DUNE Systematic Flux Uncertainties

Ian D. Kotler FRAS on behalf of the DUNE **Collaboration**

APS DPH-PHENO 2024

May 14th, 2024

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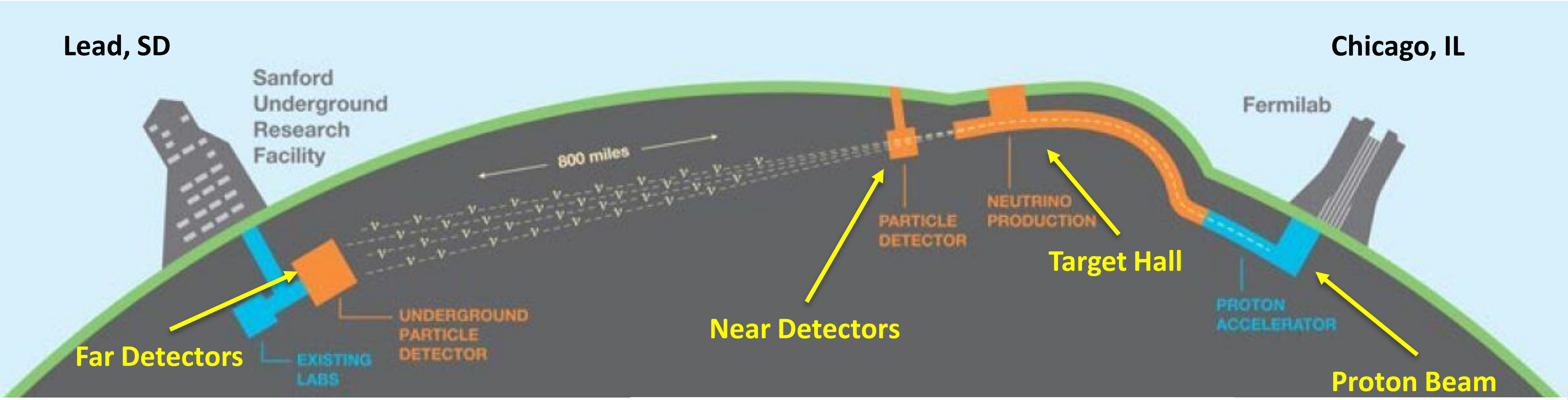
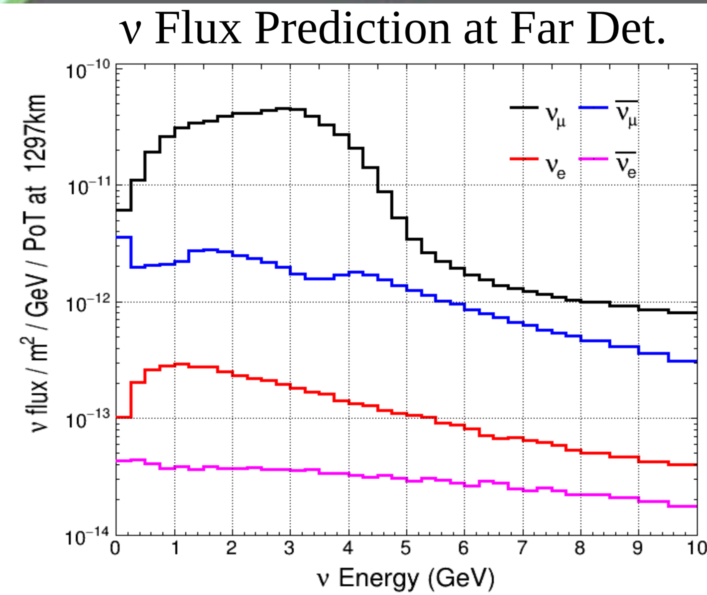
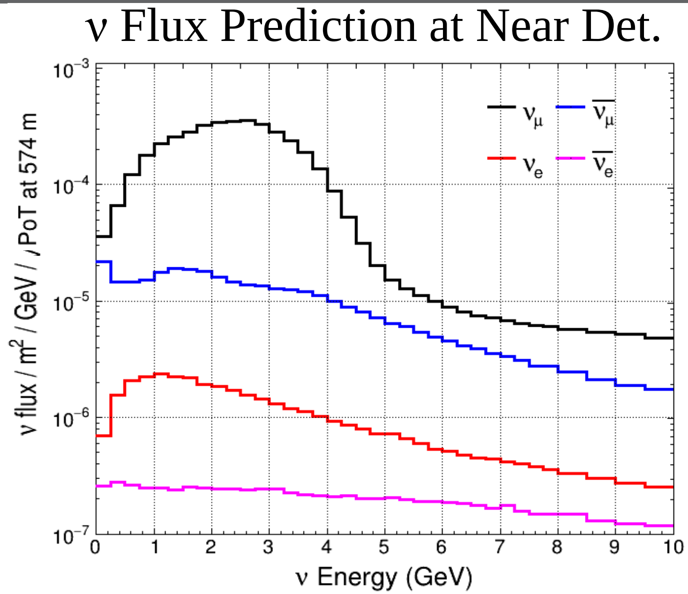
What is DUNE?

- The Deep Underground Neutrino Experiment hosted at Fermilab
- Comprised of 1400+ collaborators across 35+ countries.
- Physics goals include (but not limited to):
  - Address Baryon Asymmetry of the Universe (BAU)
    - Measure δ_{CP} in lepton sector.
  - Determine the neutrino mass ordering
    - Sign of $\left|\Delta m^2_{32}\right|$?
  - Determine the octant of θ_{23}.
    - Is θ_{23} greater or less than $\frac{\pi}{4}$?
  - Near Detector Complex hosts a suite of rich physics programs .
    - Suite of detectors {LAr, GAr, SAND, TMS, PRISM …}
  - And so much more!
    - Interested in joining DUNE? Get started here.

How does DUNE work?

