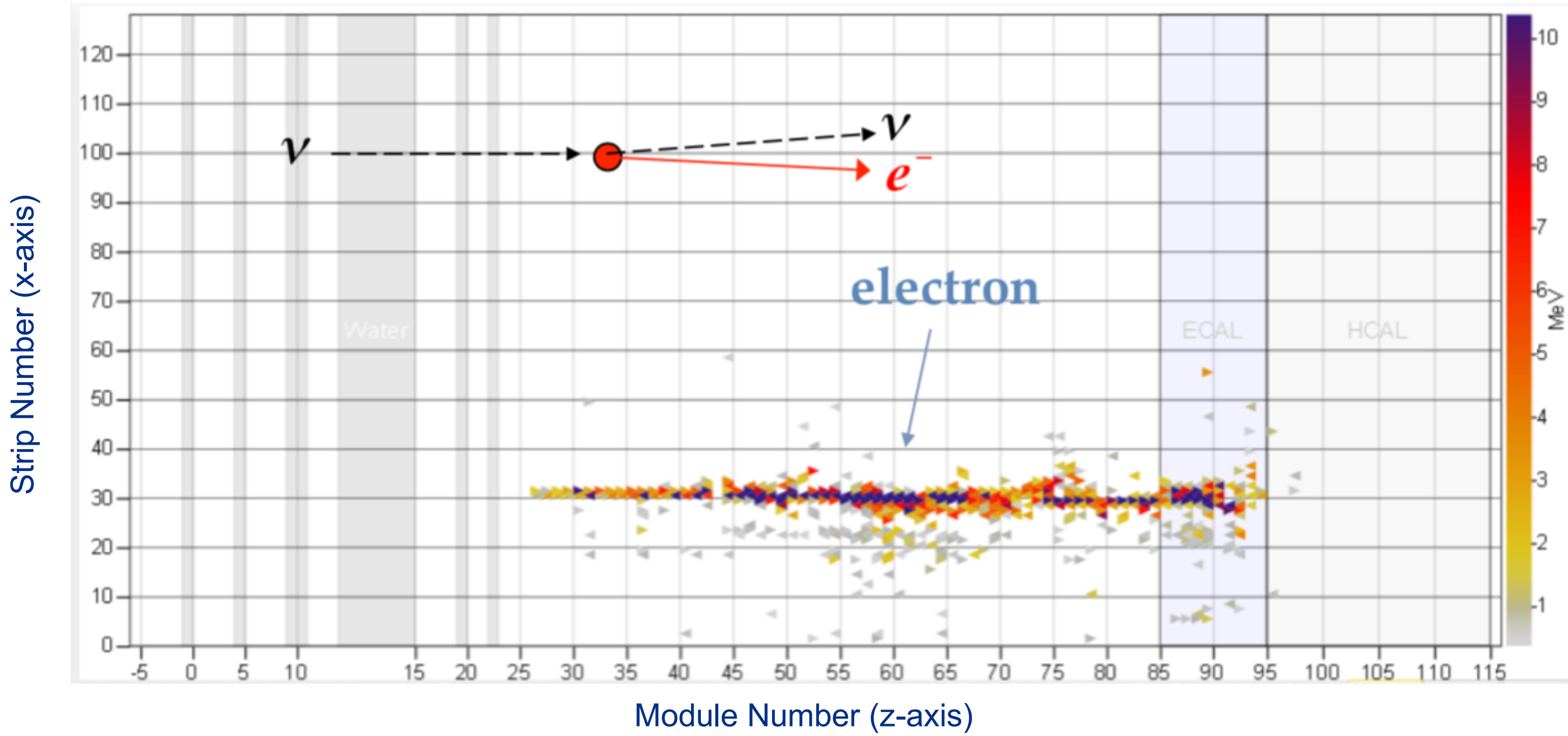
Let us see how ???



$\nu_\mu + e \rightarrow \nu_\mu + e$

ν – e event selection

- Experimental signature is a very forward single electron state.
- Good angular resolution is important to isolate a signal.



<u>Caveat</u> : Limited statistics due to very small cross section (1/2000 times the neutrino- nucleus cross-section)

Background

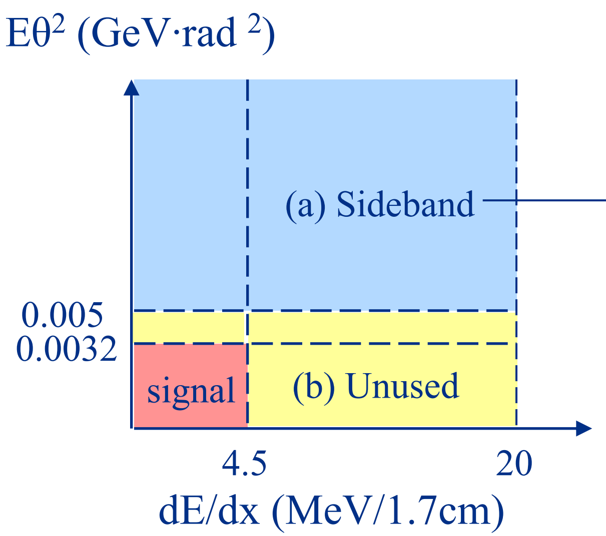
Background prediction is affected by the flux and physics model

- ν_μ Neutral Current
- Coherent & diffractive π^0

} ~ 50% of background

- ν_μ Charged Current } ~ 20% of background
- ν_e interactions } ~ 30% of background

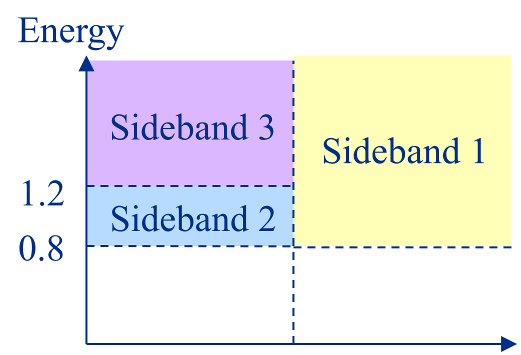
The background predicted by the simulations is constrained by four kinematic sidebands.

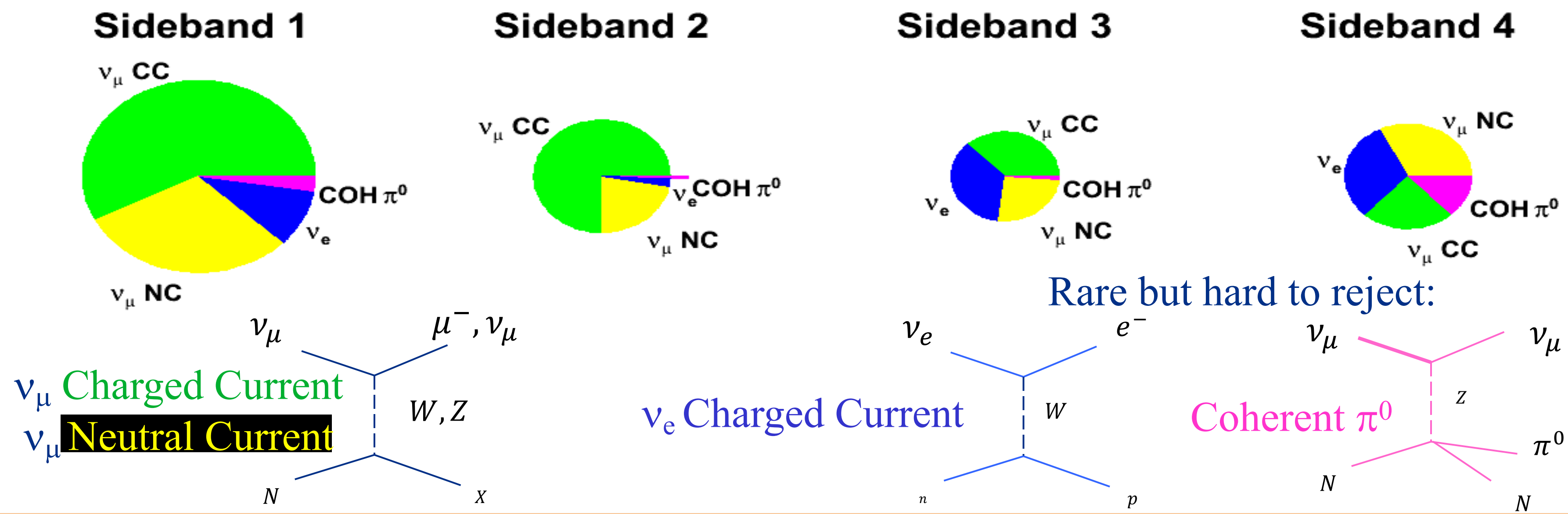


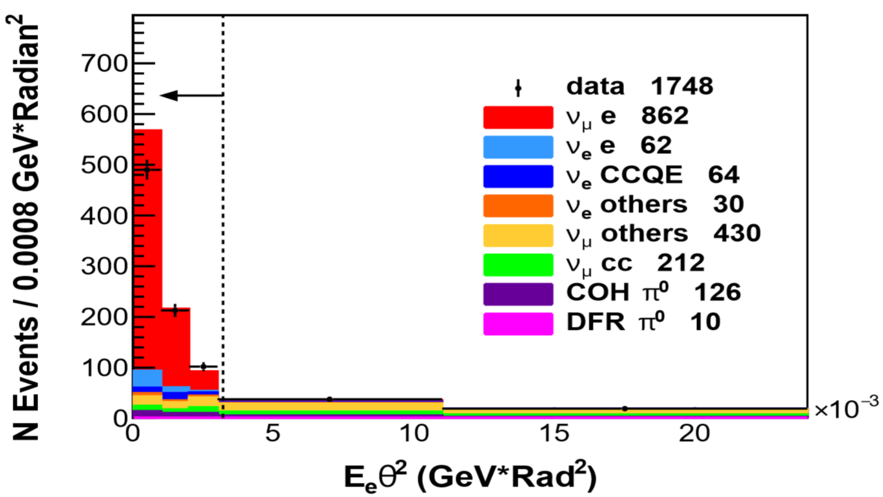
Sideband 4 (Coherent π^0 rich region)

