Beam Simulation: What It Is and How You Use It

DUNE Near Detector Working Group Meeting

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8 October 2015

Outline

- Overview of the DUNE Beam Simulation
- Interface to the Fast MC and other Monte Carlo's
- Flux systematic uncertainties

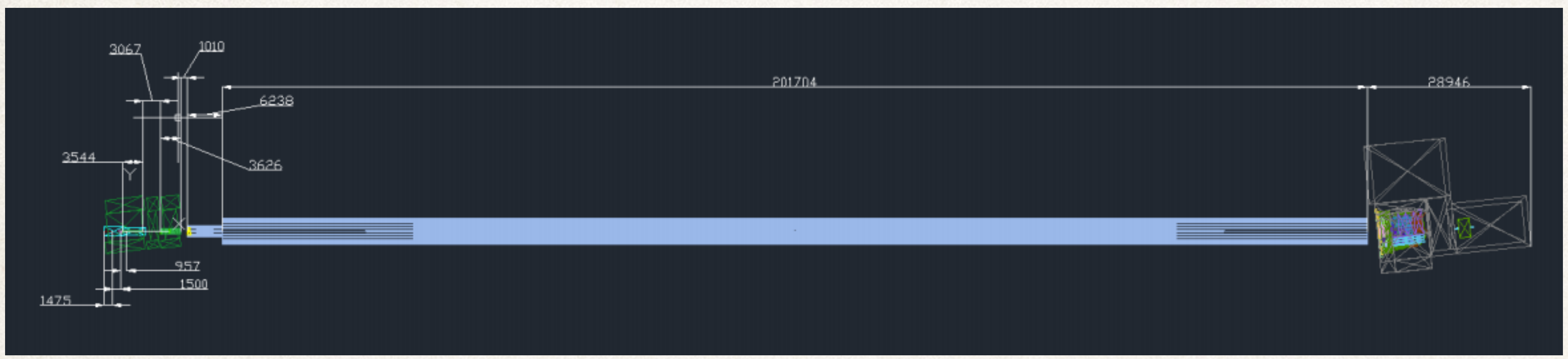
DUNE Beam Simulation

- The DUNE beam simulation is (for the moment) called G4LBNE
- It is documented here:
  - https://cdcvs.fnal.gov/redmine/projects/lbne-beamsim/wiki

DUNE Beam Simulation

- It is a highly-configurable Geant4-based simulation of the beamline, from primary proton beam to hadron absorber:

Visualization of the G4LBNE Geometry:

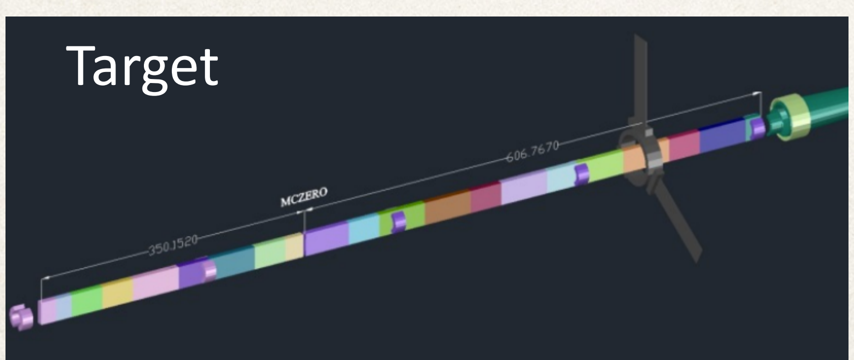


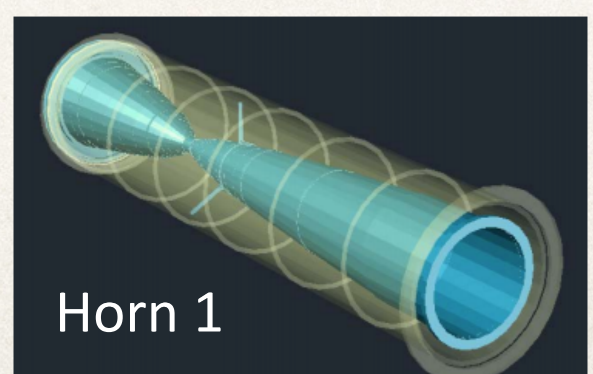
Seongtae Park

Target/Horns/Shielding

Decay Pipe

Hadron Absorber





An option to use Fluka instead of Geant4 is also in the works

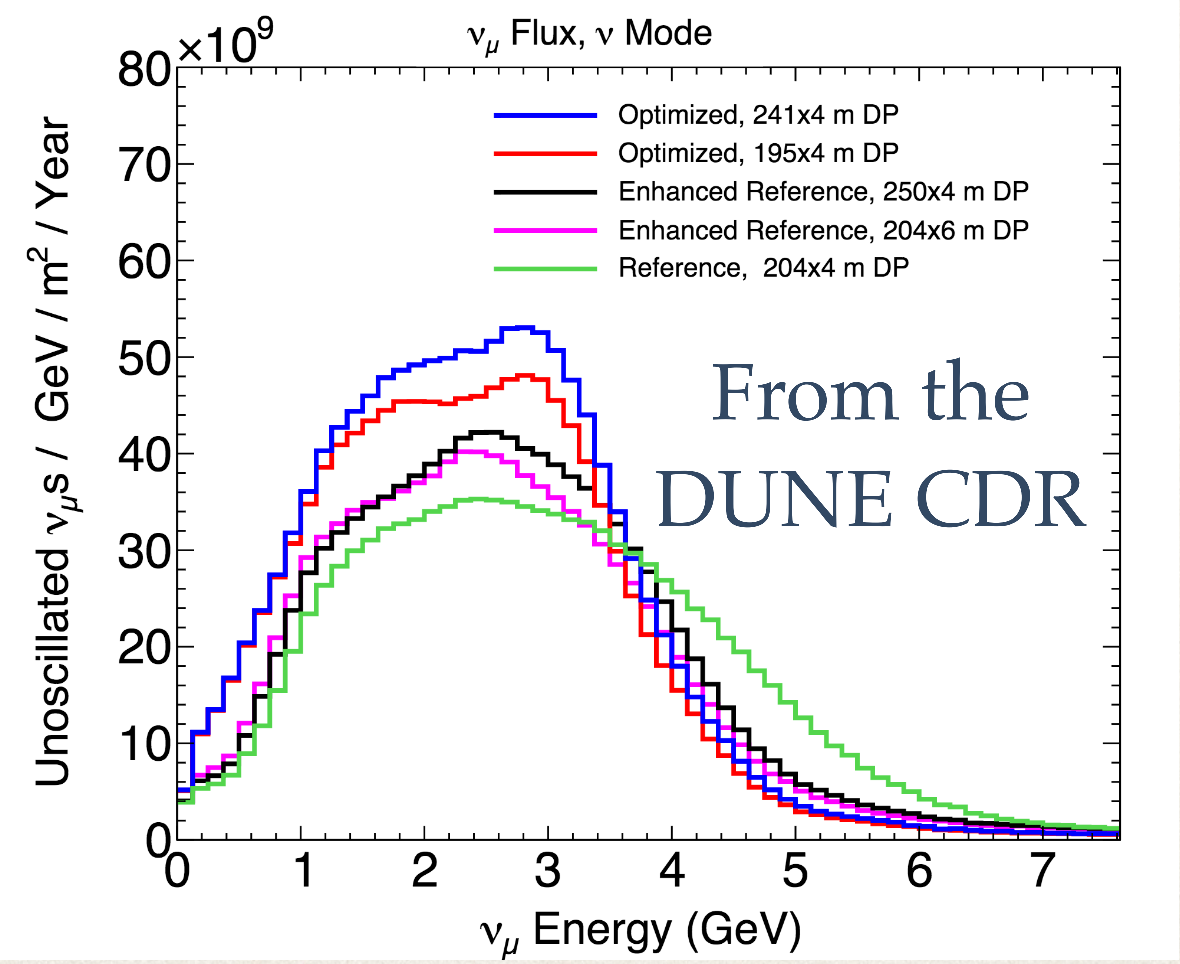
A MARS simulation of the beam line also exists. It is primarily used for radiological & energy deposition studies