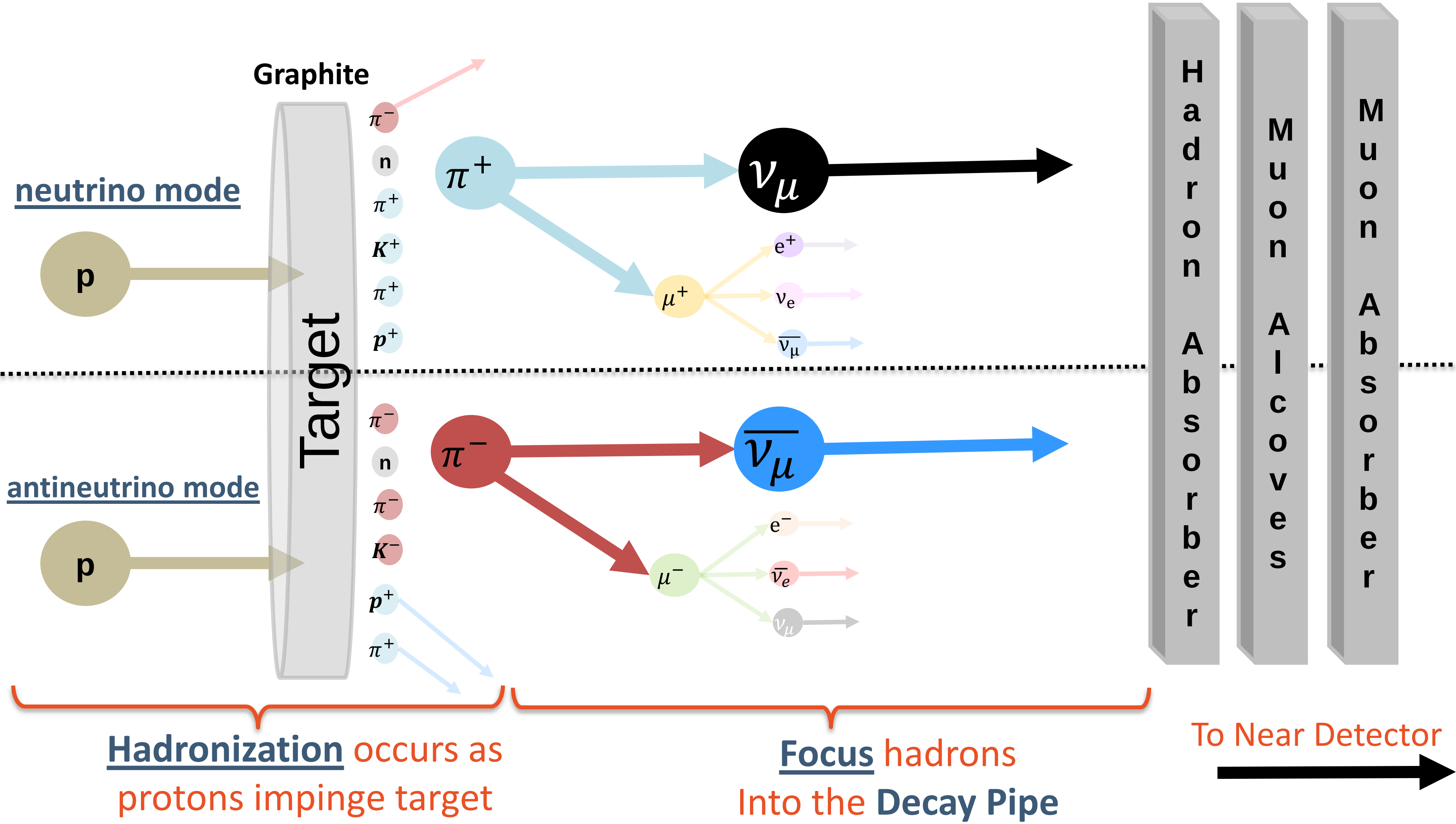






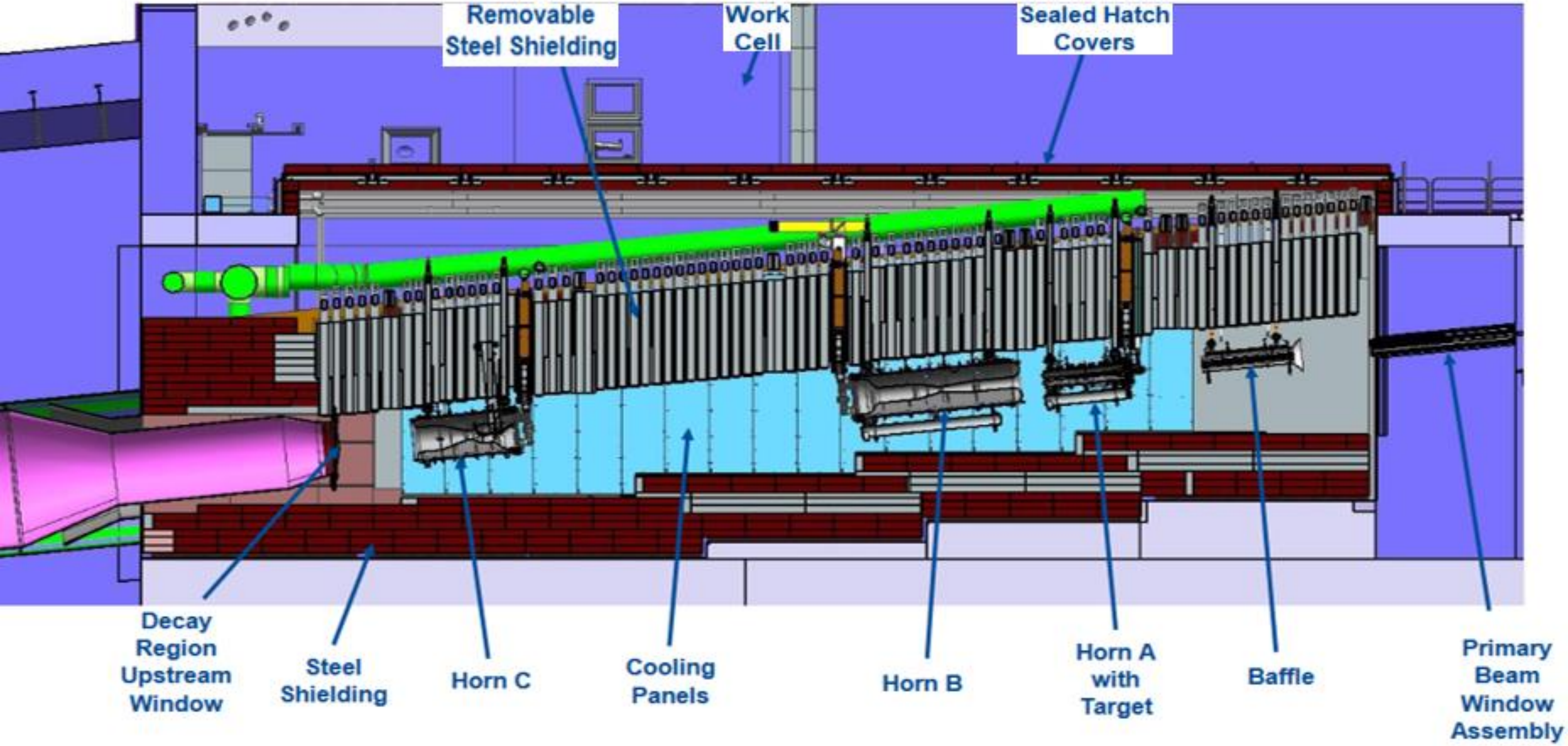
- Protons impinge target.
- Secondary beam of pions is created and focused.
- Pions decay to neutrinos and muons.
- Near Det. samples the neutrino beam.
- Neutrinos oscillate and experience matter effect.

Hadron Production for DUNE



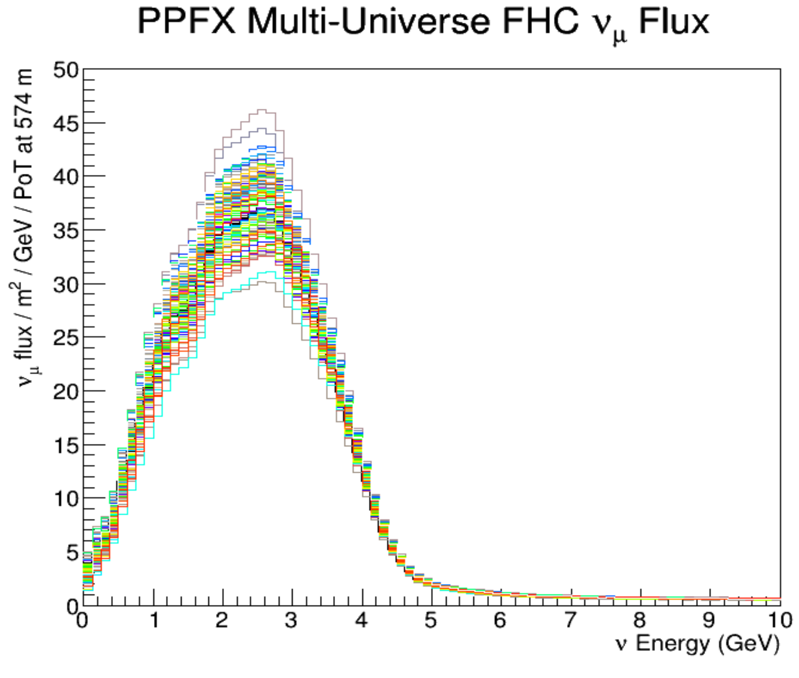
Focusing Effects

- 3 Horn Focusing System
- 2 modes of operation
  - Current: $\pm$ 300kA
- 60+ sources of beam focusing uncertainties
- Target Hall components contribute to Hadronization

