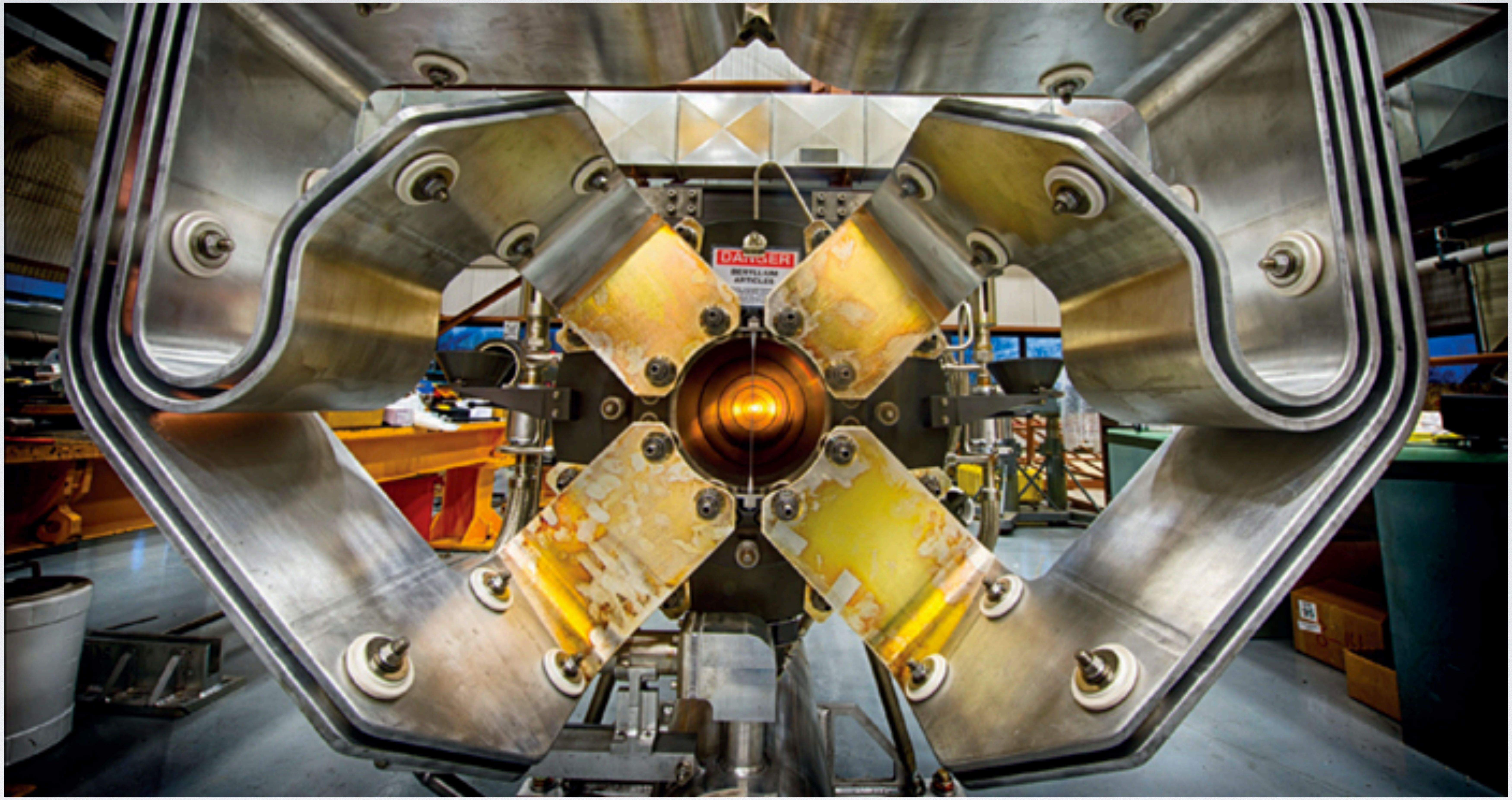


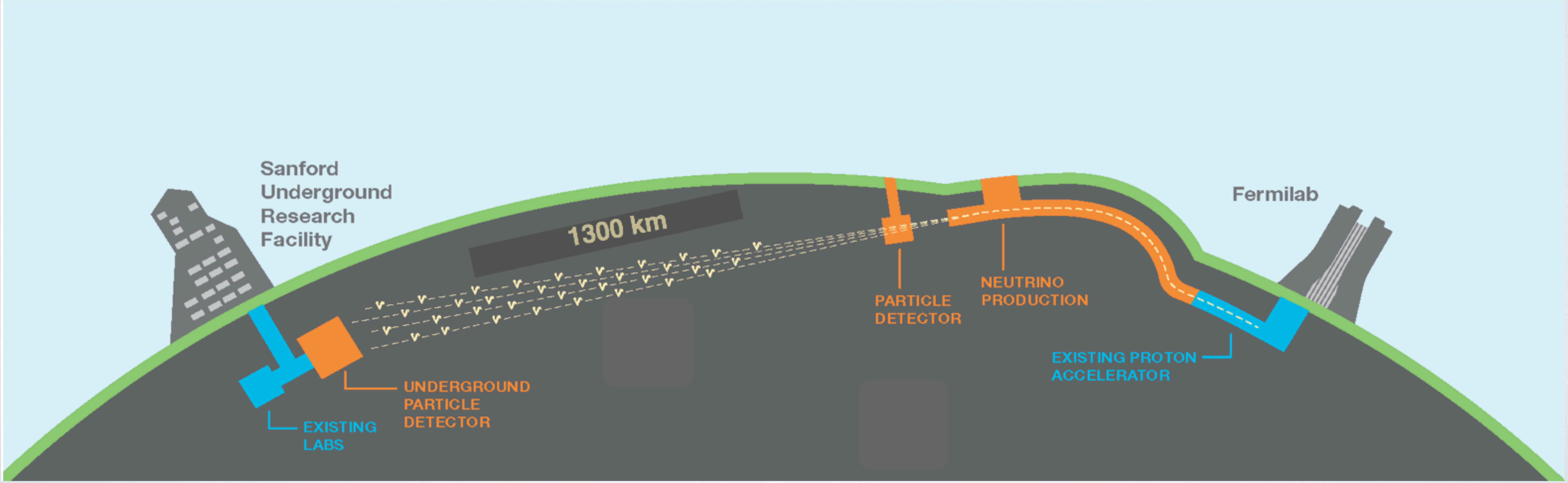
Photo: Reidar Hahn / Fermilab

DUNE FLUX AND MEASUREMENT NEEDS

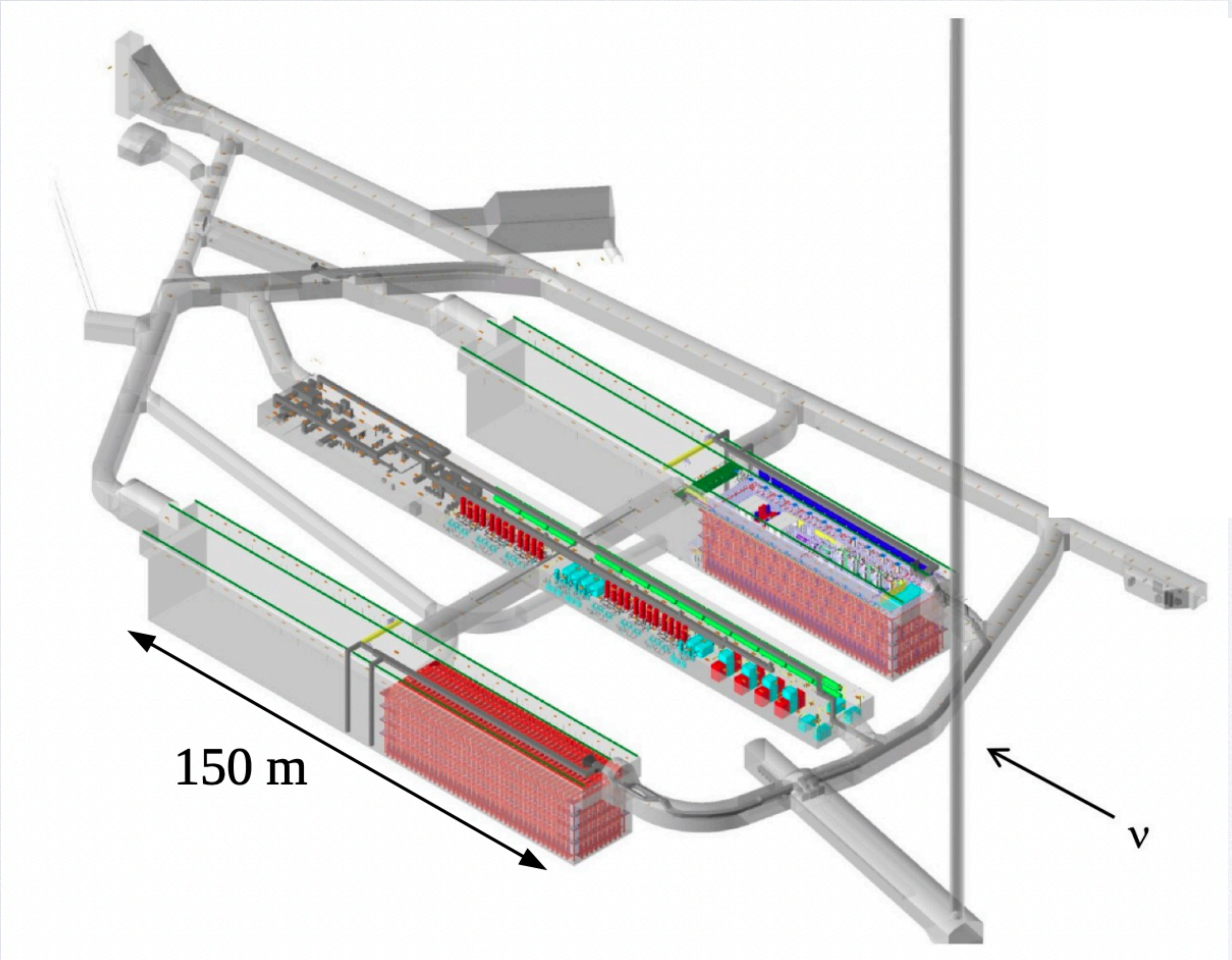
Laura Fields, University of Notre Dame
Dec 2022 NA61++ Workshop

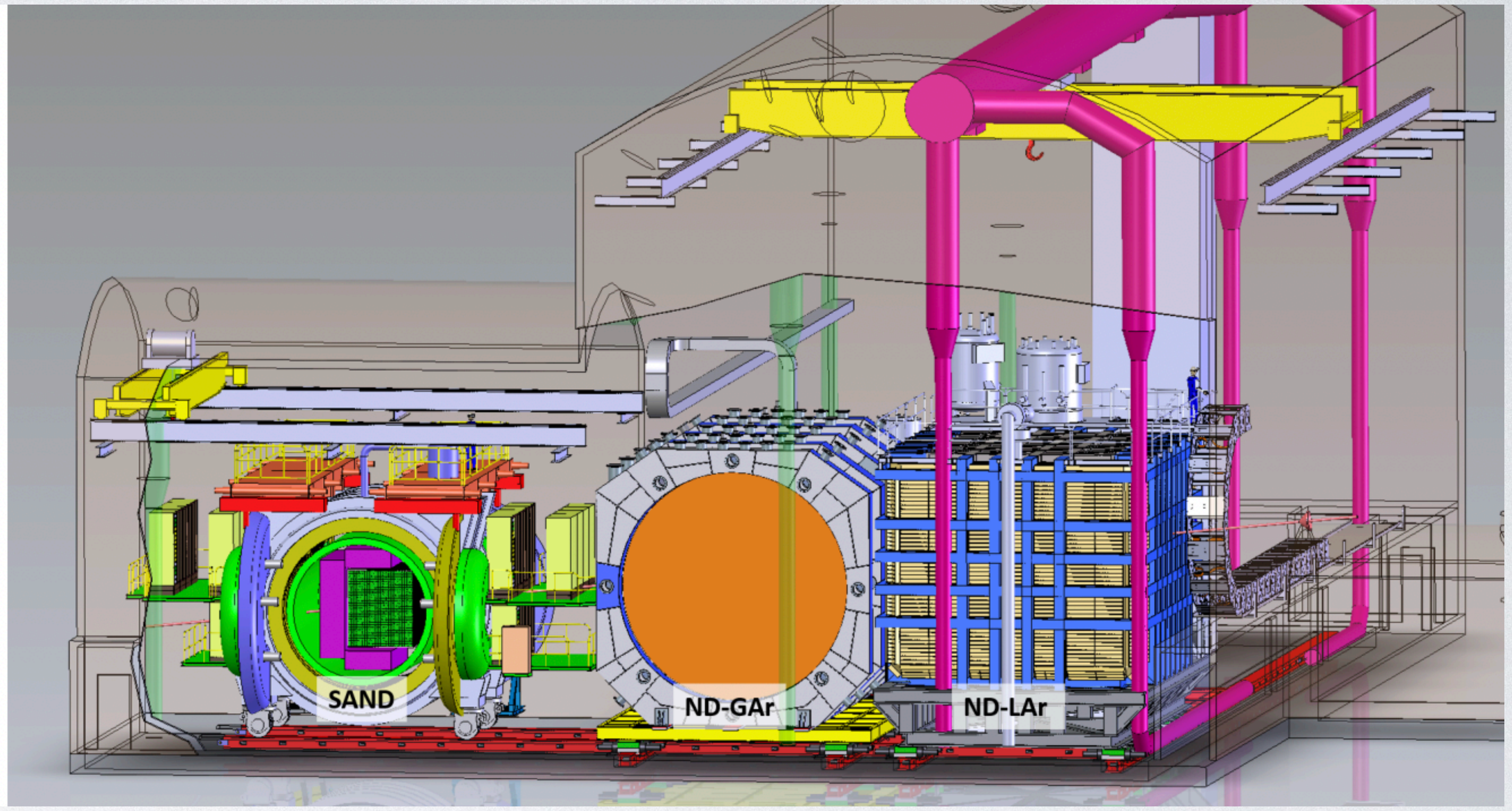
THE DUNE EXPERIMENT

- The **Deep Underground Neutrino Experiment (DUNE)** will use neutrinos created at Fermilab in Illinois and sent through the Earth to a large detector at the Sanford Underground Research Facility (SURF) in South Dakota



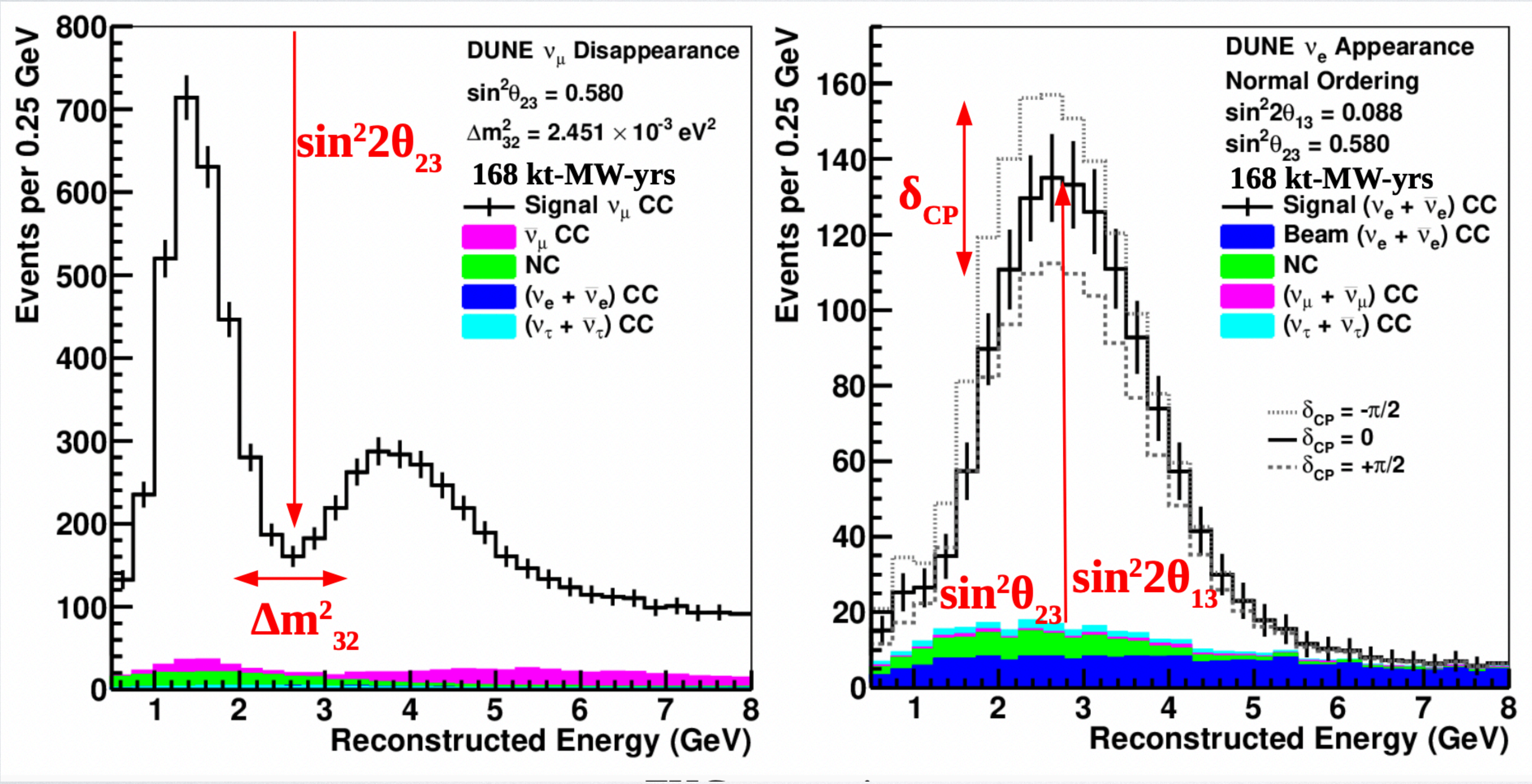
THE DUNE EXPERIMENT





The beam will encounter a capable suite of near detectors and then a large liquid Argon detector 1490 m underground at SURF, with space for 70 kTon of mass

