
FNAL Main Injector Tunnel

Photo: Reider Hahn

LBNF Beam Modeling - Status, Plans, and Opportunities for Collaboration

PASI 2015

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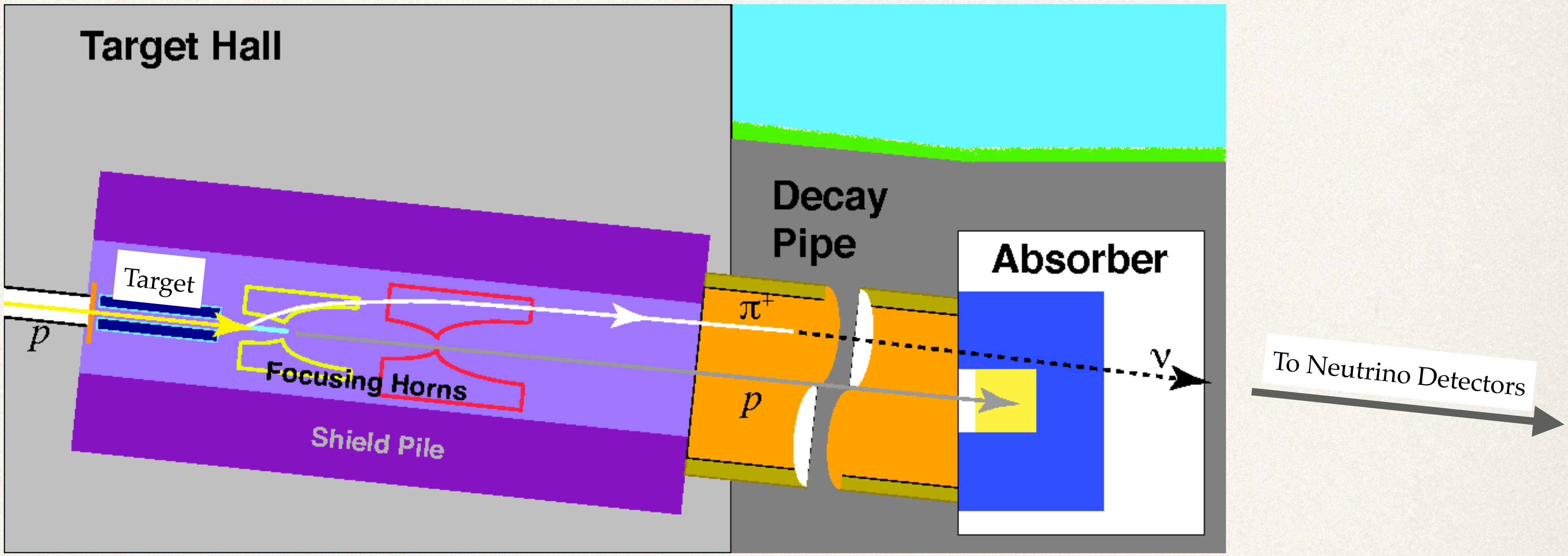
Fermilab

12 November 2015

Overview of LBNF Beam Modeling



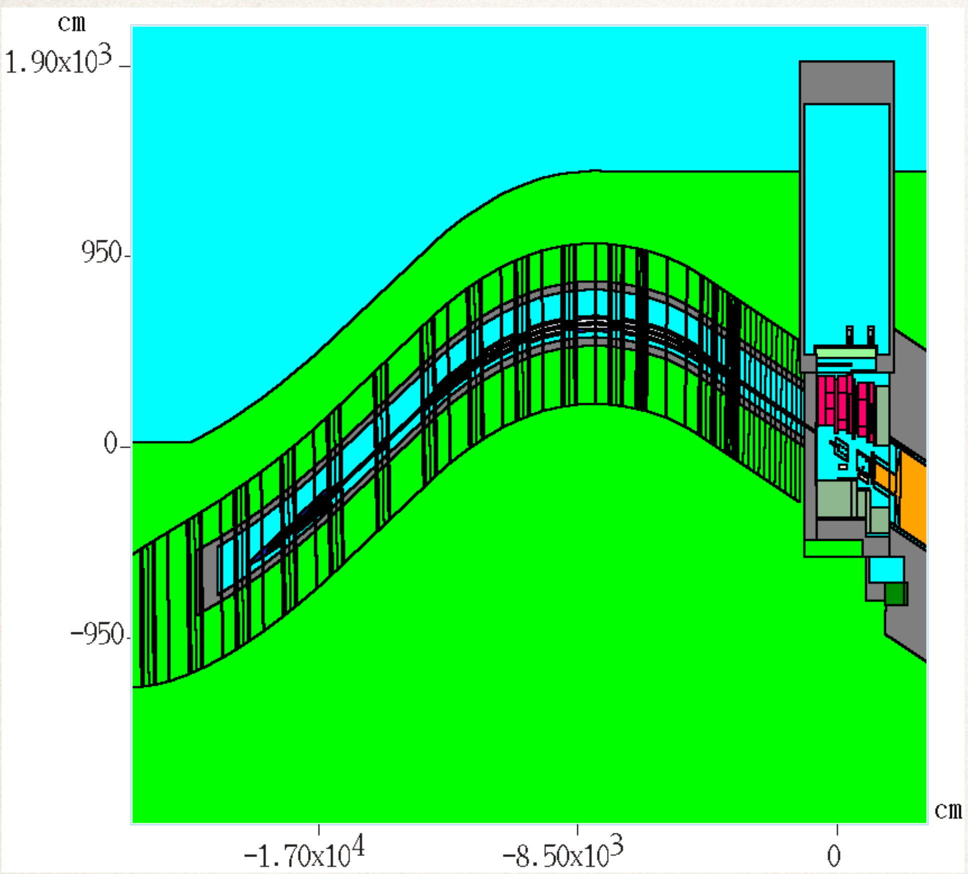
- The LBNF beam line is modeled using three different packages:
  - MARS
  - Geant4
  - Fluka

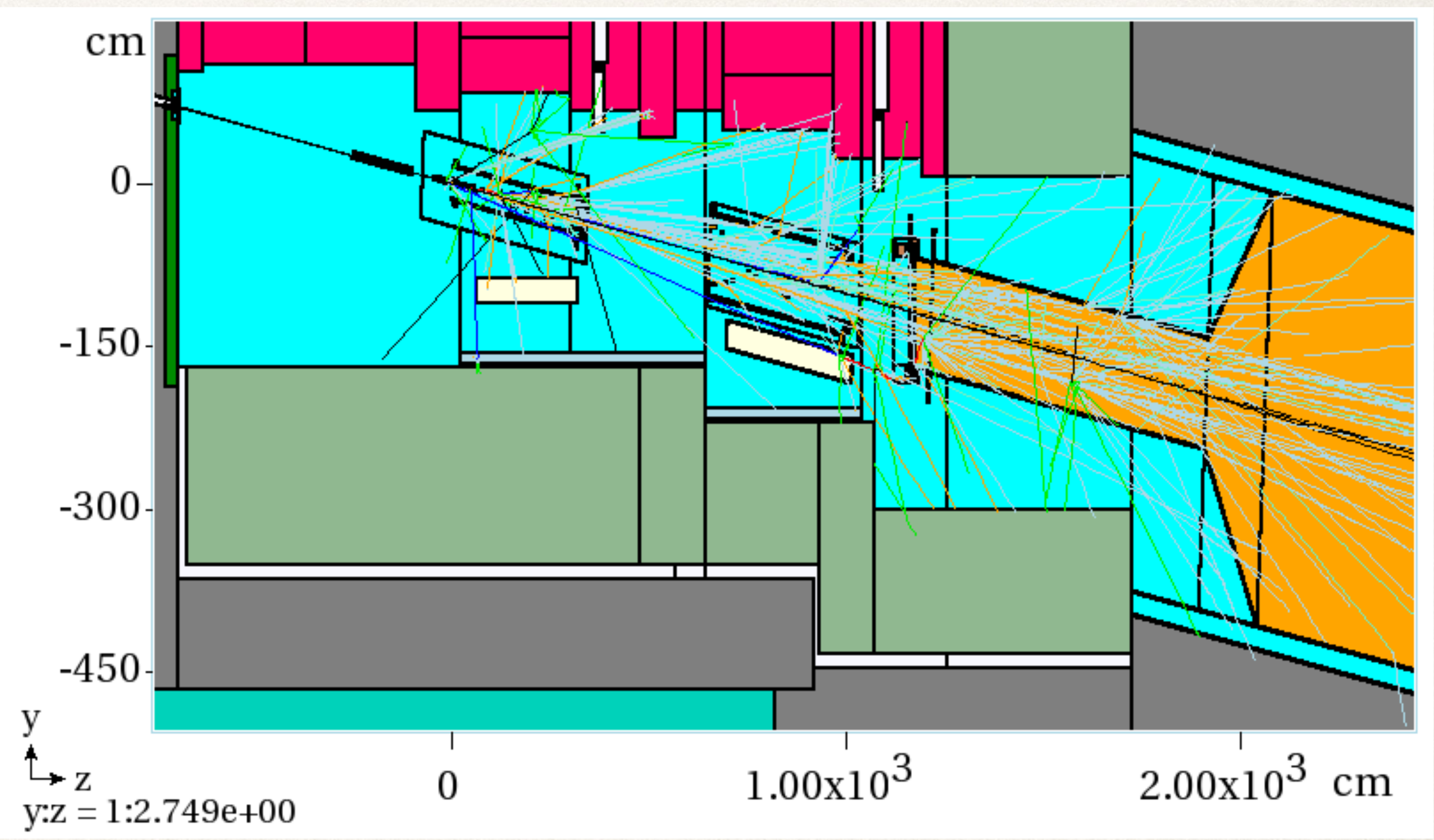
MARS Simulation

From the MARS website:

"MARS is a Monte Carlo code for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades, muon, heavy-ion and low-energy neutron transport in accelerator, detector, spacecraft and shielding components in the energy range from a fraction of an electronvolt up to 100 TeV."

Nikolai Mokhov, NBI 2014





A full model of the LBNF beam line has been implemented in MARS, from primary proton beam line to hadron absorber

MARS Simulation of LBNF

I.L. Rakhno, et al arXiv:1506.07787

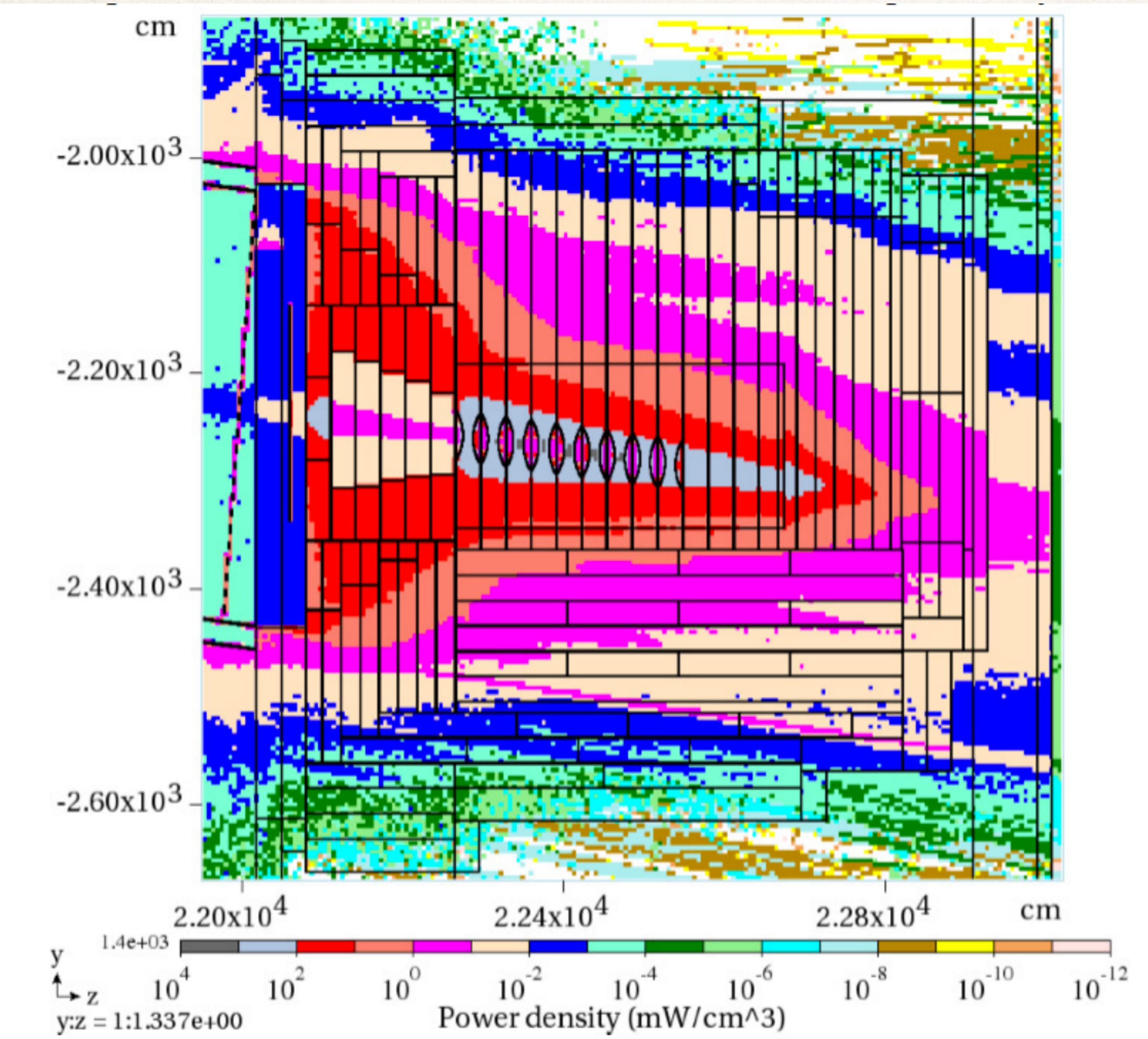
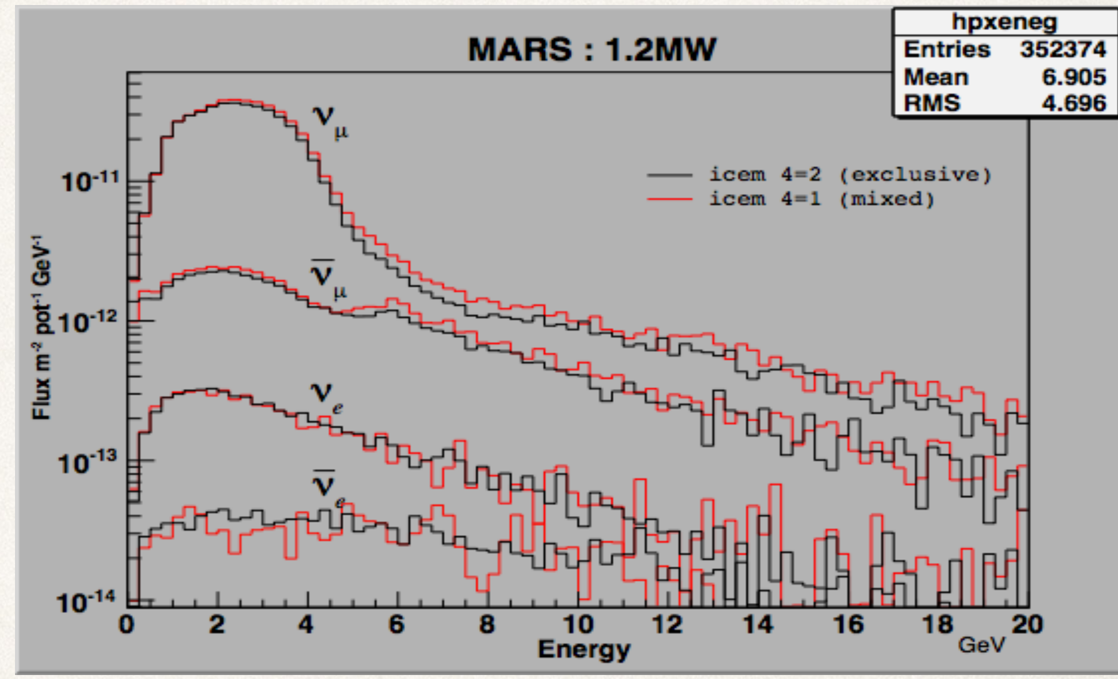