DUNE Beam Simulation

- The **basic output** of G4LBNE is an **ntuple** that
  - Contains **an entry for every neutrino** that was created along the beam line
    - With one caveat: We use importance weighting; we save fewer of the low energy neutrinos that we don't care about and more of the relatively rare high energy neutrinos that we do care about
  - Can be written in **NuMI-style or Dk2Nu format** (but not MiniBooNE-style format)
- The simulation is also capable of making **a variety of other outputs** — pion distributions, records of the geometry simulated, etc, but the stuff the NDWG cares about is the neutrino ntuple
- For a list of information that is recorded, see the **documentation** of the numi-style tuple: https://cdcvs.fnal.gov/redmine/projects/lbne-beamsim/wiki/Ntuple
- Dk2Nu stores similar information, organized differently. See: https://cdcvs.fnal.gov/redmine/projects/dk2nu/wiki

Interface to Fast MC (and other MC's)

- There are **two options** for feeding the output of the beam simulation into a neutrino event generator:
  - What nearly everyone on DUNE currently does is use **flux histograms** generated from the tuple output of G4LBNE

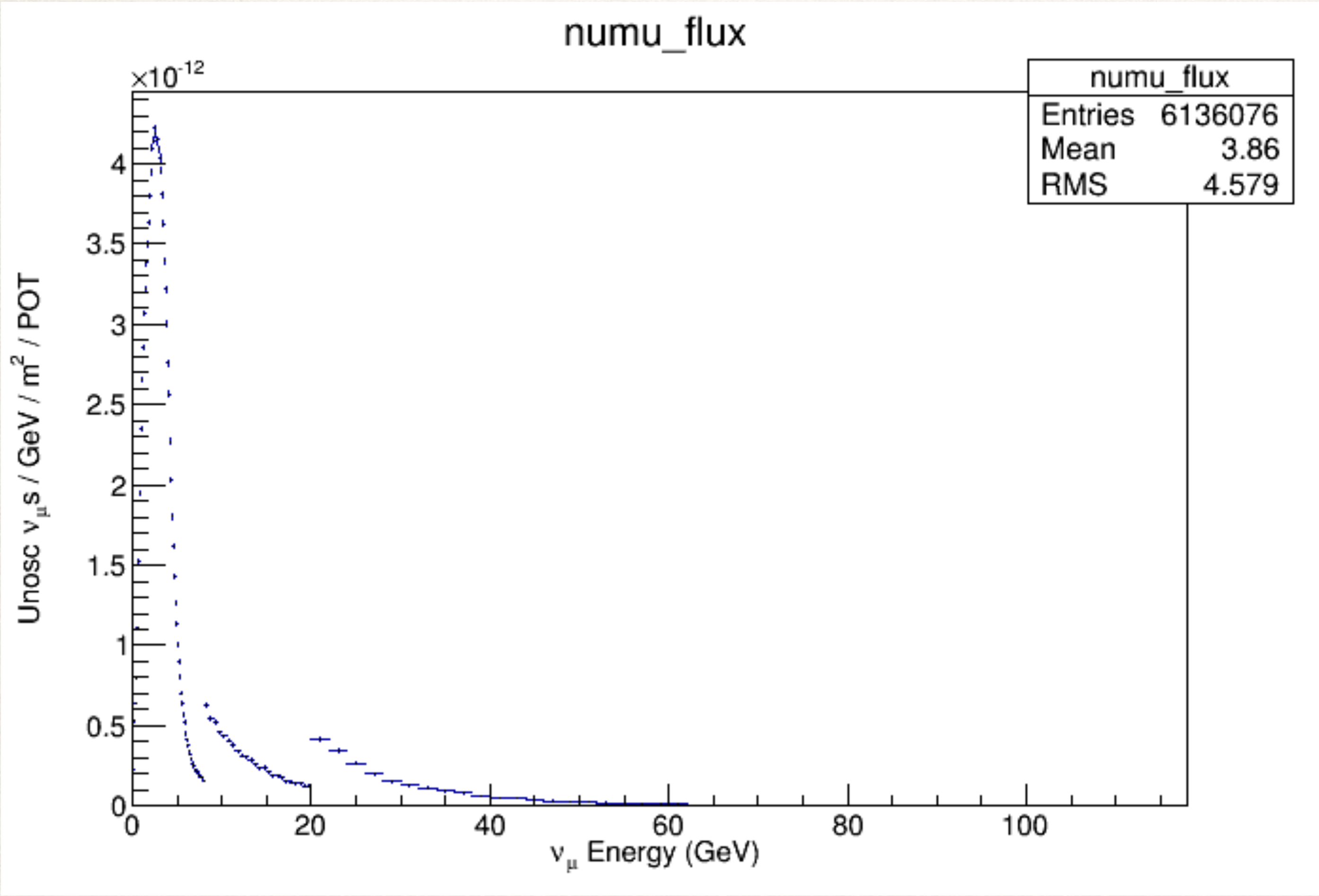


These are created picking a location where you want to plot the flux, looping over all the neutrinos in the g4lbne tuples and applying the importance weight and a "**detector weigh**t"

The detector weight gives the **relative probability that a neutrino that decayed** in some random direction along the beam line would have **decayed in the direction of your location**