DUNE PHYSICS



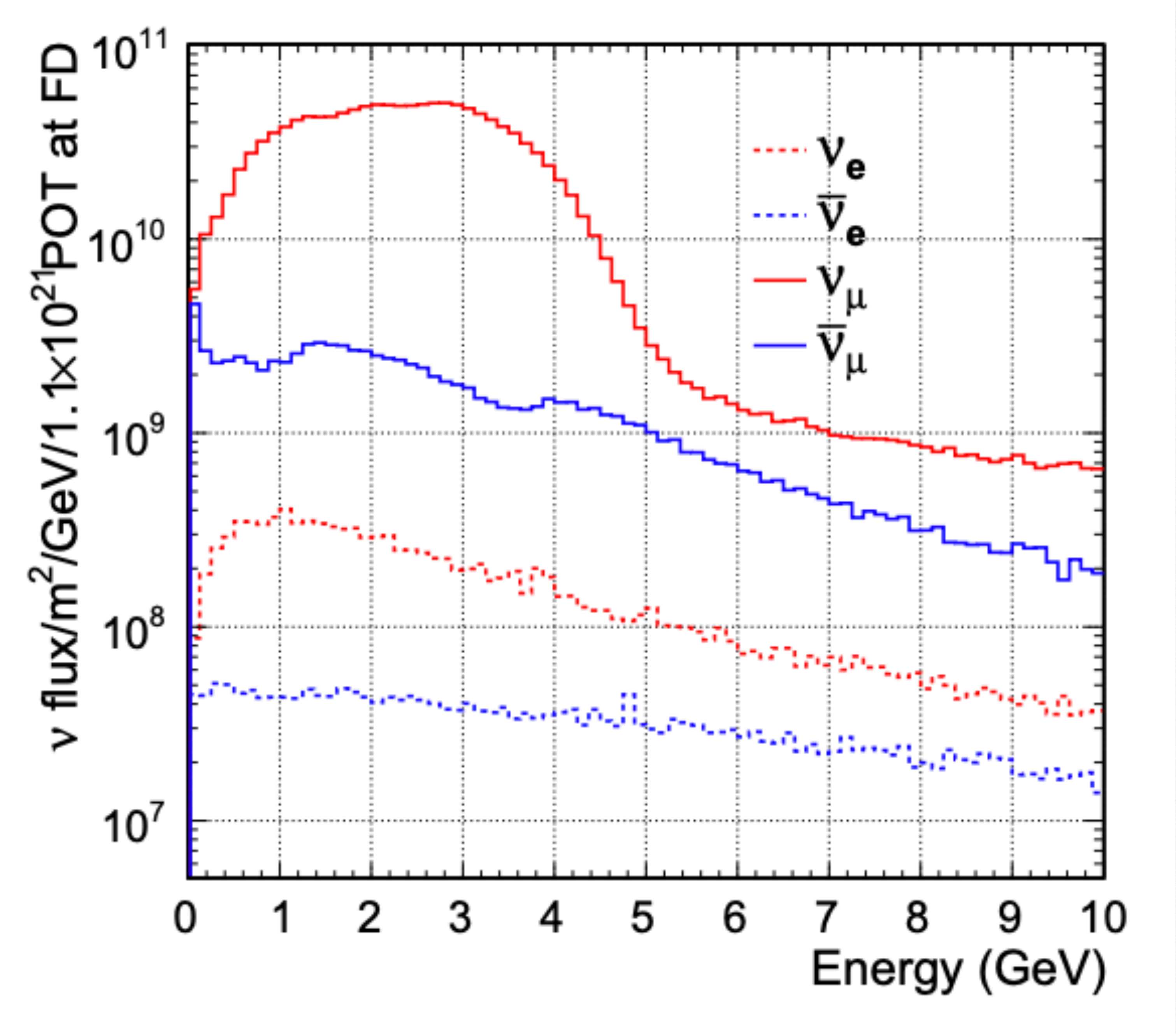
Primary goal is precision measurements of 3-flavor neutrino mixing parameters including the CP-violating phase and mass hierarchy

Many BSM searches in near and far detectors

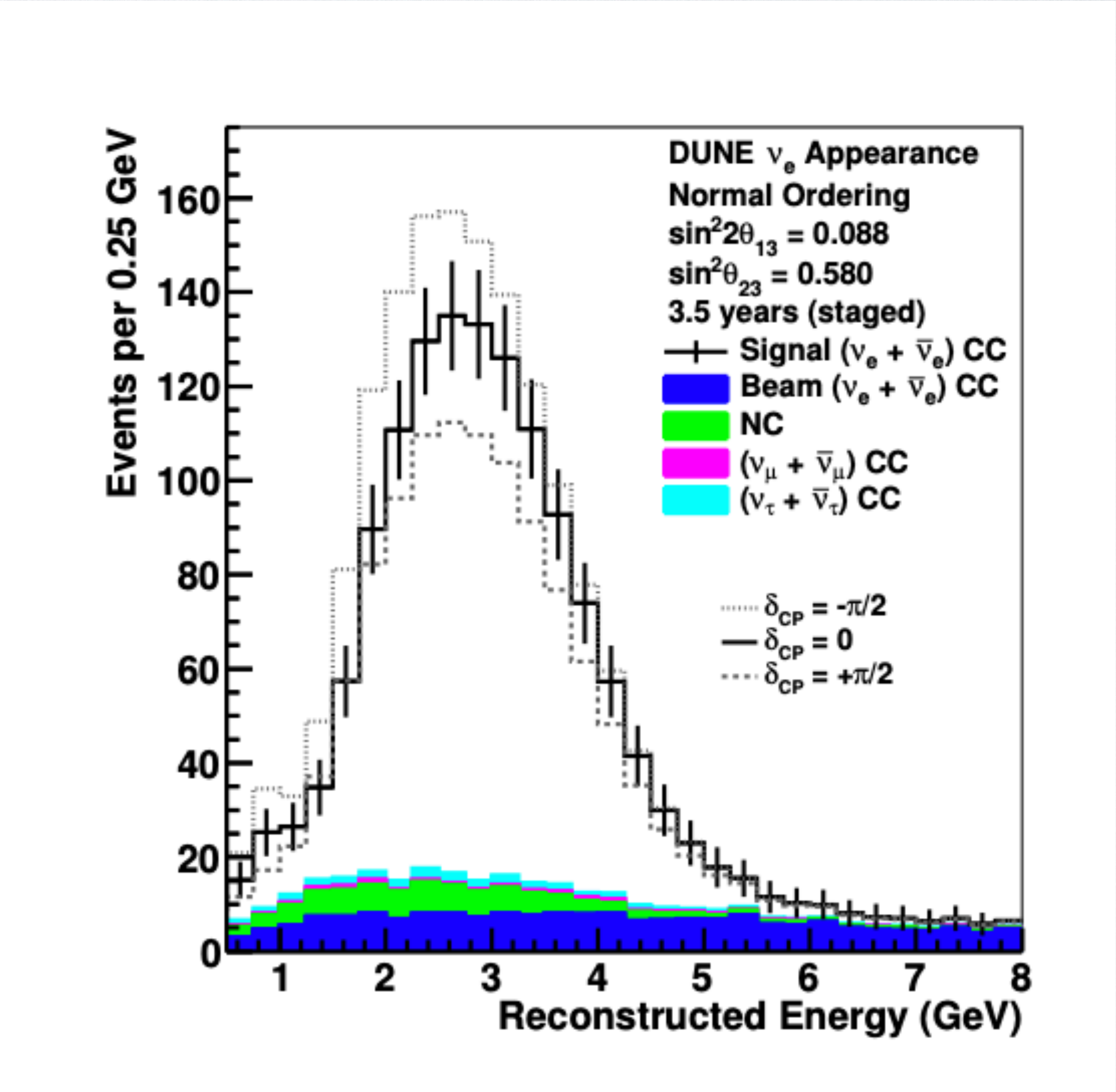
Also: supernova, solar neutrinos

DUNE PHYSICS

- Extracting oscillation parameters or finding a BSM signal in DUNE data will require precise simulations of the entire experiment, starting with the neutrino beam:

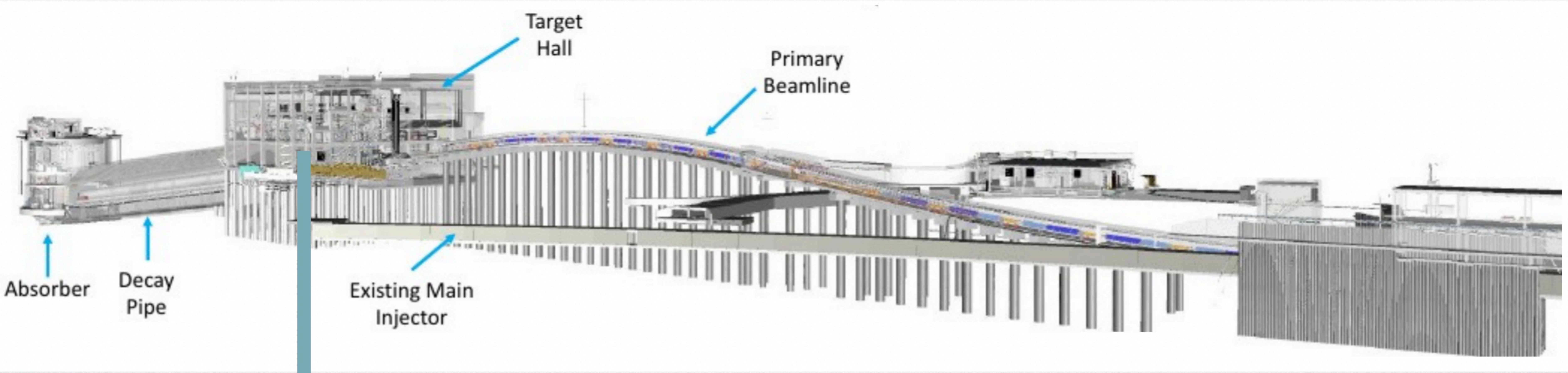


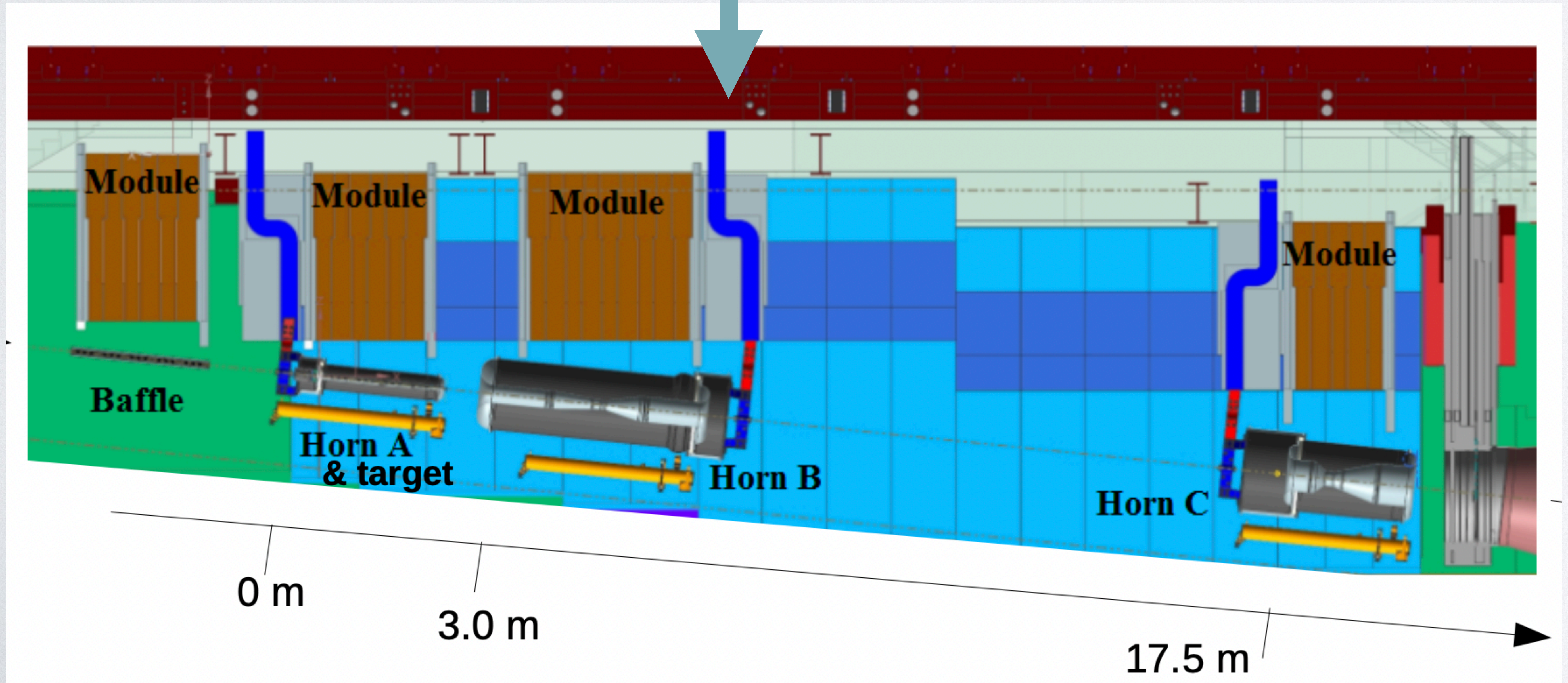
Predicted beam neutrino energy spectra



Predicted neutrino energies at DUNE, for different values of CP violation

LBNF BEAM



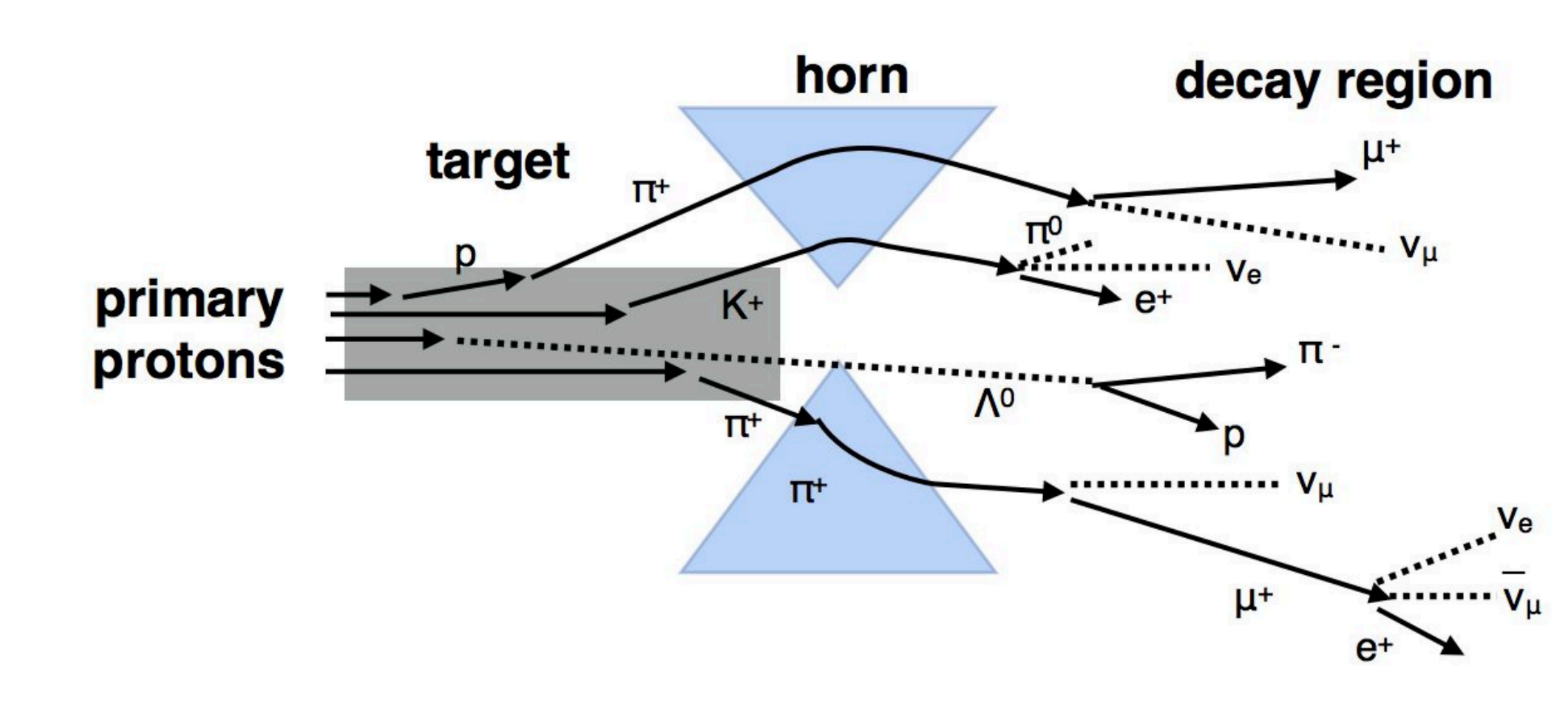


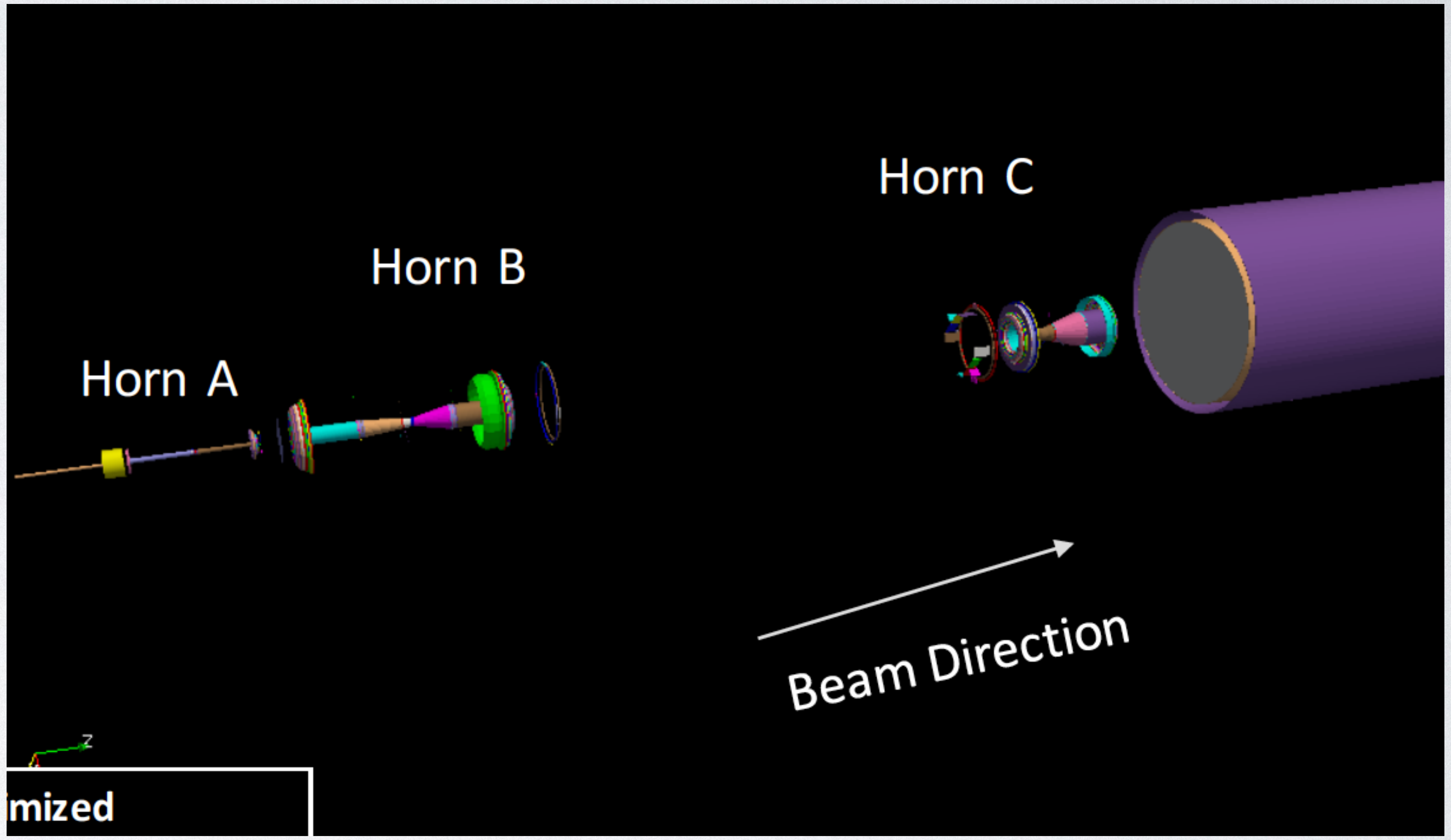
120 GeV protons @ 1.2 MW (upgradable to 2.4 MW)

3 horns + long target optimized for sensitivity to CP violation

Horn current polarity can be switched to provide neutrino or antineutrino-enriched beams