Sideband 1, 2, 3 (not sideband 4)

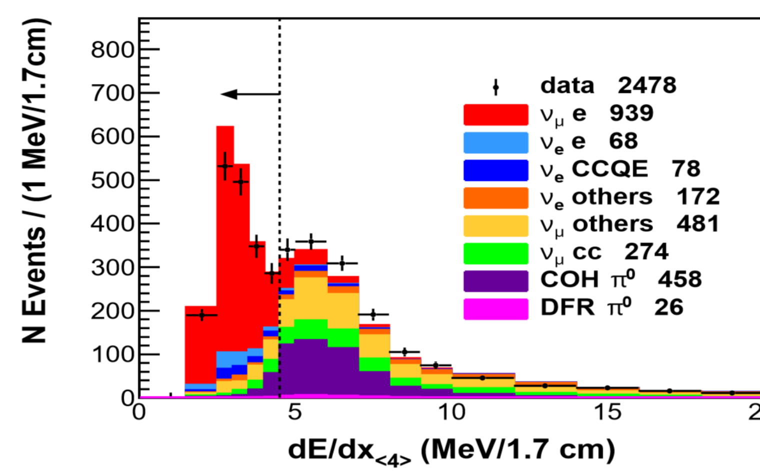
- No side-exiting muon
- Narrow shower at beginning
- $E\theta^2 < 0.1$







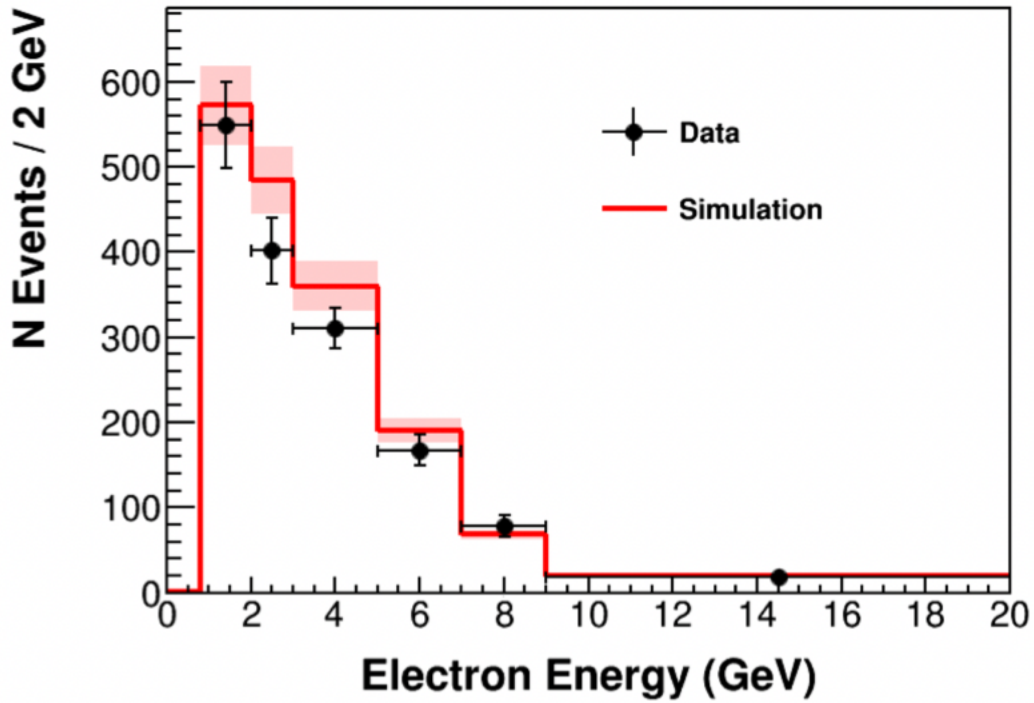
Signal events are required to have $E_e\theta^2 < 0.0032$GeV Radian^2



Average energy deposition of the electron dE/dx < 4.5 MeV/1.7 cm

Electron energy spectrum

Background subtracted and efficiency corrected distribution



- Selected events: 1021
- After background subtraction: 809
- After efficiency correction: 1188

We use this final electron energy spectra to constrain the Flux ??
Yes ! Let's see how .

Fermilab

Procedure to constrain flux

Bayes Theorem: Way of finding probability when we know certain other probabilities.

$$P(A|B) = \frac{P(A)\,P(B|A)}{P(B)}$$

how often A happens given that B happens

how likely A is on its own

how often B happens given that A happens

how likely B is on its own

Fermilab

Let’s have a picnic ! Morning is Cloudy ☹


https://www.mathsisfun.com/data/bayes-theorem.html

50% of all rainy days start off cloudy -> P(Cloud|Rain)= 0.5

40% of days start cloudy -> P(Cloud)= 0.4

This is usually a dry month (only 3 of 30 days tend to be rainy, or 10%) P(Rain)= 0.1

$$P(Rain|Cloud) = \frac{P(Rain)P(Cloud|Rain)}{P(Cloud)} = \frac{0.1 \times 0.5}{0.4} = 0.125$$

Just 12.5 % chance of rain. Let’s go for Picnic !

Procedure to constrain flux

$$P(Rain|Cloud) \propto P(Rain)P(Cloud|Rain)$$

$$P(M|N_{\nu e\to\nu e}) \propto P(M)P(N_{\nu e\to\nu e}|M)$$

Probability of some modelled ν-e electron spectrum given our data

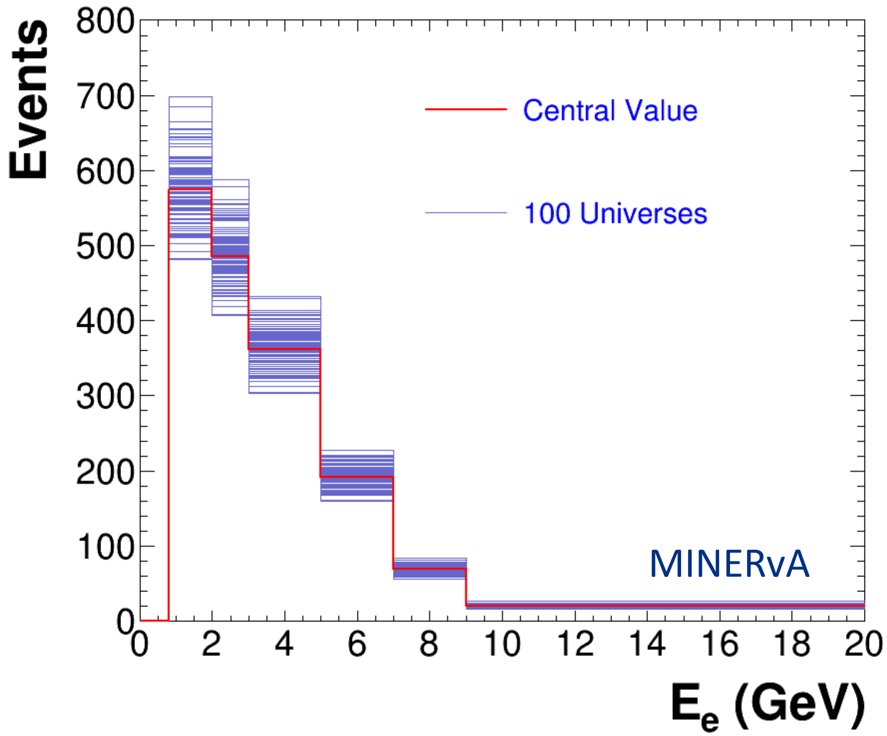
Prior probability of that modelled ν-e electron spectrum

Probability of our data given that model

Procedure to constrain flux

$$P(M|N_{\nu e\to\nu e}) \propto P(M)P(N_{\nu e\to\nu e}|M)$$

To propagate our uncertainties, we created many flux models ("universes"), each of which creates a predicted electron energy spectrum



All universes have equal prior probability.