Interface to Fast MC (and other MC's)

- The histograms that are used as inputs to the Fast Monte Carlo look similar
  - Just a little less glamorous than the ones in the CDR

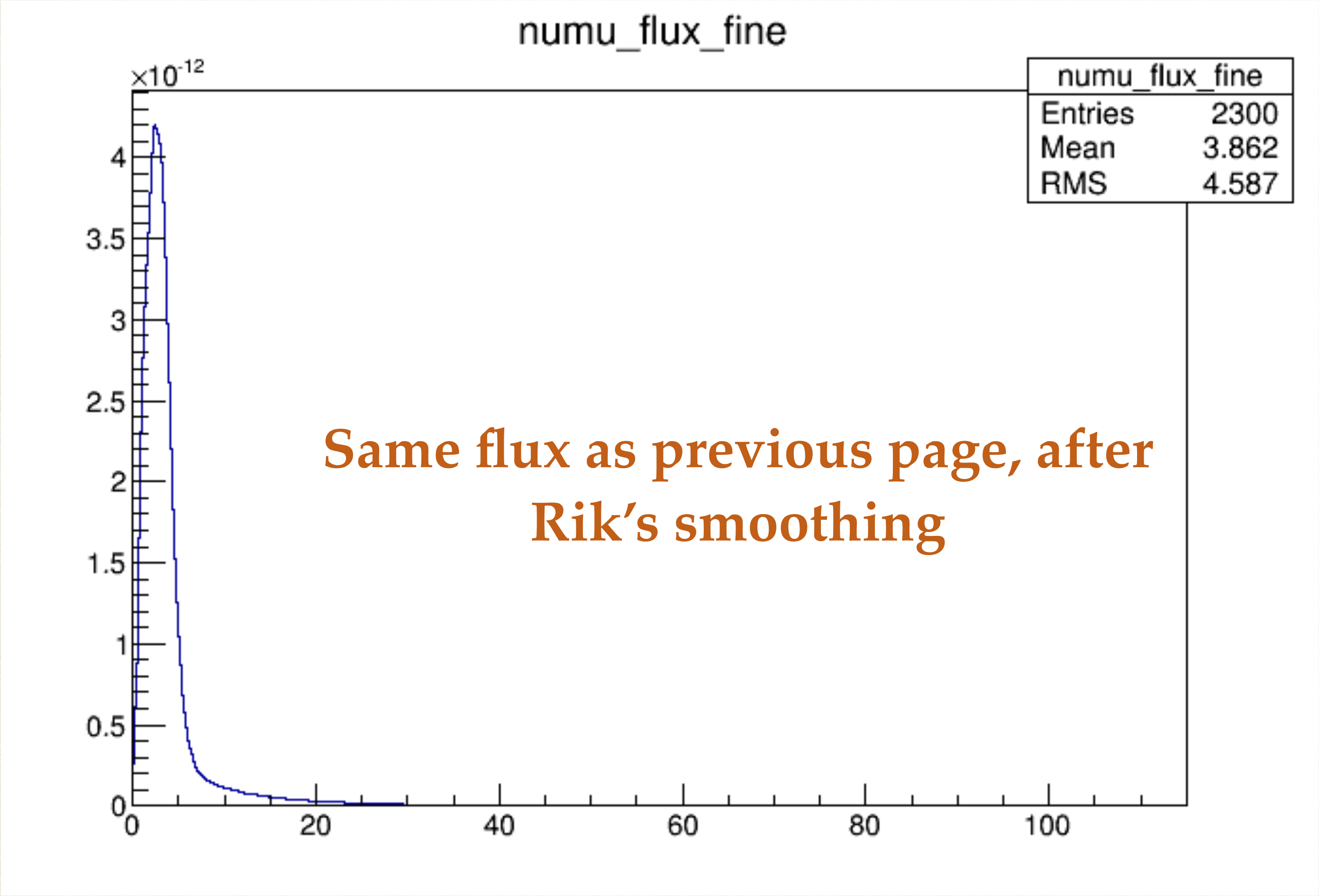


The current default flux used by the FMC (v3r2p4b / nominal)

Dan, Rik and I picked this variable binning a long time ago

Interface to Fast MC (and other MC's)

- The histograms that actually get fed into GENIE are smoothed by some **smoothing code** written by Rik Gran:



The files containing histograms also contain some **metadata** used by the Fast MC such as:

POT/year

version number

flux * argon cross section

Interface to Fast MC (and other MC's)

- For each simulated flux, we provide **12 files** to the Fast MC:

```
<lbnegpvm03.fnal.gov> ls /lbne/data/users/lblpwg_tools/FastMC_Data/flux_files/v3r2p4b/nominal/
g4lbne_v3r2p4b_FHC_FD.root               g4lbne_v3r2p4b_RHC_FD.root
g4lbne_v3r2p4b_FHC_FD_RIK.root           g4lbne_v3r2p4b_RHC_FD_RIK.root
g4lbne_v3r2p4b_FHC_FD_globes_flux.txt    g4lbne_v3r2p4b_RHC_FD_globes_flux.txt
g4lbne_v3r2p4b_FHC_ND.root               g4lbne_v3r2p4b_RHC_ND.root
g4lbne_v3r2p4b_FHC_ND_RIK.root           g4lbne_v3r2p4b_RHC_ND_RIK.root
g4lbne_v3r2p4b_FHC_ND_globes_flux.txt    g4lbne_v3r2p4b_RHC_ND_globes_flux.txt
```

- Different files for:
  - neutrino/antineutrino mode
  - near and far detectors
  - before and after smoothing
- **Each file contains 6 flux histograms:**
  - numu, numubar, nue, nuebar, nutau, nutaubar (nutaus are always empty)
  - Also provide oscillated fluxes (assuming some set of oscillation parameters) and CC and NC event rate distributions on Argon, not used by Fast MC

Interface to Fast MC (and other MC's)