LBNF BEAM SIMULATION

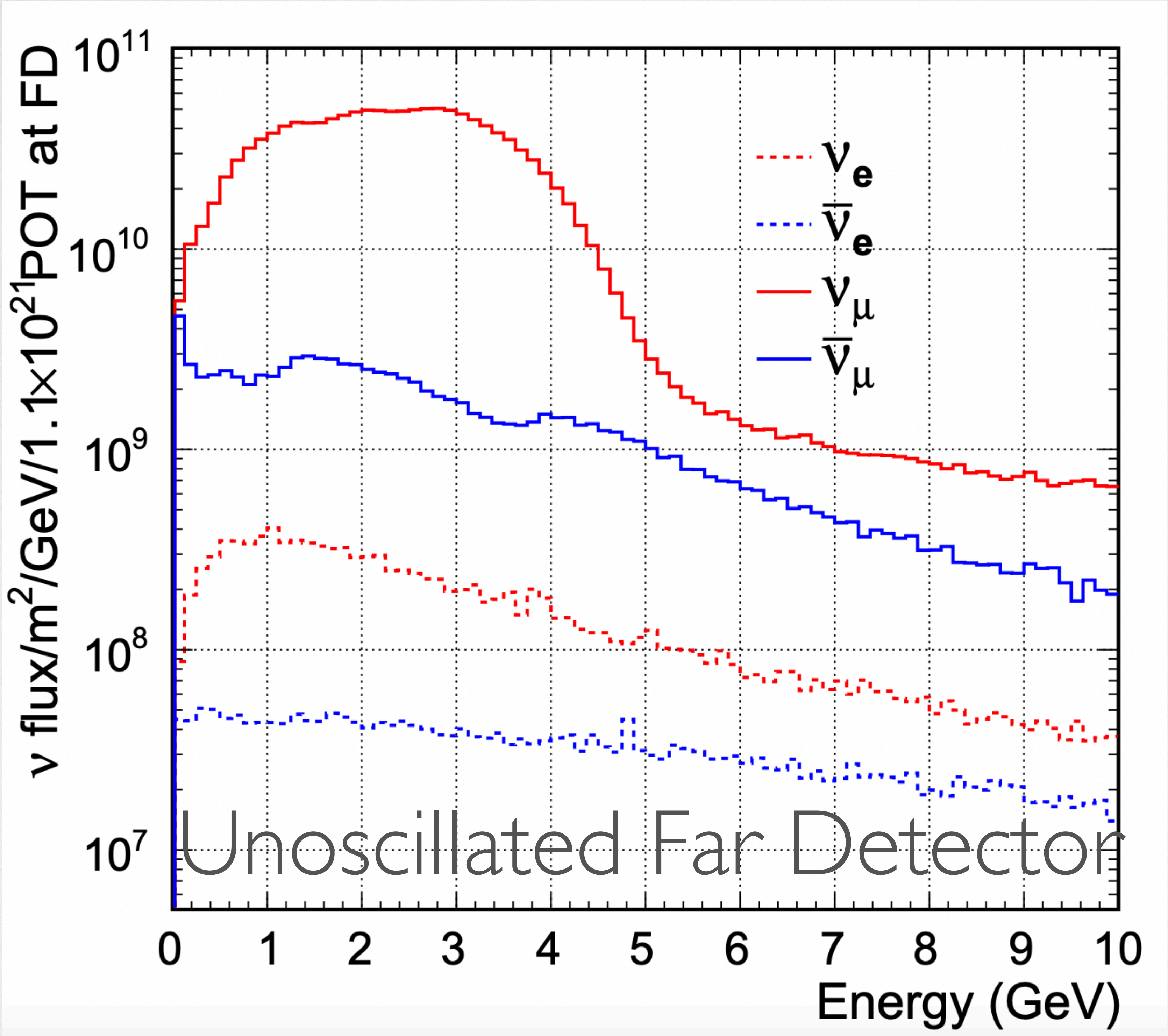


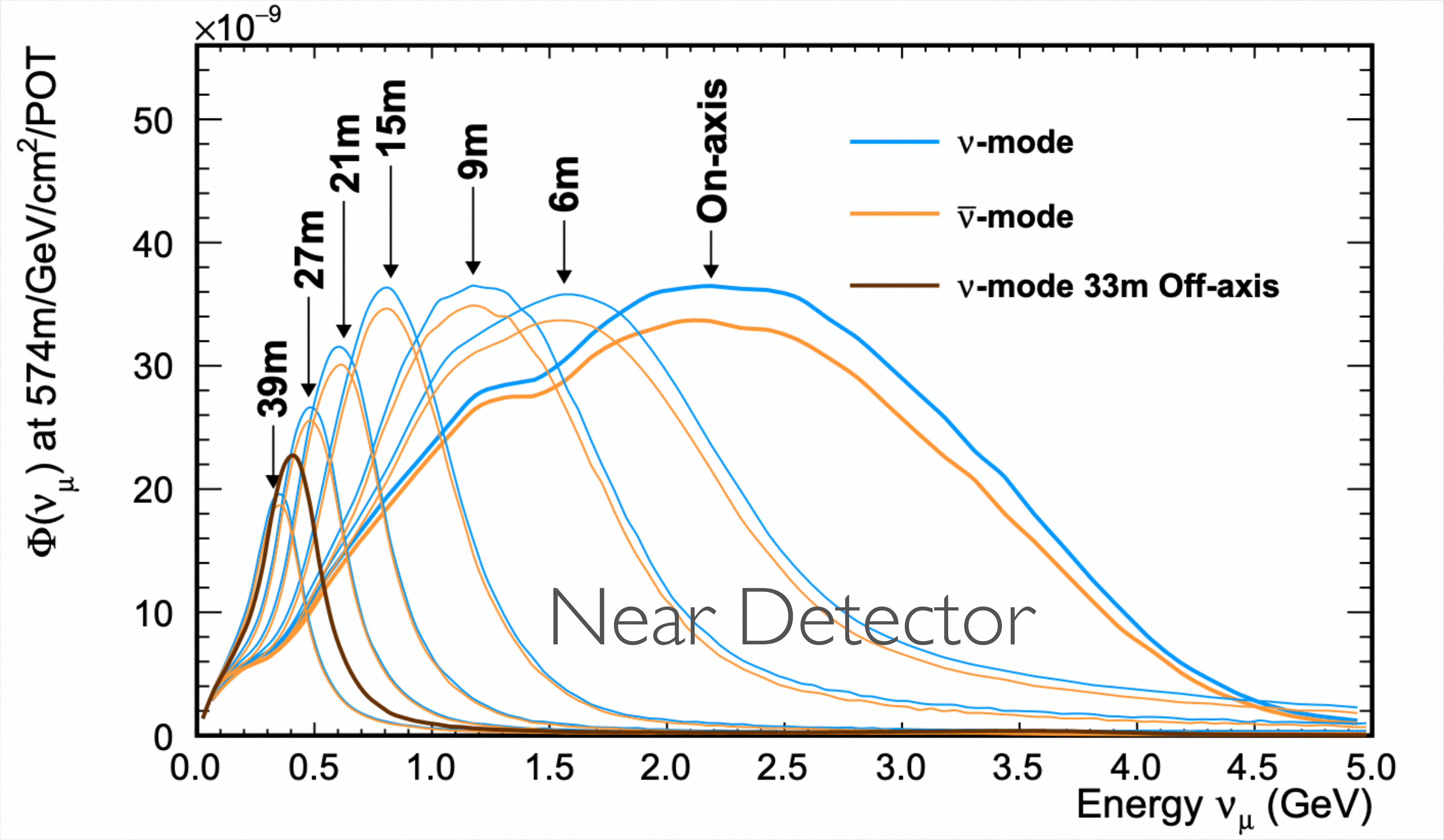


- We use **Geant4 to simulate** primary interactions of 120 GeV protons on the LBNF target, reinteractions in the target and other beam materials, and decay to neutrinos
- Currently using Geant4 version 10.3.p03 with the QGSP_BERT Physics List

LBNF BEAM SIMULATION

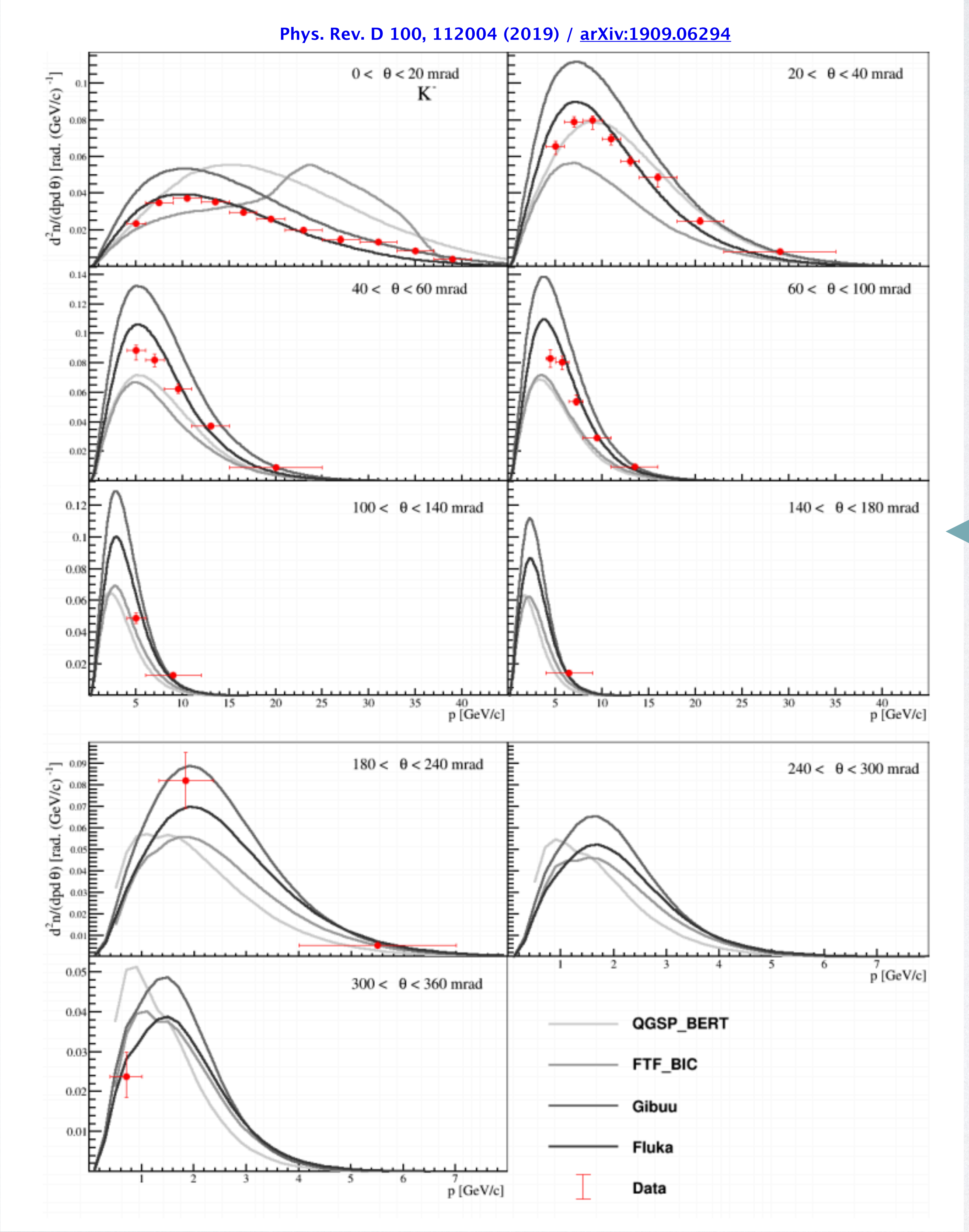
- This simulation produces predicted neutrino fluxes at all DUNE detectors:





- These are neutrino fluxes from the TDR; used for all current DUNE physics studies
- Not completely final beam design (see backup)

IMPERFECT SIMULATION



But we know that these flux predictions are not sufficiently precise to meet DUNE's needs:

Kaons in 60 GeV π^++C → K+X interactions, measured at NA61/SHINE and compared to two Geant4 models, as well as Gibuu and Fluka.

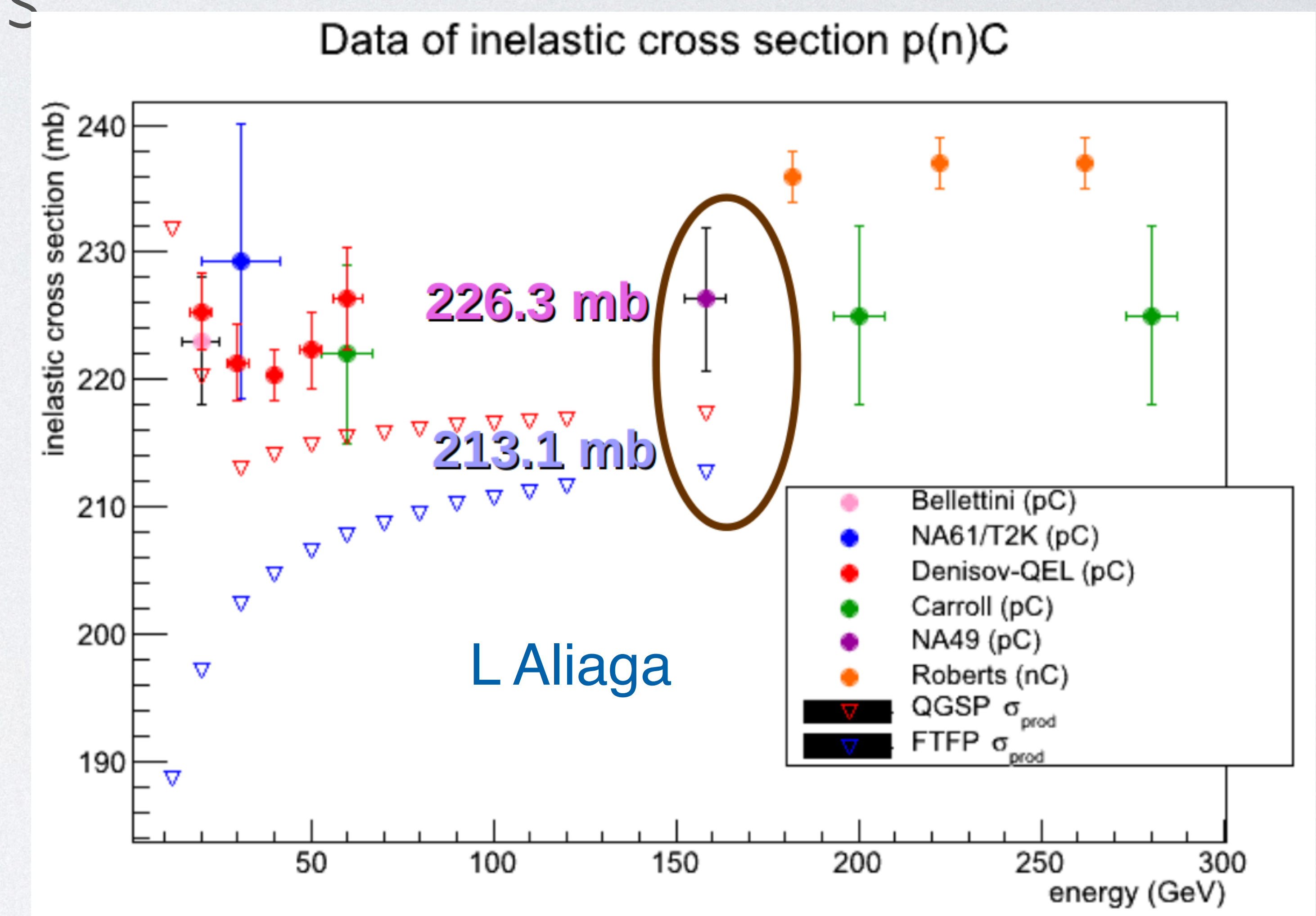
Many **models differ significantly from data**; model developers are always trying to improve, but it is not realistic to expect perfect predictions of all processes that matter to flux predictions.

CORRECTING THE SIMULATION

So we have to **fix our predictions**

- The only practical way to do this is **through reweighting**
- DUNE uses the **PPFX packaged developed for MINERvA** and also used by NOvA and SBN experiments for NuMI fluxes:
  - **Complete information about cascades** leading to a neutrino is recorded for each proton on target and stored in the flux tuples
  - Interactions **are weighted** by:

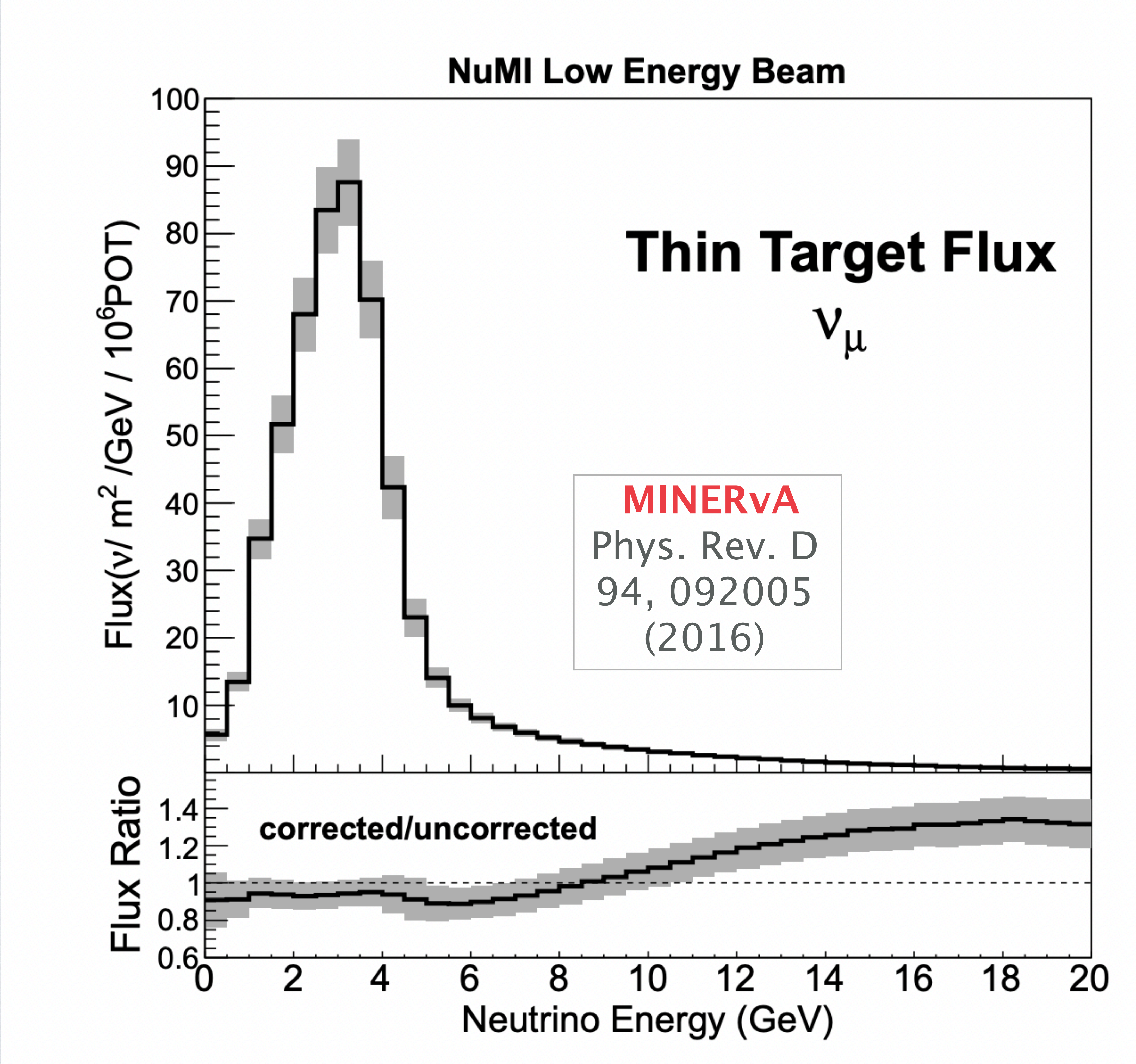
$$w_{\mathrm{HP}} = \frac{f_{\mathrm{Data}}\left(x_F, p_T, E\right)}{f_{\mathrm{MC}}\left(x_f, p_T, E\right)} \qquad f = E\frac{d^3\sigma}{dp^3}$$