Procedure to constrain flux

$$P(M|N_{\nu e\to\nu e}) \propto P(M)P(N_{\nu e\to\nu e}|M)$$

Likelihood of data given model

$$P(N_{\nu e\to\nu e}|M)\alpha\ e^{-x^2{}_M/2}$$

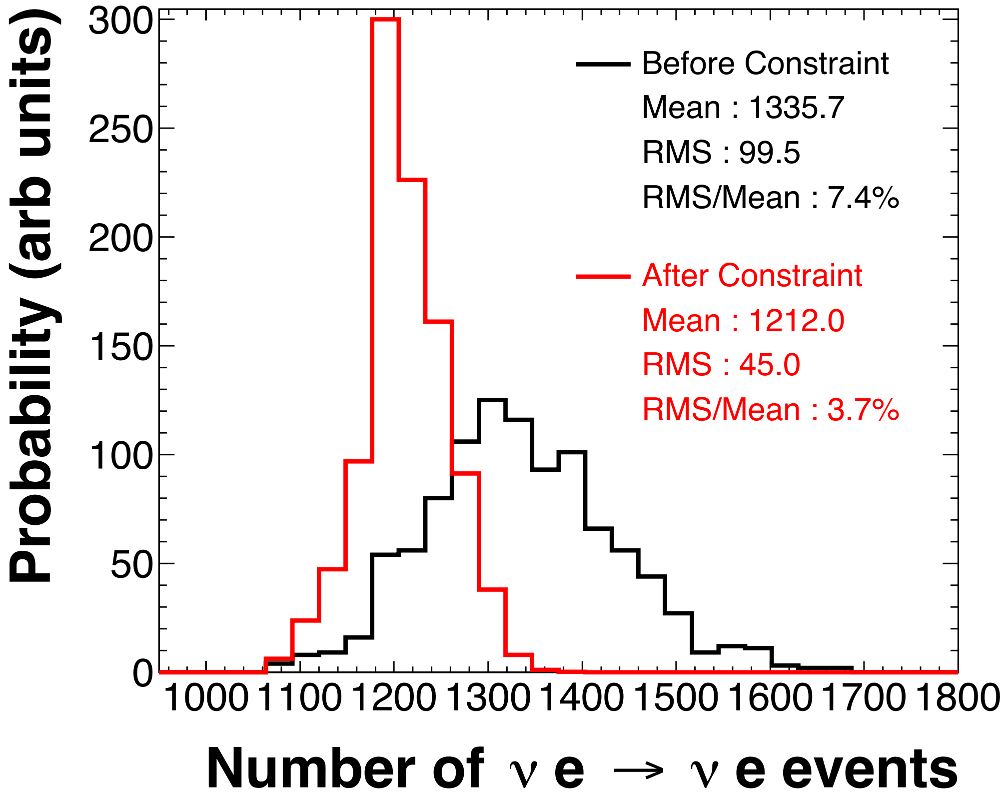
Procedure to constrain flux

$$P(M|N_{\nu e \rightarrow \nu e}) \propto P(M)P(N_{\nu e \rightarrow \nu e}|M)$$

Posterior probability distribution can be constructed by weighting prior universes by likelihood

$$P(N_{\nu e \rightarrow \nu e}|M) \alpha \; e^{-x^2{}_M/2}$$

Illustration of nu-e constraint



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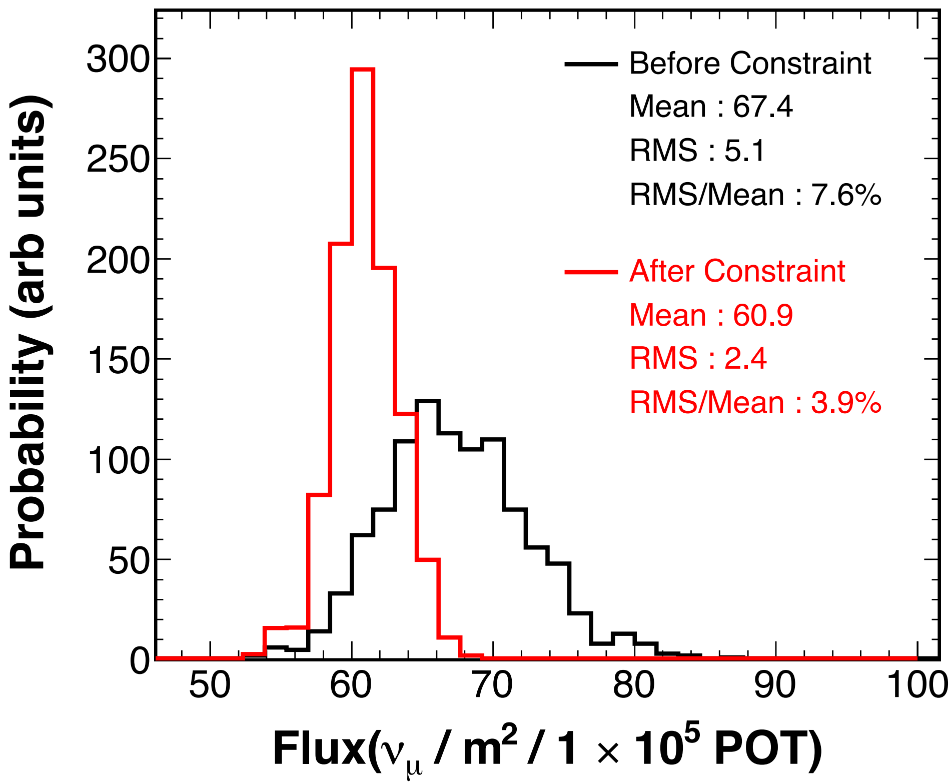
Probability distribution of simulated number of νe scatters before(black) and after(red) constraint.

Illustration of nu-e constraint



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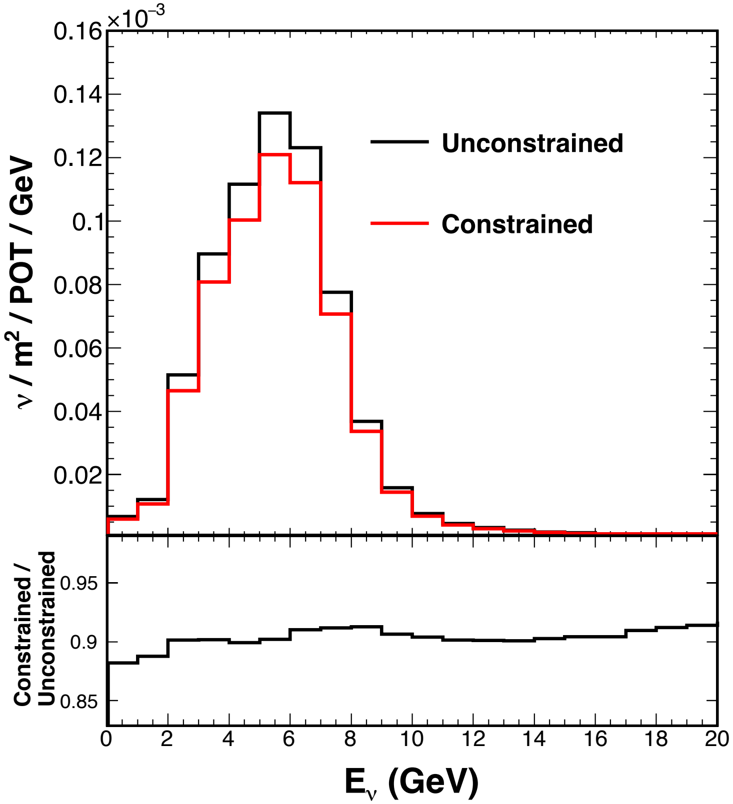
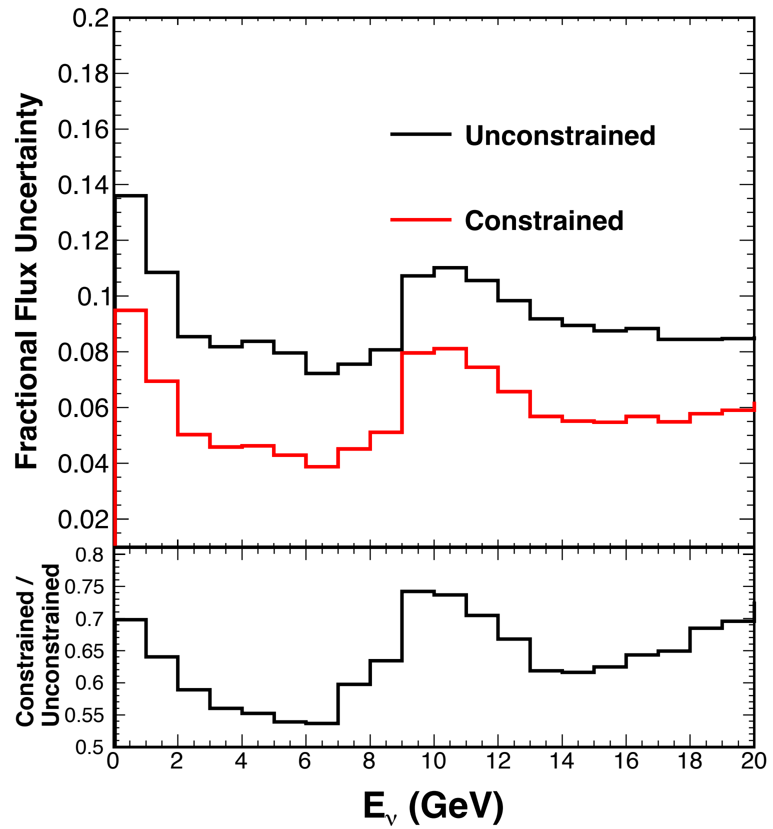
Predicted neutrino flux between 2 and 20 GeV after constraint is reduced by 9.6 % whereas the rms on the prediction is lowered by 53 %.