Figure 3: Calculated energy deposition distribution at 120 GeV for normal operation.



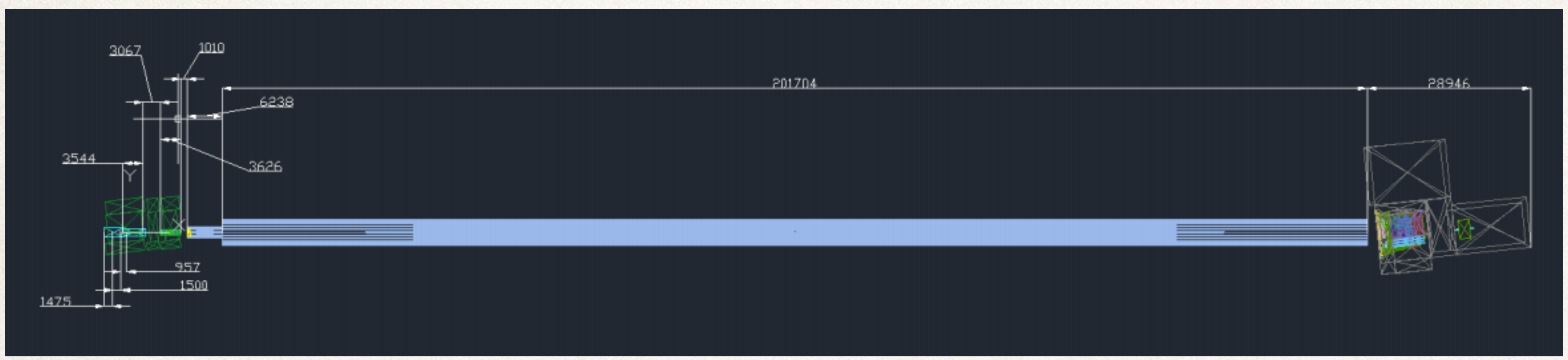
Neutrino fluxes at DUNE predicted by two different hadron production models in MARS

MARS is used primarily for energy deposition and radiological studies, but can also produce neutrino fluxes

G4LBNE Simulation of LBNF

- For most physics studies, DUNE uses a highly-configurable Geant4-based simulation of the beamline, from primary proton target to hadron absorber:

Visualization of the G4LBNE Geometry:



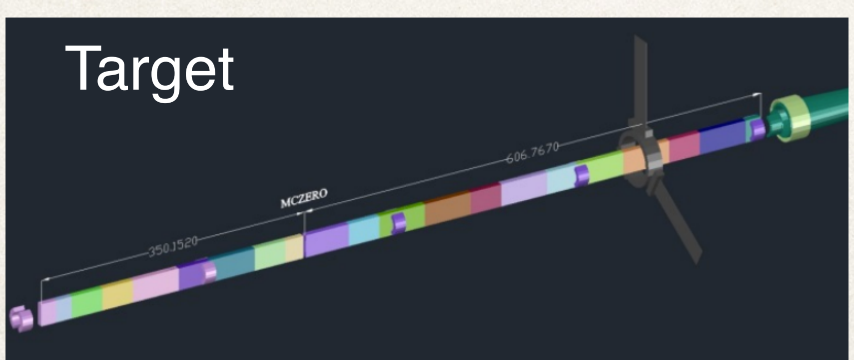
Seongtae Park

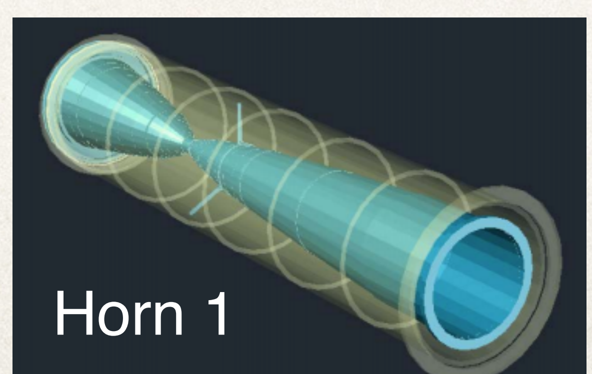
Target/Horns/Shielding

Decay Pipe

Hadron Absorber

Tries to balance need for detailed material description against flexibility in options for targets, horn decay pipe, shielding, etc





G4LBNE Simulation of LBNF

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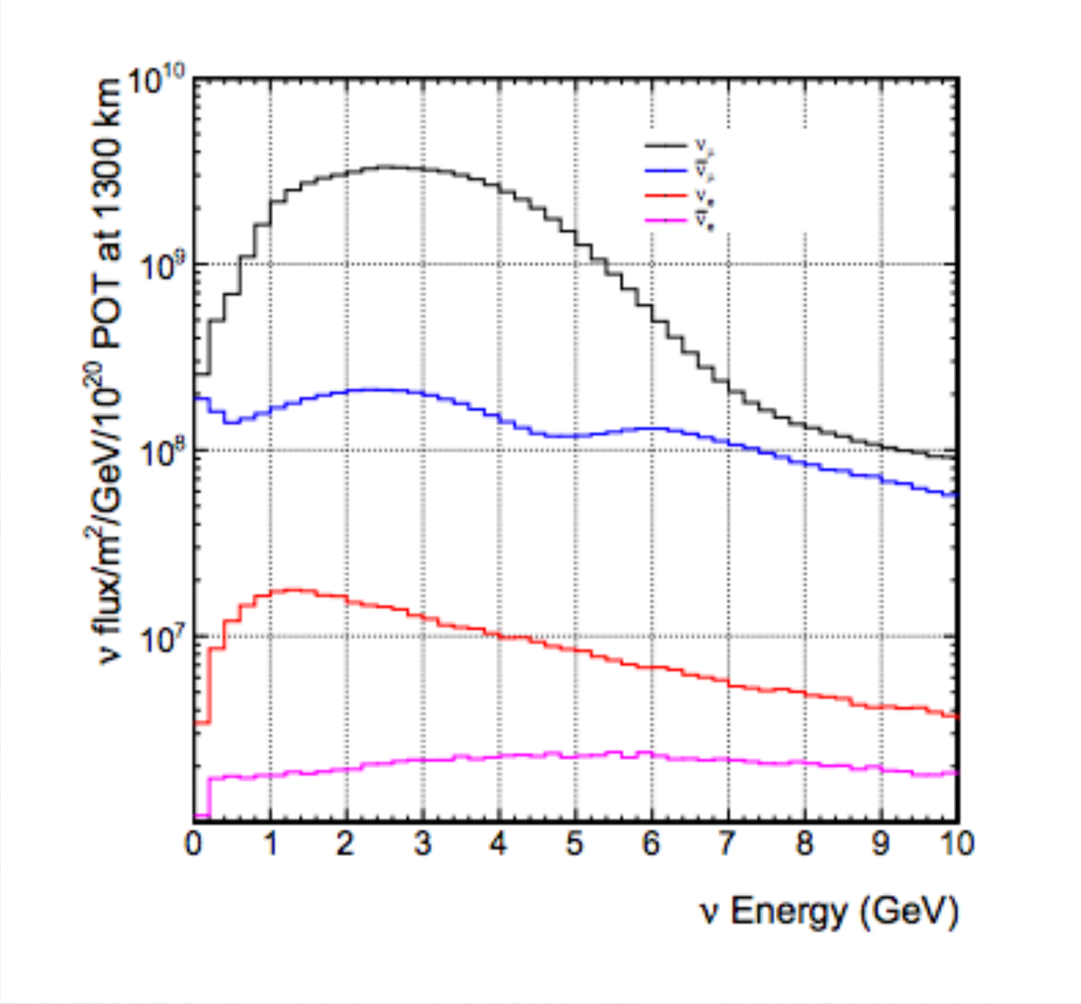