  - Weights for events with multiple interactions in the ancestor chain are the product of the weight for each interaction
  - A second weight is applied to account for assuming exponential exponential **decay of beam**:

$$w_{\mathrm{att}} = e^{-L\rho(\sigma_{\mathrm{data}} - \sigma_{\mathrm{MC}})}$$

CORRECTING THE SIMULATION

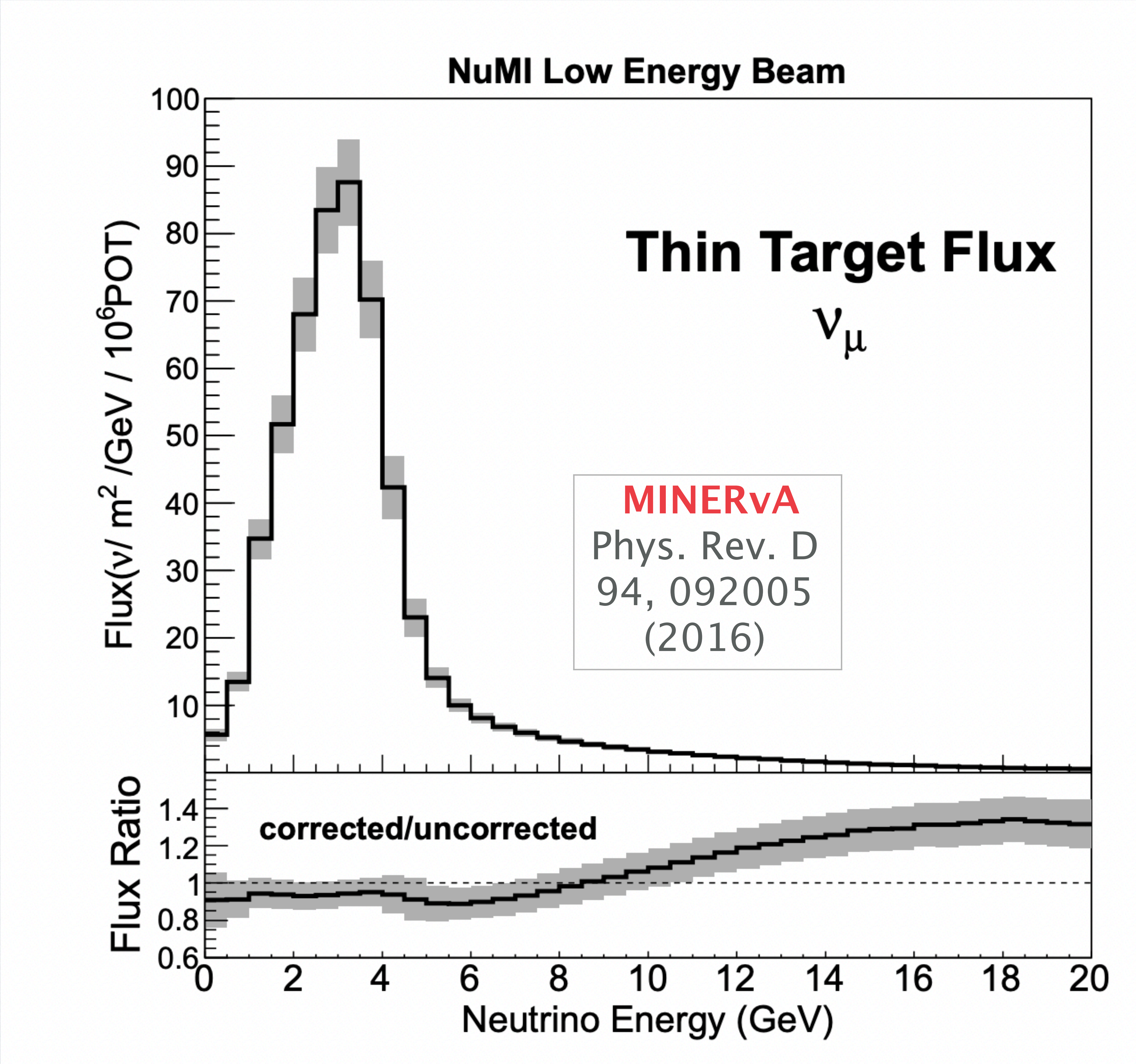


Reweighted flux for MINERvA (DUNE version not yet approved)

Kaons in 60 GeV π^++C → K+X

Small corrections needed in focusing peak; much more substantial in high energy tail

CORRECTING THE SIMULATION



Data sets currently used:

- NA49 158 GeV protons (Eur.Phys.J.C49: 897-917, 2007, Eur. Phys. J. C73, 2364 (2013))
- Barton et. al. 100 GeV protons (Phys. Rev. D **27**, 2580)
- NA49 pC → $K^{\pm}X$ (G.Tinti Thesis)
- MIPP K/pi ratios (A.V. Lebedev Thesis)
- Incorporation of new NA61 and EMPHATIC data is ongoing

Extensions of data:

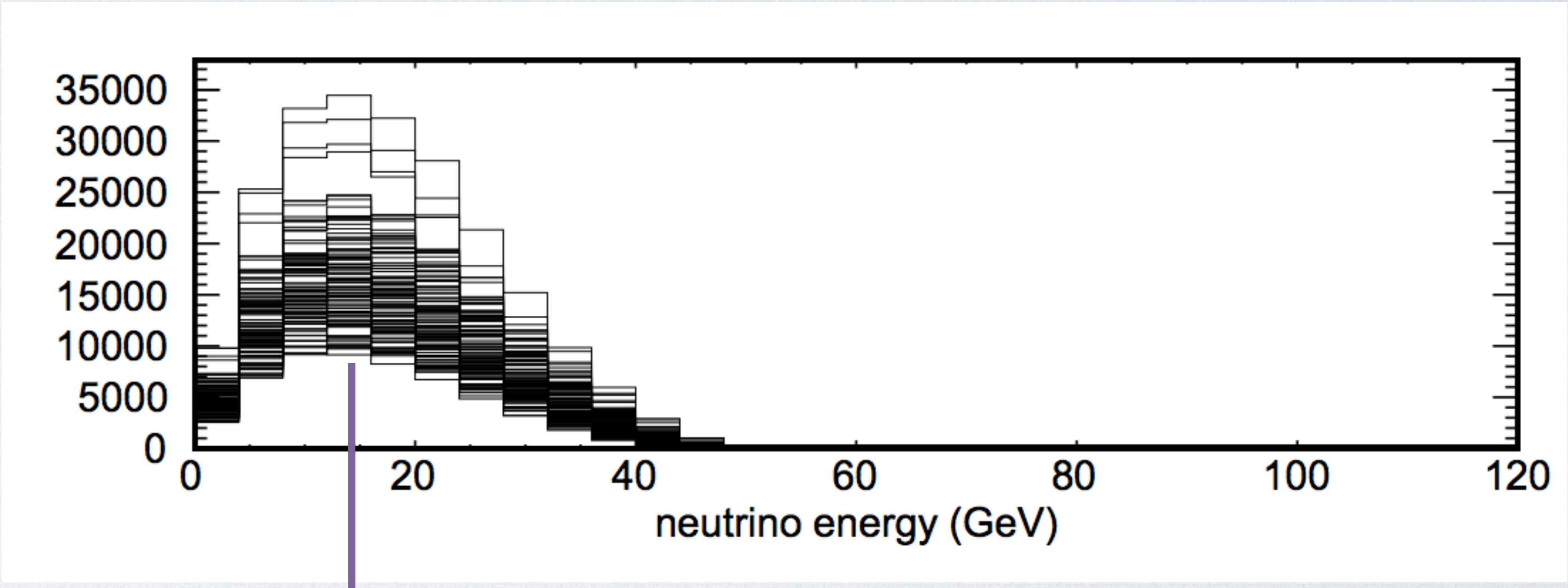
- pC → π^+X cross section assumed to be the same as nC → π^-X and vice versa (isospin symmetry)
- Carbon data used for other nuclei (with larger uncertainty — stay tuned for more discussion of uncertainties)
- 158 GeV proton data used for incident energies between 12 and 120 GeV, with scaling taken from Fluka

PROPAGATING UNCERTAINTIES

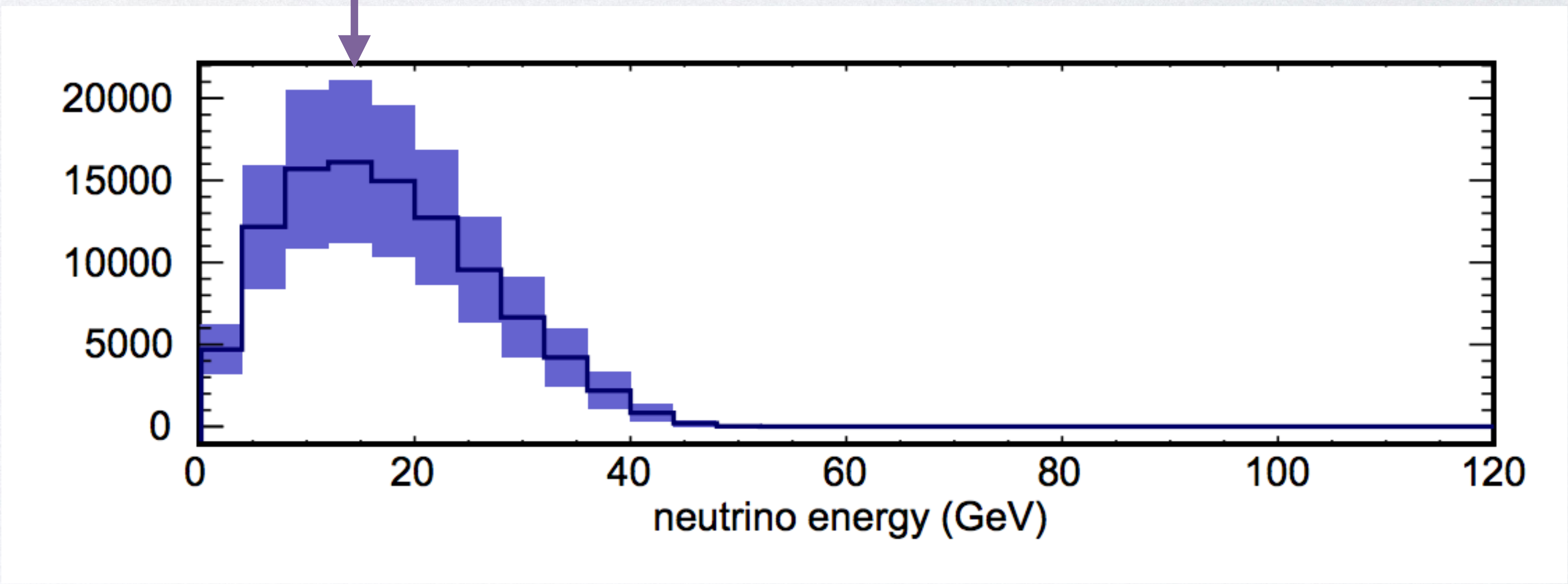
- **Uncertainties** on the external data constraints are propagated to uncertainties on our flux and other simulated distributions using a **“Many-Universes”** method:
    - For each event, in addition to the central value weights we have discussed:

$$w = e^{-L\rho(\sigma_{\mathrm{Data}}-\sigma_{\mathrm{MC}})} \left(\prod_{\substack{\text{reweightable} \\ \text{interactions}}} \frac{f_{\mathrm{Data}}\left(x_F, p_T, E\right)}{f_{\mathrm{MC}}\left(x_f, p_T, E\right)} \right)$$

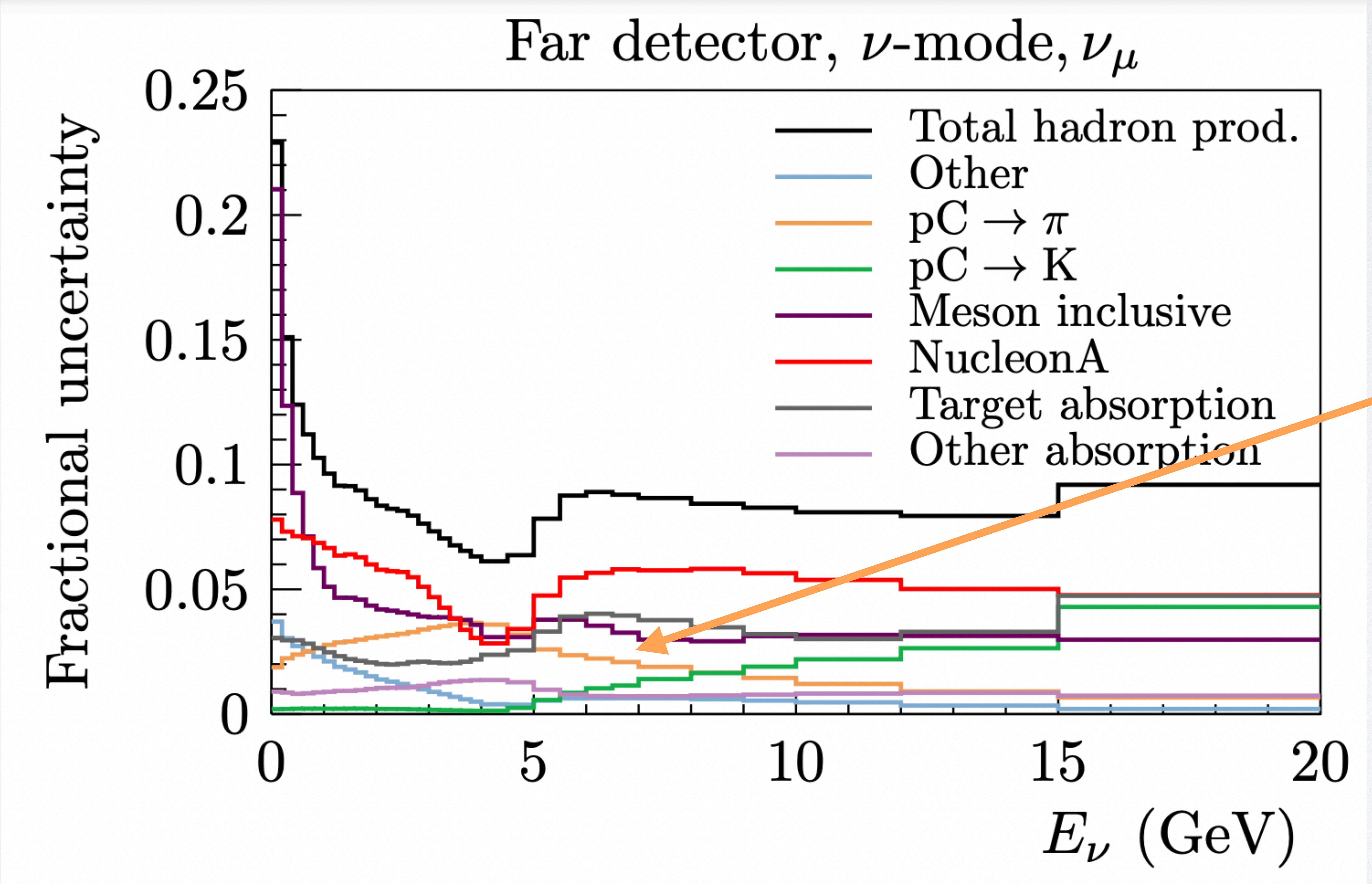
    - We also store many (~1000) weights constructed from data cross sections varied according to their uncertainties (taking into account correlations)
    - For interactions uncovered by data, large (40%) are assumed