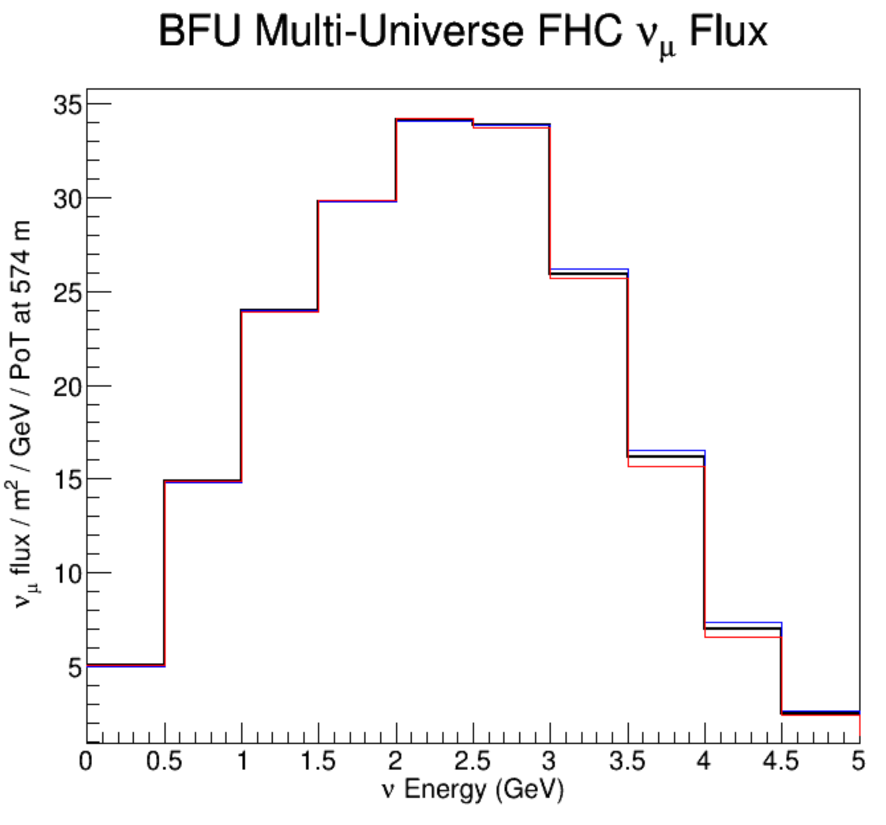


Modeling the DUNE Flux

- **Nominal** flux is **input into PPFX**.
- **Varies the flux** parameters across **100 universes**.
- Specialized **reweighters** and **external inputs** account for **Hadron Production** processes.

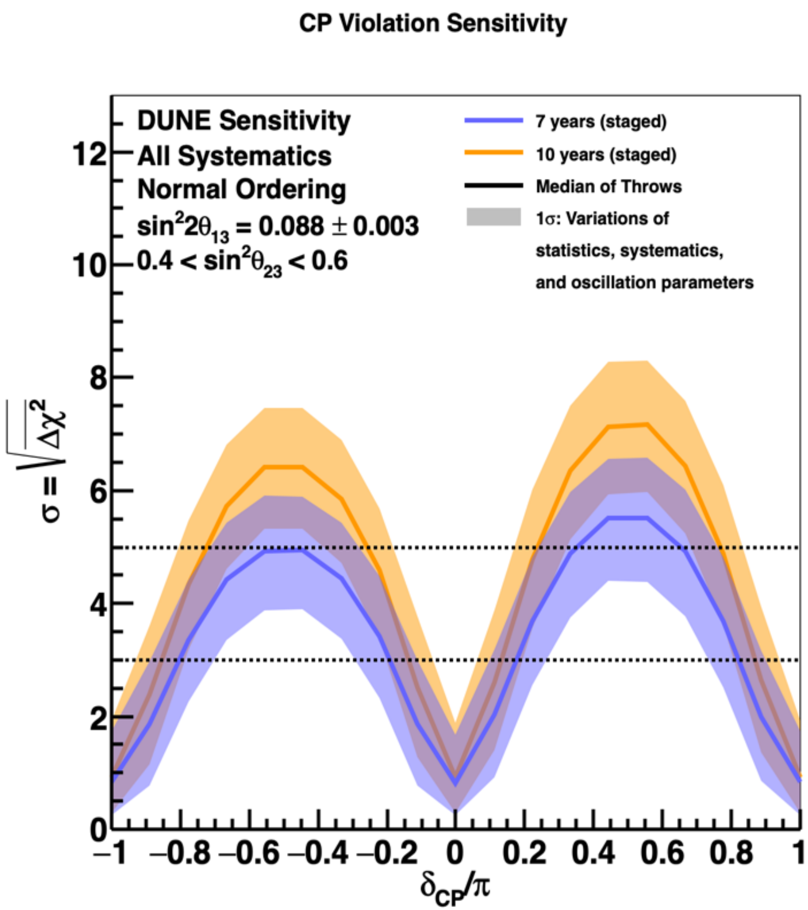


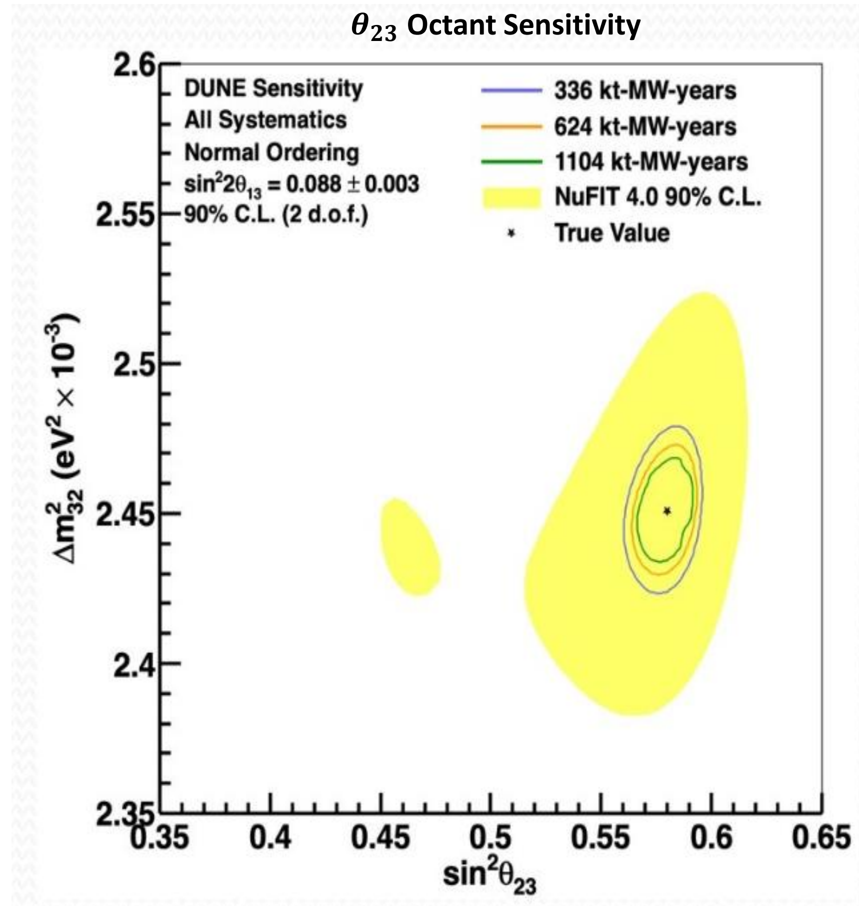
- Nominal flux is generated in g4lbne
- Varies nominal by engineering tolerance.
  - Results **in 2 universes, $\pm 1\sigma$**.



The Importance of Systematics

- See upcoming publication, "The DUNE Neutrino Flux Simulation" details on covariance.