Flux and Fractional Uncertainty:





ν_μ flux in bins of neutrino energy before(black) and after(red) constraint is reduced by ~ 10 %

The flux uncertainty is reduced from 7.6 % to 3.9 % .

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Summarizing so far …

- ν-e scattering is a powerful technique to measure fluxes.
- MINERvA used this technique to constrain the flux uncertainties.
- *This measurement reduces the flux uncertainty from 7.6 % to 3.9%.*

PHYSICAL REVIEW D100,092001 (2019)

- Will this analysis benefit other analyses of MINERvA ?

  ME MINERvA analysis will be using this constraint to reduce the flux systematics.

  PhysRevLett.124.121801
- Is this study crucial for Future experiments ? Yes (DUNE)
- Can this tool be used for DUNE ? Yes

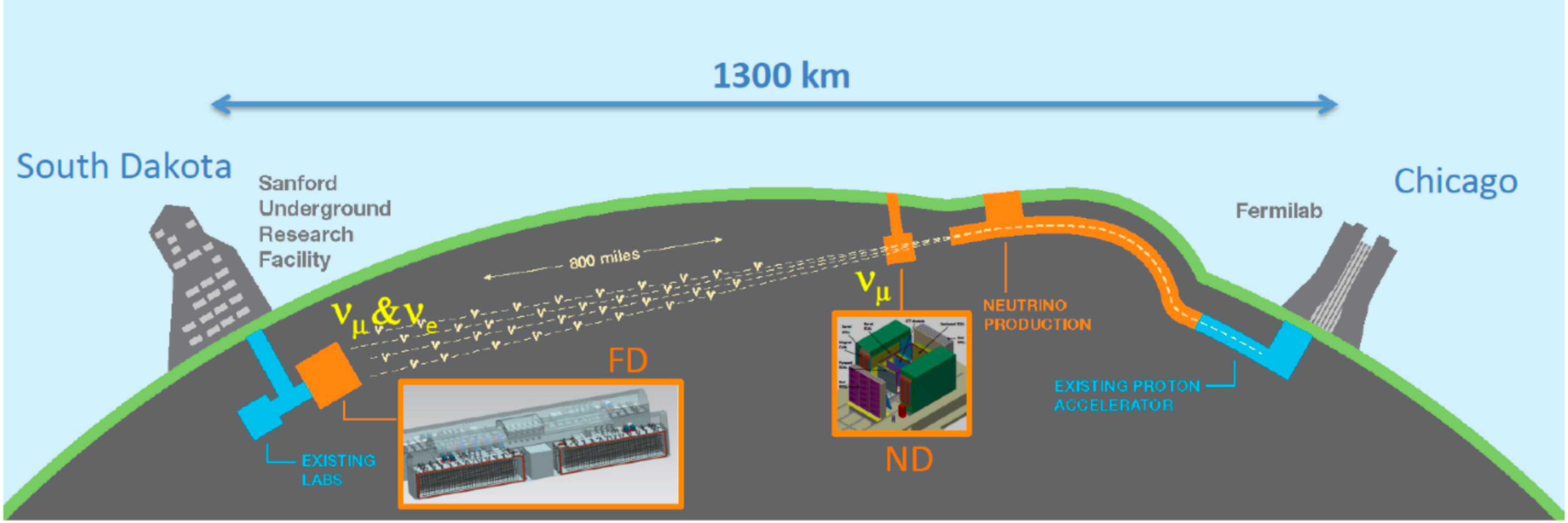
Let's look into the future - DUNE

Fermilab

DUNE

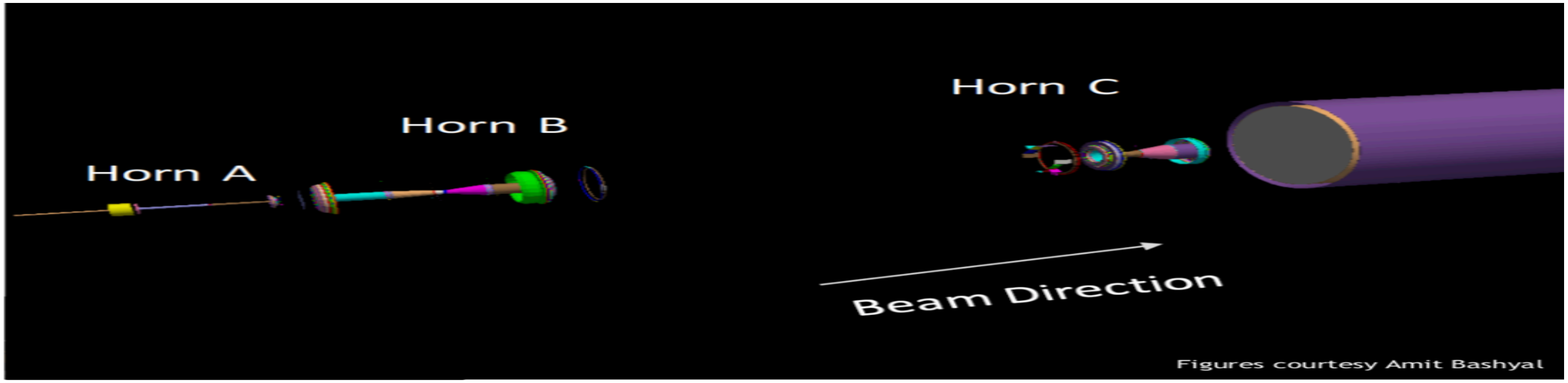
LBNF (Long Baseline Neutrino Facility) and DUNE (Deep Underground Neutrino Experiment):

- Neutrinos from high power primary proton beam @ 60 - 120 GeV from the Main Injector
- 1.2 MW from day one; upgradeable to at least 2.4 MW
- Massive underground Liquid Argon Time Projection Chambers
- 4 x 17 kTon (fiducial mass of more than 40 kTon)



Near detector system at Fermilab is critical for constraining systematic uncertainties

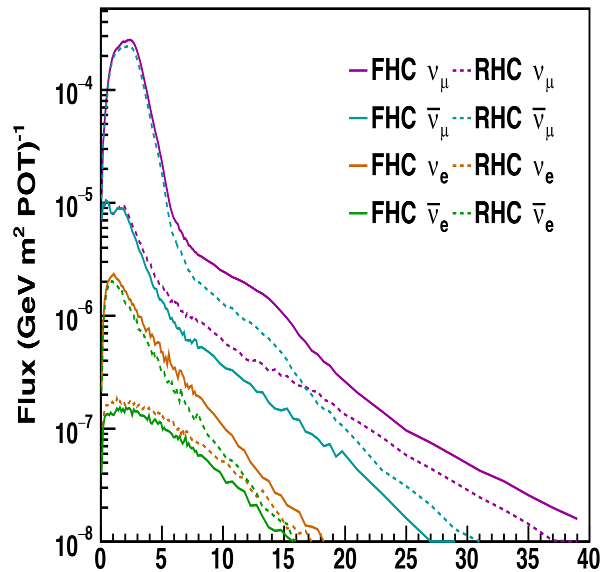
LBNF Optimized Beamline and Flux



LBNF uses an optimized beamline which is different from NuMI from some aspects :

- Three horns (2 in NuMI) running at 300kA
- A ~ 1.5m long graphite target fits inside Horn A
- A 194m long decay pipe (shorter than NuMI)

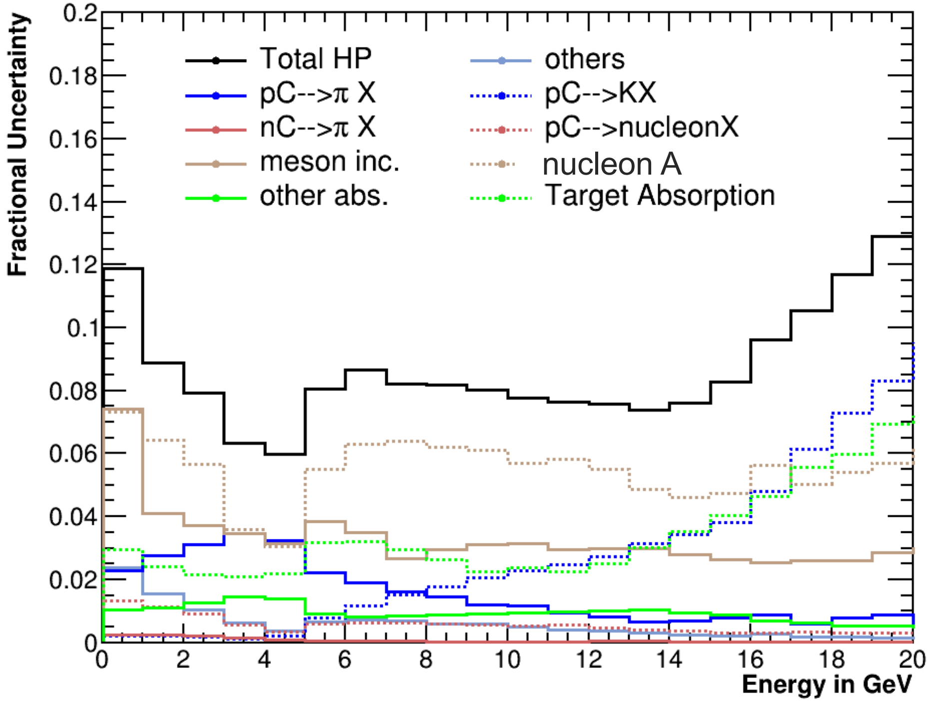
Predicted flux for different neutrino flavors both in neutrino and antineutrino mode.



arXiv:1910.10996

Hadron production uncertainties in DUNE

PPFX tool developed by MINERvA is used to evaluate HP uncertainties.