RMS of resulting weighted distributions gives uncertainty on those distributions

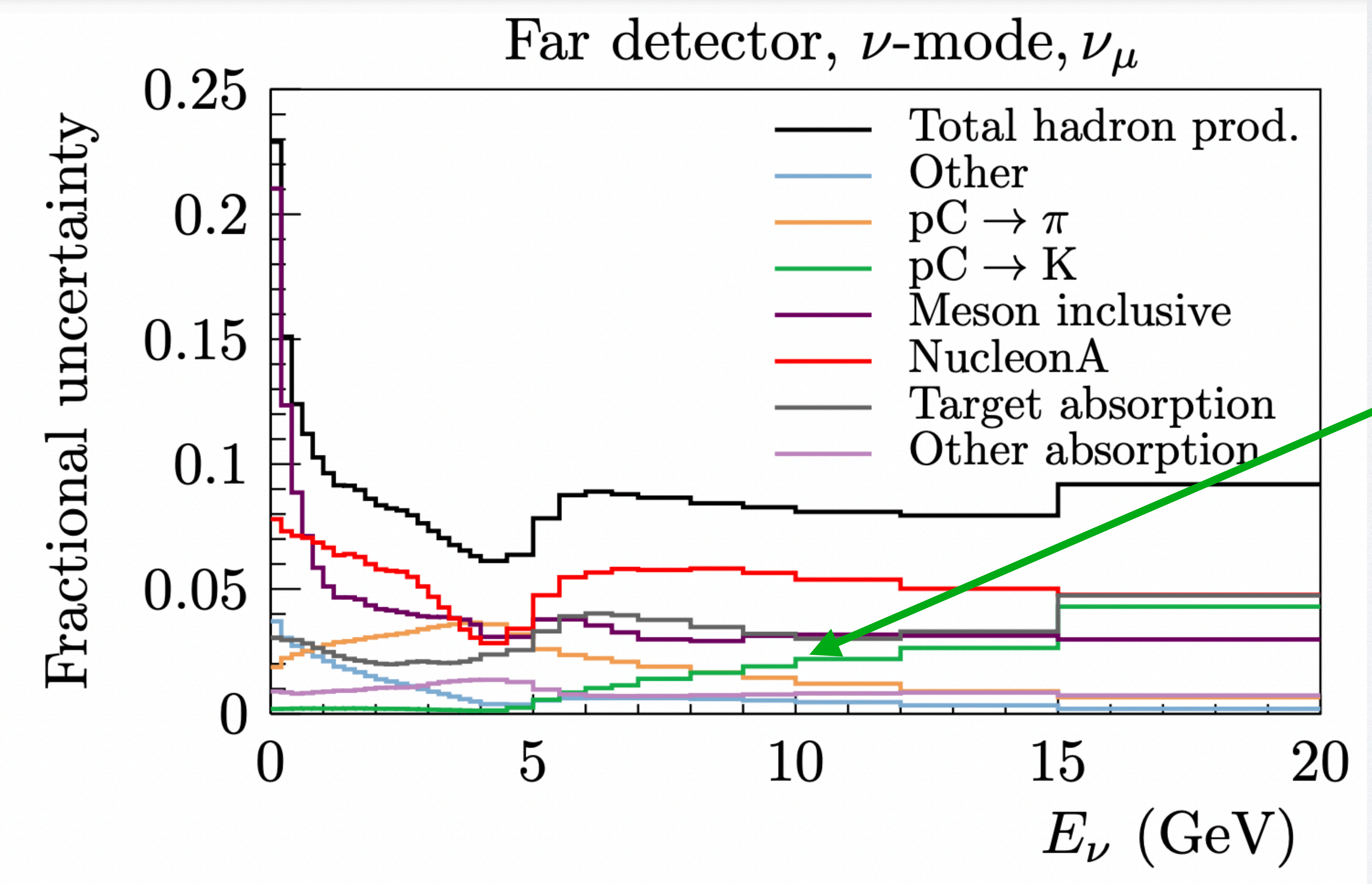


HP FLUX UNCERTAINTIES



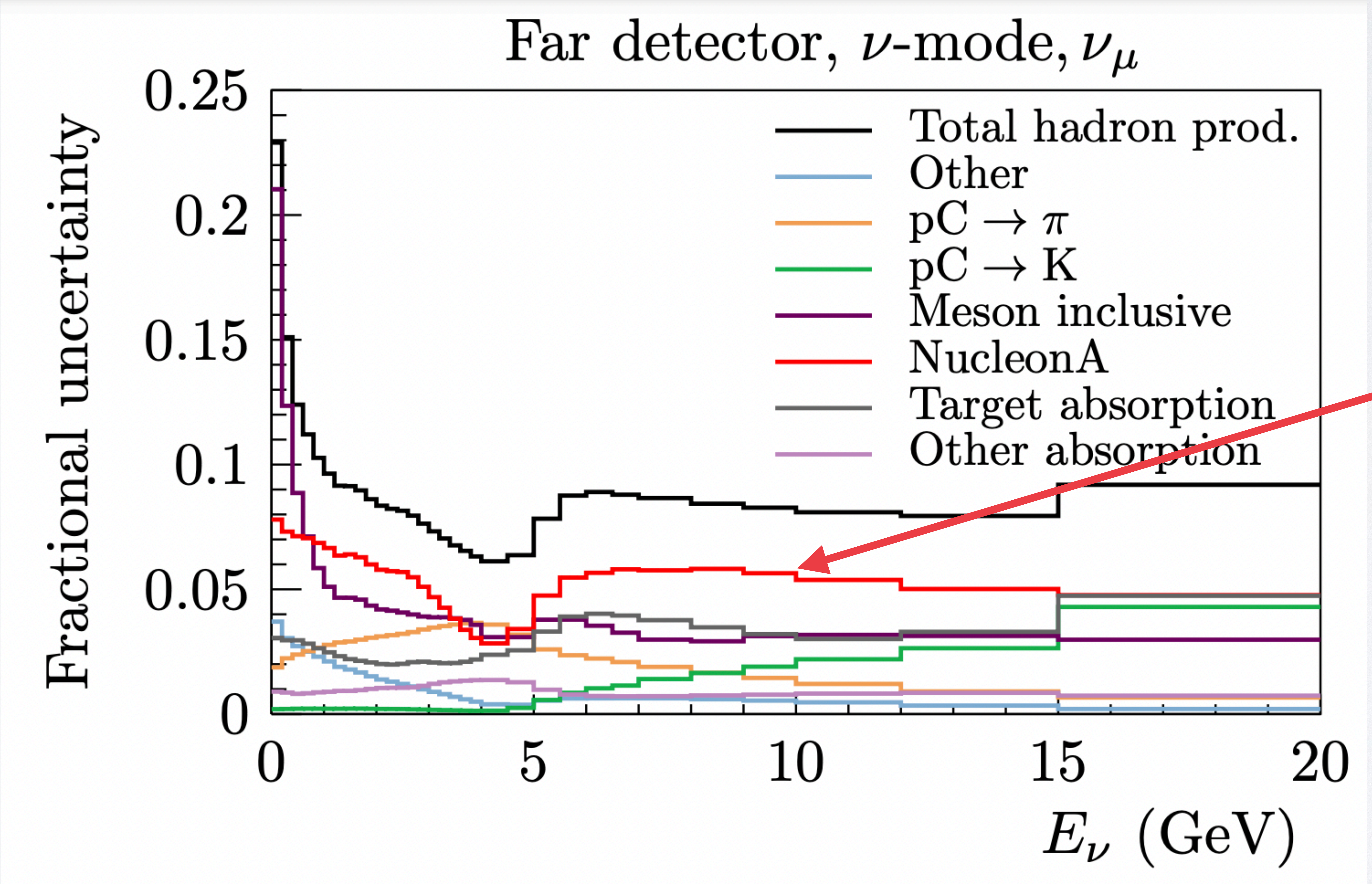
Pion production from proton interactions with carbon that are covered by external data

HP FLUX UNCERTAINTIES



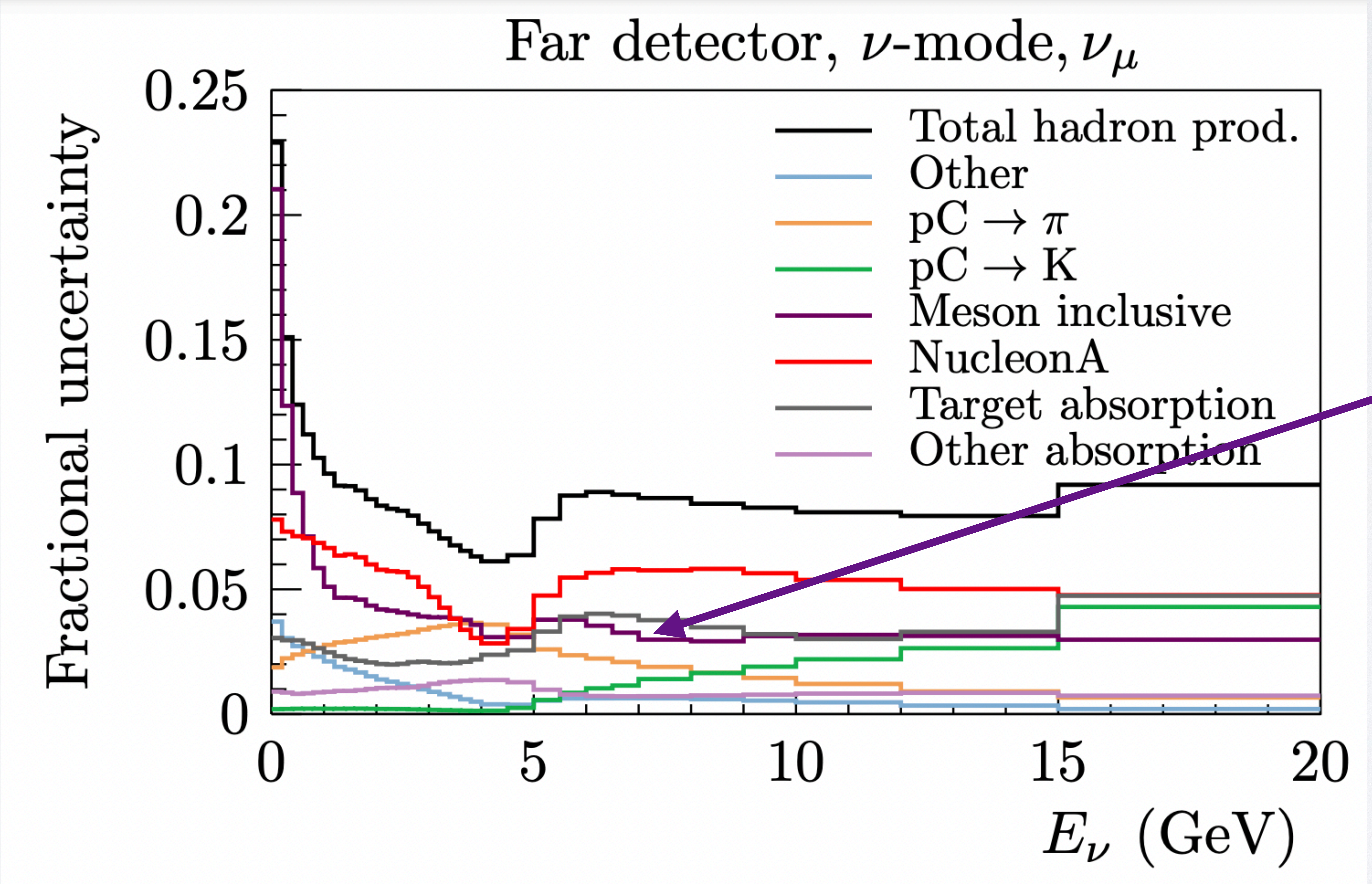
Kaon production from proton interactions with carbon that are covered by external data

HP FLUX UNCERTAINTIES



Proton and neutron interactions that are not covered by data

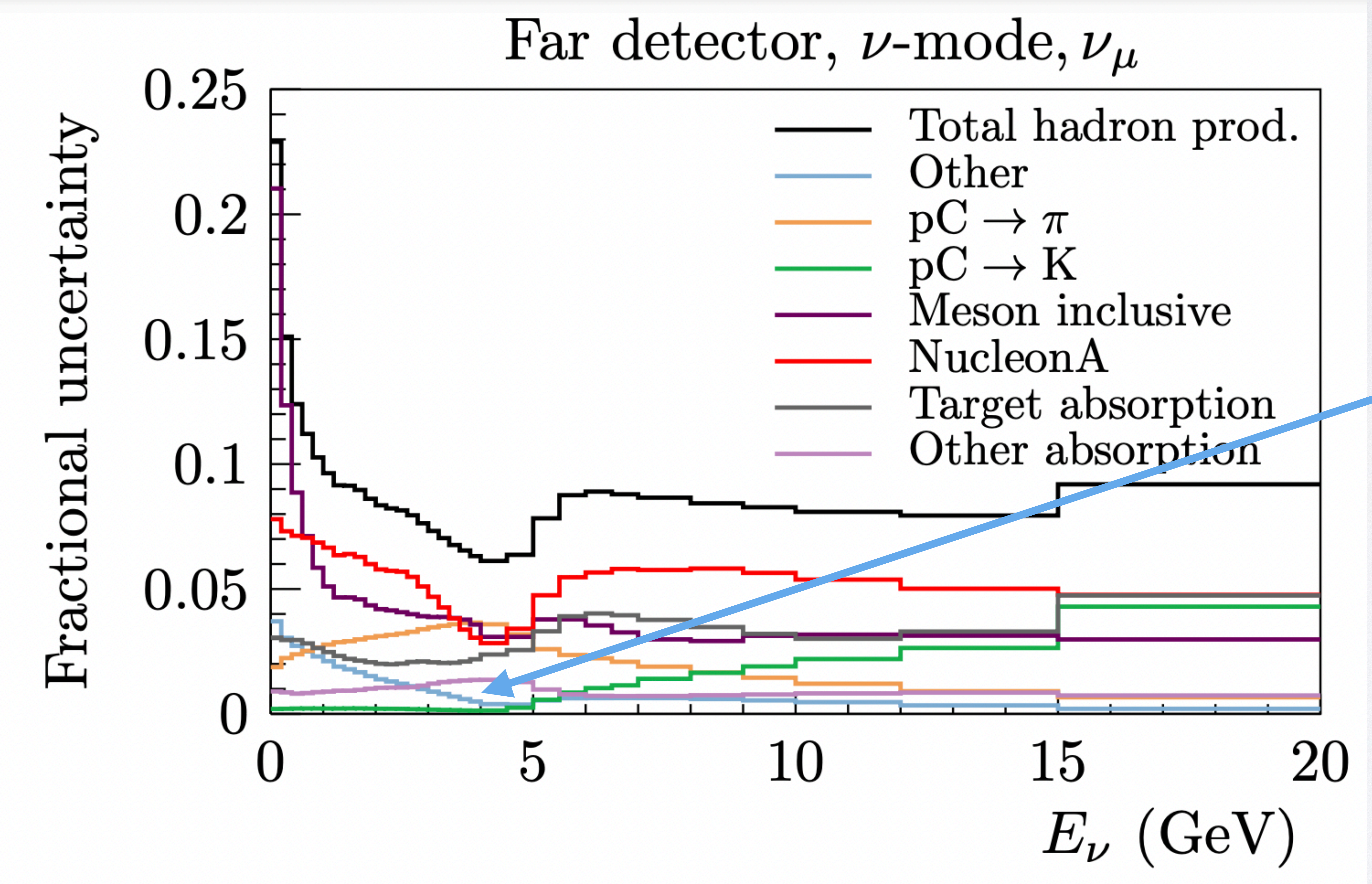
HP FLUX UNCERTAINTIES



Pion and Kaon incident interactions

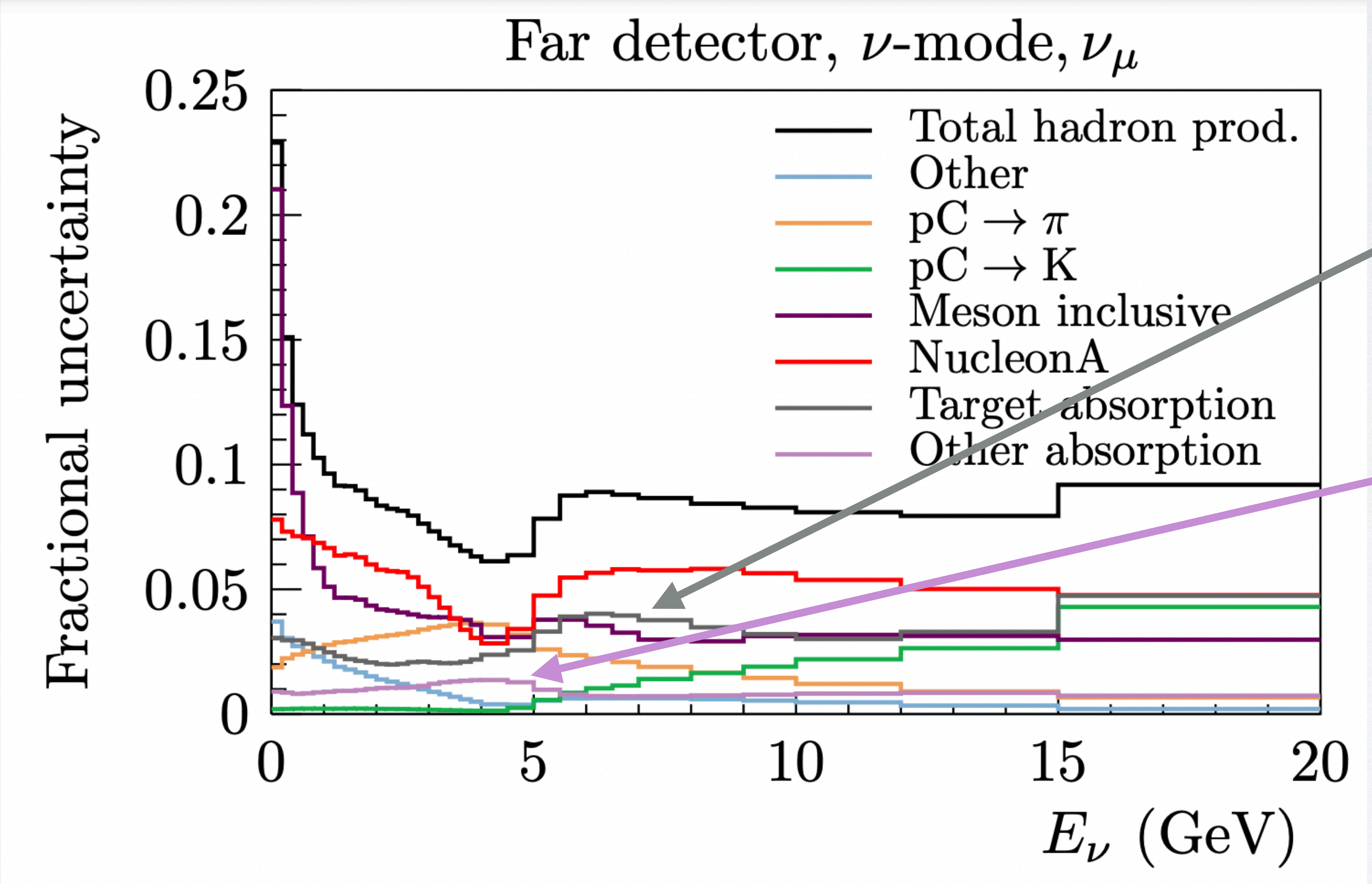
(Should become much smaller once recent NA61 data is incorporated!)

HP FLUX UNCERTAINTIES



All other interactions (not proton/neutron/pion/kaon incident)