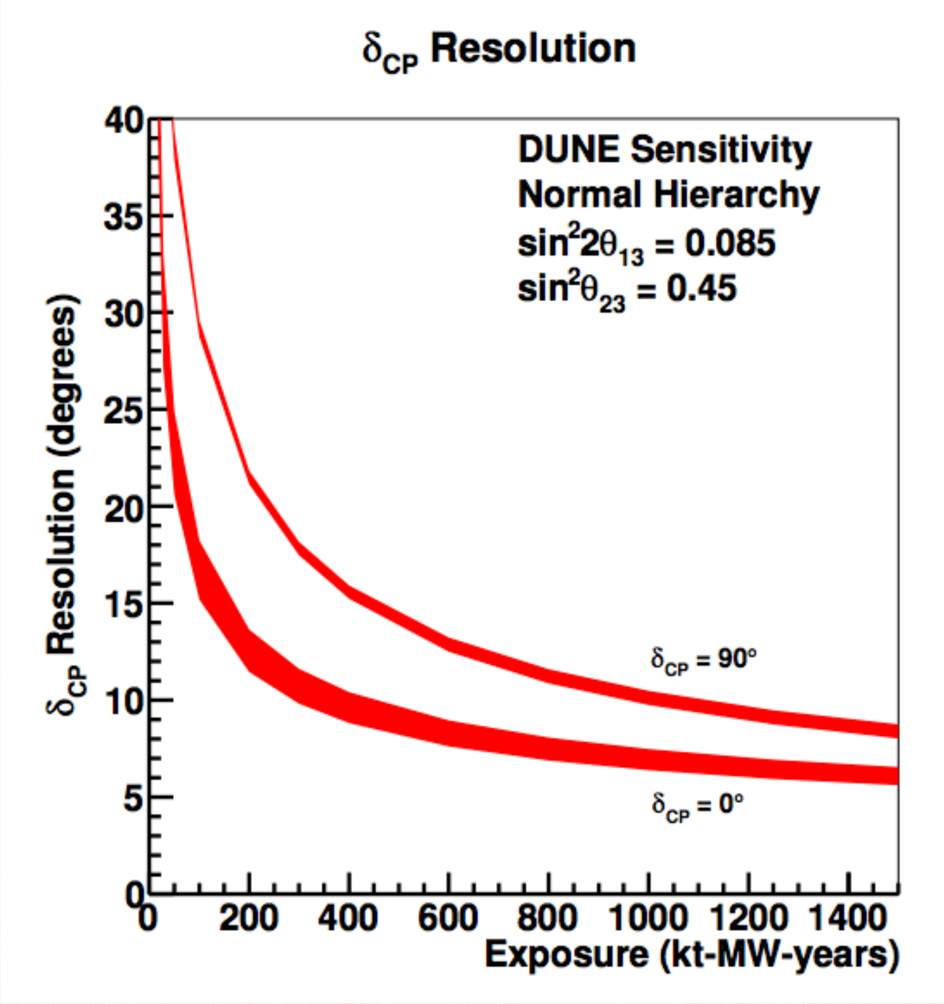

Detailed model needed as input to physics studies

G4LBNE Simulation of LBNF

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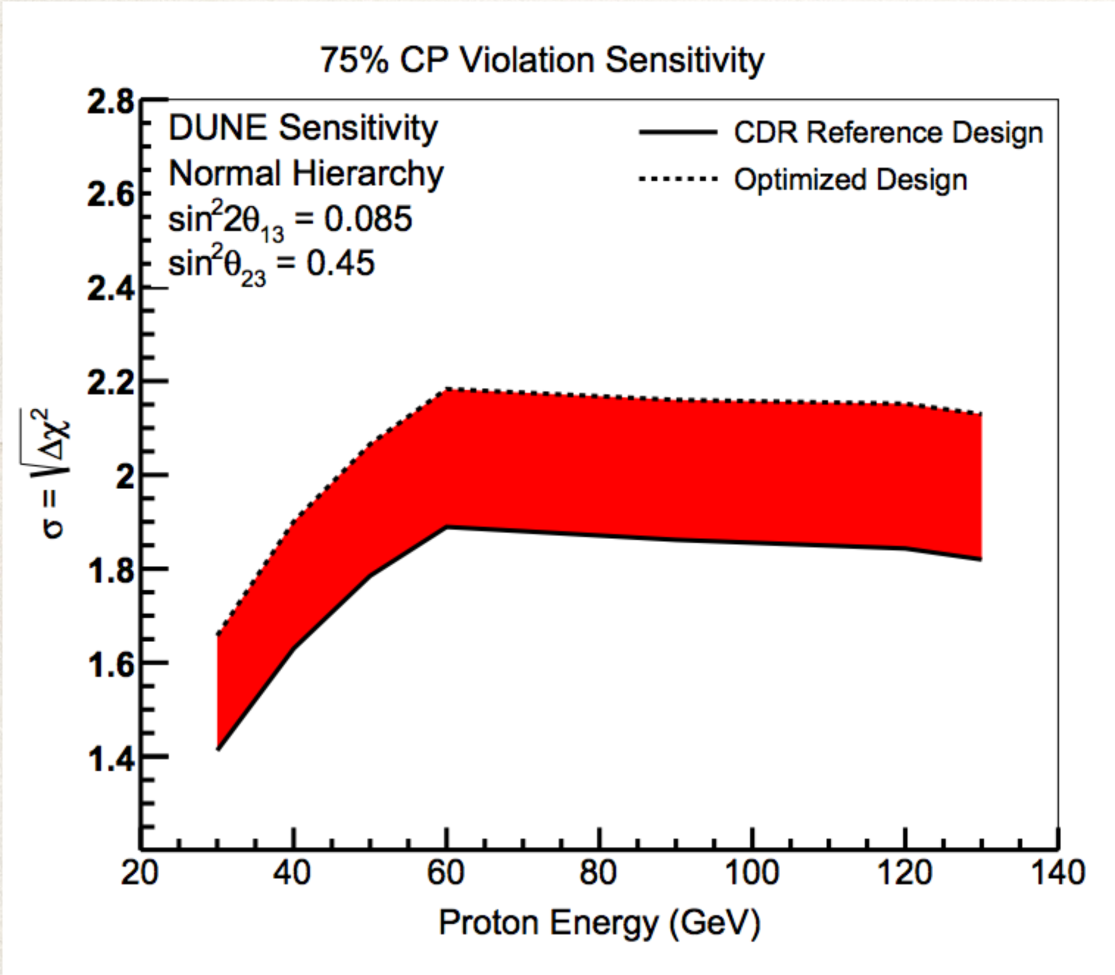
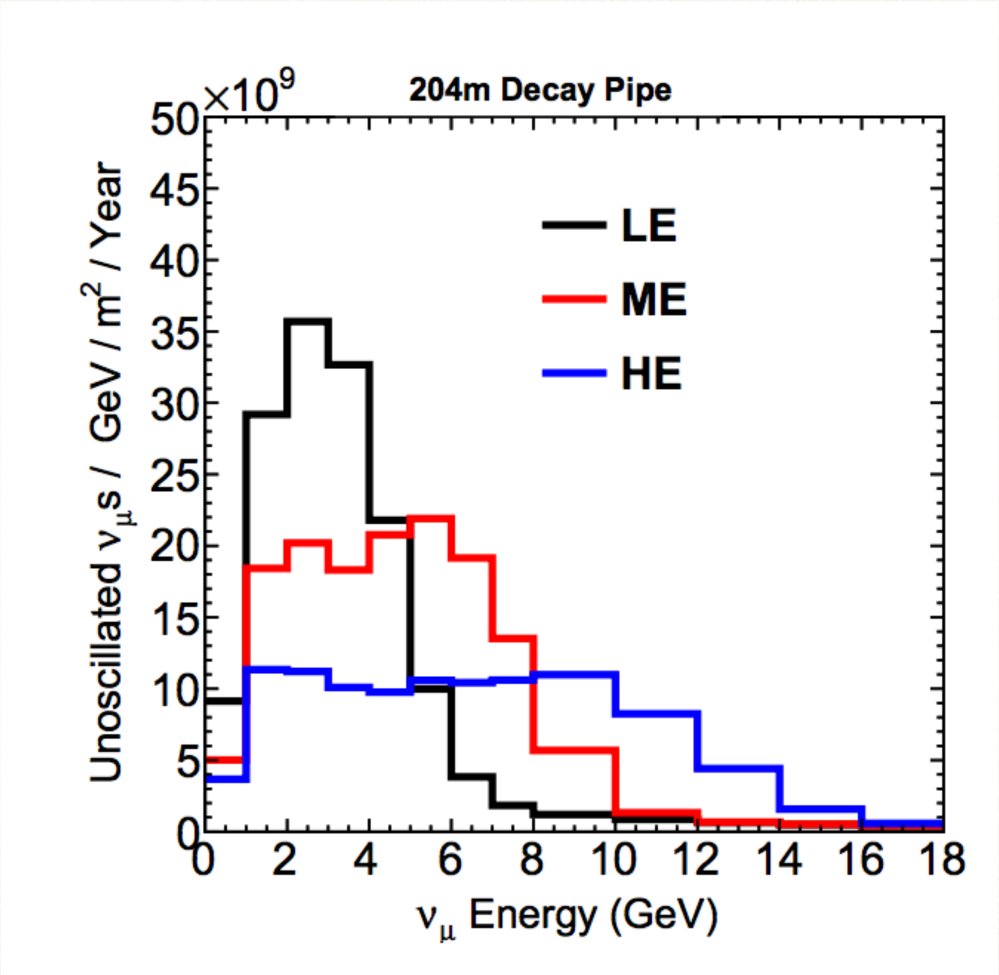


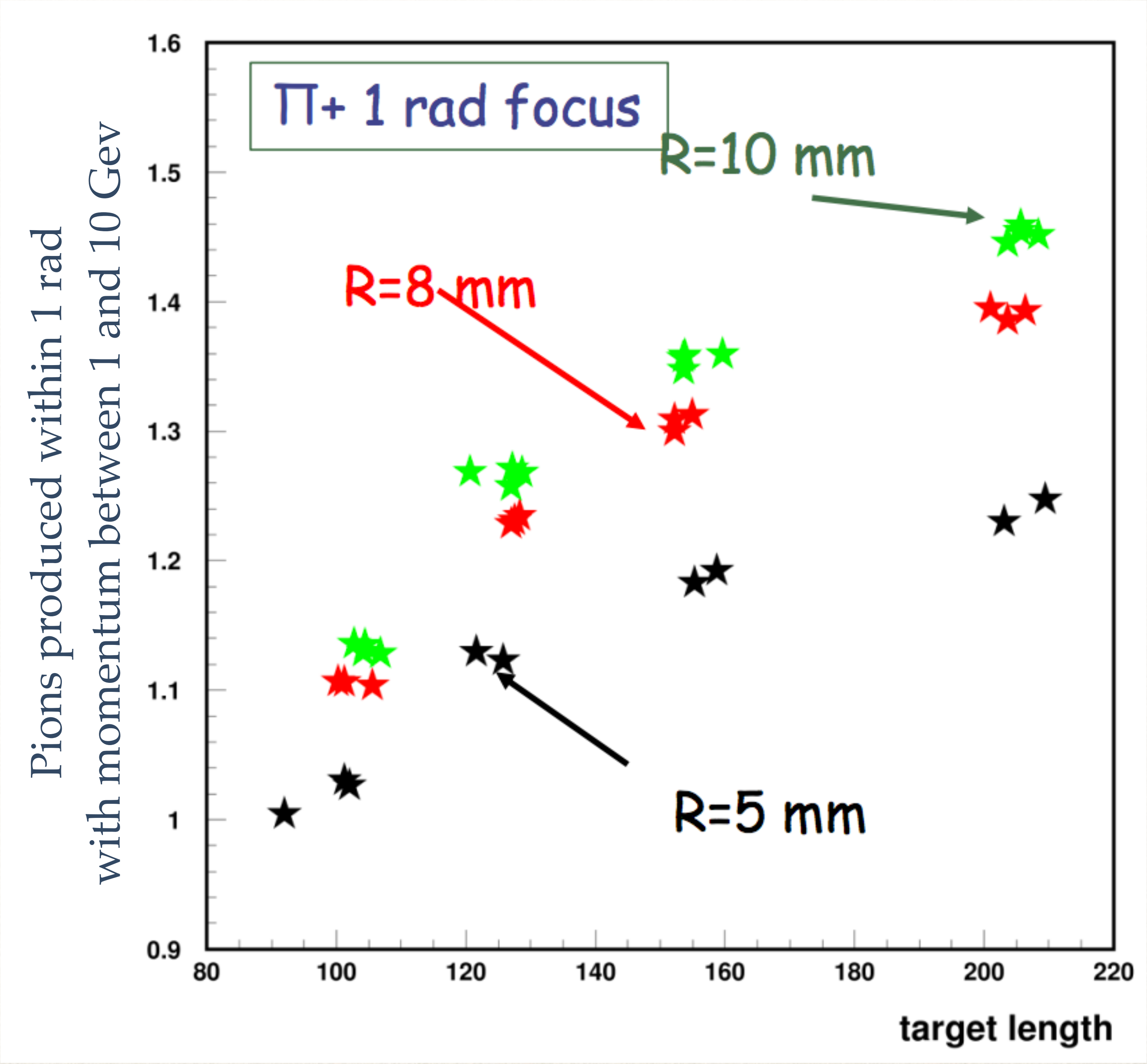


Significant flexibility needed for beam design studies

FLUKA Simulation of LBNF

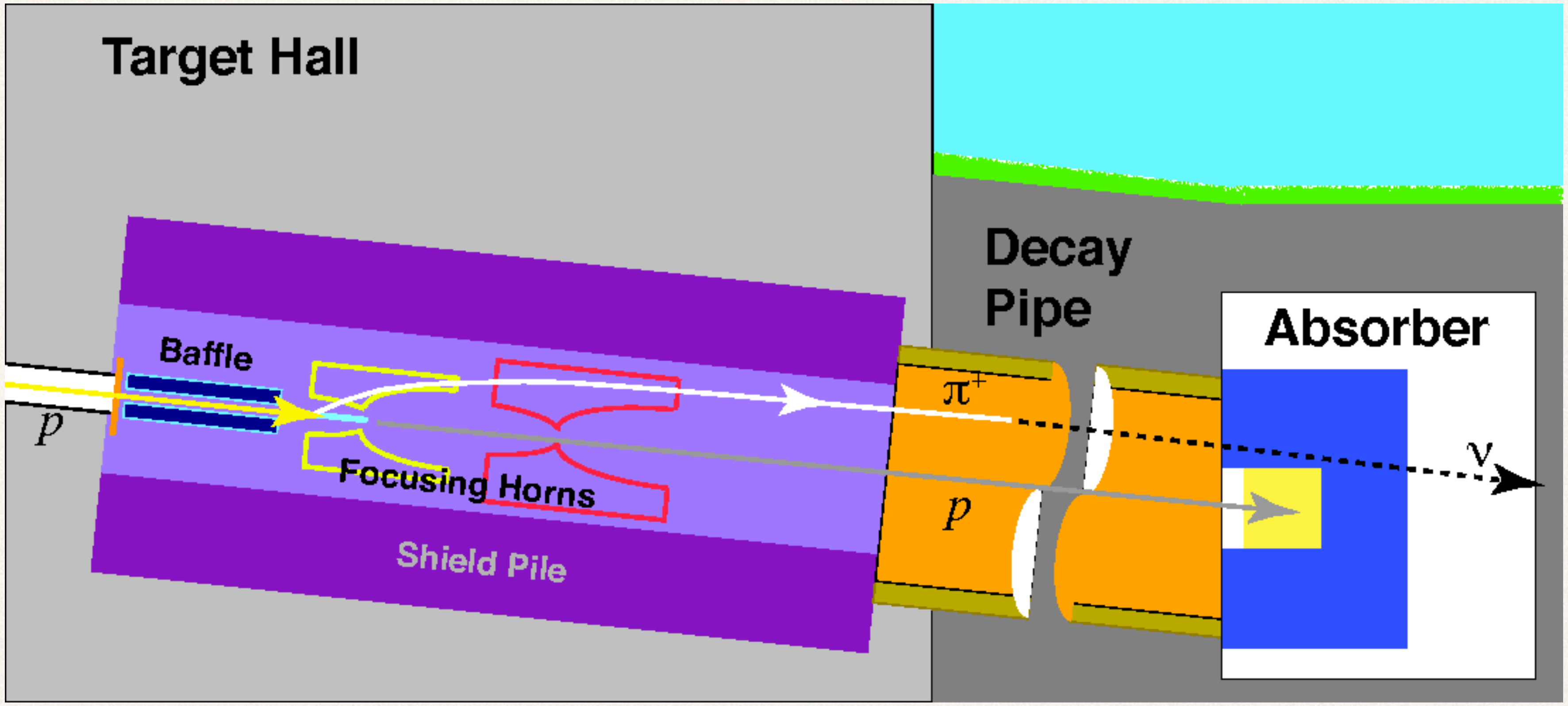
FLUKA simulation is very new and still in development