- The fast Monte Carlo has A LOT of different fluxes available to it:

```
r2p4b/pvm03.fnal.gov> ls /lbne/data/users/lblpwg_tools/FastMC_Data/flux_files/v3r
198kA
230kA
AllOptimizations
AllOptimizations_RealisticPower
BaffleScraping0.25Percent
Baseline_120GeV_ExtendedDP
Baseline_120GeV_StandardDP
Baseline_80GeV_ExtendedDP
Baseline_80GeV_StandardDP
BeamSigmaX1.4mm
CylindricalTarget_10.2mm_1.7mmbeam
CylindricalTarget_5.1mm_1.7mmbeam
DecayPipeLength250m
DecayPipeRadius1.9m
DecayPipeRadius3m
DecayPipeRadius3m_230kA
DecayPipeRadius3m_DecayPipeLength250m
DecayPipeRadius3m_ProtonP80GeV
DecayPipeRadius3m_TargetBe
FTFP_BERT
Horn1XOffset0.5mm
Horn1XTilt0.5mm
Horn1YOffset0.5mm
Horn1YTilt0.5mm
Horn2XOffset0.5mm
Horn2XTilt0.5mm
Horn2YOffset0.5mm
Horn2YTilt0.5mm
LBNO_HPPSLE
LBNO_HPPSLE_RealisticPower
LBNO_Optimized_100GeV_ExtendedDP
LBNO_Optimized_110GeV_ExtendedDP
LBNO_Optimized_120GeV_ExtendedDP
LBNO_Optimized_120GeV_StandardDP
LBNO_Optimized_120GeV_WideDP
LBNO_Optimized_130GeV_ExtendedDP
LBNO_Optimized_30GeV_ExtendedDP
LBNO_Optimized_40GeV_ExtendedDP
LBNO_Optimized_50GeV_ExtendedDP
LBNO_Optimized_60GeV_ExtendedDP
LBNO_Optimized_70GeV_ExtendedDP
LBNO_Optimized_80GeV_ExtendedDP
LBNO_Optimized_80GeV_StandardDP
LBNO_Optimized_80GeV_WideDP
LBNO_Optimized_90GeV_ExtendedDP
Nominal_230kA
NuMI_Improved_100GeV_StandardDP
NuMI_Improved_110GeV_StandardDP
NuMI_Improved_120GeV_ExtendedDP
NuMI_Improved_120GeV_StandardDP
NuMI_Improved_120GeV_WideDP
NuMI_Improved_130GeV_StandardDP
NuMI_Improved_20GeV_StandardDP
NuMI_Improved_30GeV_StandardDP
NuMI_Improved_40GeV_StandardDP
NuMI_Improved_50GeV_StandardDP
NuMI_Improved_60GeV_StandardDP
NuMI_Improved_70GeV_StandardDP
NuMI_Improved_80GeV_ExtendedDP
NuMI_Improved_80GeV_StandardDP
NuMI_Improved_80GeV_WideDP
NuMI_Improved_90GeV_StandardDP
NuMI_Improved_Be8p7_120GeV_ExtendedDP
NuMI_Improved_Be8p7_120GeV_StandardDP
NuMI_Improved_Be8p7_120GeV_WideDP
NuMI_Improved_Be8p7_80GeV_ExtendedDP
NuMI_Improved_Be8p7_80GeV_StandardDP
NuMI_Improved_Be8p7_80GeV_WideDP
NuMI_Improved_Be_120GeV_ExtendedDP
NuMI_Improved_Be_120GeV_StandardDP
NuMI_Improved_Be_80GeV_ExtendedDP
NuMI_Improved_Be_80GeV_StandardDP
Optimizations-CP_run3-177
Optimizations-CP_run3-3544
Optimizations-CP_run3-4177
Optimizations-CP_run3-6177
Optimizations-CP_run3-6911
Optimizations-CP_run3-7177
Optimizations-CP_run3-7772
Optimizations-CP_run3-7862
Optimizations-CP_run3-8177
Optimizations-CP_run3-8186
Optimizations_CP_run3_177
Optimizations_CP_run3_3544
Optimizations_CP_run3_4177
Optimizations_CP_run3_6177
Optimizations_CP_run3_6911
Optimizations_CP_run3_7177
Optimizations_CP_run3_7772
Optimizations_CP_run3_7862
Optimizations_CP_run3_8177
Optimizations_CP_run3_8186
Optimizations_CP_run5_3318
Optimizations_ME_run1_3634
POTNorm
Perfect_120GeV_ExtendedDP
Perfect_120GeV_StandardDP
Perfect_120GeV_WideDP
Perfect_80GeV_ExtendedDP
Perfect_80GeV_StandardDP