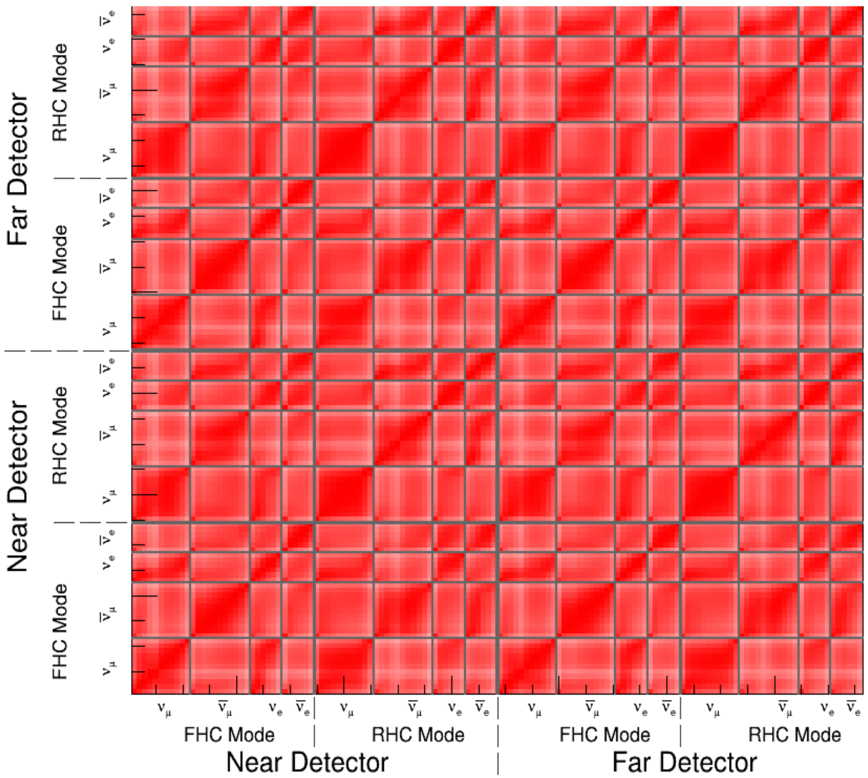




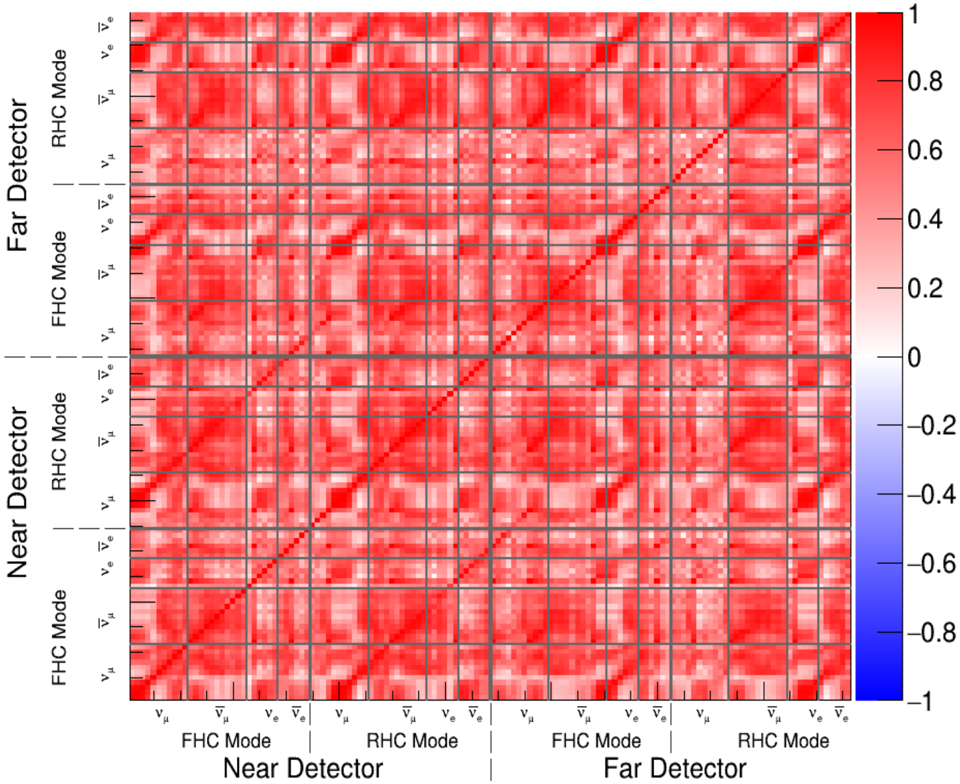
Determining the Correlations

- The **Correlation** Matrices **reveal the magnitude** of the **relations** amongst the various **sources of uncertainty** across all **modes**, **detector locations** and **neutrino species**.

Hadron Production Correlations

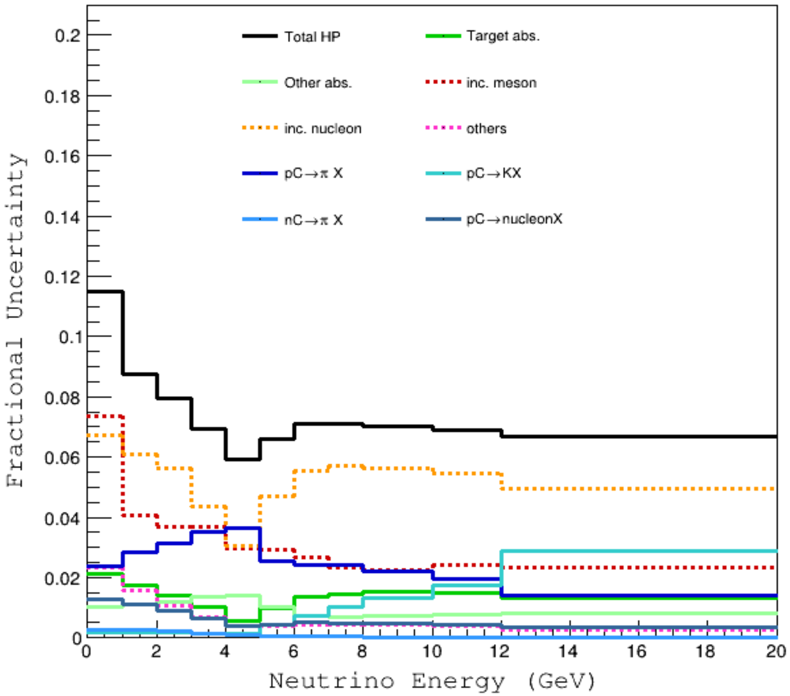


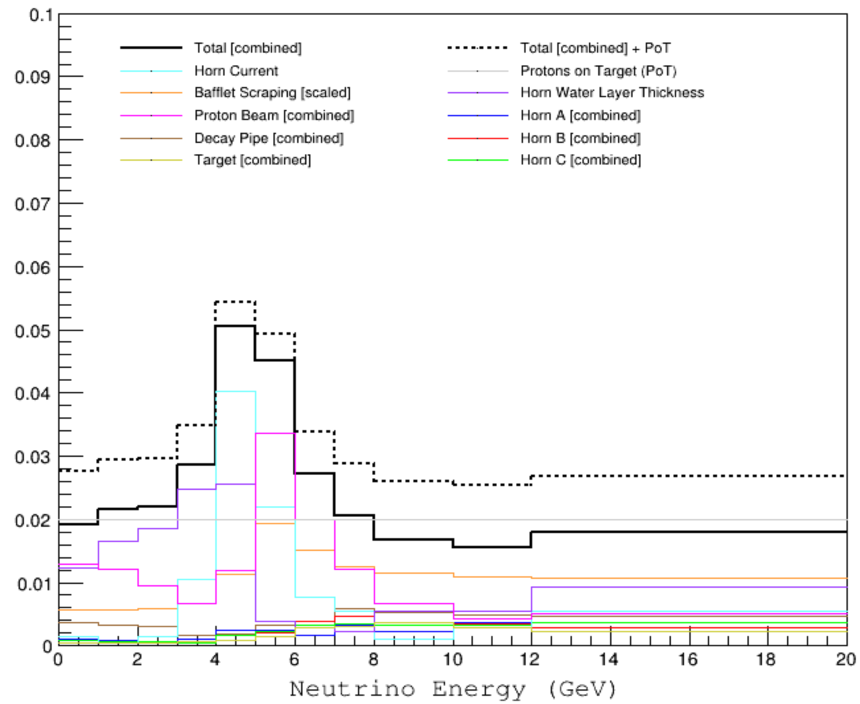
Beam Focusing Correlations



Individual Uncertainties

- Taking the **square root** of the **diagonals** of each matrix yields the **individual uncertainties**.