First results have concentrated on studying pion yields off target (while focusing system is developed)



P. Sala

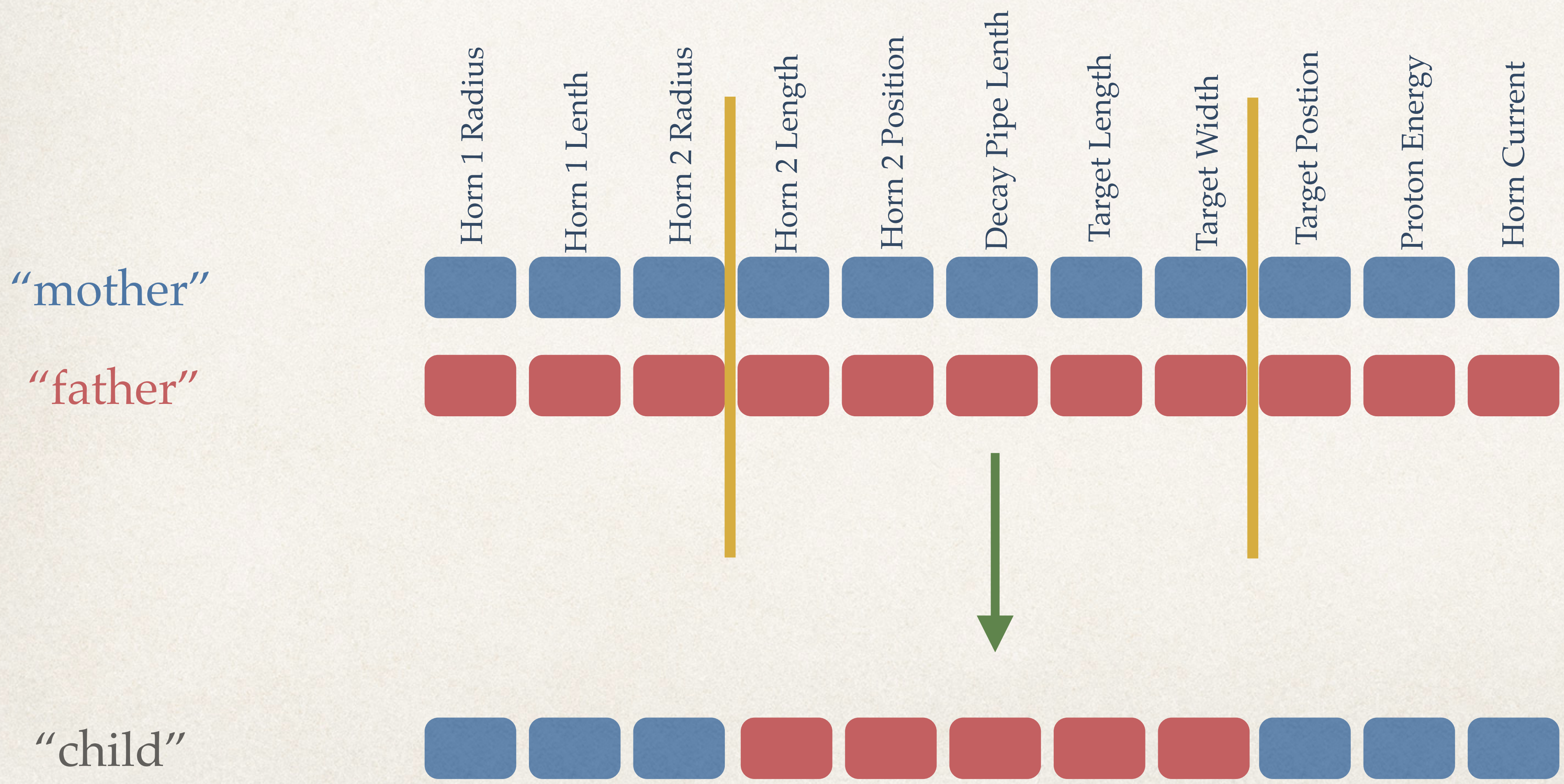
LBNF Beam Optimization Overview



- Much of the modeling effort over the past year has focused on identifying optimal configurations of beam parameters such as proton energy, target and horn dimensions, horn currents, etc

LBNF Beam Optimization Overview

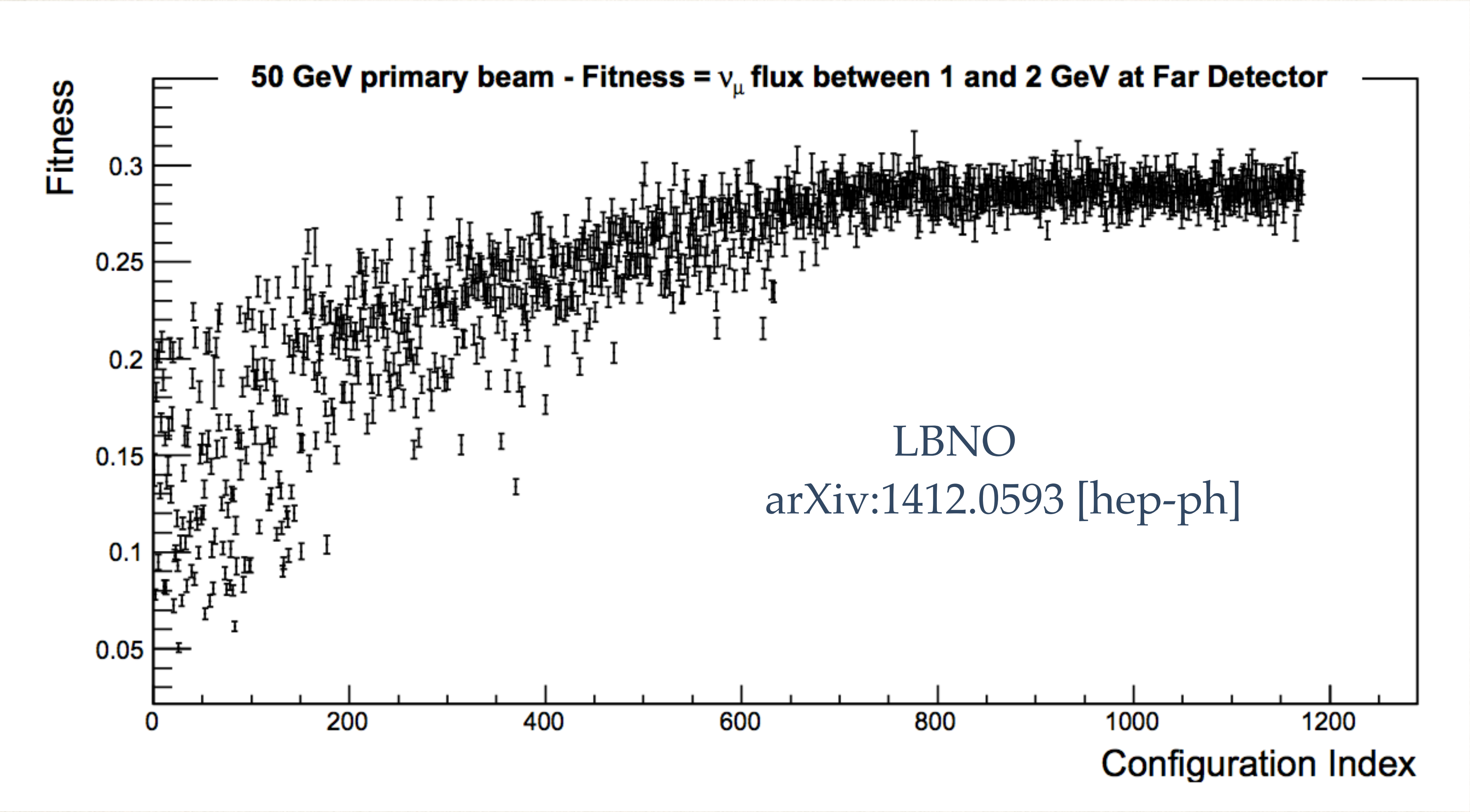
- The hot new thing in beam line design is genetic algorithms:
  - View each **beam configuration** as an organism; initially, a population with **randomly generated traits** is simulated
  - Configurations are judged based on fitness (number of neutrinos or some physics deliverable) and mated together to form new (and better) configurations



See also yesterday’s talk on “Metaheuristic Algorithms in nuSTORM and MICE” by Ao Liu

LBNF Beam Optimization Overview

- Repeating this **survival-of-the-fittest** procedure over **many generations** eventually converges on an **optimal beam design**

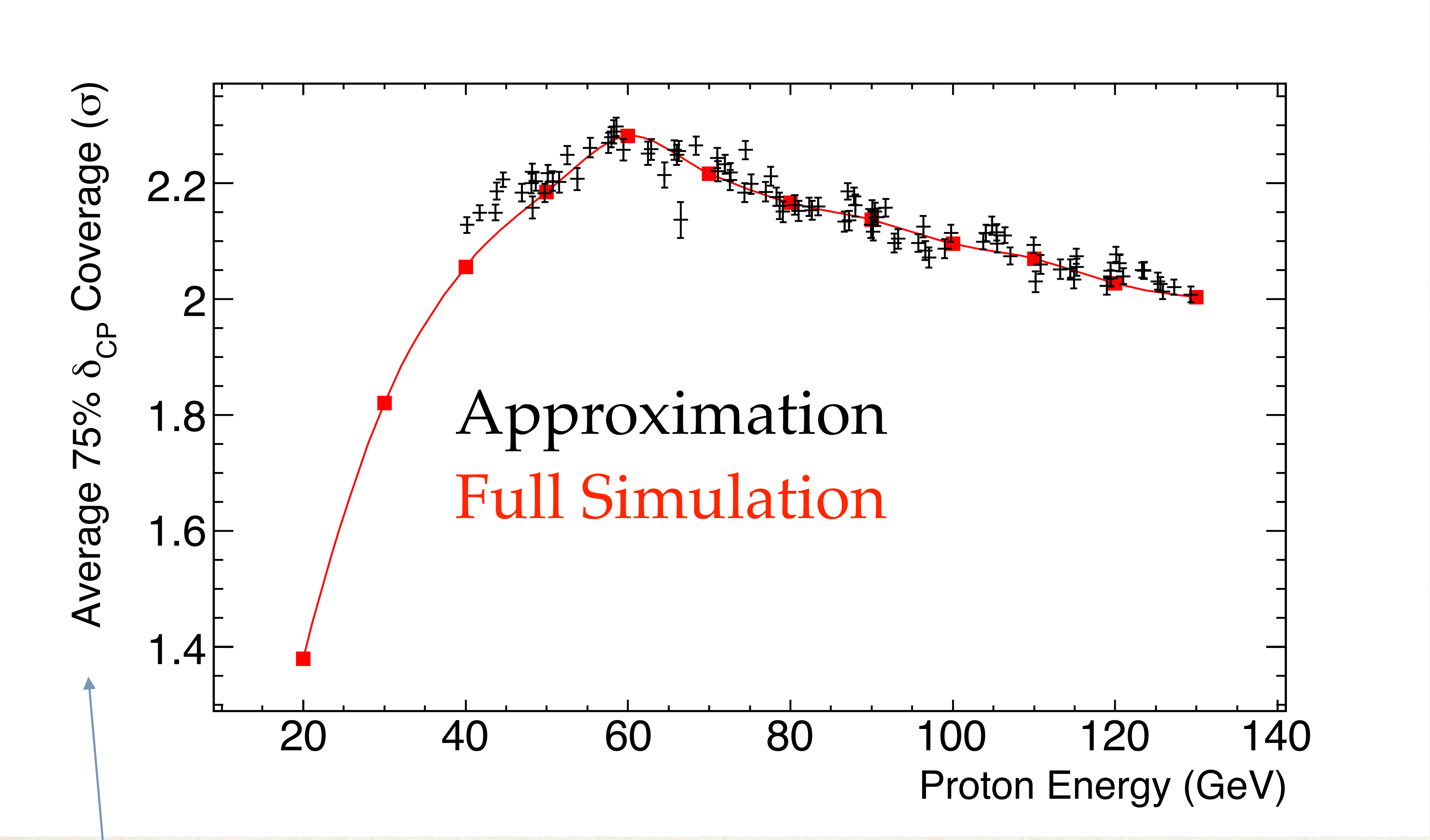


We know these algorithms give us **good beam designs**

We can **never know** whether they have given us **the best** possible beam designs