Perfect_80GeV_WideDP
ProtonP100GeV
ProtonP100GeV_230kA
ProtonP100GeV_RealisticPower
ProtonP110GeV
ProtonP110GeV_RealisticPower
ProtonP130GeV
ProtonP130GeV_RealisticPower
ProtonP140GeV
ProtonP140GeV_RealisticPower
ProtonP150GeV
ProtonP150GeV_RealisticPower
ProtonP20GeV
ProtonP20GeV_RealisticPower
ProtonP30GeV
ProtonP30GeV_RealisticPower
ProtonP40GeV
ProtonP40GeV_RealisticPower
ProtonP50GeV
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ProtonP60GeV
ProtonP60GeV_230kA
ProtonP60GeV_RealisticPower
ProtonP70GeV
ProtonP70GeV_RealisticPower
ProtonP80GeV
ProtonP80GeV_230kA
ProtonP80GeV_RealisticPower
ProtonP90GeV
ProtonP90GeV_RealisticPower
SkinDepth6mm
TargetBe
TargetBe_230kA
TargetBe_DecayPipeLength250m
TargetBe_ProtonP80GeV
TargetDensity1.8156
Test
fhcnuenuebar0p5to1GeVPlus10per
fhcnuenuebar0to0p5GeVPlus10per
fhcnuenuebar10to15GeVPlus10per
fhcnuenuebar15to20GeVPlus10per
fhcnuenuebar1to2GeVPlus10per
fhcnuenuebar20to120GeVPlus10per
fhcnuenuebar2to3GeVPlus10per
fhcnuenuebar3to4GeVPlus10per
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fhcnumu5to6GeVPlus10per
fhcnumu6to7GeVPlus10per
fhcnumu7to8GeVPlus10per
fhcnumu8to9GeVPlus10per
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fhcnumubar10to15GeVPlus10per
fhcnumubar15to20GeVPlus10per
fhcnumubar1to2GeVPlus10per
fhcnumubar20to120GeVPlus10per
fhcnumubar2to3GeVPlus10per
fhcnumubar3to4GeVPlus10per
fhcnumubar4to5GeVPlus10per
fhcnumubar5to6GeVPlus10per
fhcnumubar6to7GeVPlus10per
fhcnumubar7to8GeVPlus10per
fhcnumubar8to9GeVPlus10per
fhcnumubar9to10GeVPlus10per
nominal
rhcnuenuebar0p5to1GeVPlus10per
rhcnuenuebar0to0p5GeVPlus10per
rhcnuenuebar10to15GeVPlus10per
rhcnuenuebar15to20GeVPlus10per
rhcnuenuebar1to2GeVPlus10per
rhcnuenuebar20to120GeVPlus10per
rhcnuenuebar2to3GeVPlus10per
rhcnuenuebar3to4GeVPlus10per
rhcnuenuebar4to5GeVPlus10per
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rhcnuenuebar6to7GeVPlus10per
rhcnuenuebar7to8GeVPlus10per
rhcnuenuebar8to9GeVPlus10per
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rhcnumu0p5to1GeVPlus10per
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rhcnumu10to15GeVPlus10per
rhcnumu15to20GeVPlus10per
rhcnumu1to2GeVPlus10per
rhcnumu20to120GeVPlus10per
rhcnumu2to3GeVPlus10per
rhcnumu3to4GeVPlus10per
rhcnumu4to5GeVPlus10per
rhcnumu5to6GeVPlus10per
rhcnumu6to7GeVPlus10per
rhcnumu7to8GeVPlus10per
rhcnumu8to9GeVPlus10per
rhcnumu9to10GeVPlus10per
rhcnumubar0p5to1GeVPlus10per
rhcnumubar0to0p5GeVPlus10per
rhcnumubar10to15GeVPlus10per
rhcnumubar15to20GeVPlus10per
rhcnumubar1to2GeVPlus10per
rhcnumubar20to120GeVPlus10per
rhcnumubar2to3GeVPlus10per
rhcnumubar3to4GeVPlus10per
rhcnumubar4to5GeVPlus10per
rhcnumubar5to6GeVPlus10per
rhcnumubar6to7GeVPlus10per
rhcnumubar7to8GeVPlus10per
rhcnumubar8to9GeVPlus10per
rhcnumubar9to10GeVPlus10per
```
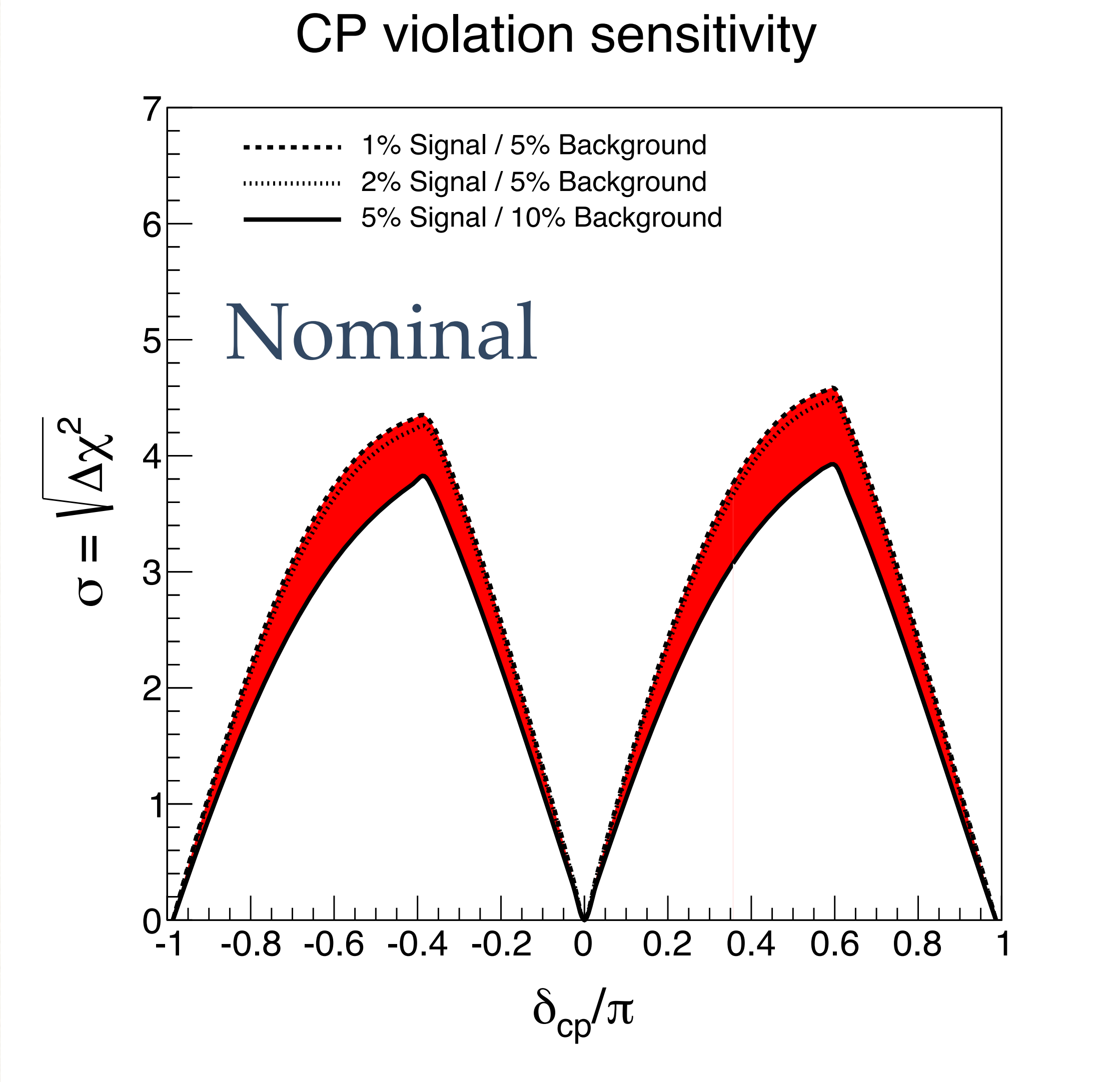
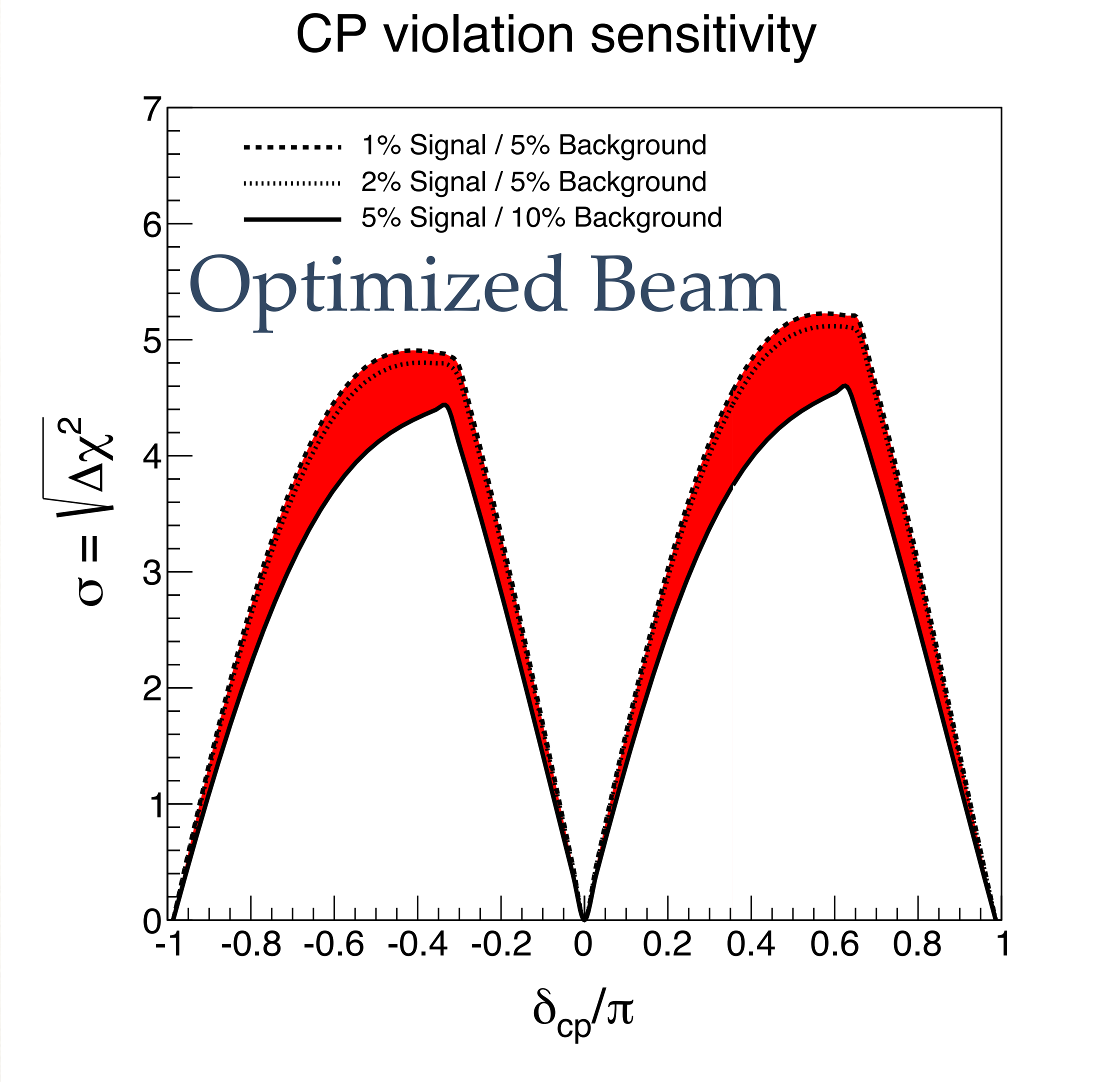