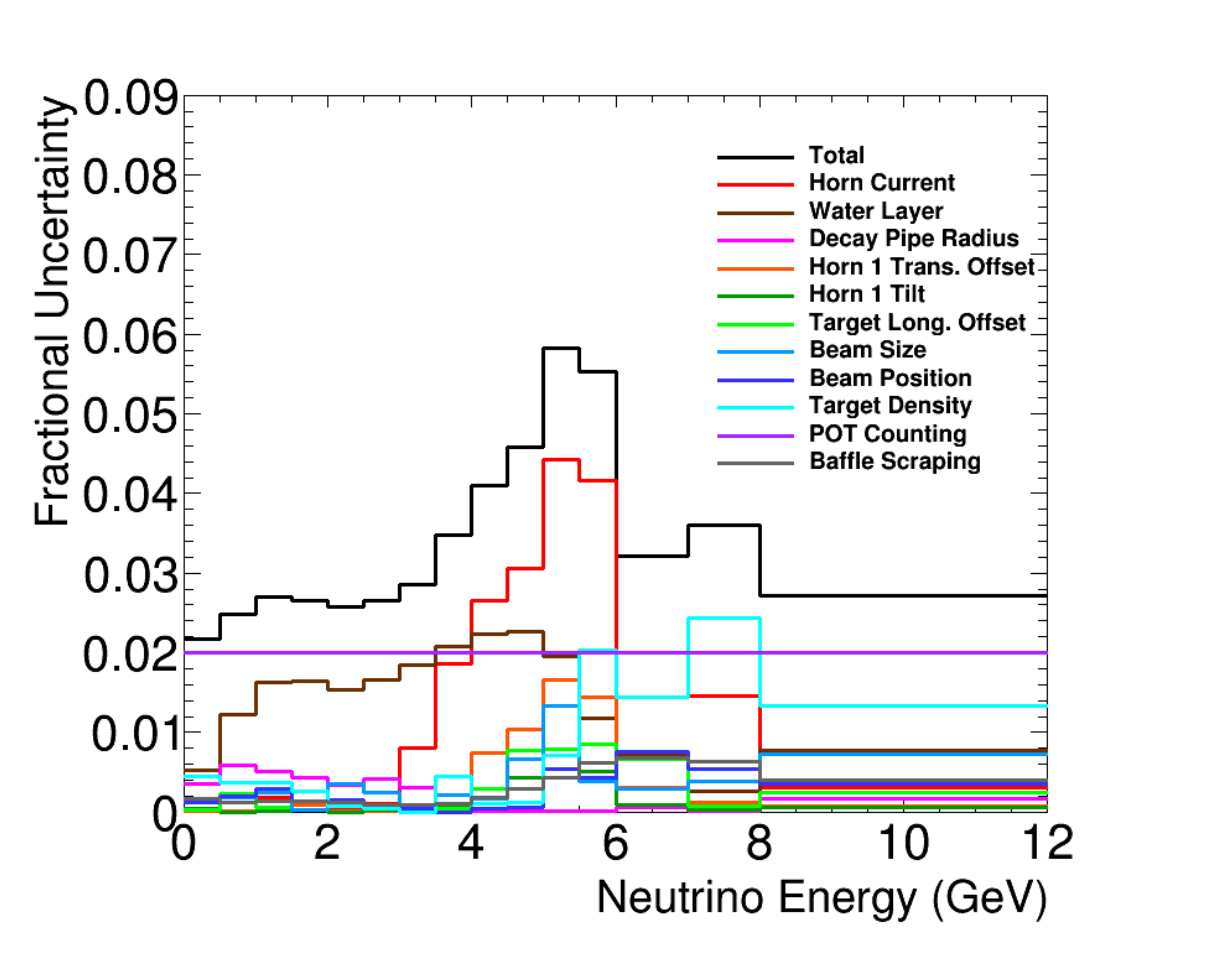
HP FLUX UNCERTAINTIES



Uncertainty associated with attenuation of the beam in the target

Uncertainty associated with absorption of particles outside the target

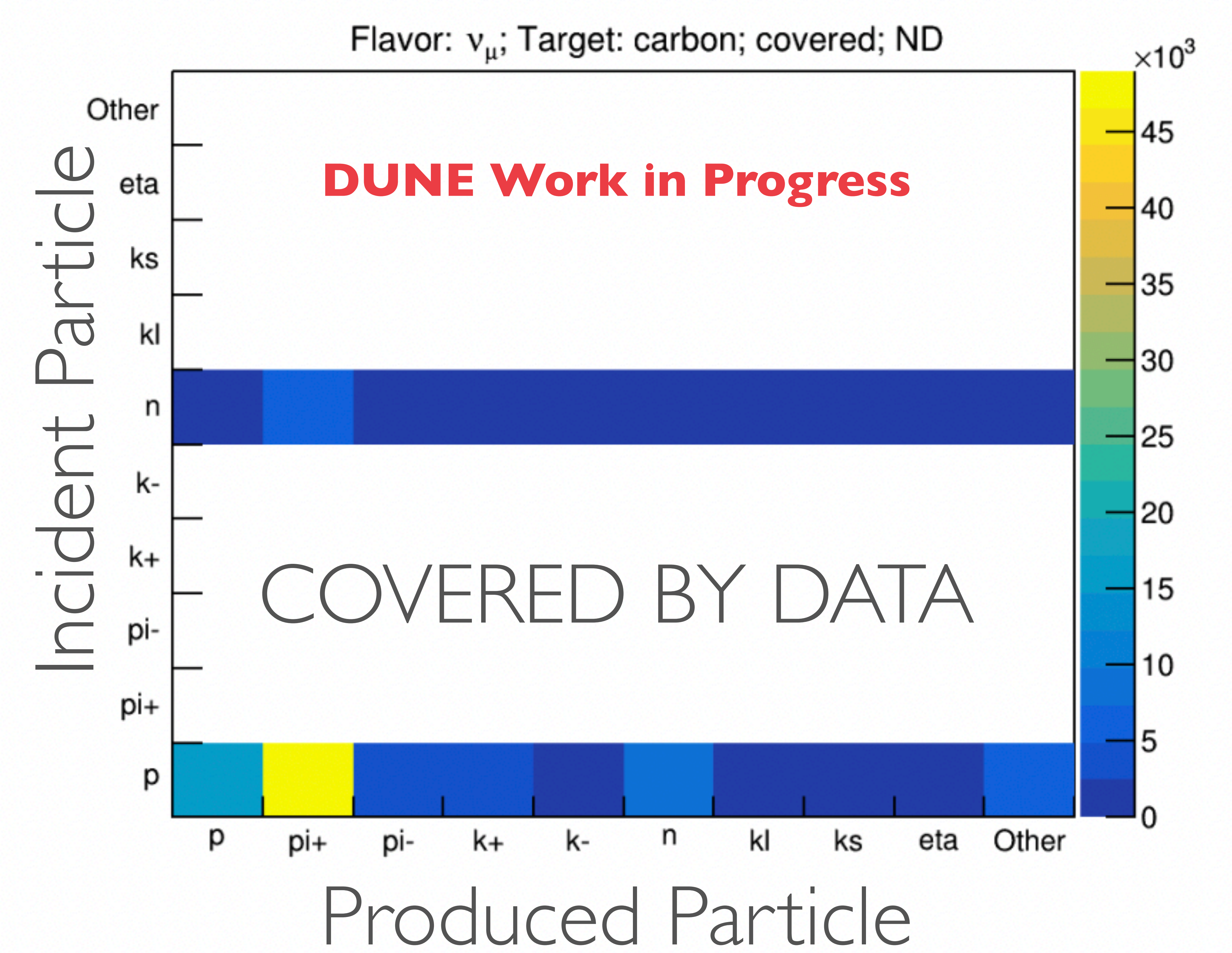
FOCUSING FLUX UNCERTAINTIES

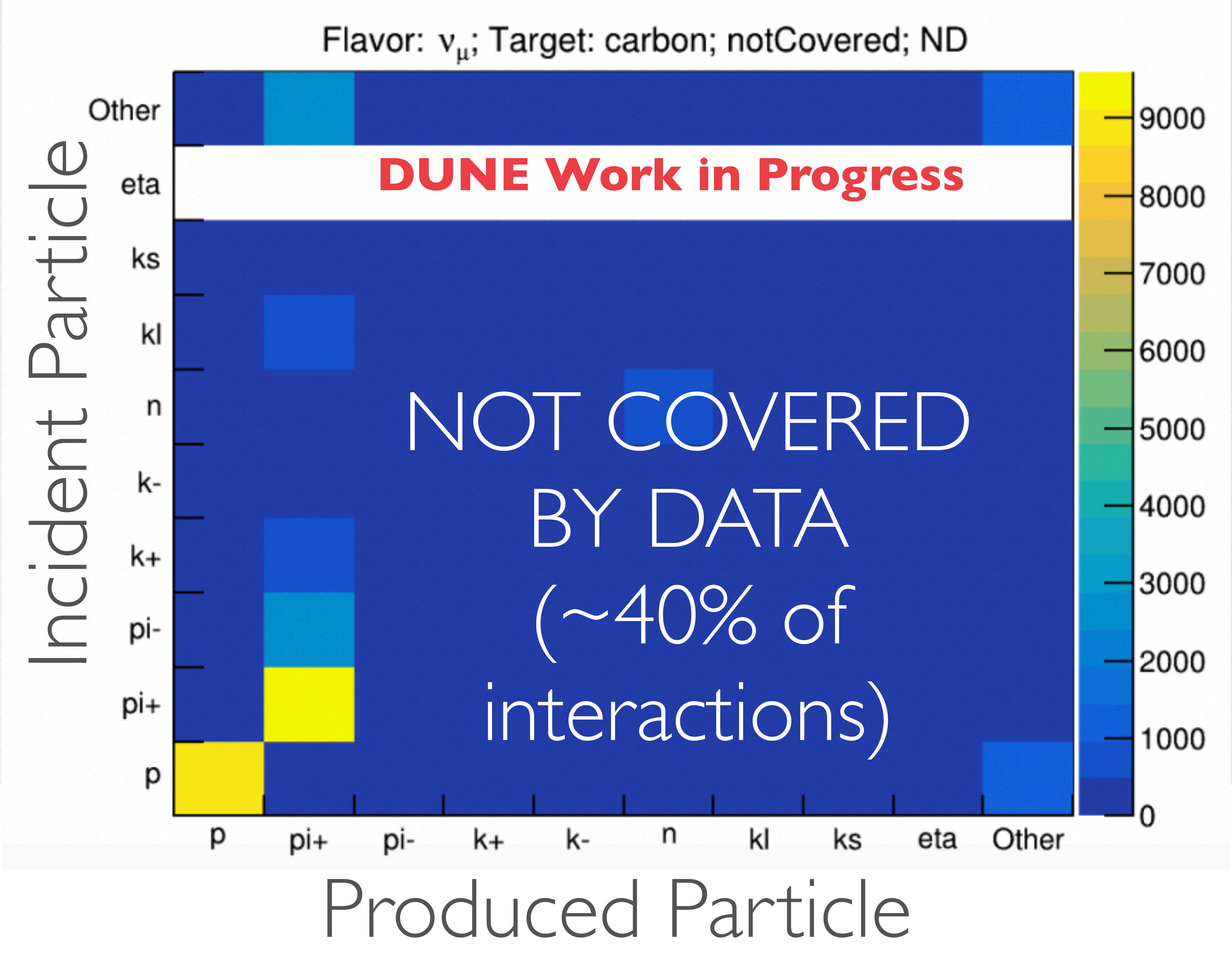


Alignment uncertainties by running a lot of simulations with alignment parameters varied

These are currently subdominant but will become more important as hadron production uncertainties go down. A major revision of these is underway now.

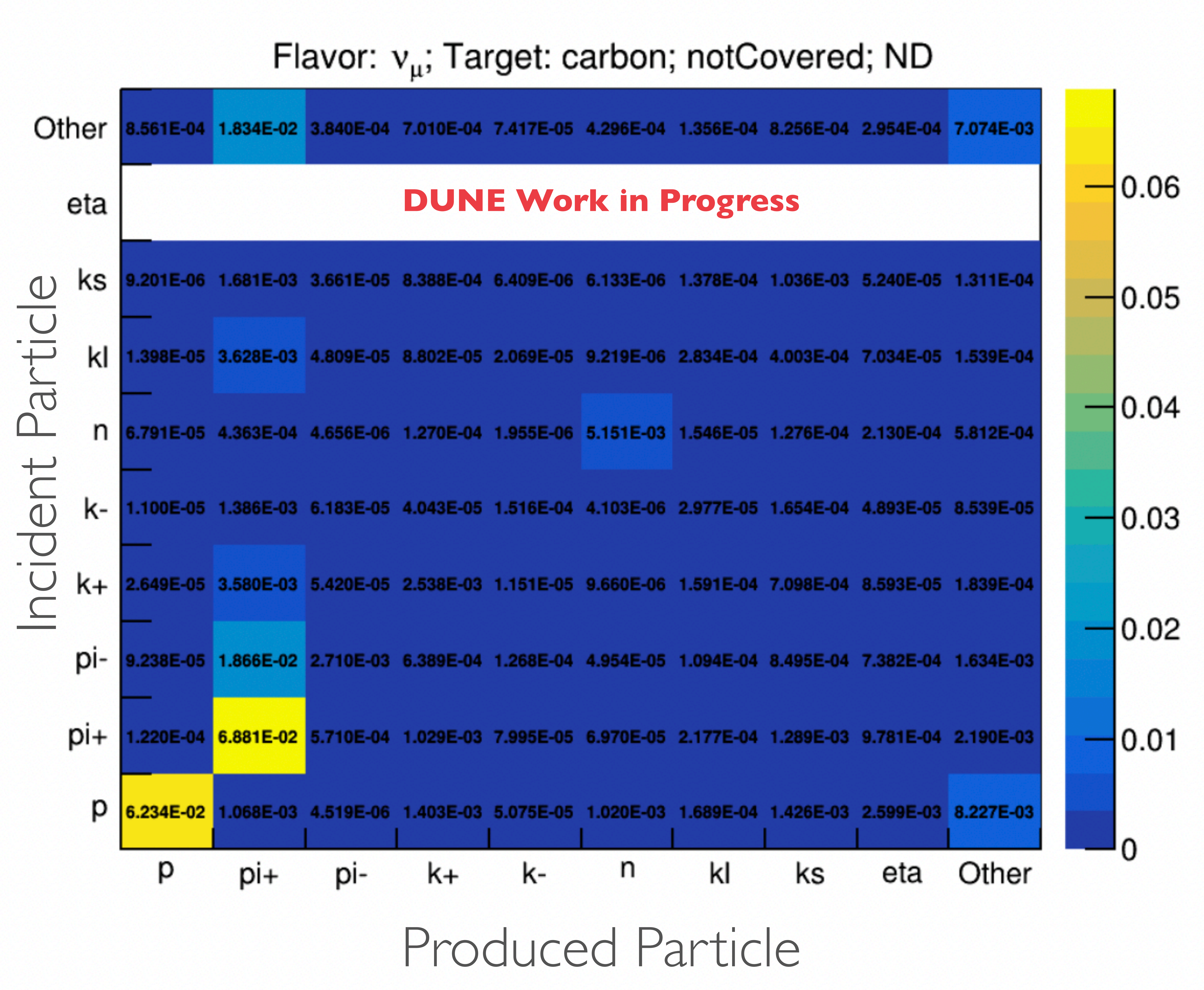
NEEDS: UNMEASURED INTERACTIONS





- "COVERED BY DATA" here means the data that is currently considered in the flux prediction; recent NA61 pion incident data or 120 GeV proton data and EMPHATIC quasi elastic data are not yet included

NEEDS: UNMEASURED INTERACTIONS

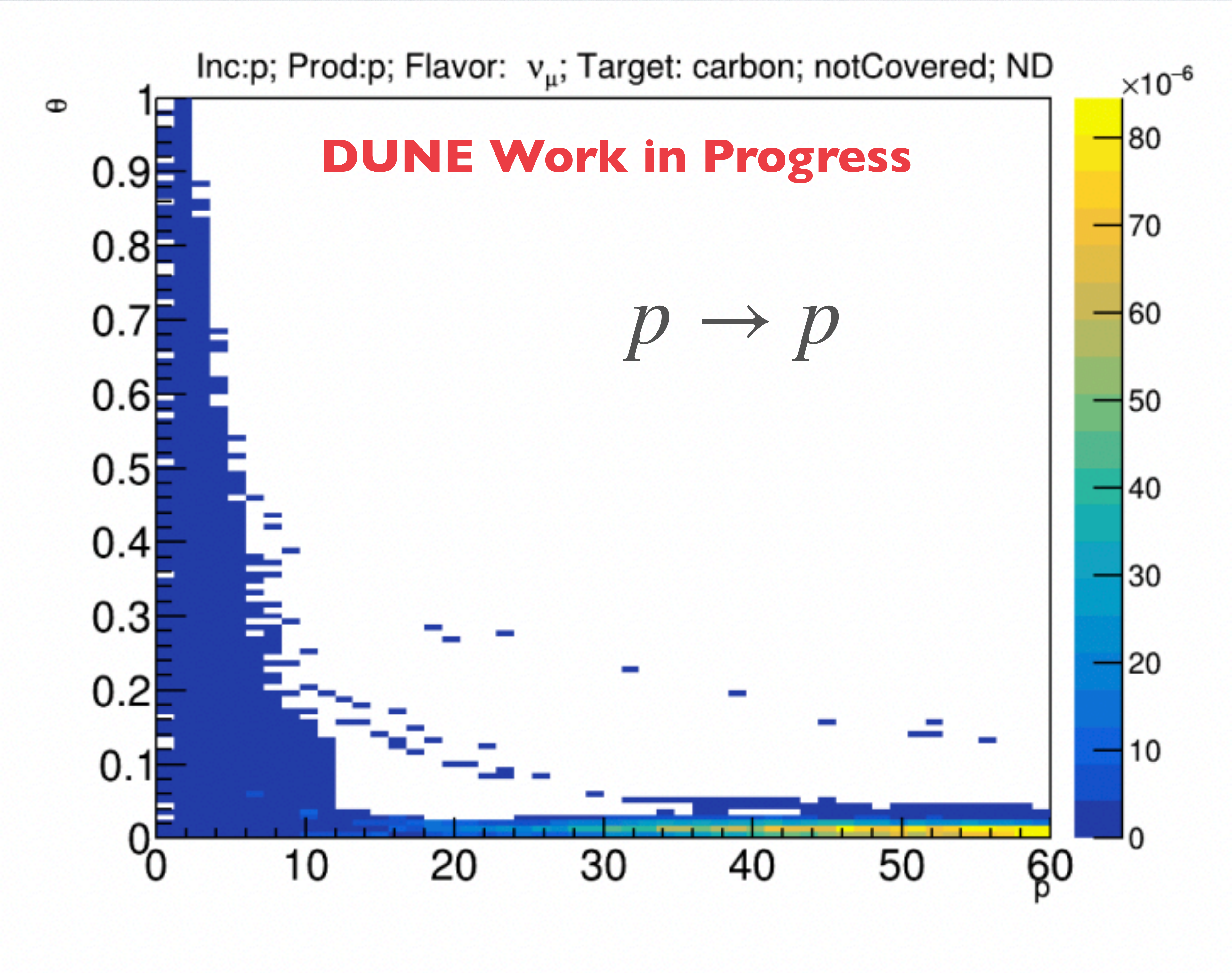


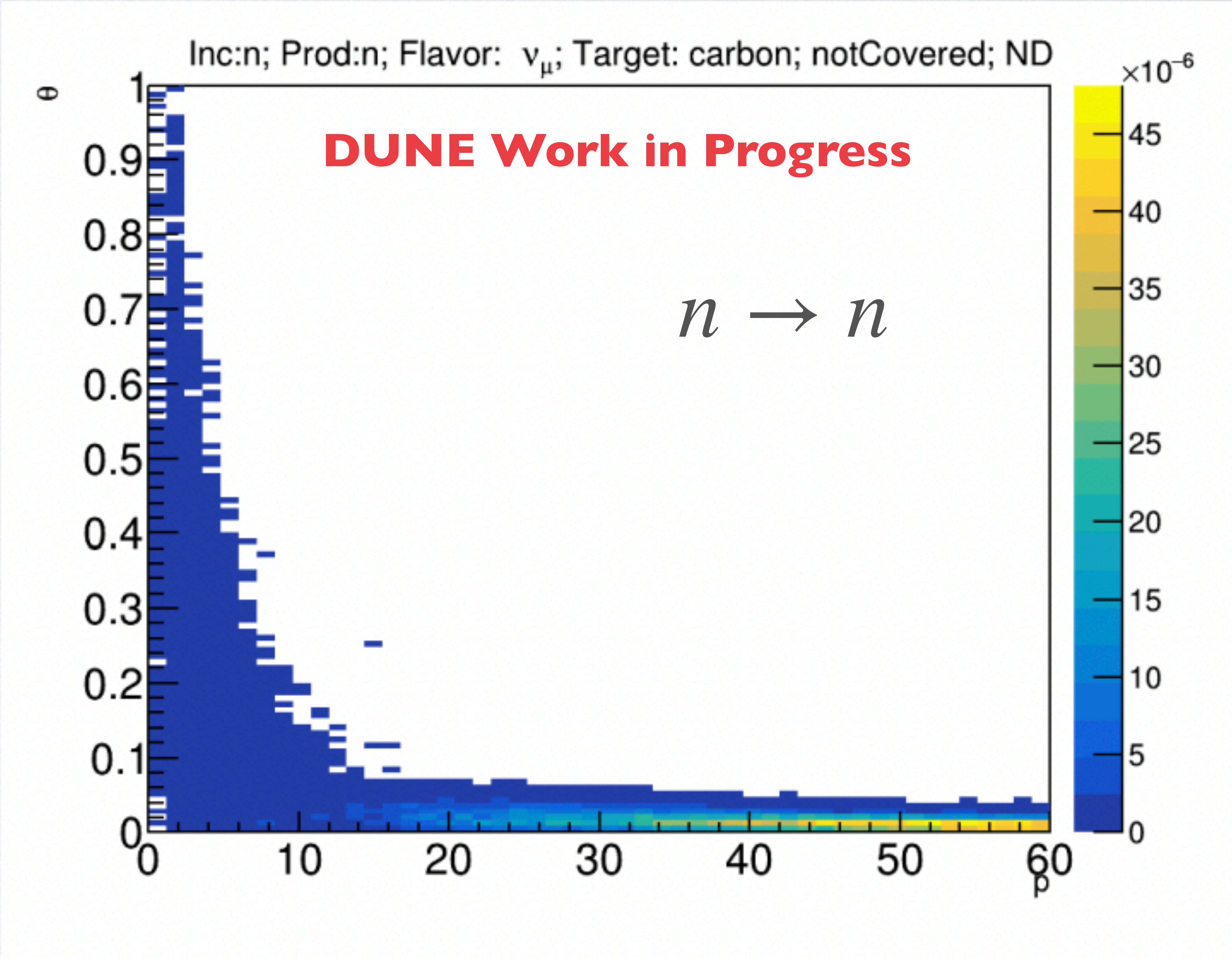
Interactions not covered by data, normalized to neutrino flux