Past Optimization Work

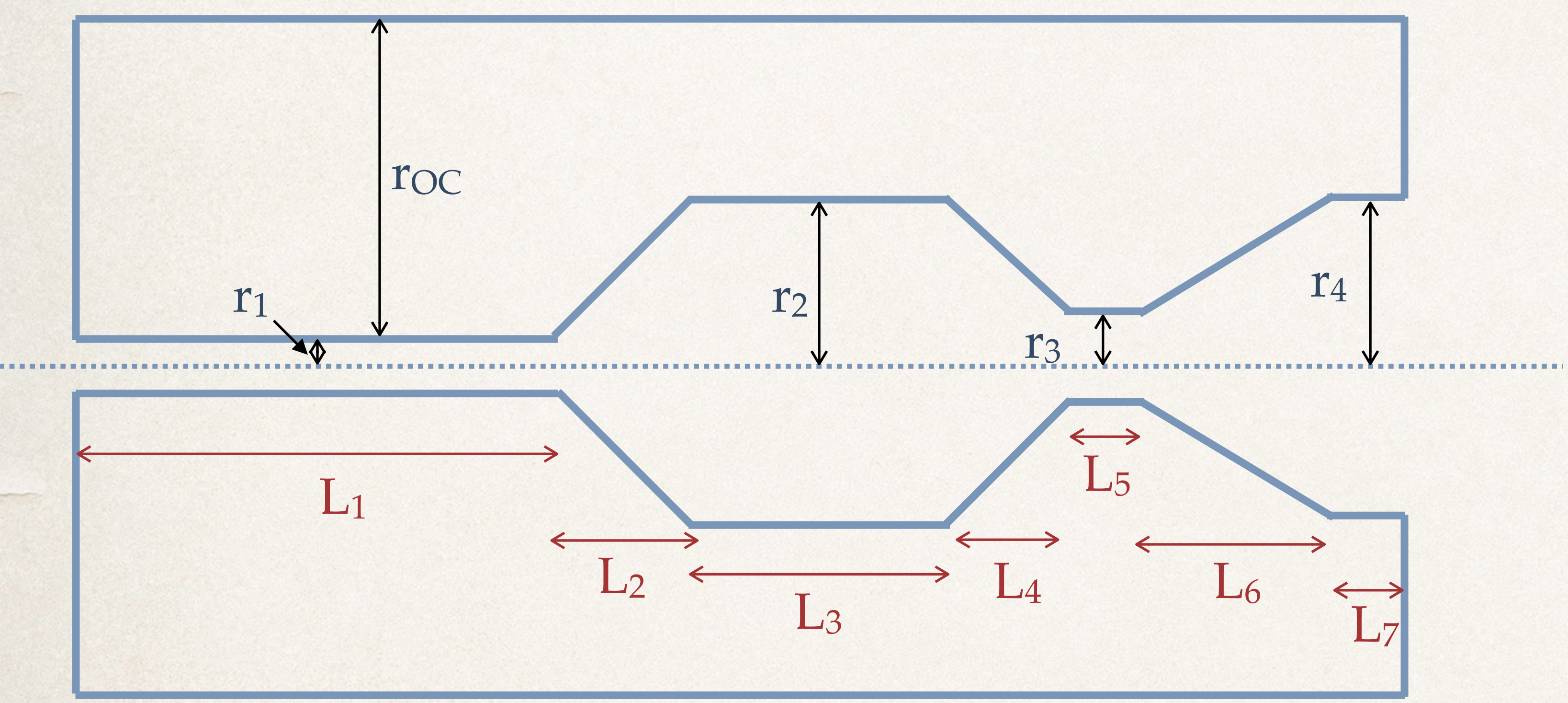
- Have also implemented a fast approximation of CP sensitivity



Fast approximation **reduces computation time** from ~ a week to ~ an hour, and tracks full simulation well

Metric chosen for optimization is 75% CP coverage after 6 years of running, averaged over hierarchies

Past Optimization Work

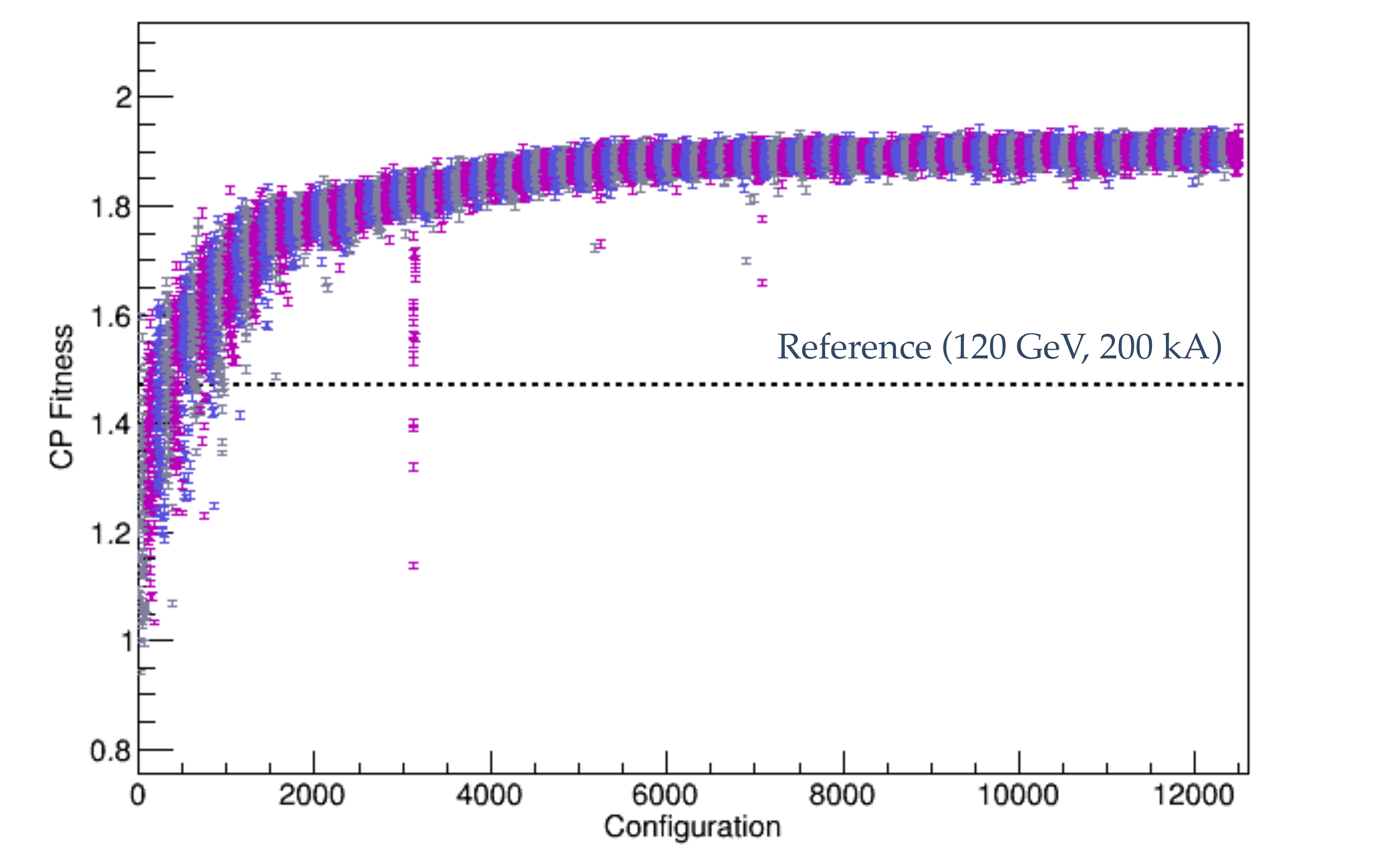


Using that fast CP estimator, a procedure similar to what was done for LBNO has been done for the LBNF beam line

In addition to a dramatically different shape for horn 1, we also varied:

Target width and length
Horn currents
Proton energy
Horn 2 dimensions
Horn 2 position

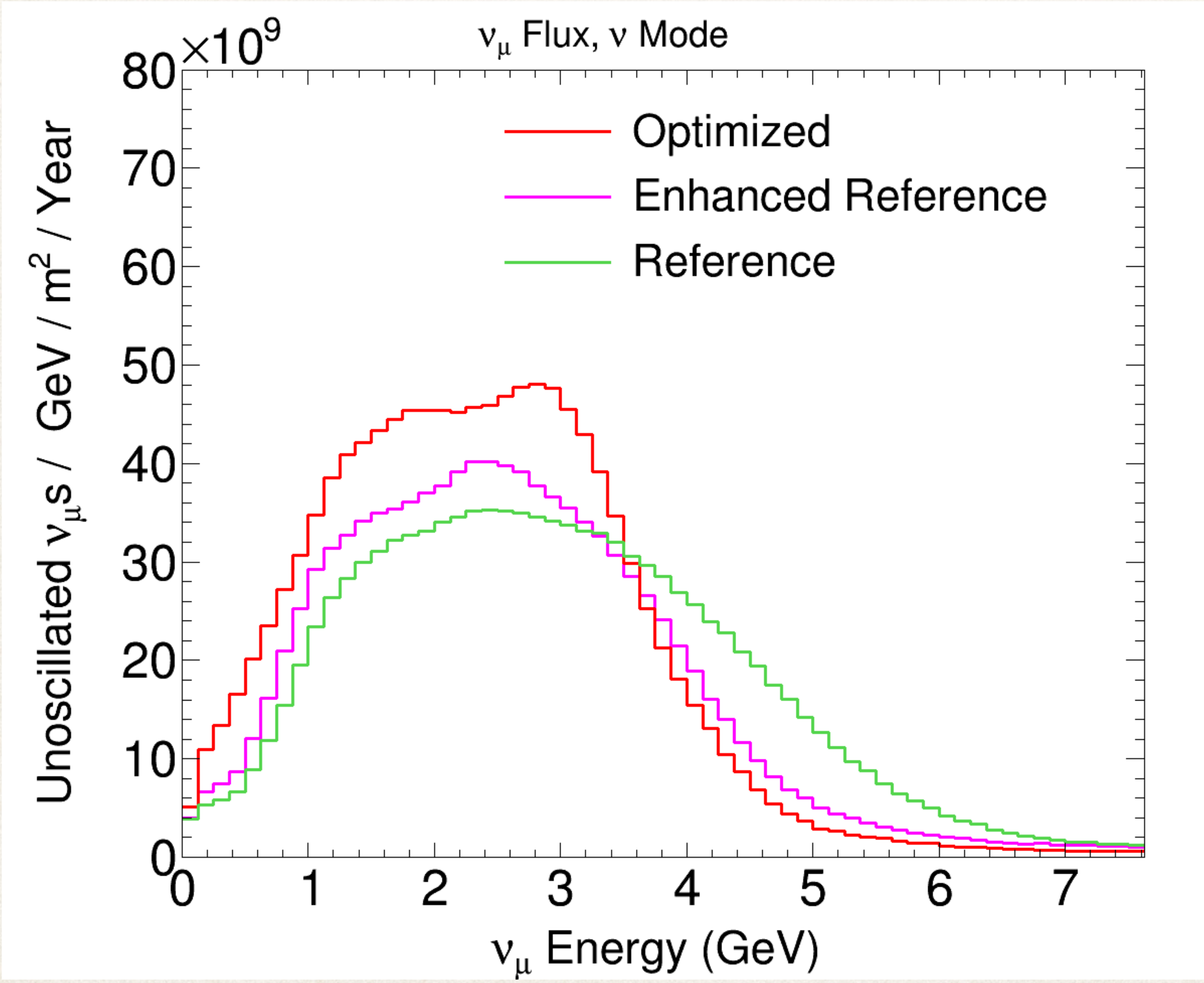
Past Optimization Work

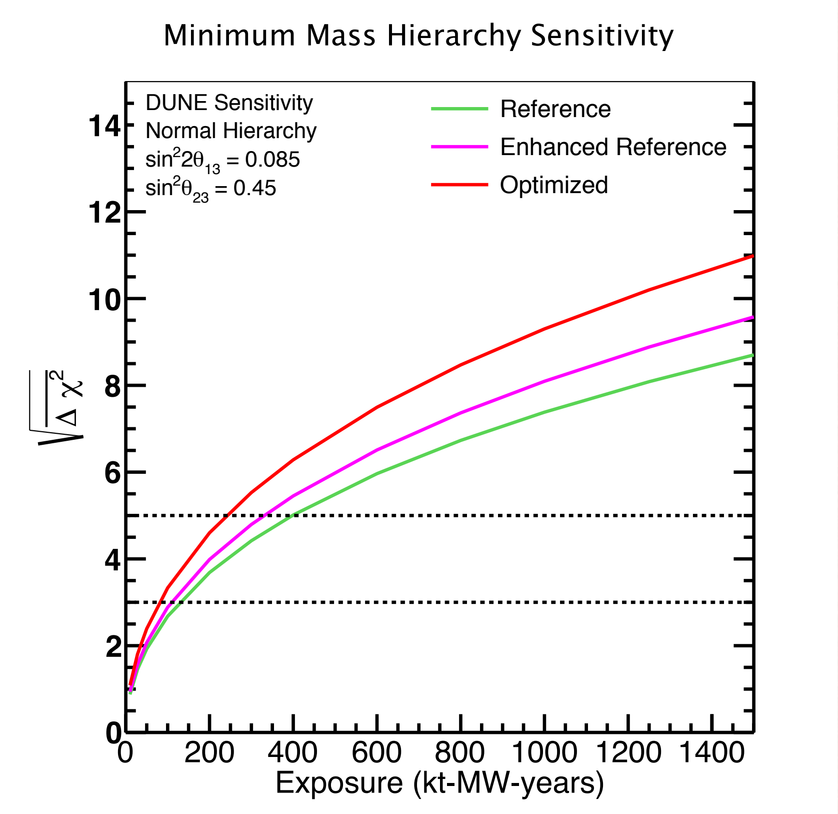


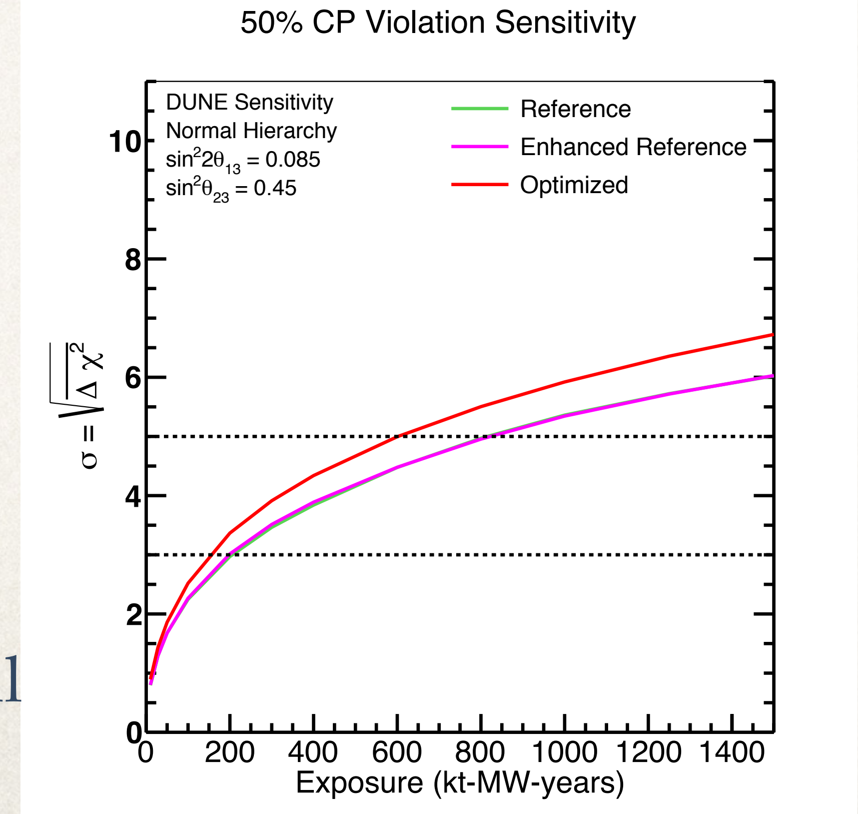
After ~13000 simulated beams, optimization converged on beam design with ~33% better CP sensitivity than reference beam