- Some are 1-sigma knob turns of various beam focusing systematics
- One is an alternate hadron production model
- Most are alternate beam configurations that the beam group has wanted to understand the physics implications of (or fluxes used to generate the beam optimization CP sensitivity metric)

Interface to Fast MC (and other MC's)

- When the Fast MC is run, it always gives GENIE the default flux (currently v3r4p2b / nominal)
  - But (if configured to do so), it also stores neutrino energy-dependent weights that allow us to produce simulated event distributions and sensitivities for any of the zillions of flux options on the slide 8 without rerunning the fast MC:





Interface to Fast MC (and other MC's)

- The **other option** is to feed a **g4lbne ntuple** directly to GENIE
  - GENIE's **flux driver** handles calculation of the location weight and spreading the flux across a real detector geometry
  - The main advantages to this:
    - **Preserves information** about the neutrinos other than energy, e.g. what kinds particles made them
    - It would make the G4LBNE+GENIE **interface much smoother**
      - **Takes out the middle man** (ie me) needing to generate histograms and keep up with renaming them, making metadata, etc
      - Also propagates **POT normalization**
  - **We should definitely do this** — Robert is going to talk about how to do it next
  - **Could still study alternate beam configurations** with energy-dependent weighting as we do now

Systematic Uncertainties

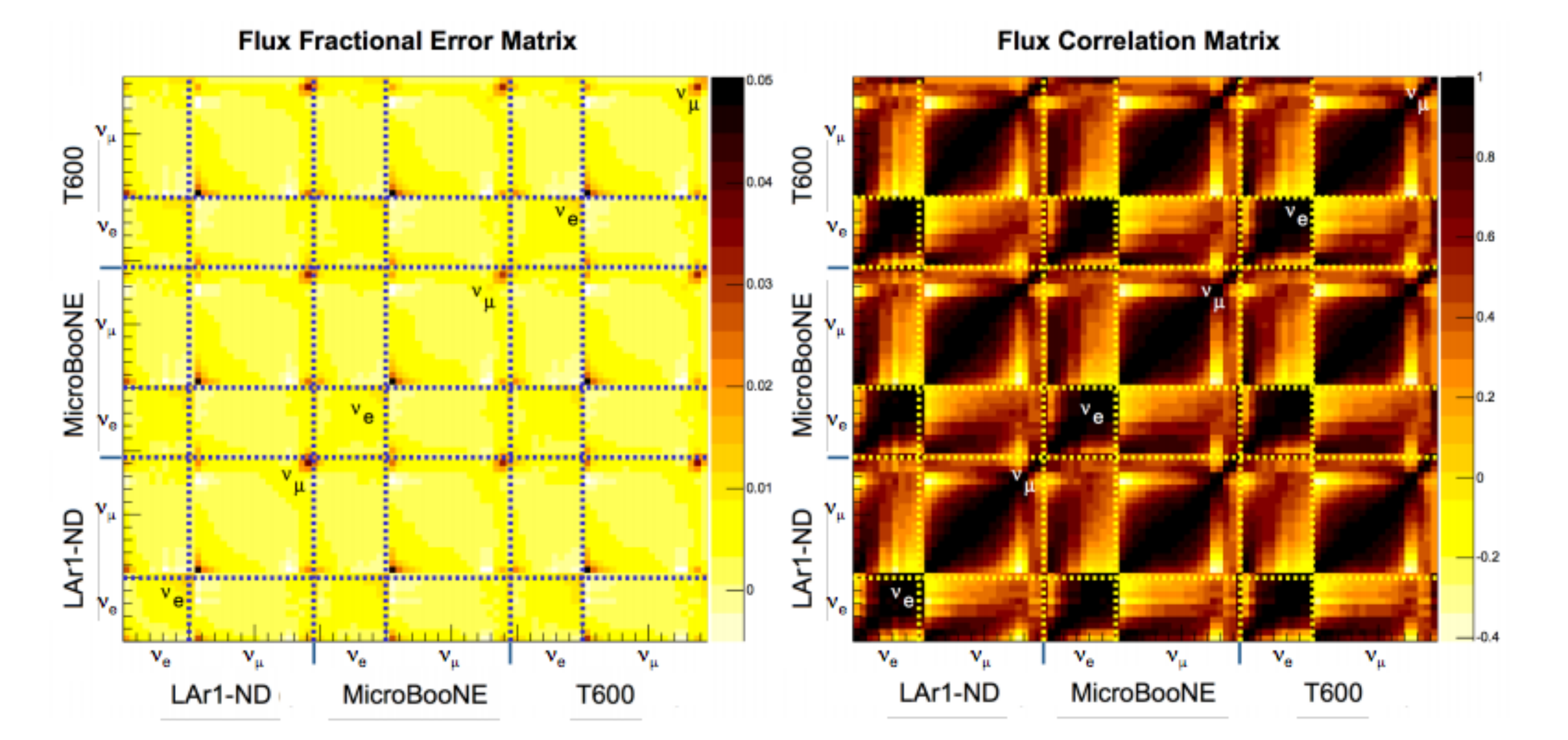
- In addition to a flux prediction, you guys also need **systematic uncertainties** on the flux
  - You want to be able to propagate errors on all of the uncertain parameters in the beam simulation to any sort of physics distribution, **taking into account correlations**
- The problem
  - We do not know exactly **what beam we are going to build**
  - We definitely **don't know exactly what flux uncertainties** are going to be
    - Depends on a lot of things — what beam we build, what hadron production data is taken, what in situ instrumentation is present
- I encourage this group to **consider a variety of uncertainty scenarios**
  - Large, uncorrelated uncertainties, small correlated uncertainties , etc
- That said, here is a **plan for getting you the best uncertainty estimates we can now**