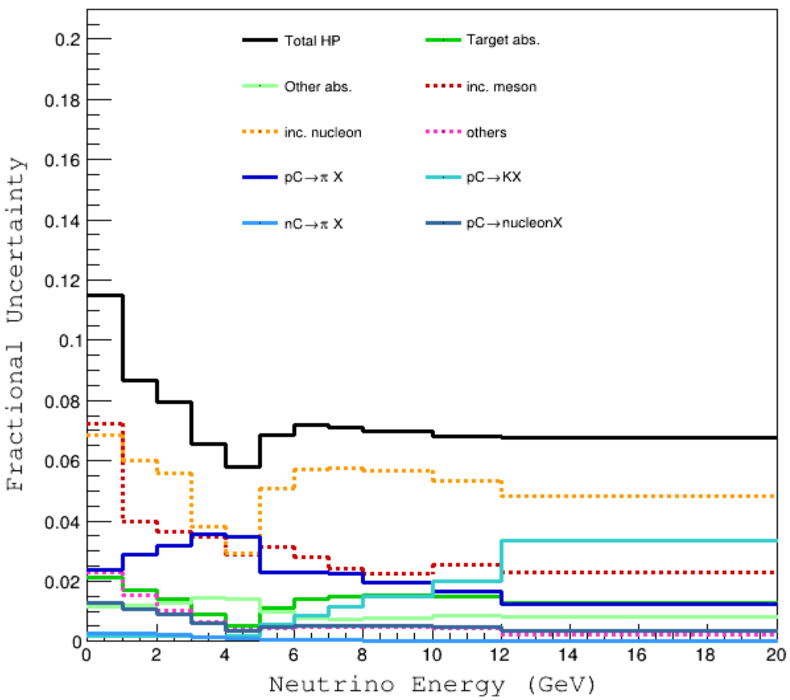


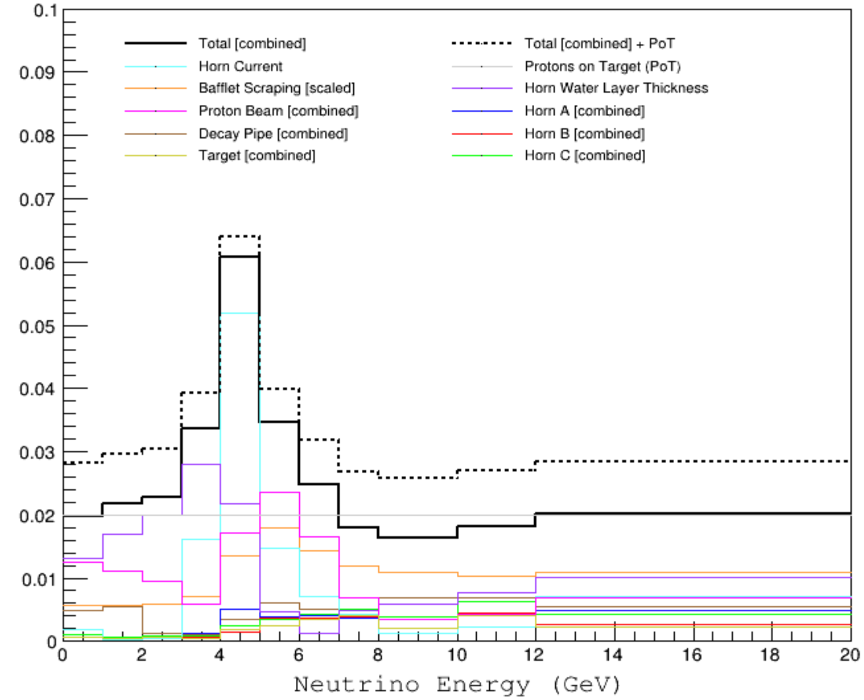


Mode	Location	Species	Mode	Location	Species
neutrino	Far Det.	ν_μ	neutrino	Far Det.	ν_μ
Hadron Production			**Beam Focusing**		

Individual Uncertainties

- Taking the **square root** of the diagonals of each matrix yields the **individual uncertainties**.

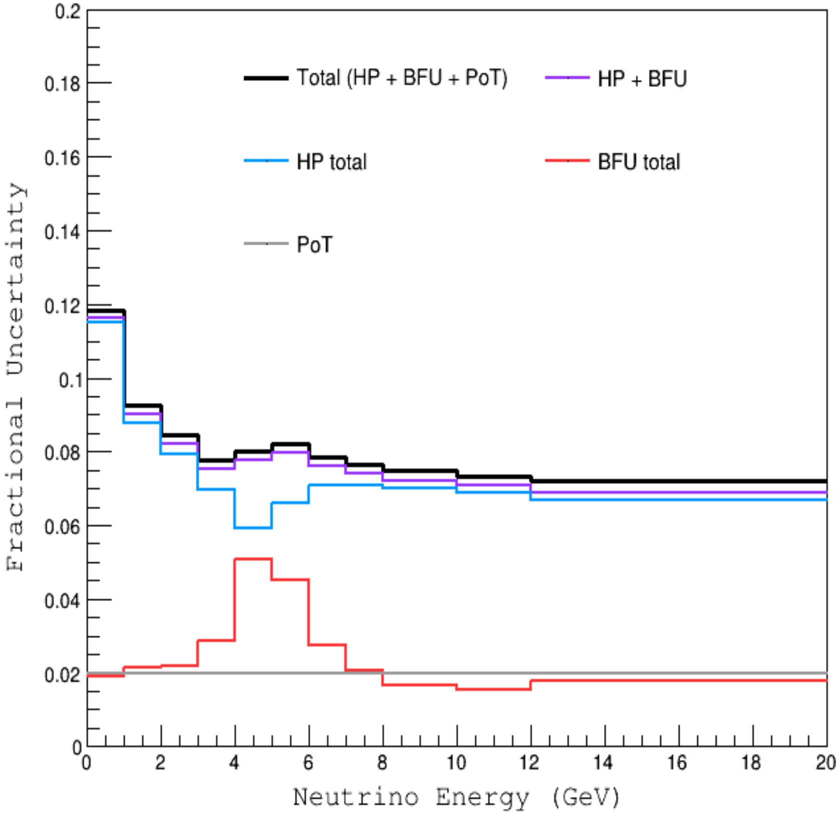


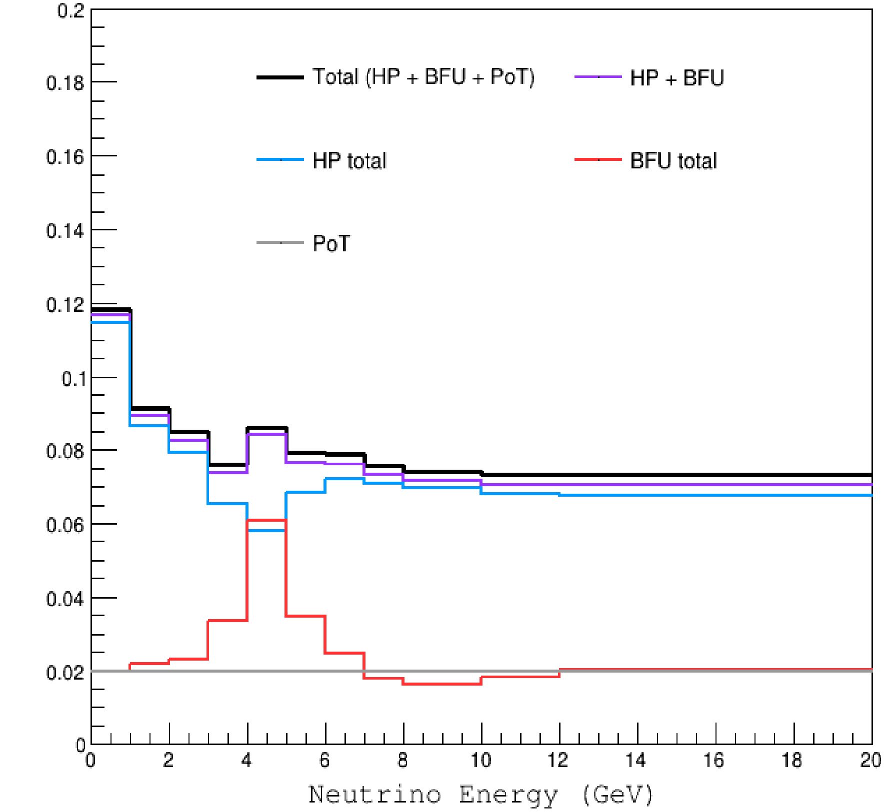


Mode	Location	Species	Mode	Location	Species
neutrino	Near Det.	ν_μ	neutrino	Near Det.	ν_μ
Hadron Production			**Beam Focusing**		