Past Optimization Work

- **Performance estimates** supported by detailed simulations and sensitivity calculations





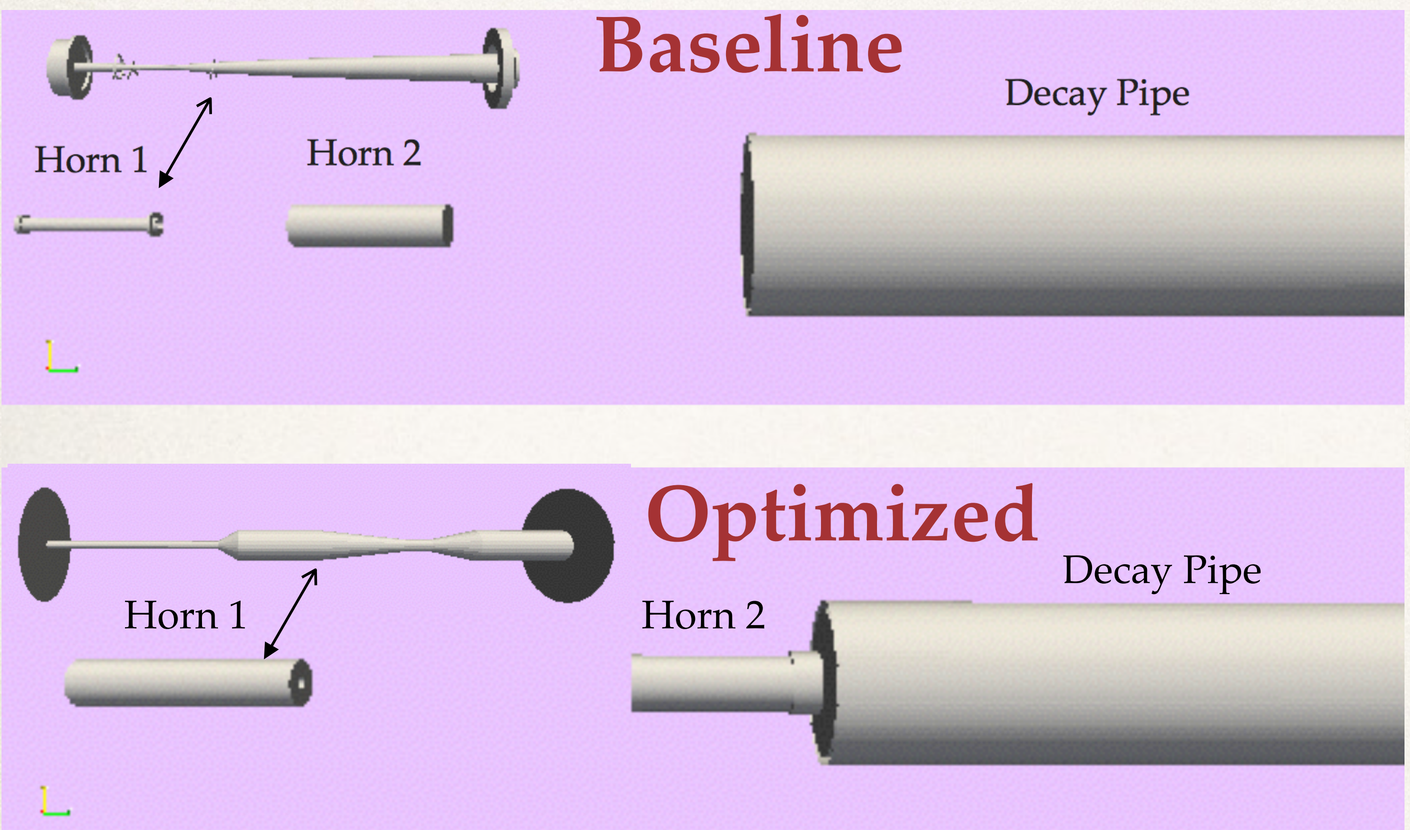


DUNE CDR

Note that reference beam has a more realistic material description that the optimized beam

Past Optimization Work

- Preferred beam has **significant changes** from baseline design:



- Substantial changes to the shape, size and position of **horns** — longer and wider horns
- Higher **horn current**
- A much **longer target** (> 1.5 m vs 1 m in baseline)
- **Larger target chase** (~28 m) needed to accommodate optimized horns (now included in baseline design)
- Target transverse dimensions and proton beam not substantially altered

Current Optimization Status

- Most of that work was done as part of the of the **LBNO/LBNE organizations**
- When the new DUNE collaboration formed this year, the spokespeople made completion of this work the focus of **one of three near-term task forces** (along with near detector and far detector optimization)
- Goals of beam optimization task force:
  - **Further develop** the physics-driven **optimization** of the beamline, including the target, horn configuration, and decay pipe
  - **Identify potential options** and develop a first-order cost-benefit analysis
  - **Produce a first report** by July 2016 summarizing the finding and a final report by December 2016

Current Optimization Status

- Task force work plan into three phases:

Phase I:
Optimization

Phase II:
Identifying Final Beam Designs

Phase III:
Studies of Final Beam Designs

Task Force Plans

- Details of phase I:

- **Identify list of parameters** not considered in past optimization algorithms that should be included
- **Work with engineers** to produce a detailed list of engineering constraints of optimized beam
- **Implement changes** to beam simulation to accommodate new parameters
- **Rerun optimization**
- **Other studies** — Downstream high Z, Helium vs Water cooling, Parabolic Horns
- **Update optimization metric**
  - Using latest sensitivity calculations
  - Consider quantities other than 75% CP sensitivity after 6 years
- **Develop software infrastructure** for studies of final beam designs

Much of this is ongoing now

Aim to complete first round of optimization by end of 2015, with iterations continuing through next summer

Task Force Plans

- Details of phase II:

- Work with engineers to understand **basic cost implications** of differences between standard horn/target design and output of optimization algorithm, and to **convert idealized optimized design into a realistic optimistic design**

- Simulate realistic version of designs with approximations of material such as spider supports, striplines, ribs and welds **will have significant impact on flux & sensitivities**

- **Choose one (or several)** beam designs to recommend to the collaboration, with estimated cost

This is the area of the program that is most in need of help.

New collaborators welcome (here and elsewhere)

Task Force Plans

- Details of phase III:

- Compute **physics sensitivities** of beam designs with detailed MC simulation
- Estimate **systematic uncertainties** given currently available data on default and optimized beam.
  - Detailed comparison of parentage phase space of the two beams
- Study **near-to-far extrapolation methods** for optimized beams
- **Energy deposition and radiological** studies of recommended designs

Some work is ongoing here.

This is another area where new contributions would be very useful.