Interactions covered by thin target data

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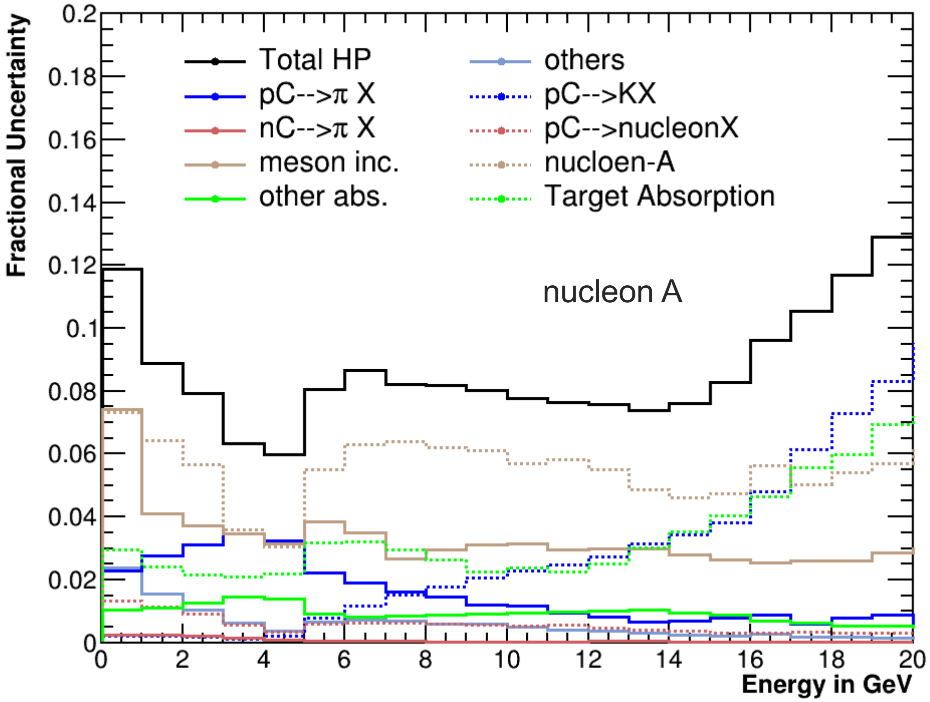

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Not covered by Data:

nucleon-A : For any other nucleon interaction not covered by data, we use our best guess uncertainty based on data which is 40 %. Quasi-elastic interactions outside the range of thin target data.

Meson inc : Pion and kaon reinteractions. No data correction is applied for interactions incident with mesons. A 40% uncertainty is also applied for this case.

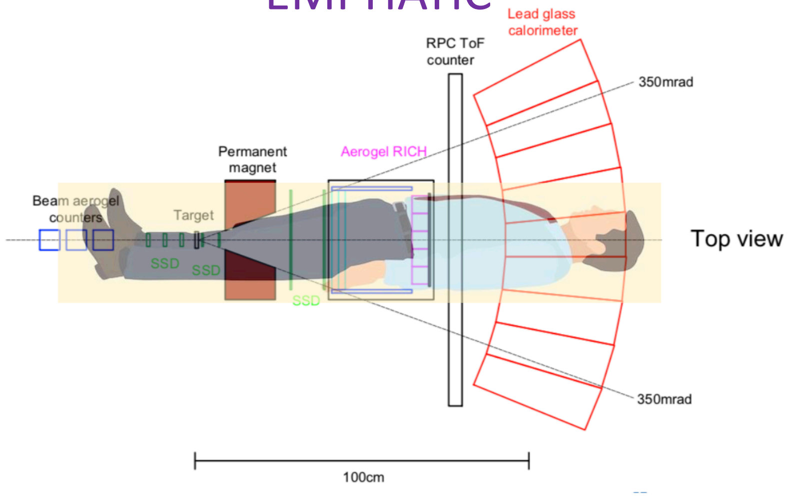
The HP uncertainties are smaller for interactions that have been measured and dominant for interactions not measured.

New hadron production measurements being done will increase confidence level in a-priori flux prediction

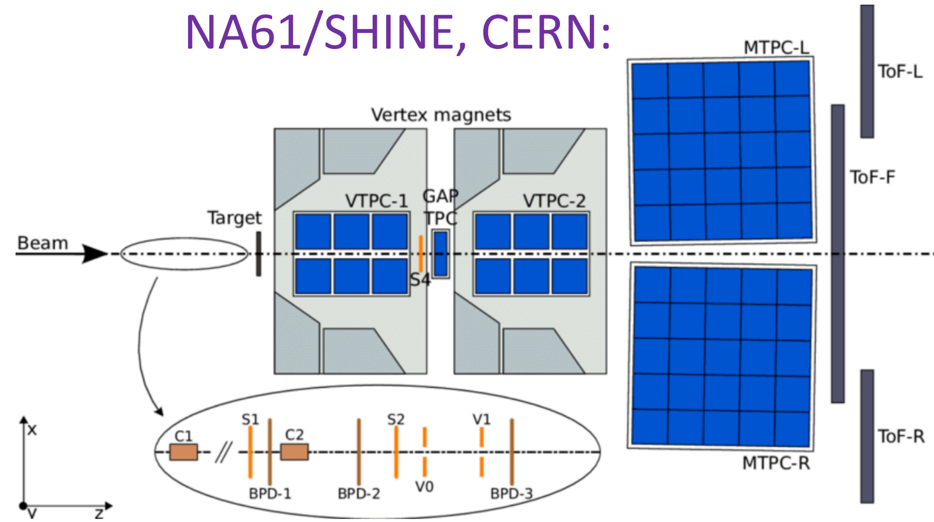
Flux Uncertainties

Experiments like EMPHATIC and NA61 are taking new hadron production measurements to improve flux predictions.

EMPHATIC

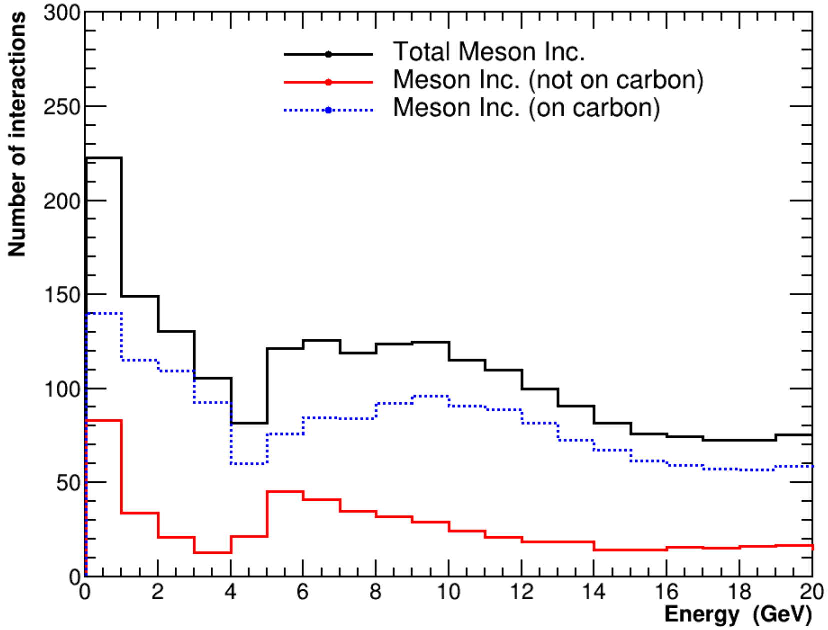


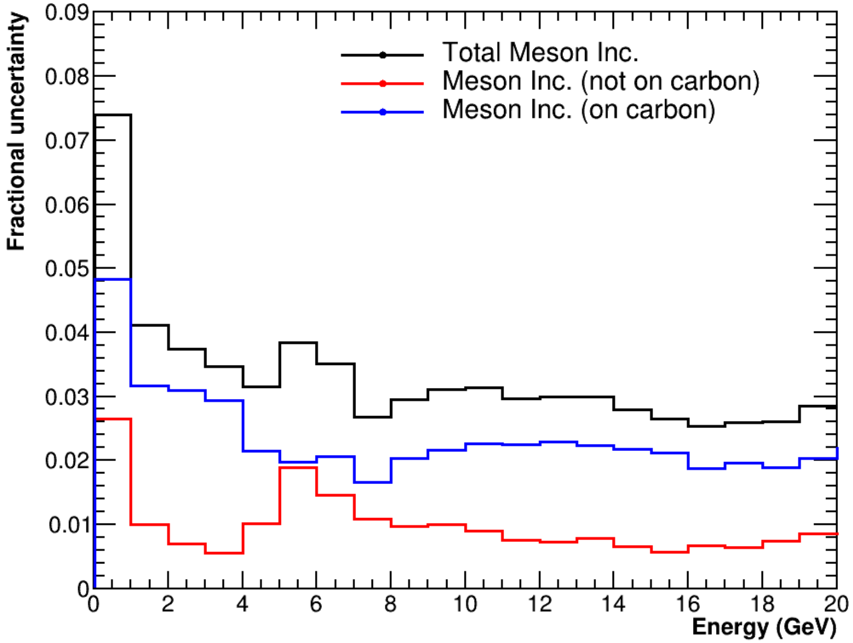
NA61/SHINE, CERN:



- Most of the Hadron production (HP) data is on Carbon.
- HP experiments wanted to know how important it is for them to make measurements on other nuclei..
- Looking into the interactions and uncertainties that happen on Carbon and other nuclei.