Total Systematic Uncertainties

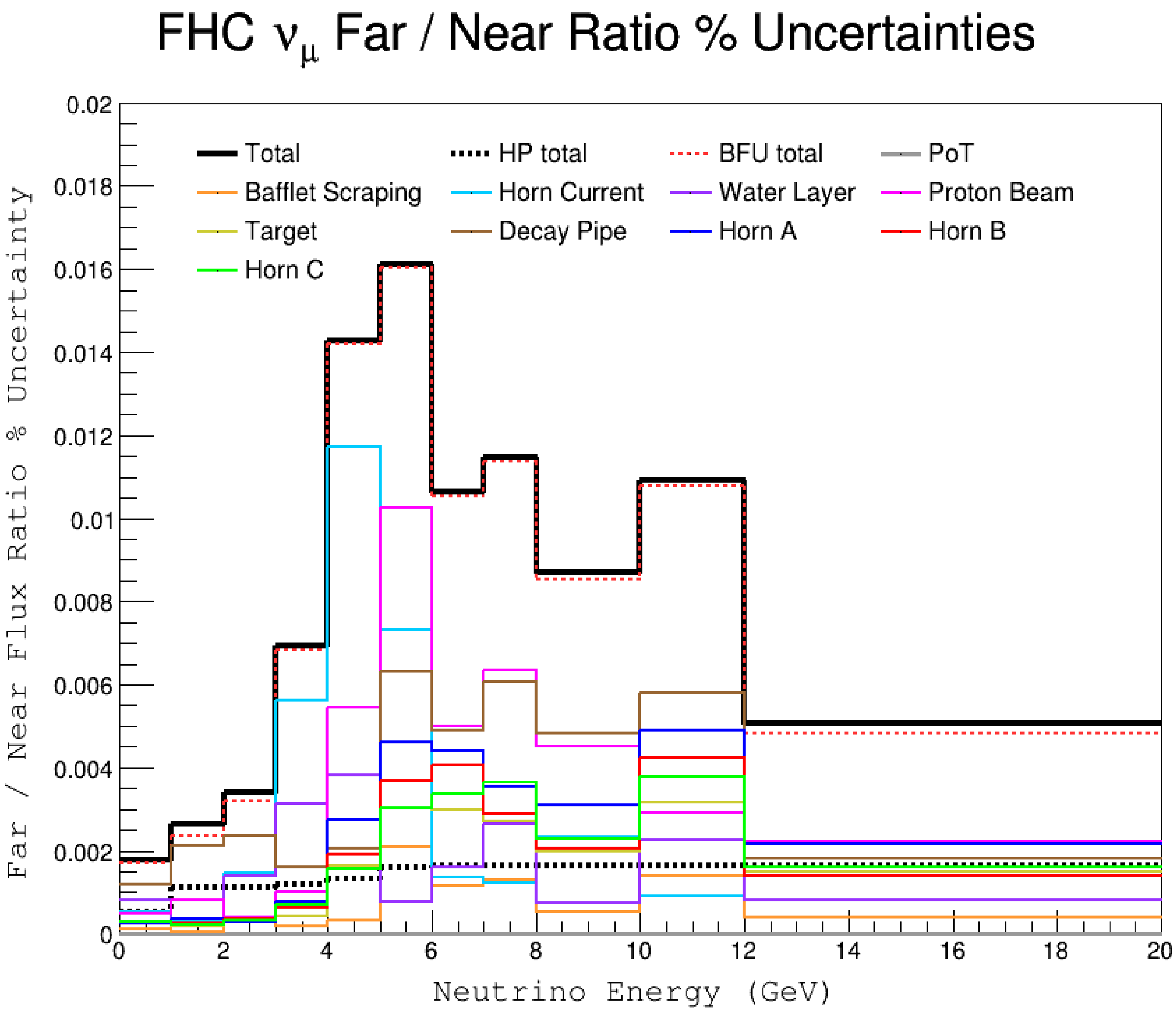
- **Adding** Hadron Production and Beam Focusing **Covariances** to obtain **Total Beam Covariance**.





Mode	Location	Species	Mode	Location	Species
neutrino	Far Det.	ν_μ	neutrino	Near Det.	ν_μ

The Far to Near Flux Ratio



- Beam **Focusing dominates.**
- Hadron Production now < 0.2%
- Previous max of 6% at 4.2 GeV ~ 1.5%
- Flux Peak Unc. at 2.5 GeV ~ 0.4%

Conclusions

- DUNE is an accelerator-based **neutrino experiment** hosted at **Fermilab**
- Among **DUNE's many goals** includes determining:
  - δ_{CP}
  - **neutrino mass hierarchy**
  - **octant of** θ_{23}
- To achieve the **high sensitivity** required to measure parameters **requires covariance matrices** for all Systematic Uncertainties
- The **covariance** matrix **encapsulates** the **all** information regarding **uncertainties and correlations**.
- **Hadron Production** and **Beam Focusing** are the **largest contributors** to beam systematics **uncertainties**.

Back Up Slides

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May 14th, 2024

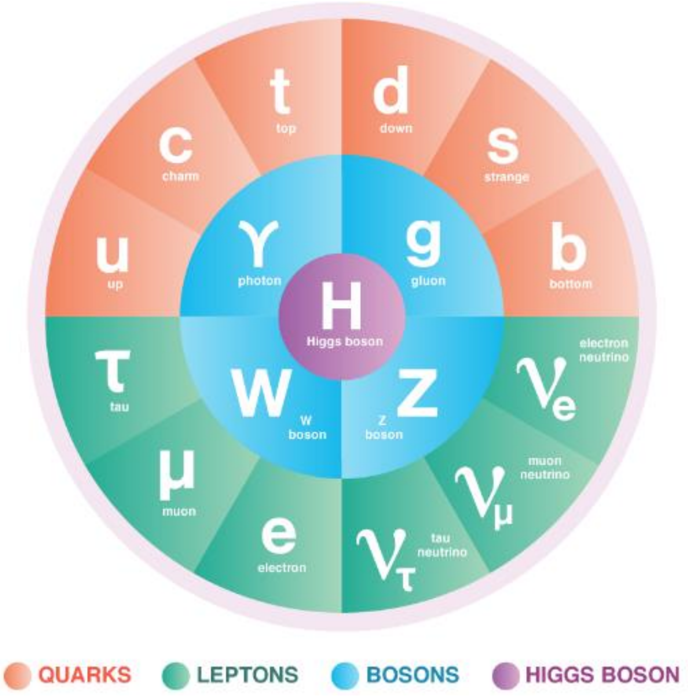
(2:30 - 2:45) pm

David Lawrence Hall, 107

University of Pittsburgh

What are neutrinos?

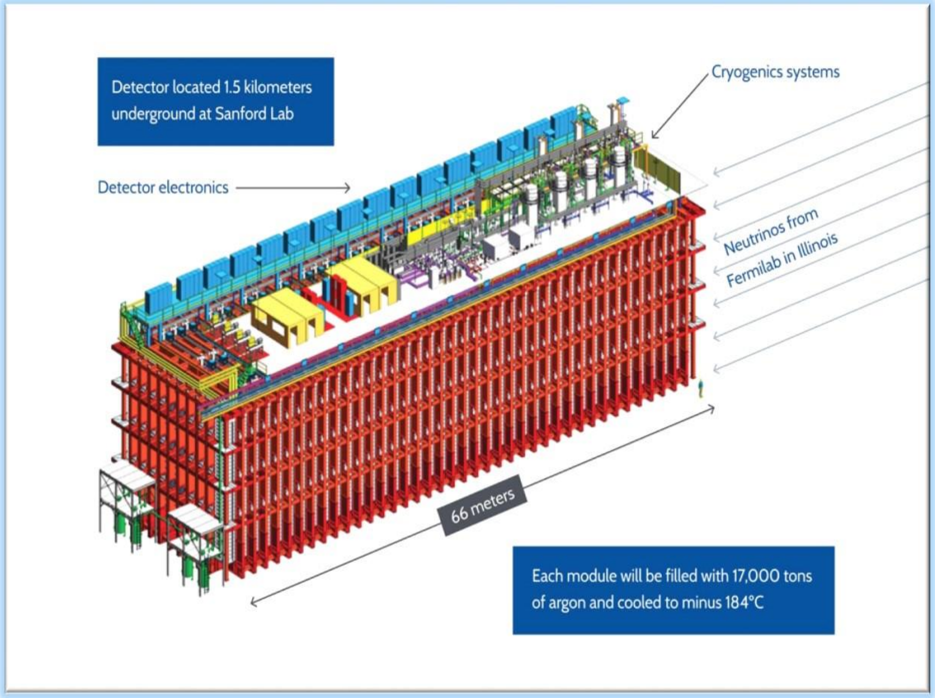
- Fundamental particles of the SM.
- Colorless, neutral leptons
- 3 distinct flavors: ν_e , ν_μ , ν_τ
- 3 distinct masses: ν_1 , ν_2 , ν_3
- Can oscillate between flavors, governed by the PMNS matrix.