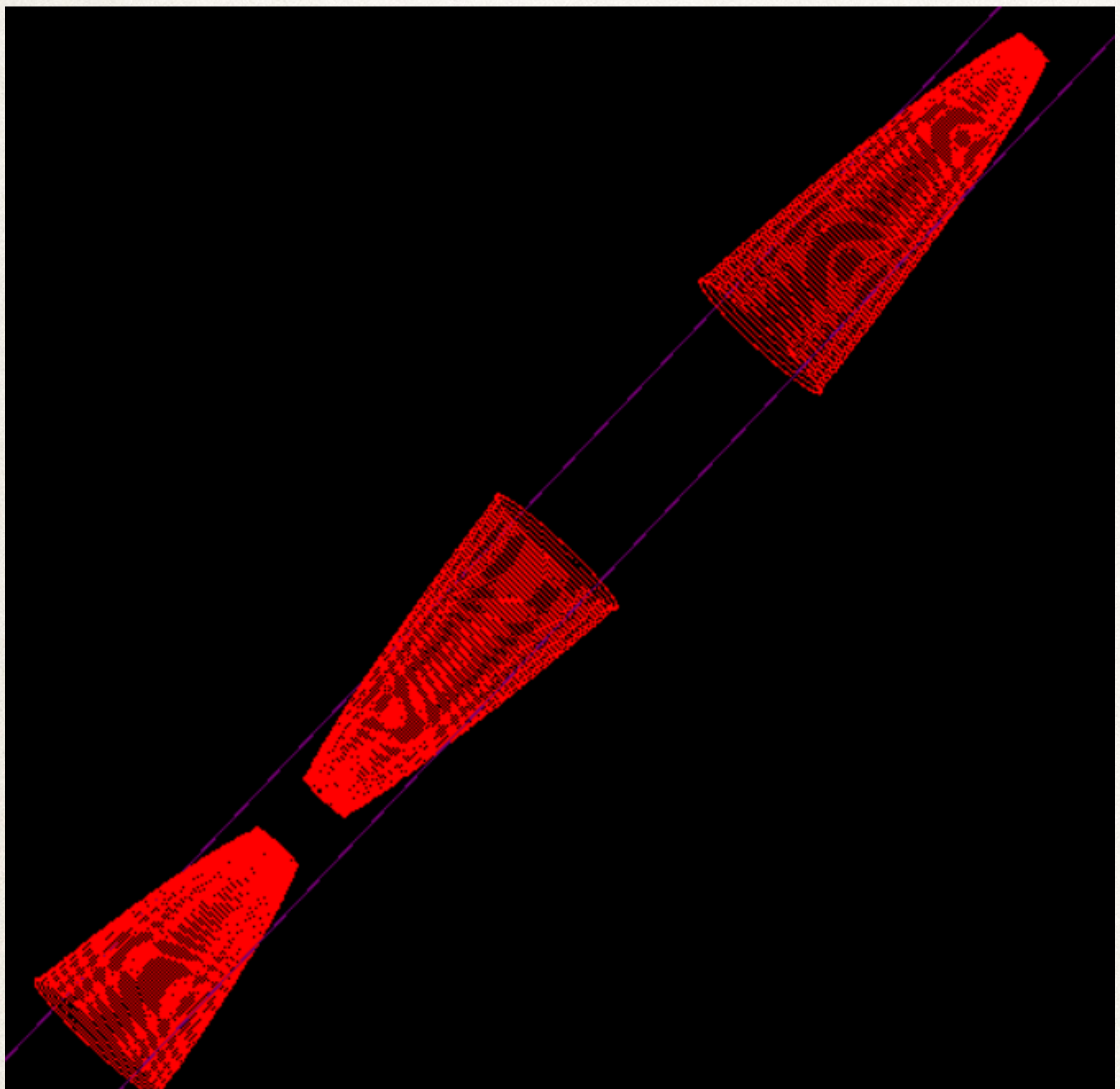
Task Force Status

- **Three(+) parameterized horn option** has been implemented in simulation

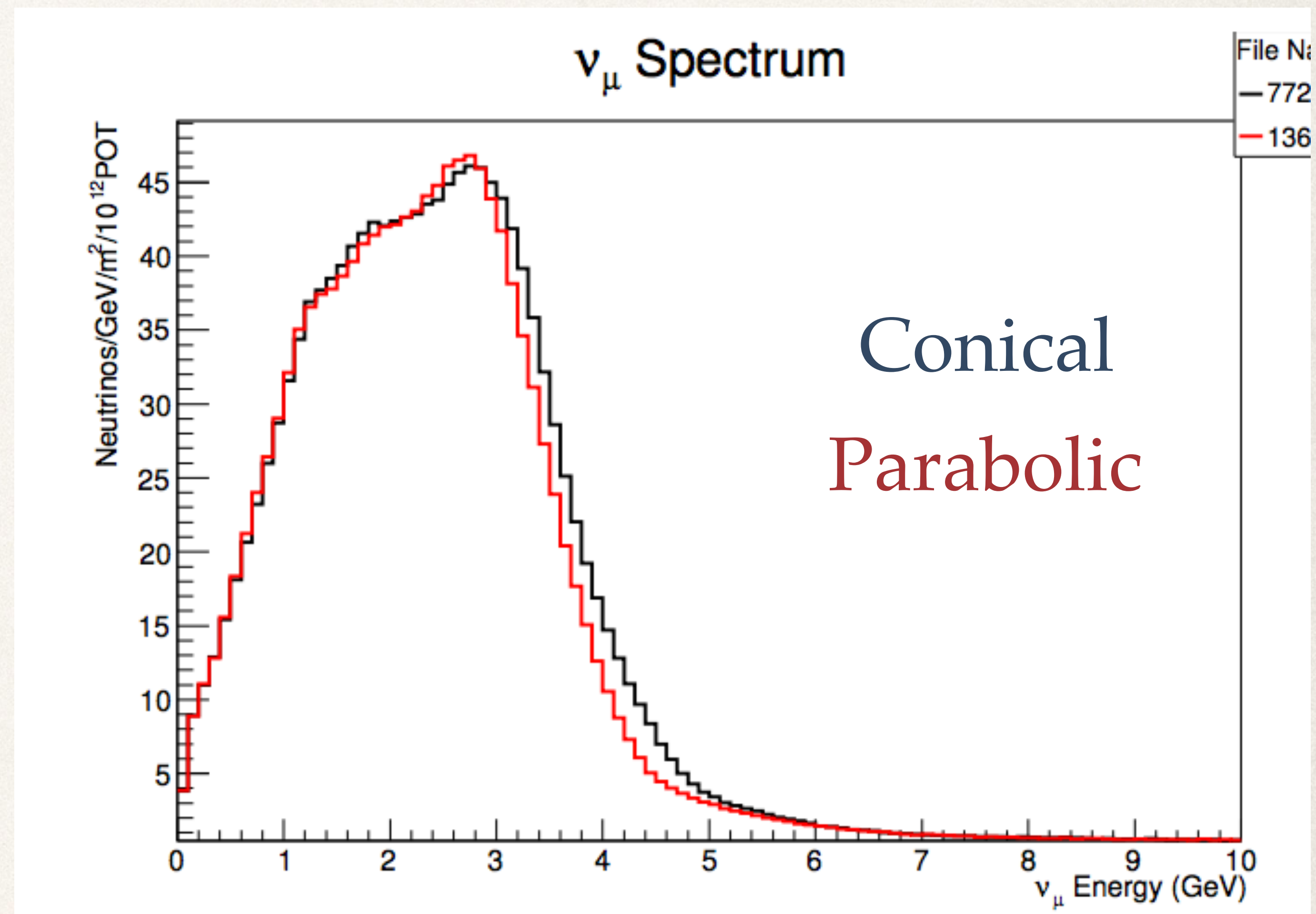
- Multidimensional optimization is **in progress** with this option
- An **alternate implementation of the genetic algorithm** (and exploration of alternatives to genetic algorithm) is also being setup at LBL
  - Makes use of **multithreading GEANT4 capabilities and NERSC**

Task Force Status

- Parabolic horn option has been implemented



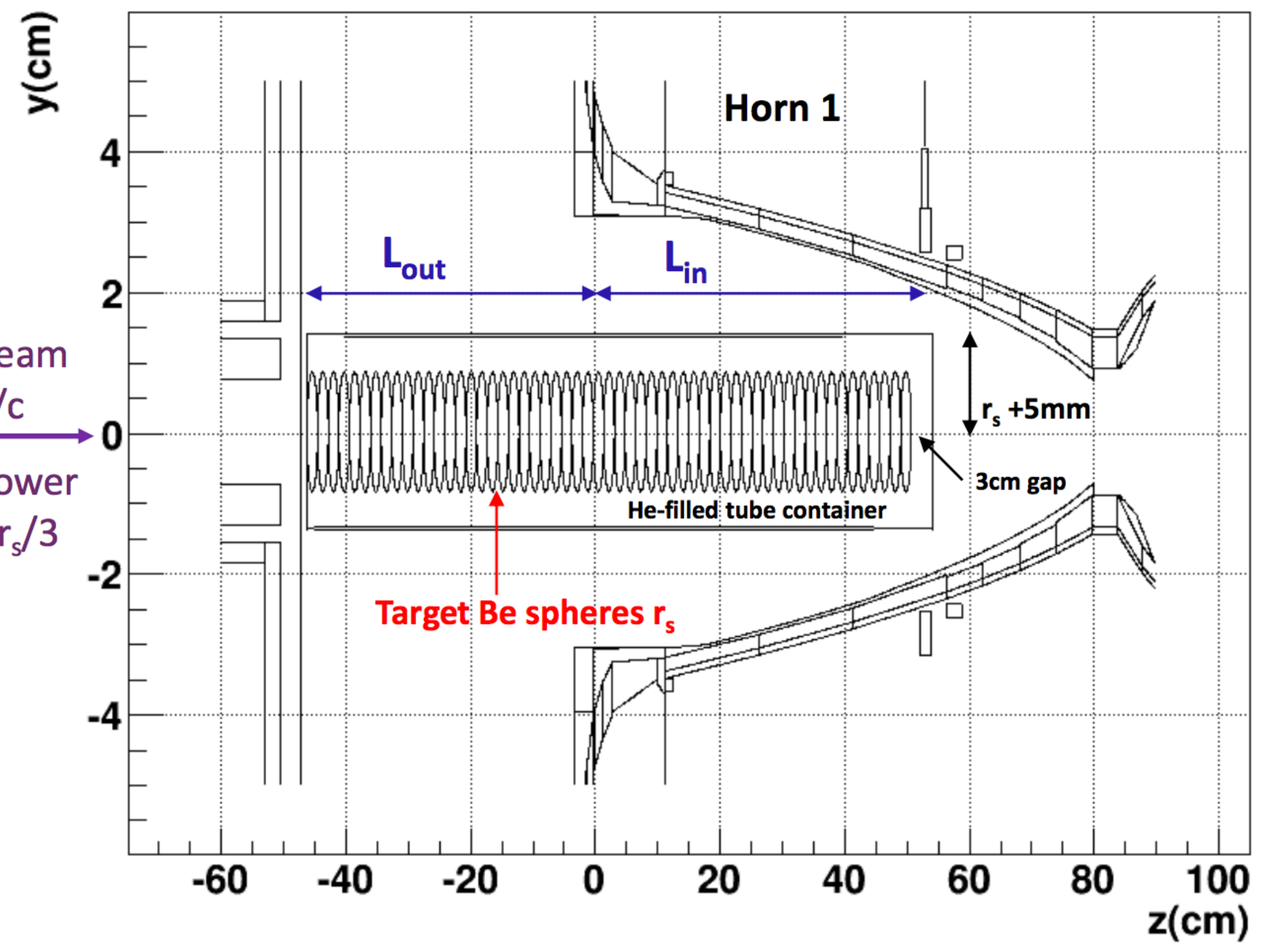
J. LoSecco



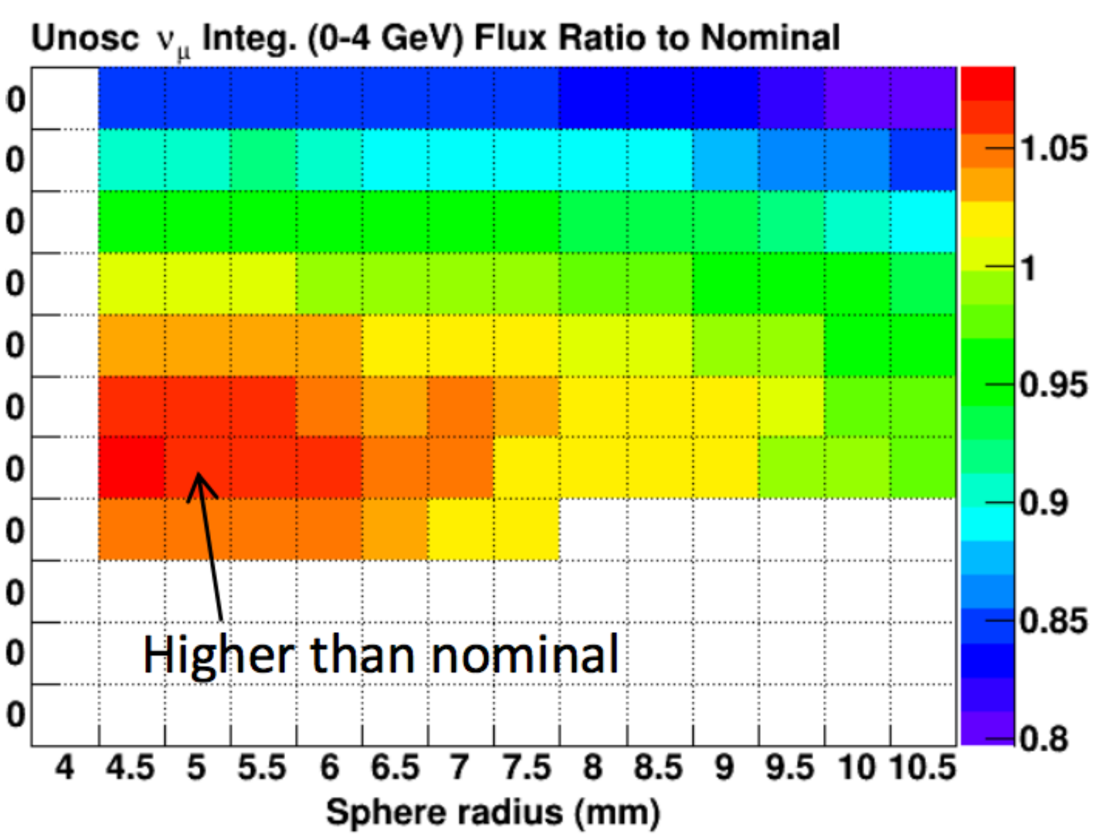
Parabolic shape has modest impact on flux in this configuration

Task Force Status

- Alternate target options, such as a Beryllium Sphere Array Target (SAT) are being considered



Engineering considerations: minimum feasible Be sphere radius $r_s \approx 6.5$ mm

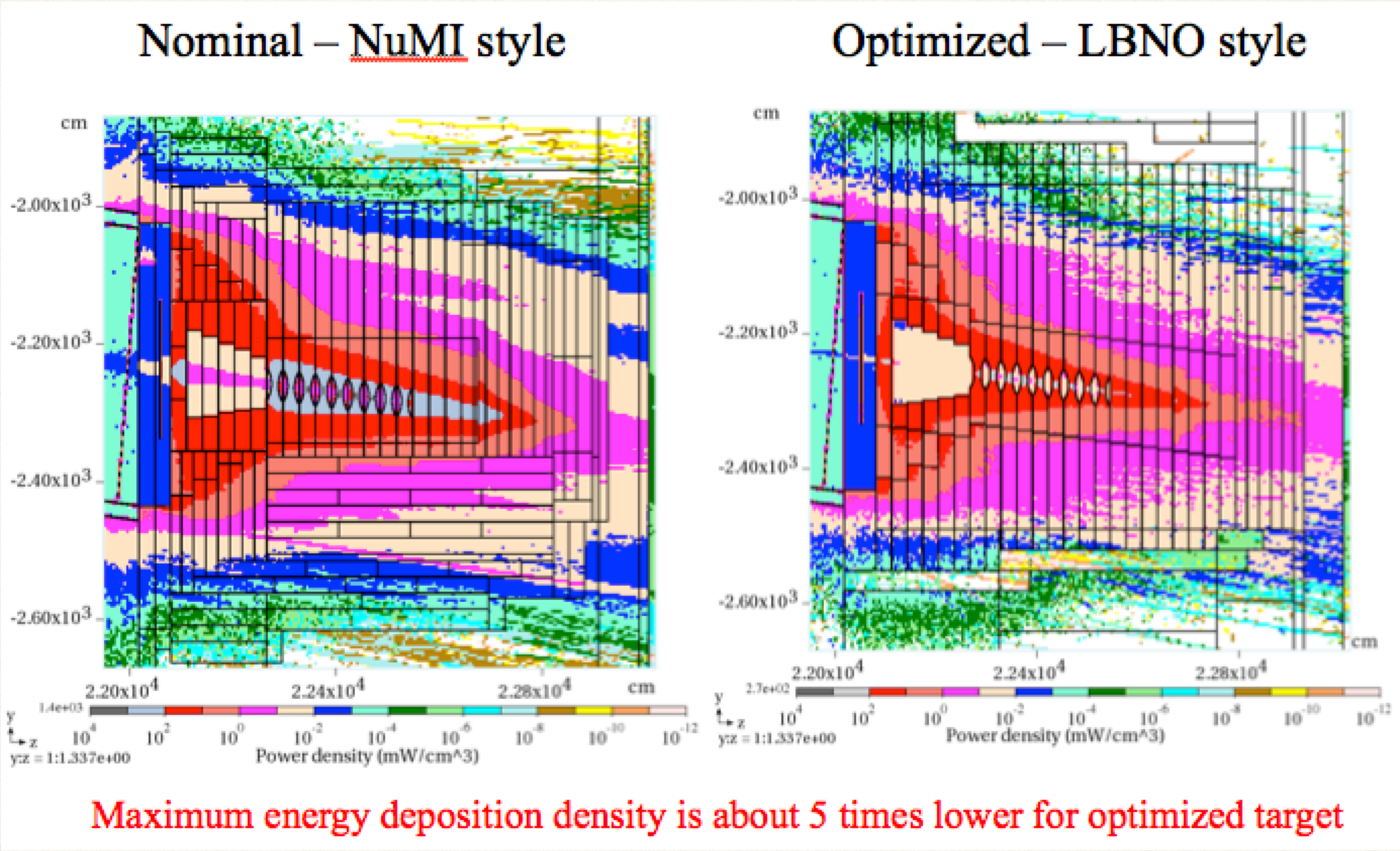


J. Back

So far, this target has just been studied in the context of the reference (NuMI-like design). Should also be studied w/ optimized horns