These are the thin target interaction measurements that are most critical to DUNE

NEEDS: UNMEASURED INTERACTIONS

- Phase space of unmeasured interactions:





NEEDS: UNMEASURED INTERACTIONS

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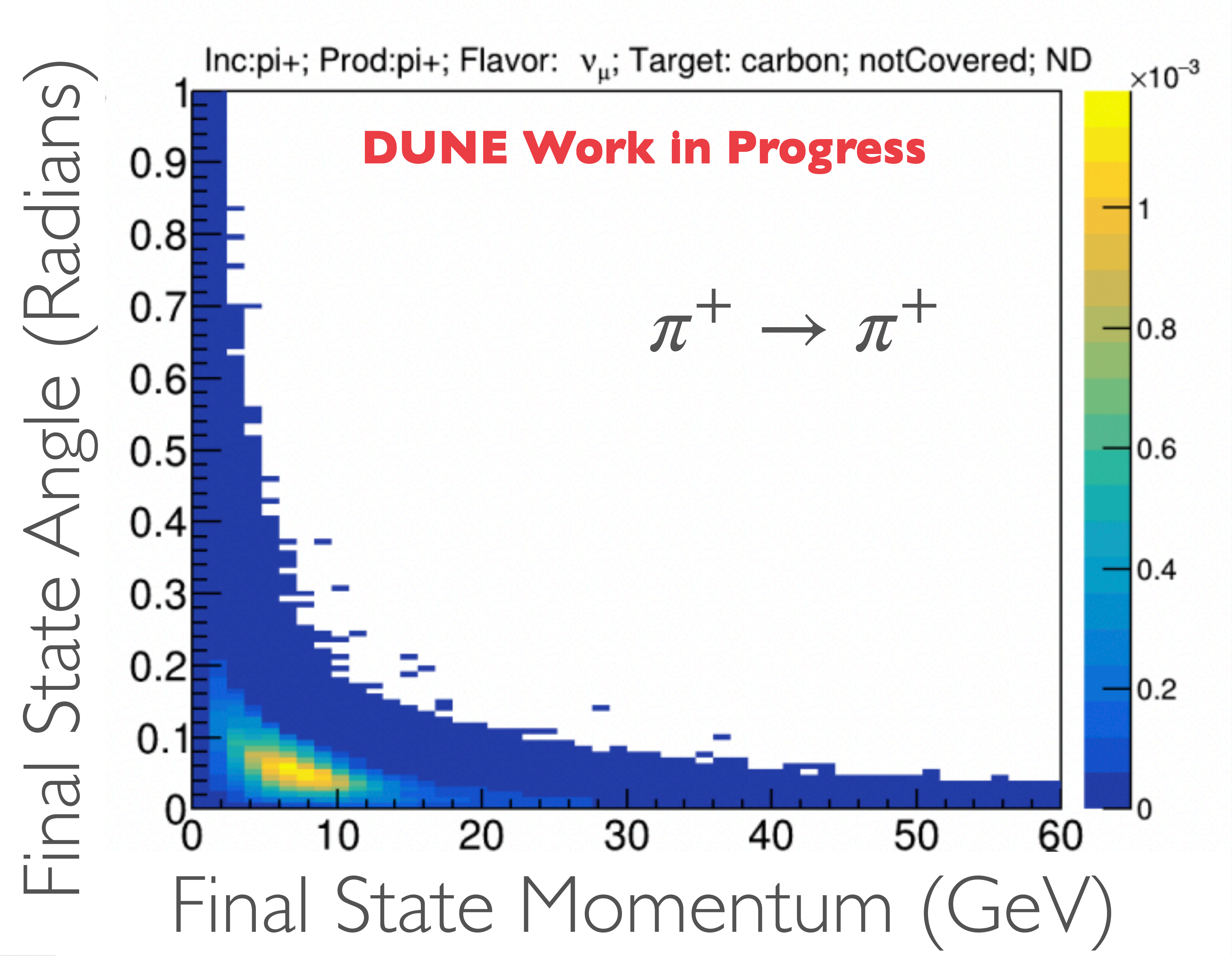
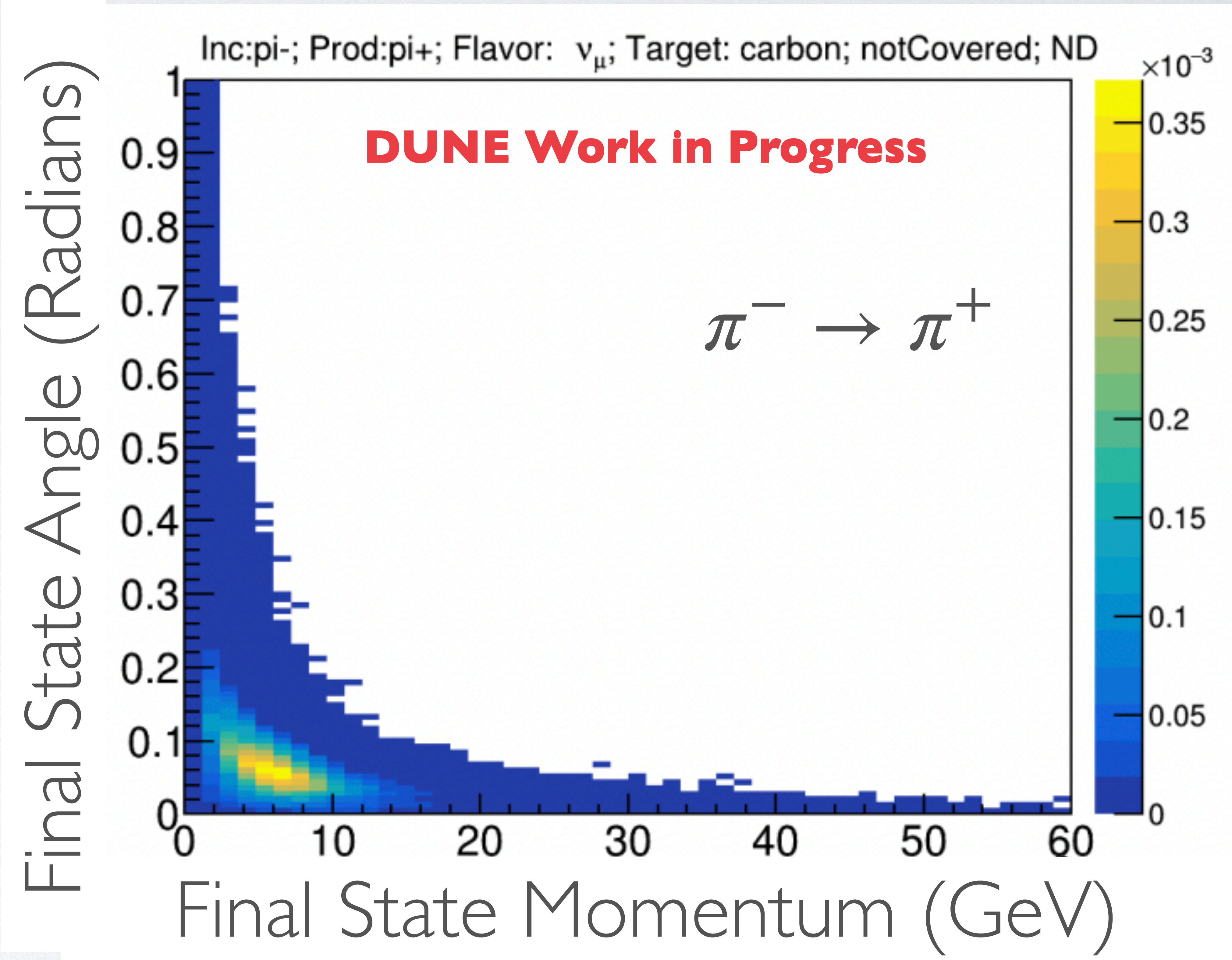
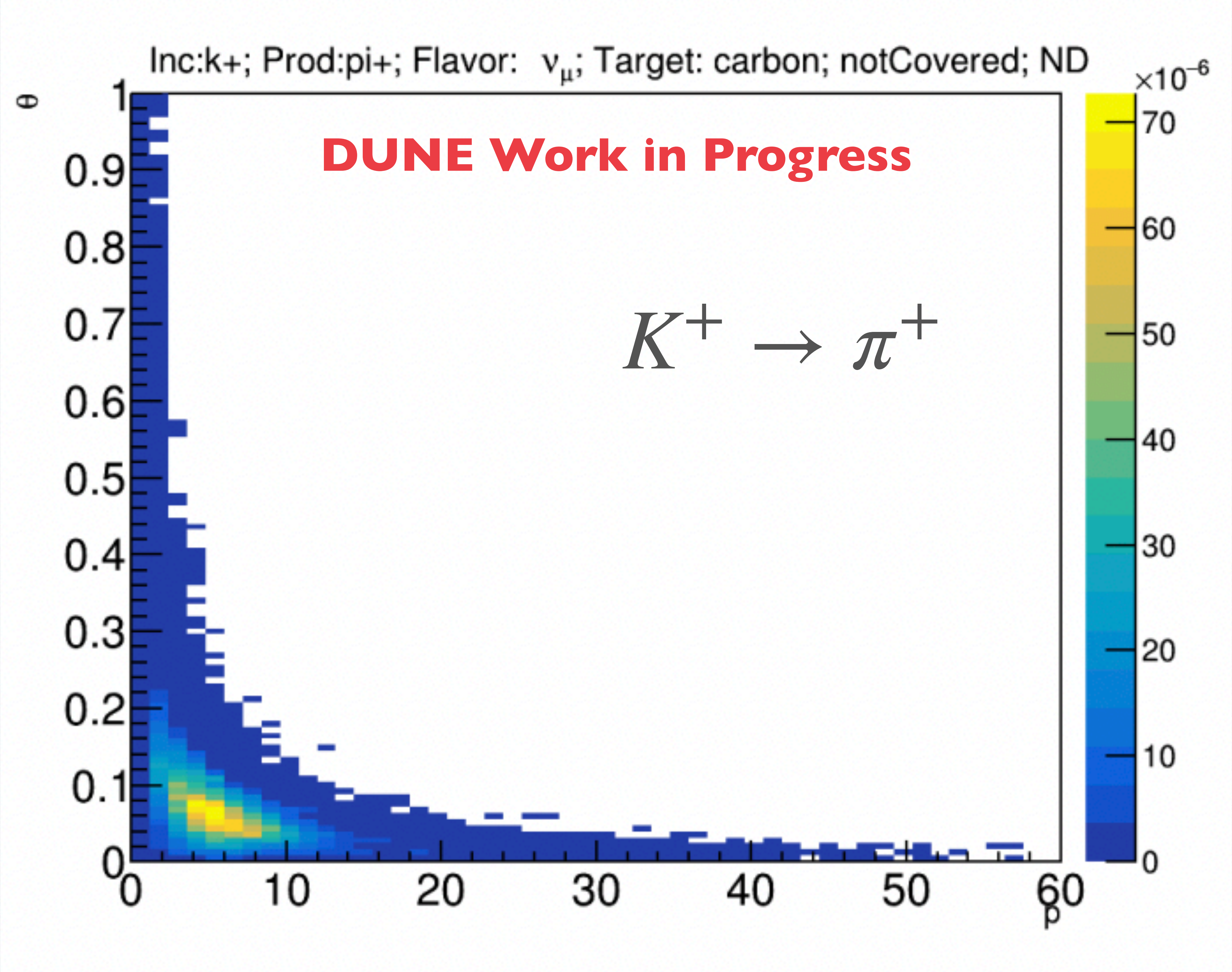
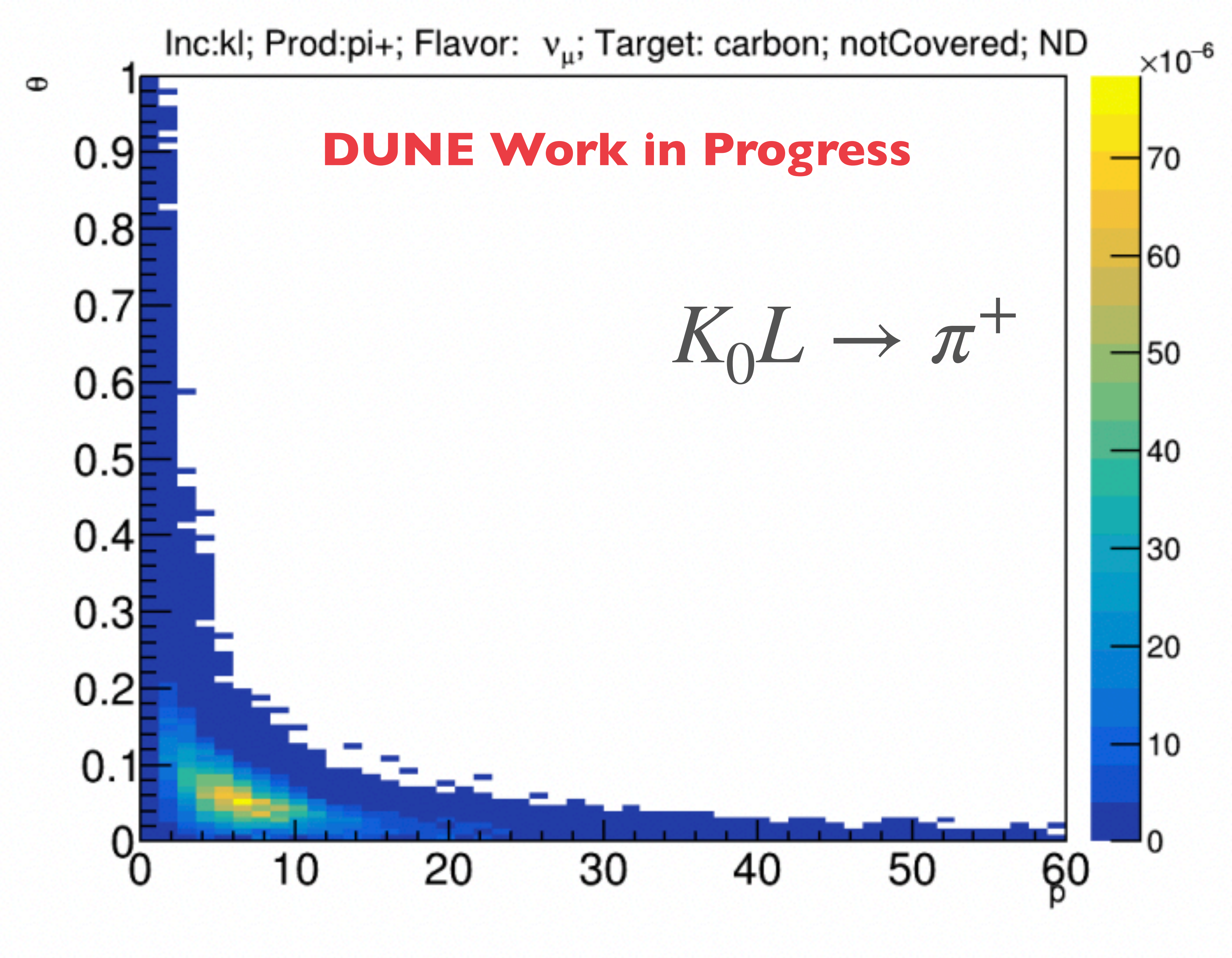




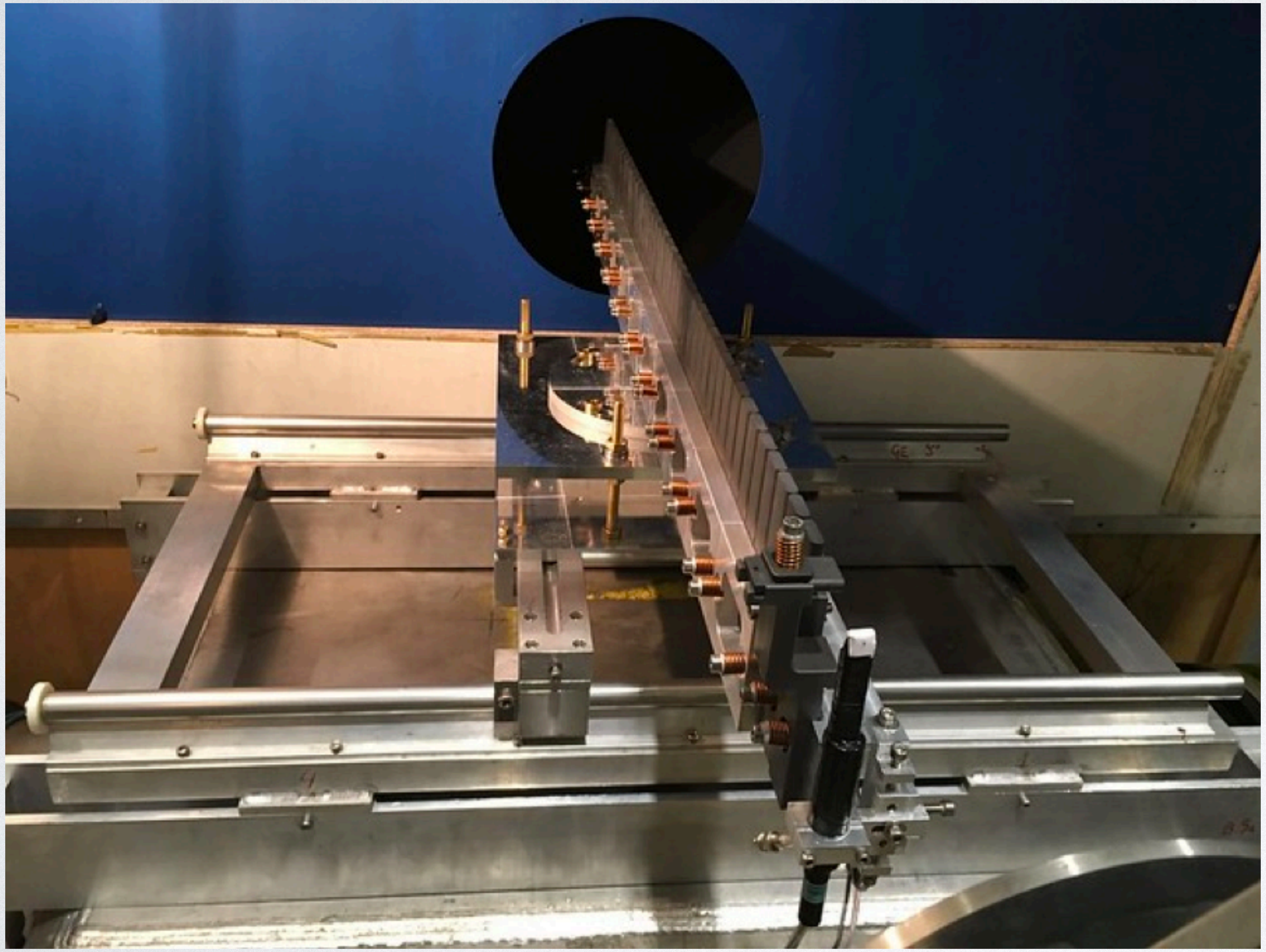
NEEDS: UNMEASURED INTERACTIONS

- Phase space of unmeasured interactions:





NEEDS: LONG TARGET DATA



Replica target measurements have proven to be the **gold standard** of hadron production measurements for neutrino experiments

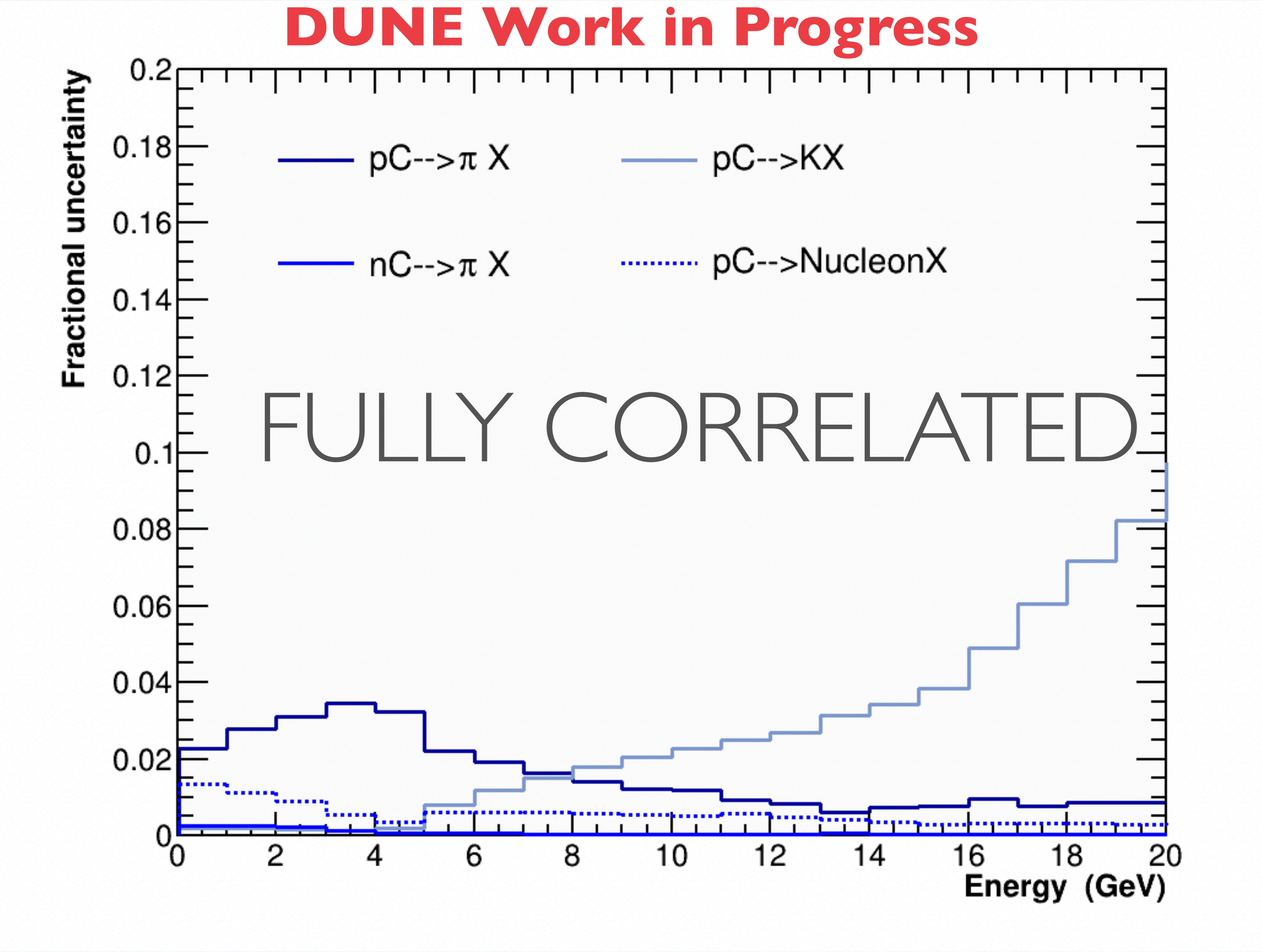
DUNE will **definitely need replica target measurements**; first planned for ~2024

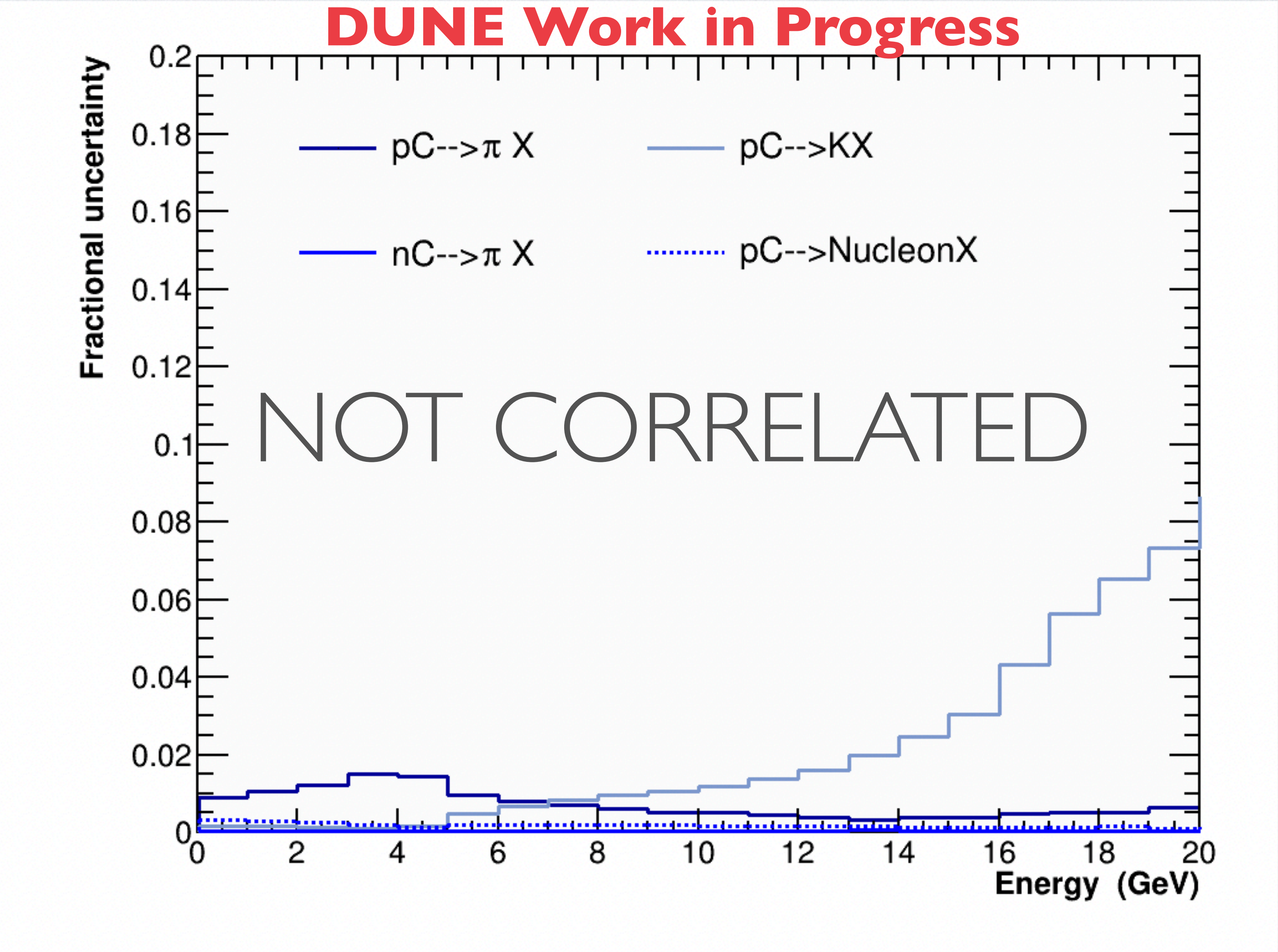
Ongoing upgrades of the target will require **repeated replica target measurements** over the course of DUNE's run

Initial **prototype will be 1.5 m long**; length will eventually be **extended to 1.8 m** if feasible

NEEDS: CORRELATION MATRICES

- Results of a study that looked at the impact of hadron production correlations on a portion of the DUNE hadron production flux uncertainties:





- Flux uncertainties are strongly dependent on assumed correlations of flux uncertainties
  - In most cases, the data we are using have not reported correlation matrices and we are guessing at what they might look like
  - We *really* need accurate correlation matrices

OTHER NEEDS

Recall that even the "covered by data" interaction make some **leaps of faith**:

- p C → π +X cross section assumed to be the same as n C → π −X and vice versa **(isospin symmetry)**
- **Carbon data used for other nuclei** (with larger uncertainty)
- 158 GeV proton data used for **many incident energies**

Hightest priority for thin target data are the "not covered" interactions, but also need guidance on extrapolation across different incident energies, nuclei and validation of isospin assumptions

DUNE would also greatly benefit from **more overlap between the people producing hadron production measurements and people implementing** those in flux predictions

CONCLUSION

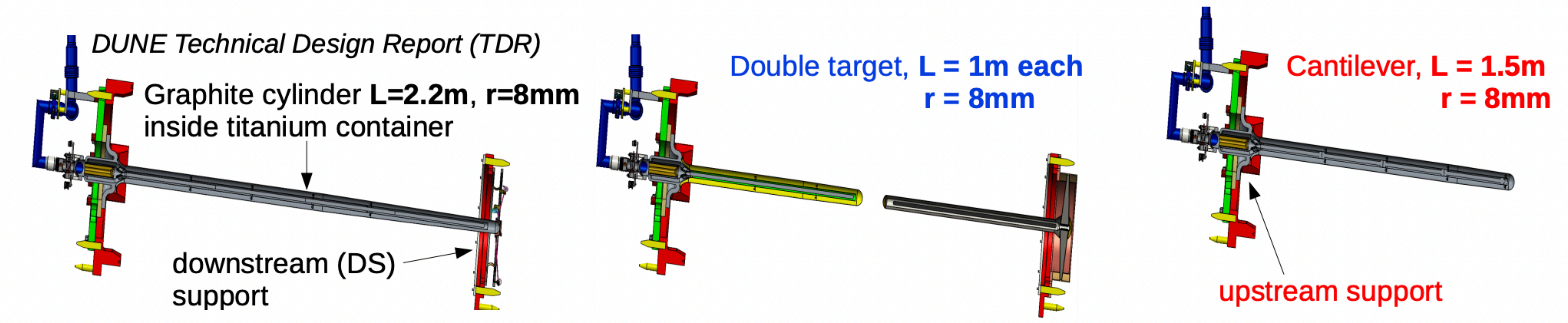
- DUNE will make precise measurements of **neutrino oscillation parameters** and search for CP-violation and a variety of **BSM physics**
- All of DUNE's accelerator-based measurements rely on an **accurate beam simulation**
- **Many of the interactions** that will create neutrinos in the LBNF beam line have **never been measured** and are not well understood theoretically
- Highest DUNE hadron production needs
  - **Replica target** measurements (but will have to make these repeatedly)
  - Interactions **not currently covered** by data
  - Data over a range of **incident energy and target nucleus**
  - **Covariance matrices** for all datasets
  - **Help from the HP community** using these data

Thank You for Listening!

BACKUP

RECENT CHANGES TO BEAM LINE

- Since the TDR design of the beam has progressed, with some changes that affect the neutrino flux
  - **Target**
  - Horn A
  - Horn B
  - Horn C



TDR DESIGN

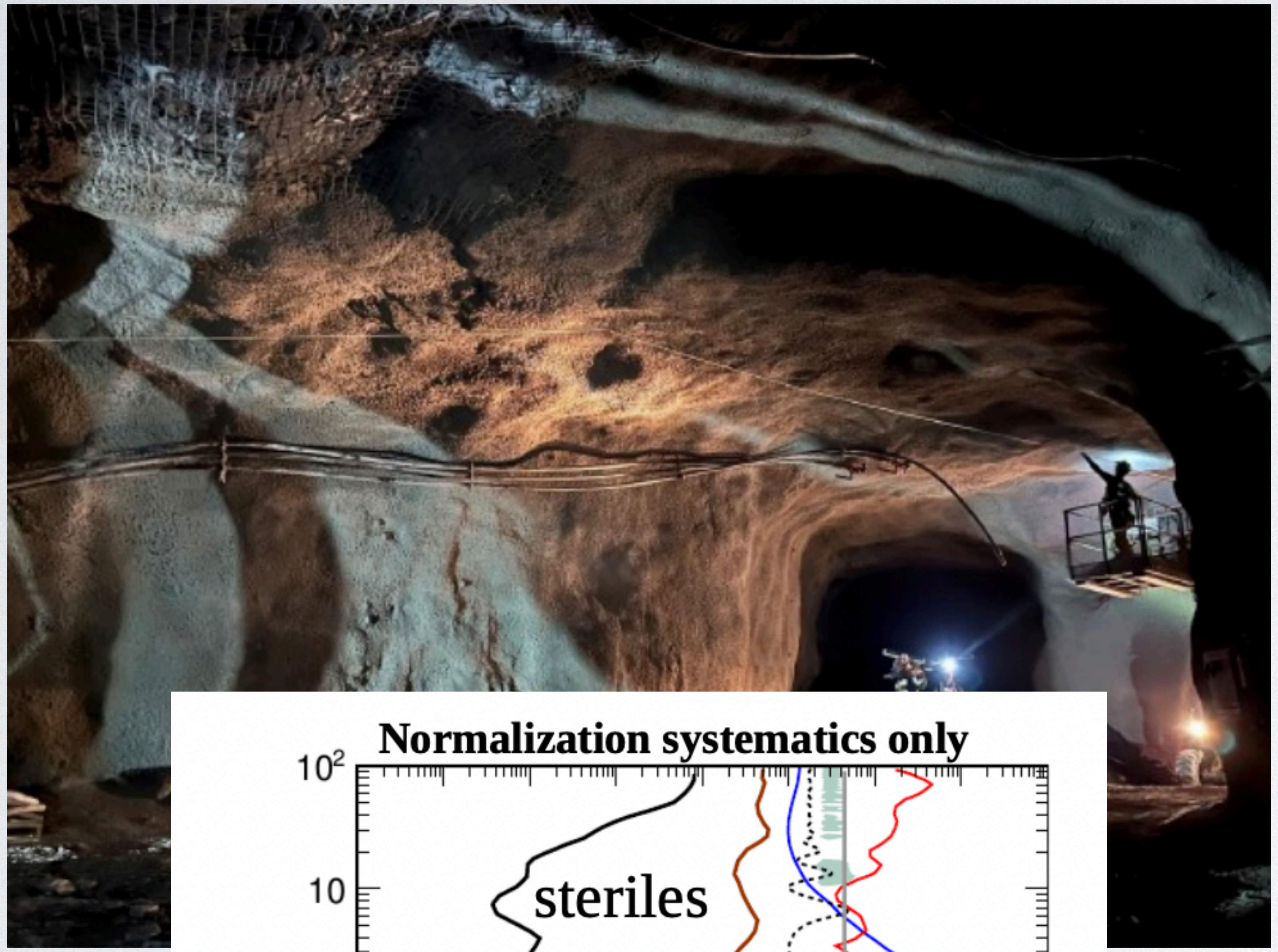
Current Design
(Hopefully will be extended to 1.8 m)

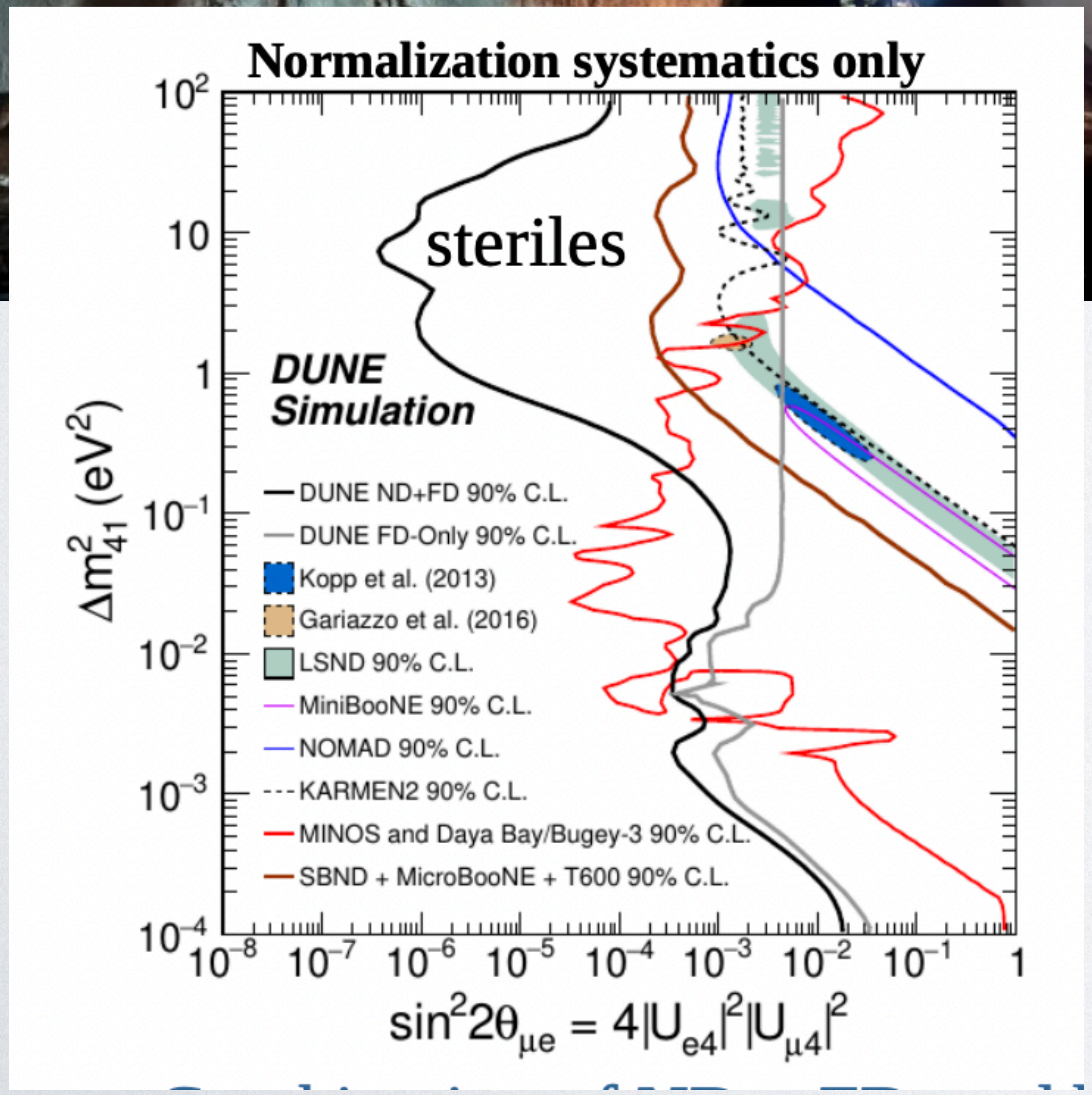
RECENT CHANGES TO BEAM LINE

- Since the TDR design of the beam has progressed, with some changes that affect the neutrino flux
  - Target
  - **Horn A**
  - Horn B
  - Horn C

To Be Added

DUNE PHYSICS





Many different handles for Beyond the Standard Model:

- Non-standard Oscillations
  - Broad coverage for sterile neutrino searches
  - Ability to see tau neutrinos
- New particles with Cosmic Origin
  - Large mass, low backgrounds, excellent imaging
- New particles produced in hadron-nucleus interactions:
  - Intense beam, excellent near detectors at ~500