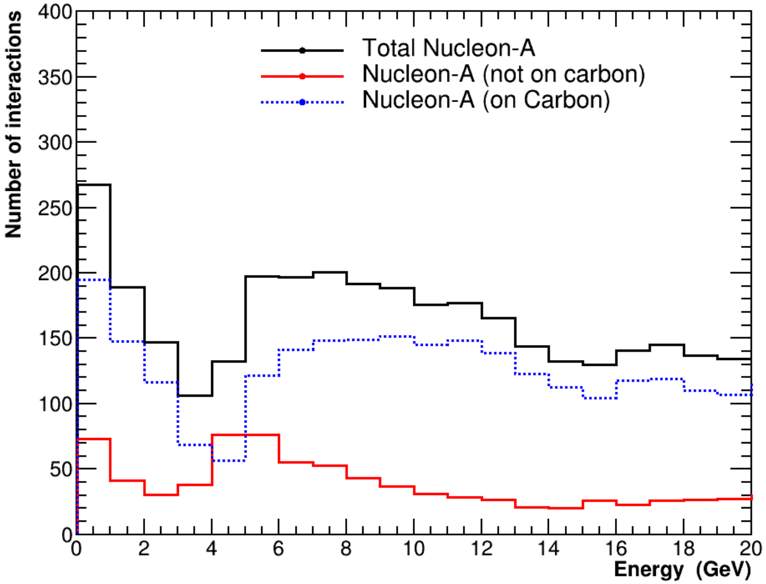
Meson inc

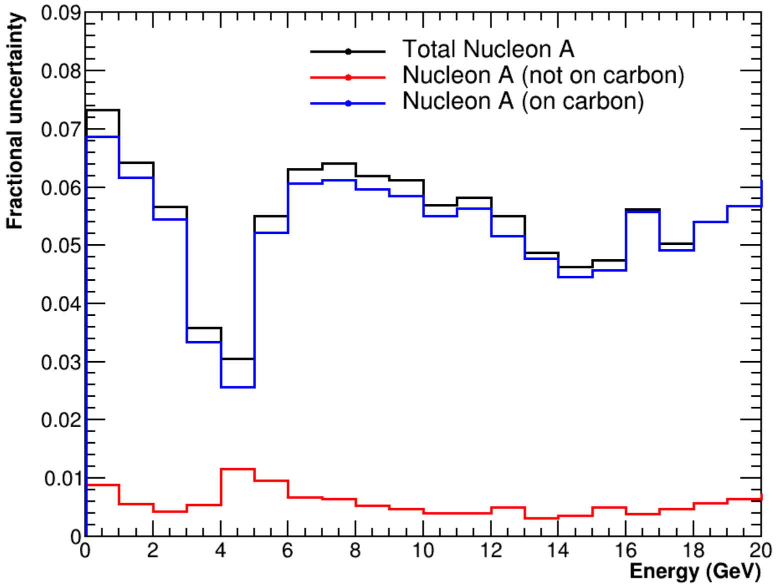




- The non-carbon interactions have lower uncertainties than on-carbon from meson inc.
- The uncertainties for non-carbon interactions are peaked at 5-8 GeV region as the interactions also dominate in that region.

Nucleon-A



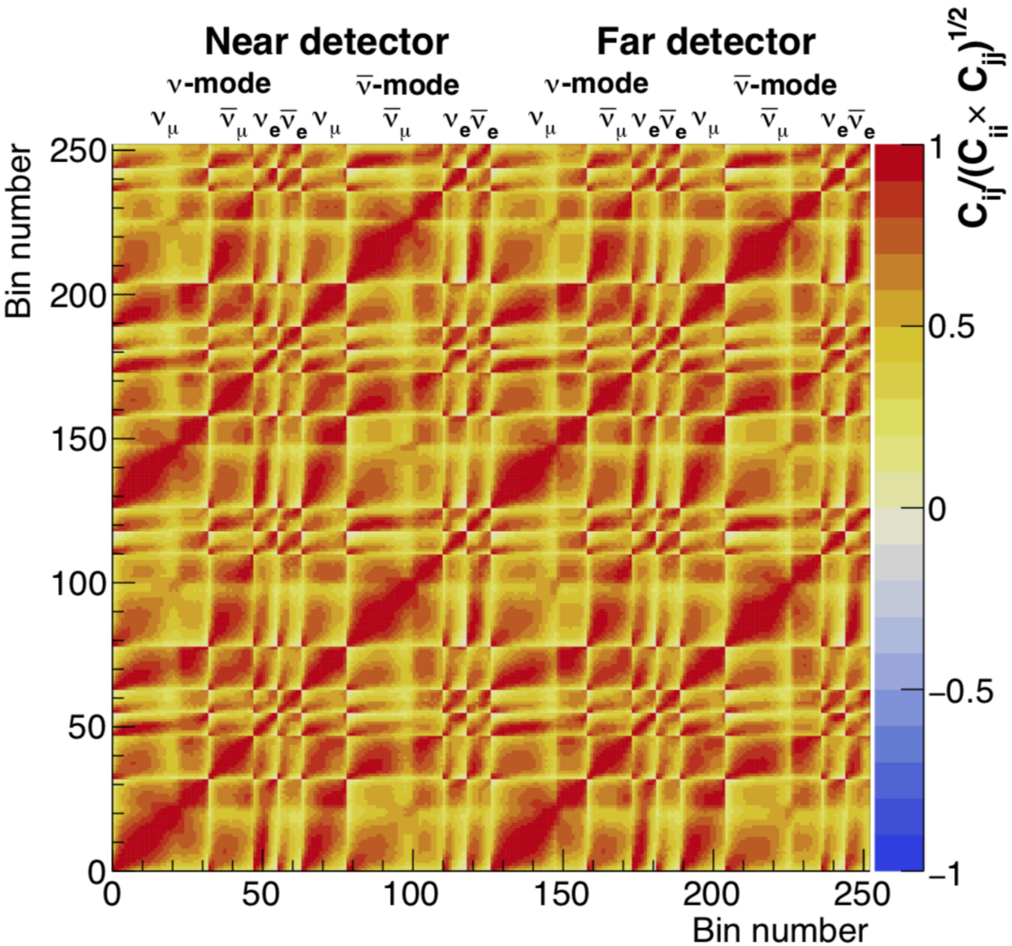


- The on-carbon interactions are mostly p+C interactions not covered by NA49 data. We apply a large (~40%) uncertainty to those interactions.
- The not-on-carbon are mostly p+notC interactions in phase space covered by NA49 data.

This study showed that other nuclei are not a dominant part of the uncertainties, so it is more critical that we expand the measurements on carbon rather than looking at other nuclei.

Correlations of the total flux uncertainties

Flux uncertainties are highly correlated across the energy bins.



HP uncertainties are evaluated by assuming the underlying data uncertainties are highly correlated across the energy bins.

Understand impact of underlying correlations on DUNE flux uncertainties and physics measurements

Summary and future plans

Future Plans : MINERvA

- DUNE vitally needs a detailed understanding of neutrino-nuclei interactions and depend heavily on models of neutrino-nucleus scattering.

- MINERvA is working with model developers and neutrino event generators to inform and improve neutrino interaction models using our data, to prepare for the DUNE era.

- Transverse kinematic imbalance measurements will allow better modeling of the neutrino-interaction models and the technique can be applied in future experiments where the effects of the nucleus are large.

- MINERvA technique to reduce flux uncertainties can be used for DUNE .

Future Plans : DUNE

- DUNE will start taking data in few years.
- My main aim will be involvement in DUNE for search of CP violation.
- In the meantime I will be working on understanding the flux better.
- Incorporating external measurements of hadron production such as EMPHATIC and NA61/SHINE to PPFX. This will bring my also exposure to these experiments.
- One another interesting study will be taking advantage of high statistics and good angular resolution in DUNE-ND, constrain flux uncertainties more nu-e scattering technique using the same technique as in MINERvA.

Conclusions

- DUNE will use a broadband beam and long baseline (1300 km) to make precise, simultaneous measurements of the mass ordering, the CP-violation phase, and the neutrino mixing angles.
- Accurate flux uncertainties are becoming increasingly important to neutrino oscillation physics
- Broad physics program.
- Neutrino oscillation experiments depend heavily on models of neutrino-nucleus scattering.
- MINERva has made a large contribution in understand the neutrino interactions with matter.