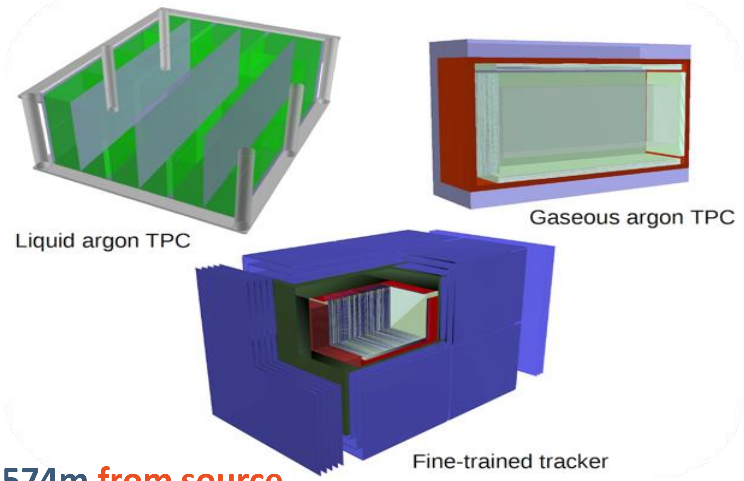


$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

DUNE Detection Systems

- 2 Detector Design (Near and Far Detectors)
- Far Det.~ 1297km from source located at SURF
- Comprised of 4, 17kt LAr TPC's
- Cooled to ~ 90 Kelvin
- Fiducial Volume of 10kt per TPC
- Primary Goal: Measure Oscillated Flux





- Near Det. ~ 574m from source
- Comprised of 3 subdetectors:
  - LAr TPC (50-ton)
  - GAr TPC (1-ton)
  - SAND (8-ton plastic scintillator)
- LAr TPC measures unoscillated flux
- GAr TPC monitors the muon flux
- SAND (Fine-trained tracker) measures:
  On-Axis beam flux, possible Neutron detection.
- Argon TPC's can move off axis (PRISM)
  Deconvolves flux from ν cross-section on Argon.
- Primary Goals:
  - Measure Unoscillated Flux /
  - Characterize the Beam

What is Hadron Production?

- **Largest source of systematic uncertainty** for DUNE **flux prediction**.
- **Sources** of Hadron Production in DUNE include:
  - **Protons impinging** on Graphite **target**: $p + {}^{12}C \rightarrow \pi^{\pm} + X$
    $p + {}^{12}C \rightarrow K^{\pm} + X$
    $p + {}^{12}C \rightarrow p(n) + X$
  - **Secondary** Interactions of **neutrons**: $n + {}^{12}C \rightarrow \pi^{\pm} + X$
  - Hadron **Absorption** both **inside** and **outside** the **target**.
  - Secondary **meson** and **nucleon interactions**
  - And many **others**!
- **Simulating** these **Hadron Production** uncertainties **requires**:
  - **Input data** from dedicated experiments [**NA49,SHINE**, **NA61***]
  - **Package to Predict the Flux** (PPFX), developed originally for Minerva by Leonidas Aliaga Soplin of U. Houston.

Beam Focusing Effects

- **2nd largest source of systematic uncertainty** in DUNE flux prediction.

- **Over 60 sources**, all arising from engineering tolerances, such as:
  - Horn Current (±300kA)
  - Thickness of Water Layer cooling Horns.
  - Scraping of proton beam against the Bafflet.
  - Various characteristics of:
    - Proton Beam characteristics (Radius, Position, Angle, ...)
    - Target characteristics (Density, Position, Length, ...)
    - Horns A,B,C characteristics (Position, Ellipticity, Tilt, ...)
    - Decay Pipe characteristics (Radius, Position, Cross-Section, ...)

Calculating BFU Covariance

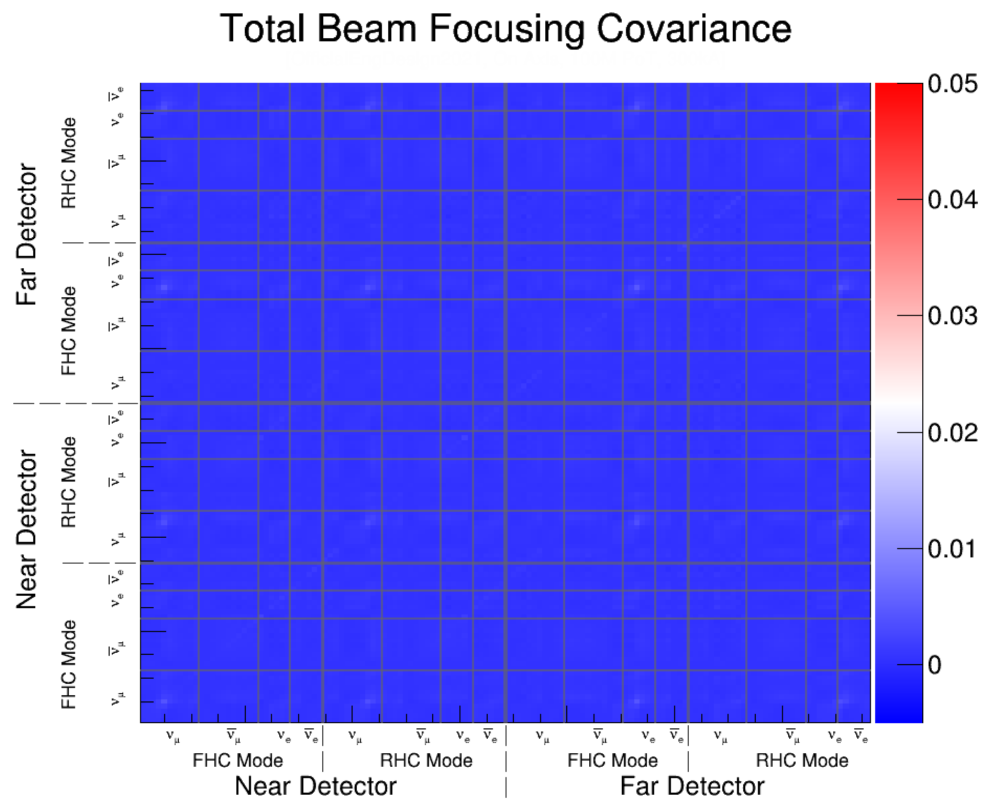
- Calculate individual covariances for each source of uncertainty (i) in both universes.

$$\mathrm{Cov}^{(i)}_{\mathrm{BFU},+}\left(x_j, x_k\right) = \frac{\left(x^{(i)}_j - \bar{x}_j\right)\left(x^{(i)}_k - \bar{x}_k\right)}{\bar{x}_j \bar{x}_k}$$

$$\mathrm{Cov}^{(i)}_{\mathrm{BFU},-}\left(y_j, y_k\right) = \frac{\left(y^{(i)}_j - \bar{y}_j\right)\left(y^{(i)}_k - \bar{y}_k\right)}{\bar{y}_j \bar{y}_k}$$

- Total BFU Covariance is average of universe covariances.

$$\left\langle \mathrm{Cov}^{(i)}_{\mathrm{BFU}}\left(x_j, x_k, y_j, y_k\right)\right\rangle = \frac{1}{2}\left[\mathrm{Cov}^{(i)}_{\mathrm{BFU},+}\left(x_j, x_k\right) + \mathrm{Cov}^{(i)}_{\mathrm{BFU},-}\left(y_j, y_k\right)\right]$$



- Here we see the BFU Covariance is quite small indicating the magnitudes of the focusing uncertainties are likewise, small.