Systematic Uncertainties

- There are **two ways to propagate flux uncertainties** that I'm aware of:
  - Vary hadron production and focusing parameters within their uncertainties to create an ensemble of event normalization weights ('**many universes**") that can be carried through an entire simulation chain
    - This **requires** the feeding a flux ntuple to a **flux driver** like I mentioned earlier
  - Vary those parameters to produce an **flux uncertainties in neutrino energy bins and their correlations**, and propagate these through the simulation chain
    - Since we simulate the beam only using neutrino energy spectra, **this is all we are capable of doing right now**
    - Also, I think i**t is all we really need** right now

Systematic Uncertainties

- Basically, we are after something like this:



From the SBN proposal — At least we only have two detectors!

Systematic Uncertainties

- **Beam focusing uncertainties** are fairly well understood
    - A **technical note** on their evaluation is available: http://lbne2-docdb.fnal.gov:8080/cgi-bin/RetrieveFile?docid=8410&filename=700kWToleranceStudy%20%282%29.pdf&version=4
    - 1-sigma knob turns of the major sources of focusing uncertainty are **available as Fast MC flux weights**

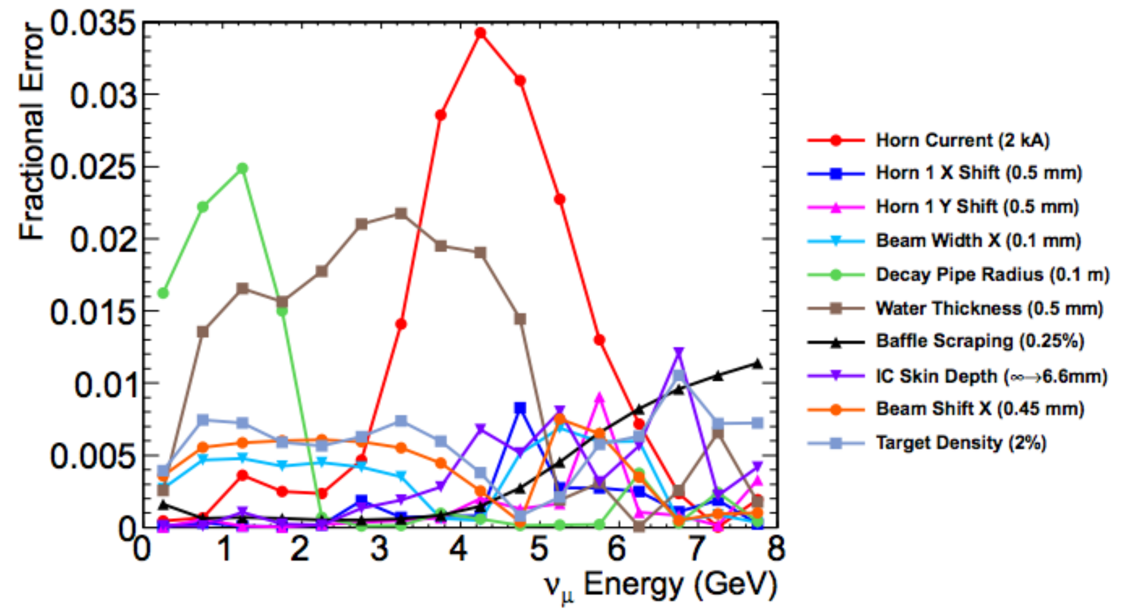


Figure 10: Summary of alignment systematic uncertainties on the flux at the near detector.

Systematic Uncertainties

- The situation is not as good for the other major source of flux uncertainty — **hadron production** off the target:
  - There is currently **no good estimate** of these for DUNE
  - The most we have done in the past is to provide fluxes with **different hadron production models**