Thank you for your attention

Leading Roles in MINERvA

- Production Coordinator
  - Involves a team of grad students.
  - production of raw data sets to pass through various stages of calibration, reconstruction, data-overlay.
  - production of mc samples for both tracker and target detector configurations.
  - Special samples for machine learning predictions, and another extended samples.
- NuMI beamline Monitoring Expert
  - I served as an expert on NuMI beamline monitoring using MINOS detector. This involves handling the MINOS framework to plot the neutrino energy spectrum stability plots. These plots provide us the information about the stability of the neutrino/anti-neutrino beam for both MINERvA as well as NOVA detectors.
- Software Development
  - Implementing and modifying the existing MINERvA software as required with time making it more purposeful for collaboration.
- MINERvA Speakers Committee
  - Served on the MINERvA speakers committee where the role of this committee is to decide the speakers from MINERvA collaboration to go to various conferences and help them practice and make their talk to be able to present in a global physics community.

Outreach Activities

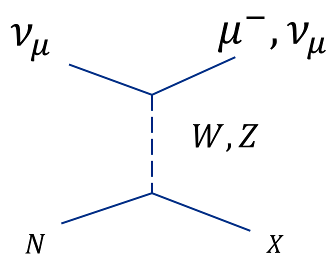
- MINERvA 101
  - Organizing MINERVA 101 which is a 3 - 4 days workshop includes lectures and exercises to learn about the Minerva software and data analysis
- FSPA Officer
  - core group of democratically elected officers which supports the community of students and postdocs by providing resources, organizing social events by holding professional development activities and organizing equity, diversity, and Inclusion related activities.
  - Member of Organizing committee for New Perspectives, 2019.
  - Involved in Users Meeting 2019.
  - Actively Organized Career seminar related talks.
- Women STEM
  - Involved in women stem workshop, 2018 for high school girls.
- MINERvA Tours
  - A tour of MINERvA detector as well as MINERvA shift control to Executive people, like Julie Payette and

Initial Background Rejection

- ν-e scattering is very rare, even for ν interactions:

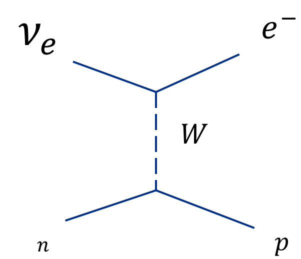
Most Events

(ν_μ Charged or neutral Current)

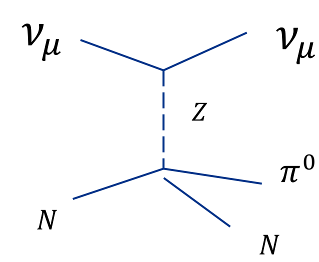


Rare but hard to reject:

ν_e Quasi-elastic (CCQE)



Coherent π^0

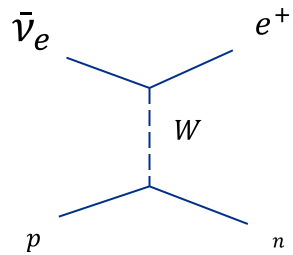


- Simple cuts can eliminate most background events while keeping high fraction of signal events
  - Obvious muon-like event rejection
  - Upstream energy rejection
    - Removes neutrino interactions upstream of detector that make μ

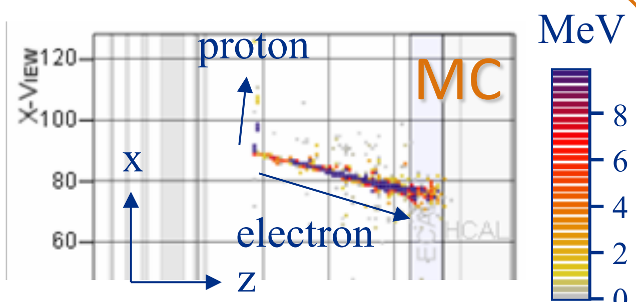
Background Events

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

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



Electron neutrino fraction in flux is small ~ 1%.



- If recoil nucleon is not observed, it looks similar to signal
- Angles of electron have wide spread while signal is very forward

Use $E\theta^2$ to select very forward signal

Neutral current single π^0

$$\nu_\mu A \rightarrow \nu_\mu A \pi^0 \quad \text{NC-coherent } \pi^0$$

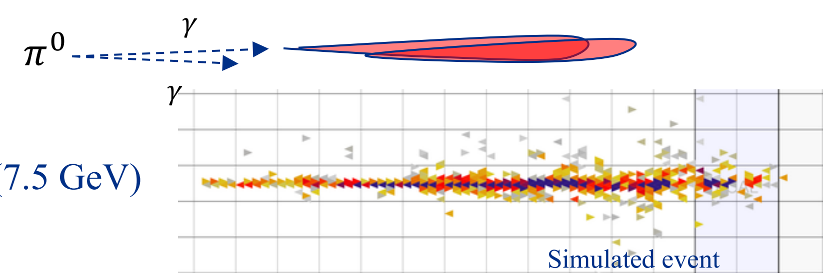
$$\nu_\mu N \rightarrow \nu_\mu N \pi^0 \quad \text{NC-resonant } \pi^0$$

Also, photon has wide spread of angle

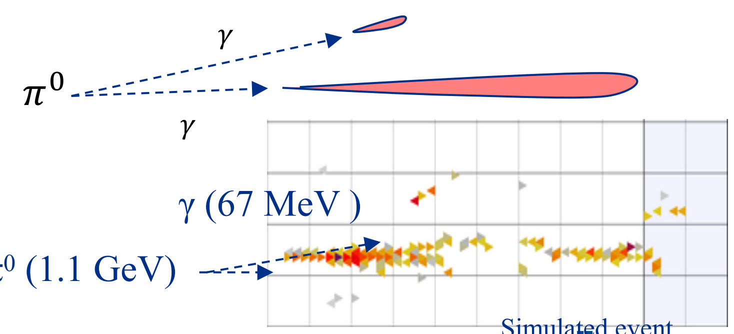
In addition, use dE/dx to reject

1. Small opening angle between two gammas

π^0 (7.5 GeV)



2. One of gammas is not observed in the detector



π^0 (1.1 GeV)

Analysis Flow and Effciency

Shower cone Reconstruction → • Electron Energy>0.8GeV • Fiducial cut → Other reconstruction quality cuts → • $E\theta^2$ • dE/dx → Signal sample

Kinematic constraint on νe scattering, using Mandelstam variables:

$$\nu e \rightarrow \nu e \quad t = \frac{s}{2}\left(1-\cos\theta^*\right) \quad y = -\frac{1}{2}\left(1-\cos\theta^*\right) \text{ in CM frame} \Longrightarrow t = -sy$$

$$u = -2E_\nu E_e(1-\cos\theta) \quad \text{in lab frame}$$

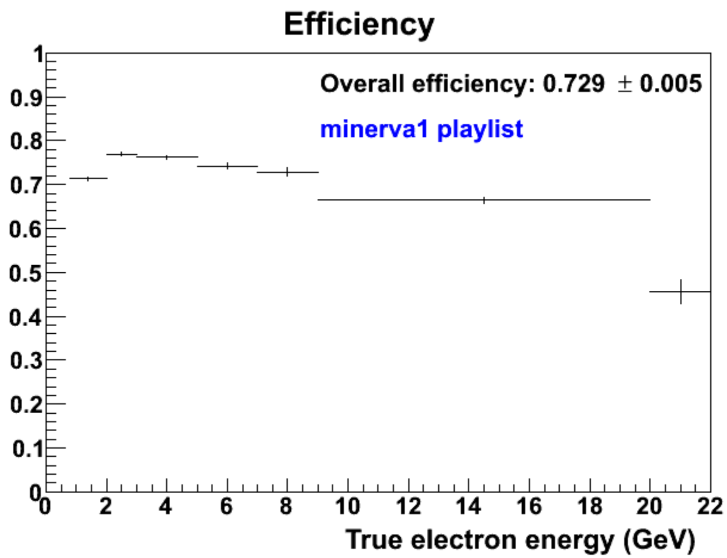
$$s + t = -u$$
$$s(1-y) = 2E_\nu E_e(1-\cos\theta)$$
$$2m_e(1-y) = E_e\theta^2$$

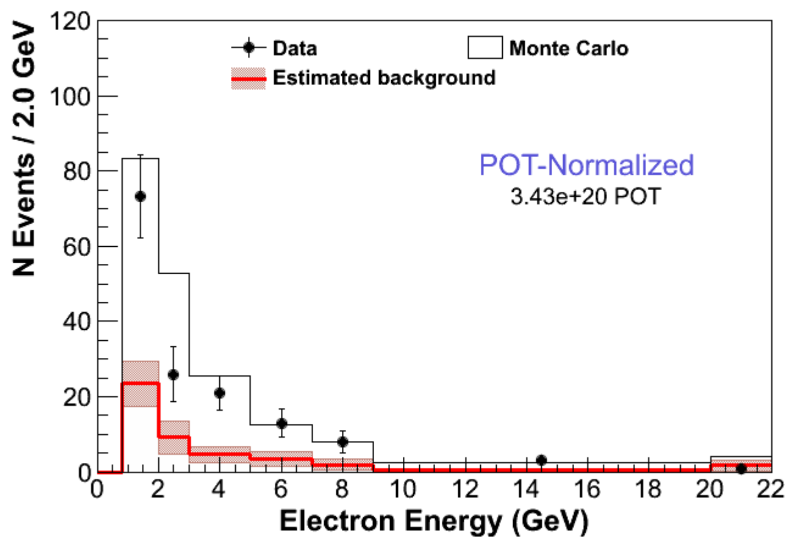
Since $0 < y < 1, \qquad E_e\theta^2 < 2m_e$