Calculating HP Covariance

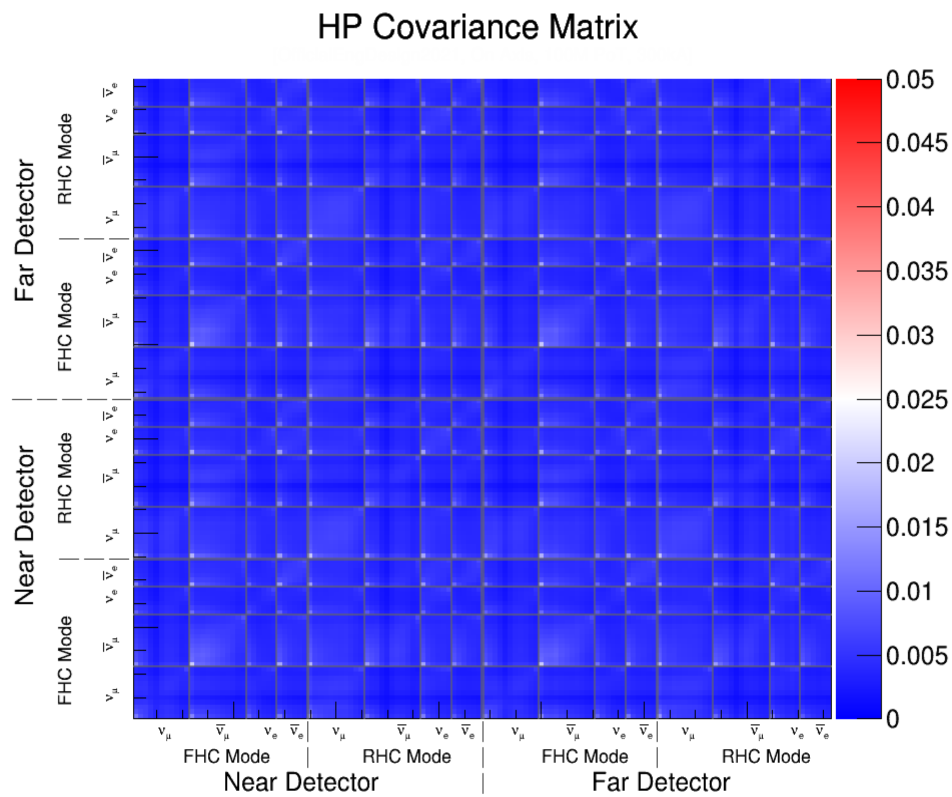
- Calculate individual covariances for each source of uncertainty (i) in both universes.

$$\left\langle \mathcal{C}\mathrm{ov}_{\mathrm{HP}}^{(i)}\left(z_j, z_k\right)\right\rangle = \frac{1}{\mathcal{N}} \sum_{u=1}^{\mathcal{N}} \mathcal{C}\mathrm{ov}_{\mathrm{HP}}^{(i,u)}\left(z_j, z_k\right) \quad \therefore \begin{cases} \mathcal{N} = 100 & \text{100 universes} \\ u = [1, \mathcal{N}] & \text{universe \#} \end{cases}$$

- Total BFU Covariance is average of universe covariances.

$$\mathcal{C}\mathrm{ov}_{\mathrm{HP}}^{(\mathrm{total})}\left(z_j, z_k\right) = \sum_{i=0}^{N} \left\langle \mathcal{C}\mathrm{ov}_{\mathrm{HP}}^{(i)}\left(z_j, z_k\right)\right\rangle$$

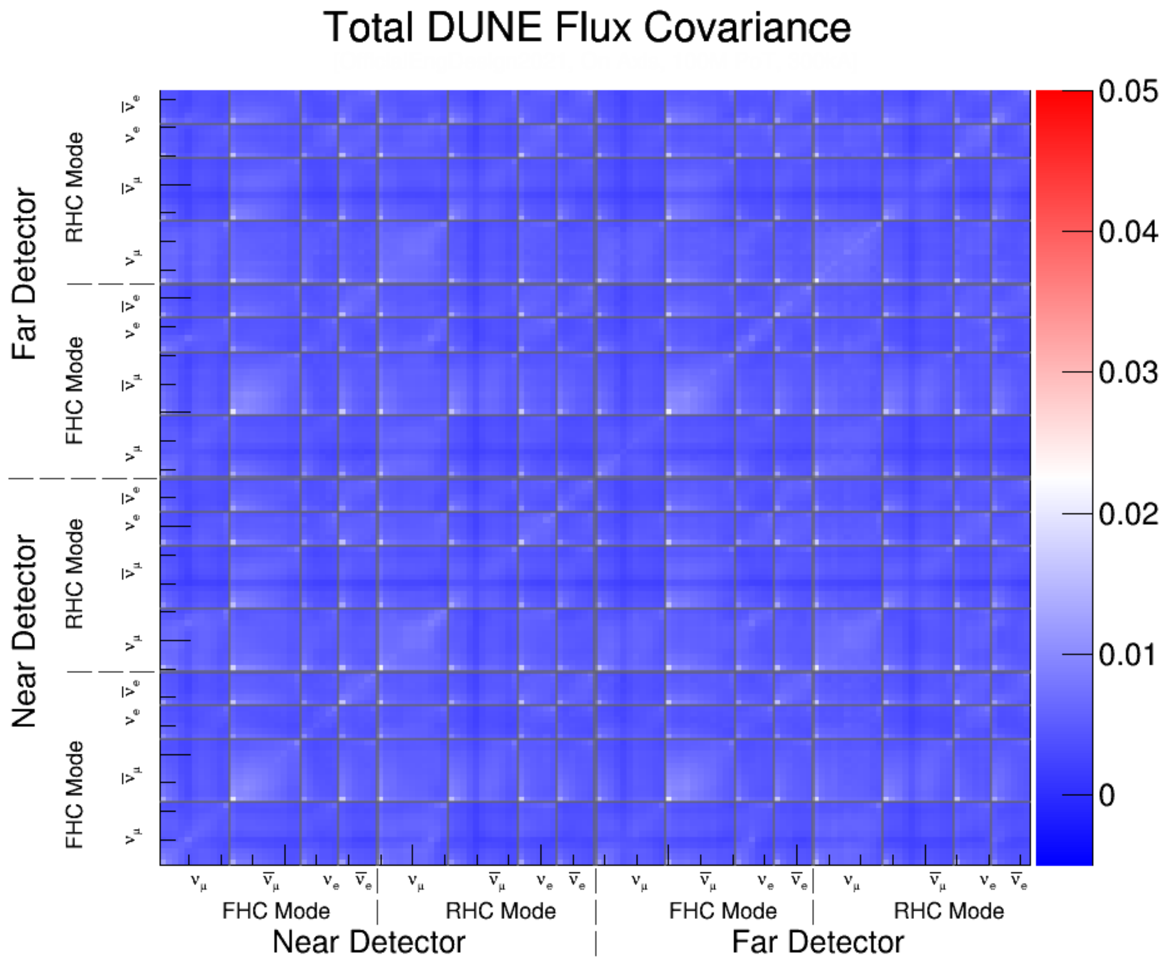
$$\therefore \left\{ N = 9 \right.$$



- Here we see the HP Covariance is likewise small indicating the magnitudes of the Hadron Production uncertainties are also, small.

The Total Covariance

- **Sum of the Hadron Production and Beam Focusing Covariance matrices.**



Total Flux Correlation

- The **Total Correlation** Matrix **reveals the magnitude** of the **relations** amongst the various **sources of uncertainty** across all **modes**, **detector locations** and **neutrino species**.