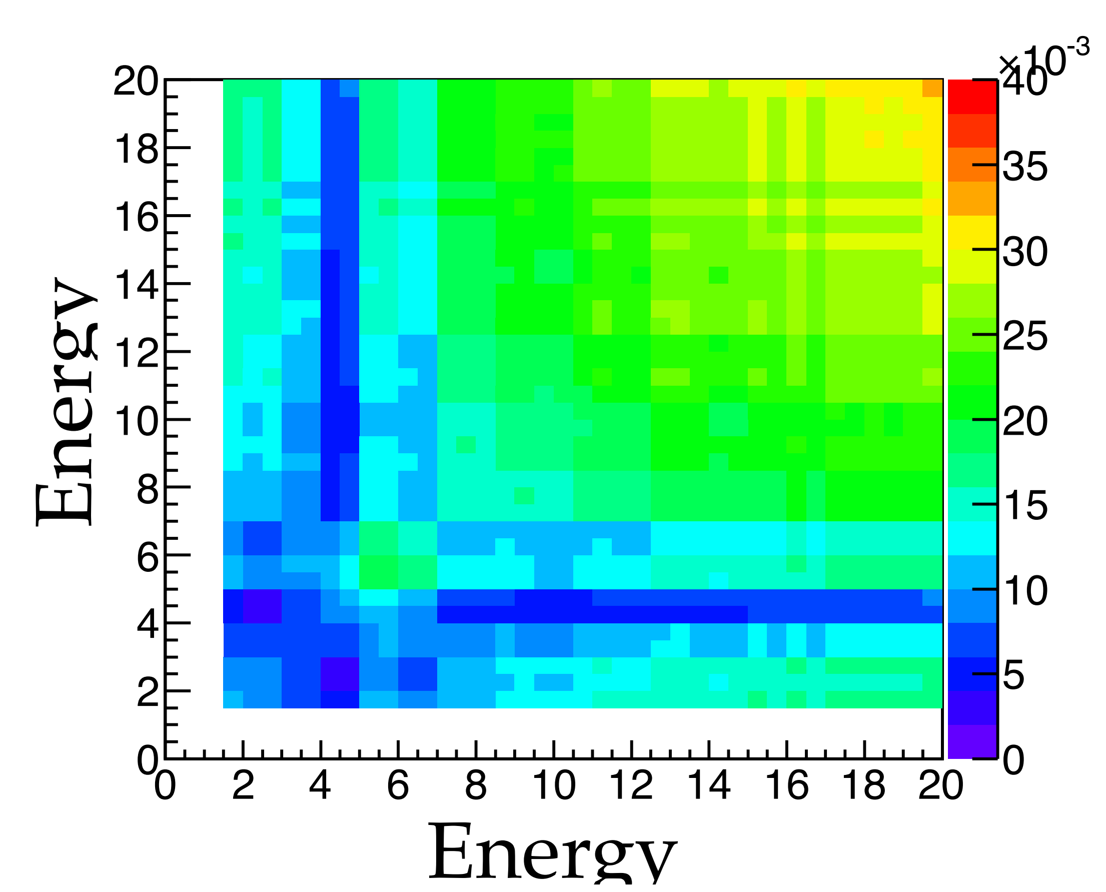
Zeroth Order Plan:

Borrow NuMI Uncertainties

Specifically, MINERvA's

Nu_mu vs Nu_e, etc and near/far correlations not available, but we can ask for them

MINERvA Flux Error Matrix



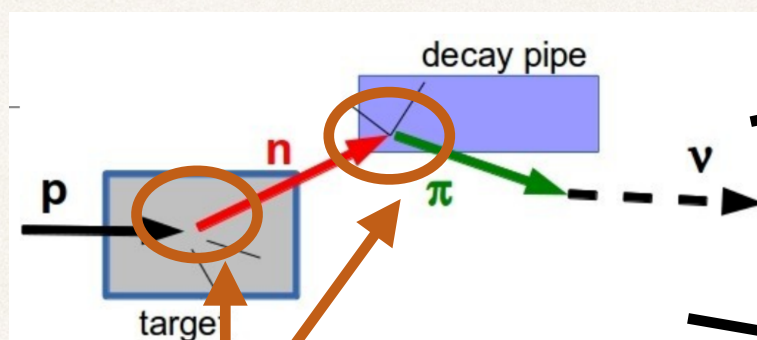
Systematic Uncertainties

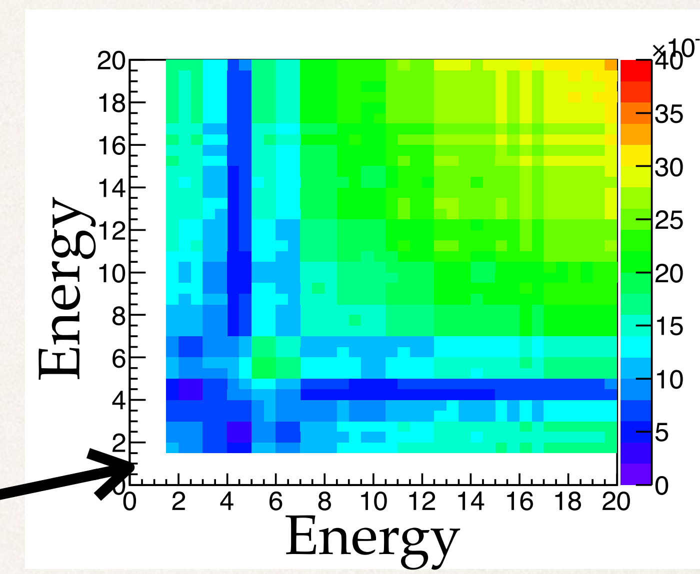
- Next step: do what MINERvA did, with our own beam simulation, leaning heavily on their infrastructure:

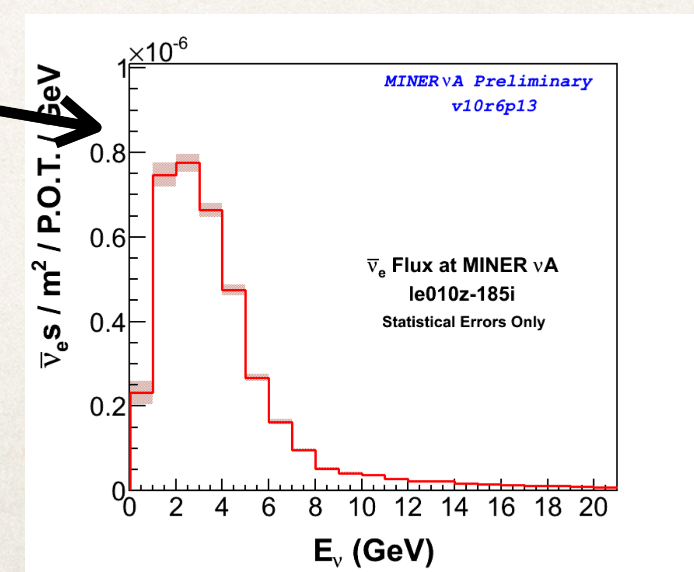
A. Bashyal & H. Schellman of OSU will apply MINERvA's procedure to DUNE

Others welcome (especially those familiar with alternative methods e.g. BMPT parameterization)

Flux event record







Each interaction in the ancestry list is adjusted and an uncertainty assigned using external data constraints (or very large uncertainty assumptions where data is unavailable)

Systematic Uncertainties

- Adapting MINERvA's procedure for DUNE will take some time
  - Will require some modifications to deal with different geometries
  - The main proponent is a graduate student taking classes
- If you have other ideas for estimating hadron production systematics, I would like to hear them

Summary — Answering Steve's Questions

- **What is in place now:**
  - Flux histograms for a variety of beam options
  - Zeroth order flux uncertainties + error matrix
- **What needs to be in place for a first, very rough run through of the whole system**
  - I think we are good to go
- **What could/should be in place:**
  - Definitely: A better estimate of numi errors + correlations
  - Hopefully: An estimate of hadron production uncertainties of the DUNE beamline
  - Hopefully: flux tuple + flux driver infrastructure for propagating more information than just neutrino energy and dealing with real detector geometries

The End