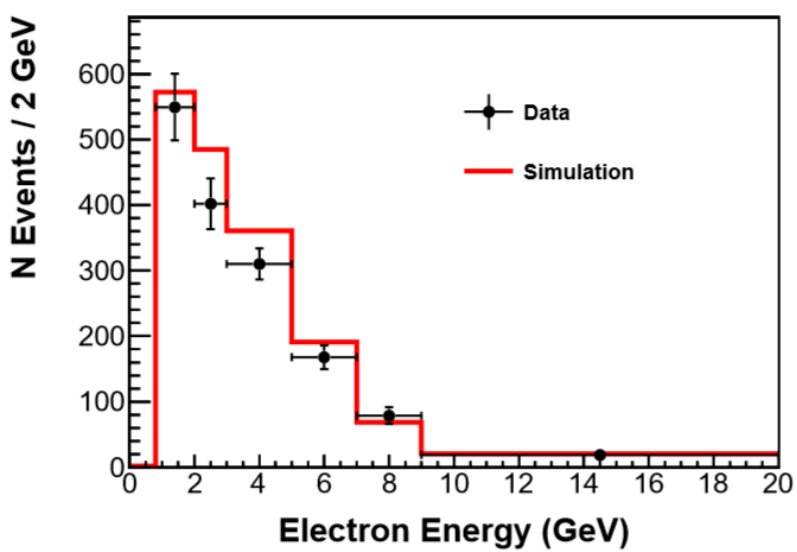
Efficiency

The signal efficiency of the event reconstruction selection after all cuts =>

Efficiency = (Reconstructed)/(Incident)



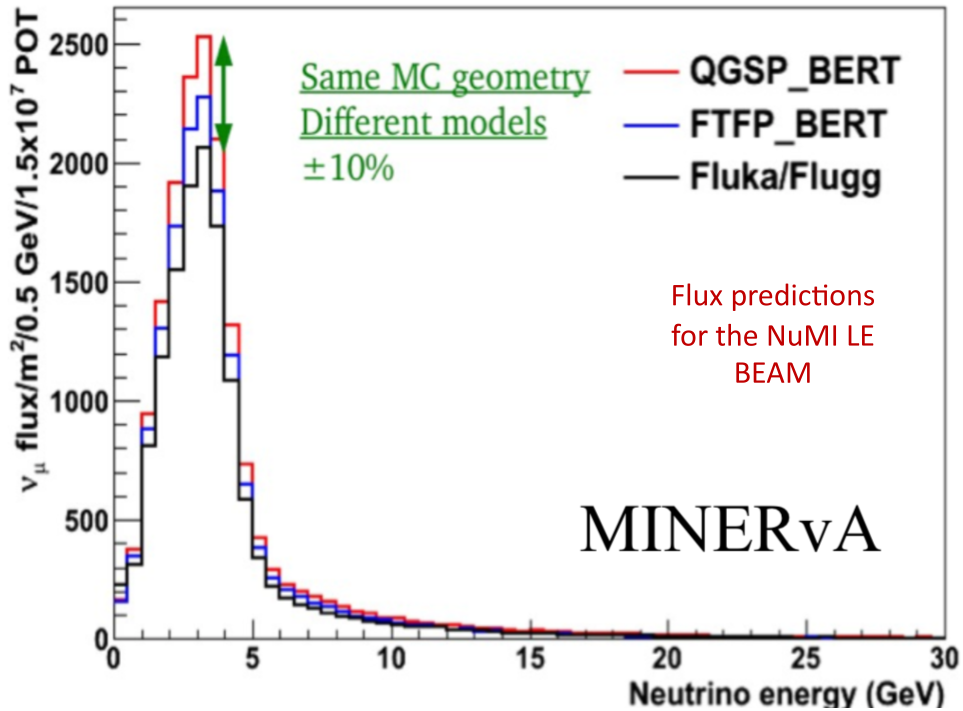




Problem with Flux simulation

There is a huge discrepancy between various models.

Model developers are always trying to improve, but it is not realistic to expect perfect predictions of all processes that matter to flux predictions



Fermilab

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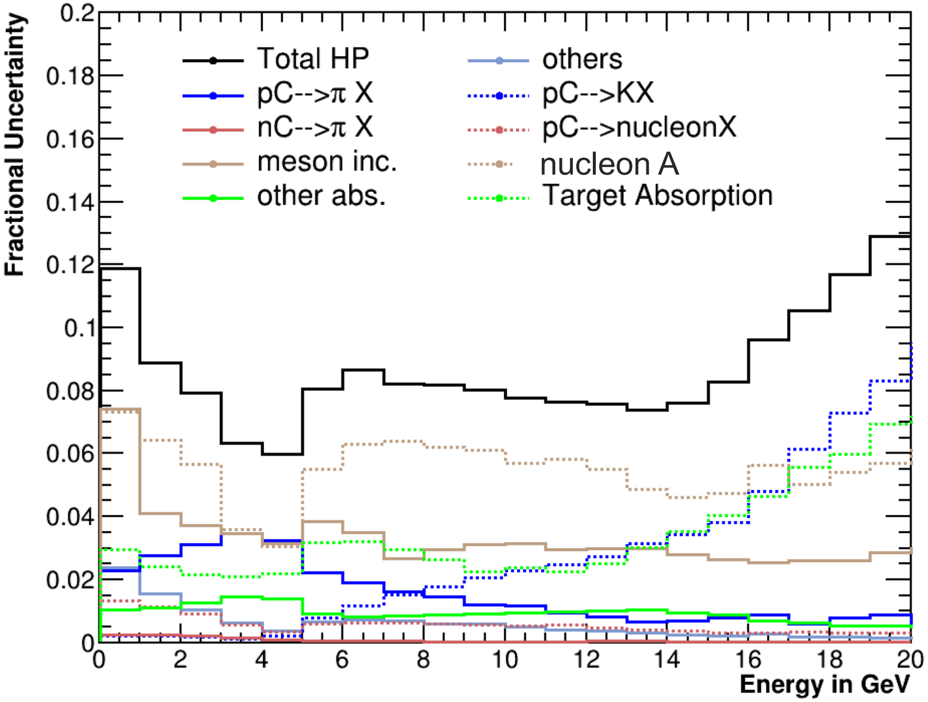

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Meson inc : Pion and kaon reinteractions. No data correction is applied for interactions incident with mesons. A 40% uncertainty is also applied for this case.

Attenuation Correction:

Target Absorption : Uncertainty on the total probability of interaction in target.

Other abs : Uncertainty on the total probability of interaction in other materials

Chi 2 and number of sigma

- Using wiggled flux:
  - chi2 = 4.5 (evaluated using data(with stat + sys uncertainties) and mc (stat + flux uncertainties)
  - The difference in total number of events for data and mc for the new nu-e scattering spectrum is = 0.7 $\boldsymbol{\sigma}$

- Using Standard flux:
  - The latest $\boldsymbol{\chi}^2$ = 5.1
  - The difference in number of events for data and mc for the new nu-e scattering spectrum is = 1.8 $\boldsymbol{\sigma}$

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Chi2 minimize for getting the fit

$$\chi^2 = (Data - MC)^T . C_{TOT}^{-1} . (Data - MC)$$

$C_{TOT}^{-1} \rightarrow Total\ Covariance\ Matrix$

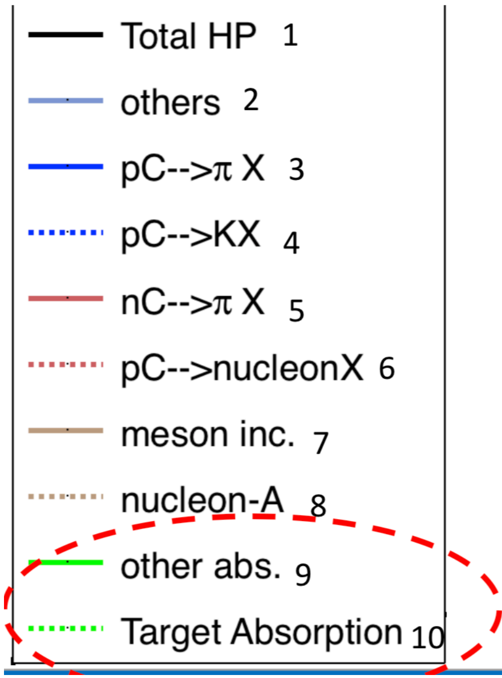
- Total Covariance Matrix is given by:

$$C_{TOT} = C_{DATA} + C_{MC,weight} + C_{MC,syst}$$

$$C_{MC,weight}[i,i] = MC_i \times \left(\frac{\delta w_i}{w_i}\right)^2 \times w_i$$

$C_{MC,systematics} \rightarrow$ Covariance matrix from MC systematics

$C_{DATA} \rightarrow$ Covariance matrix from Data



Attenuation

- When a particle traverses through the volume, correction is:
  - $\boldsymbol{c(r) = e^{-\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}}$ **[1]**

- When an interaction happens inside a volume:
  - $\boldsymbol{c(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}}$ **[1]**

  - Here:
  - C(r) is the central value correction
  - N_A is the number of atoms with atomic number A seen by the particle when it traverses the volume

Fermilab