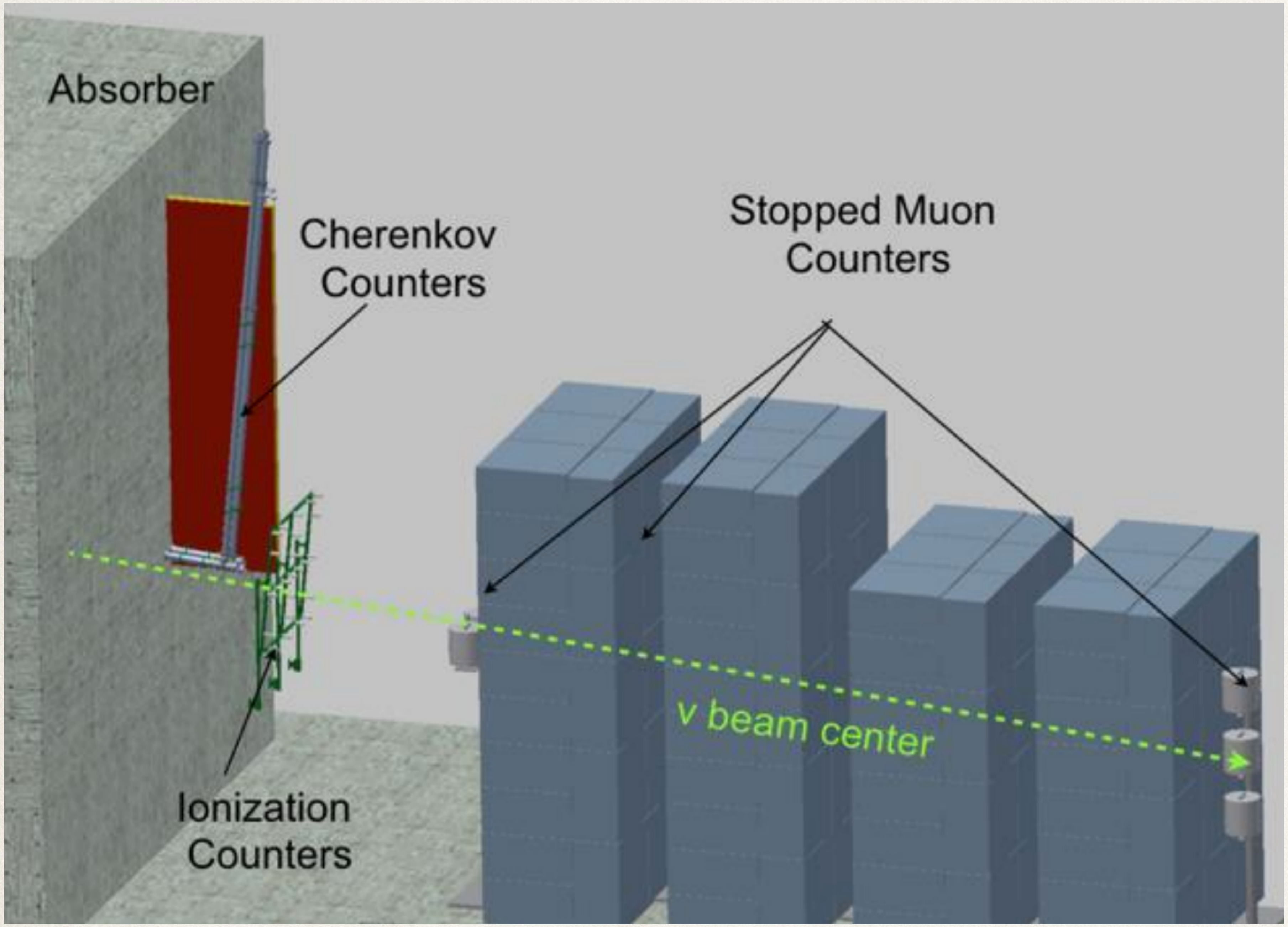
Task Force Status

- Detailed energy deposition studies on optimized design have also begun using MARS



N. Mokhov

Other Ongoing Modeling Work

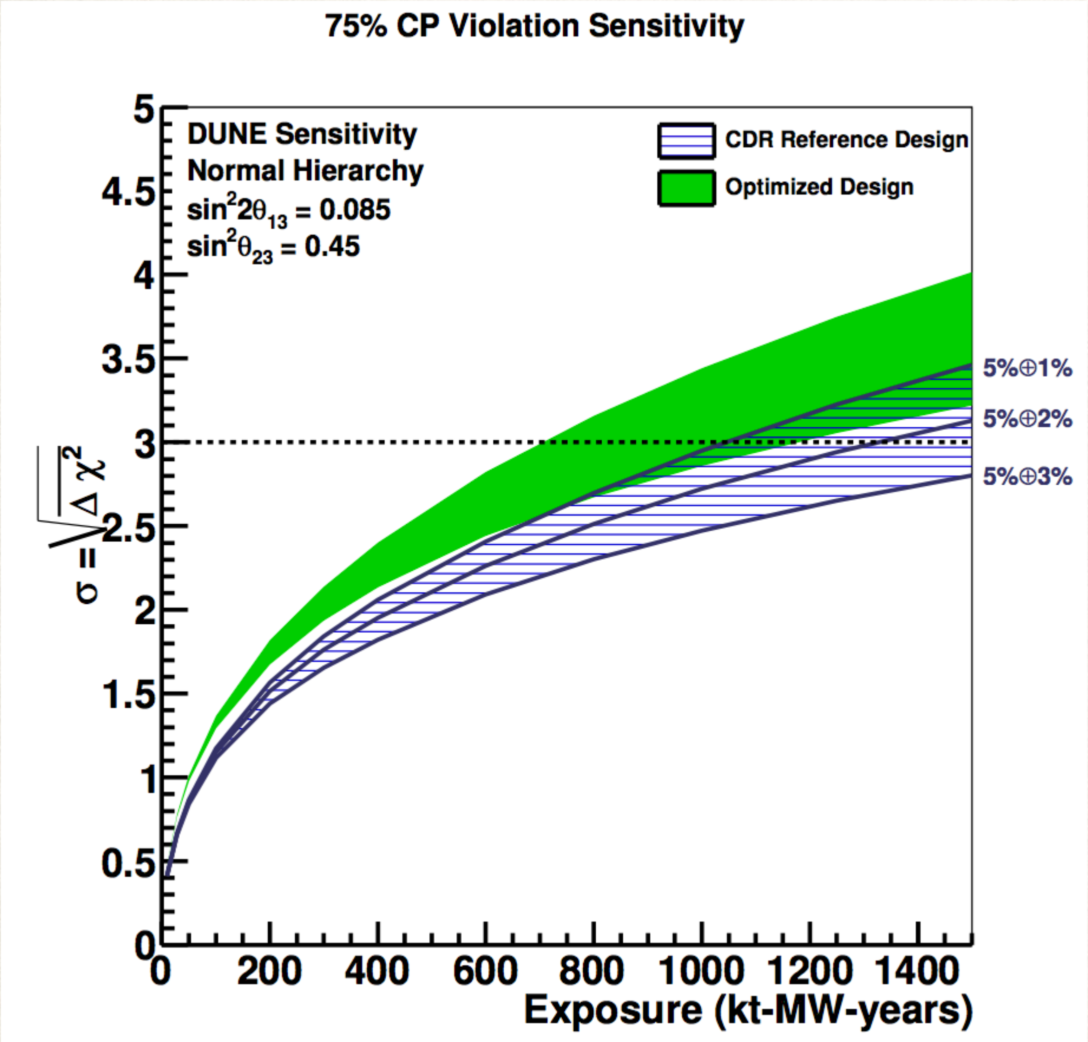


Much work ongoing to design muon monitors

New muon monitor working group has been charged with "evaluating the requirements on the muon monitor system for neutrino beam monitoring and for its potential use for neutrino flux prediction"

Most effort currently going into designing and building prototypes.
Detailed simulations and demonstration of flux constraints yet to be done

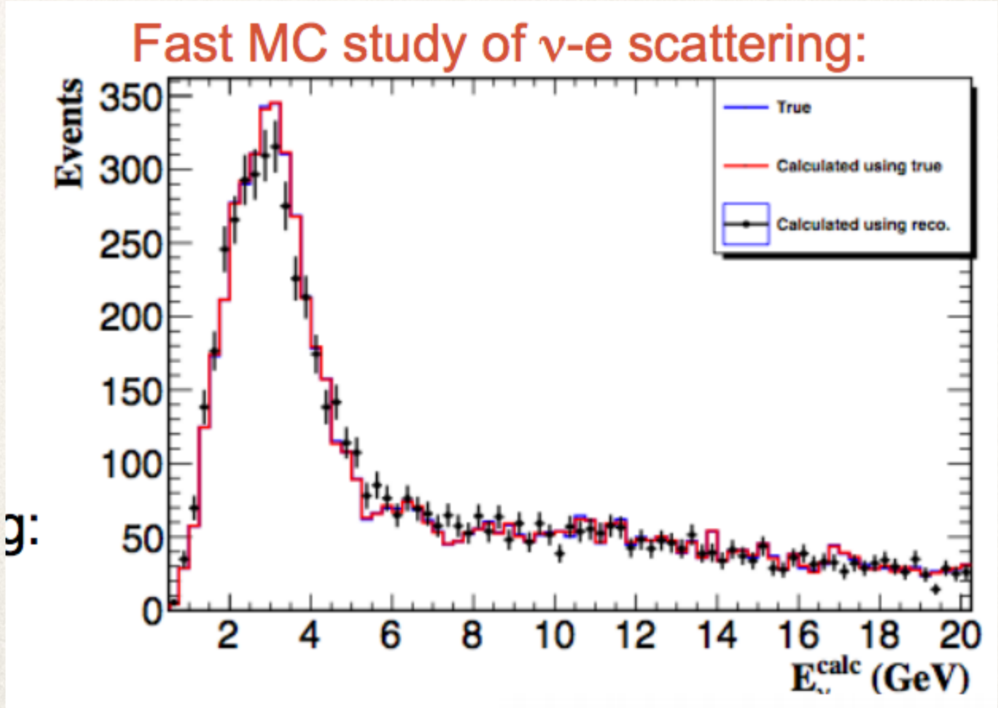
Other Ongoing Modeling Work



Most DUNE physics studies currently use very basic estimates of systematic uncertainties.

Detailed a priori flux uncertainties are needed to prepare for physics measurements and to design the near detector (which much constrain these uncertainties)

In addition to flux uncertainty, also need detailed knowledge of bin-to-bin and flavor-to-flavor correlations



Other Ongoing Modeling Work

Alignment uncertainties are understood for reference beam. Not yet evaluated for optimized beam options.

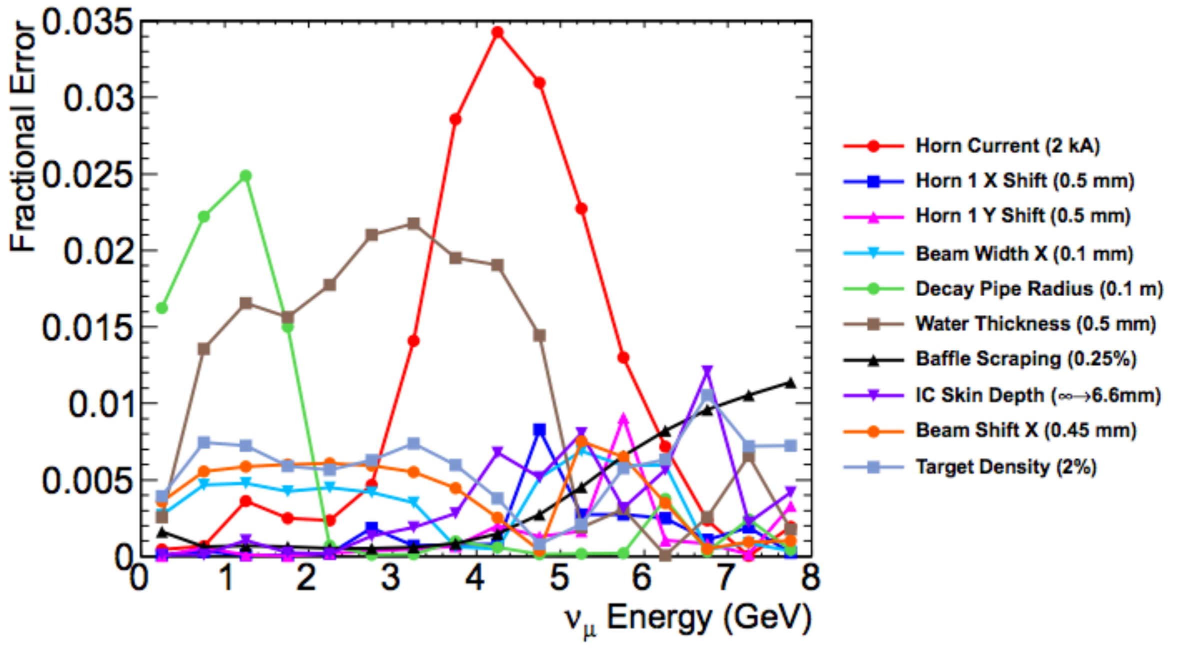
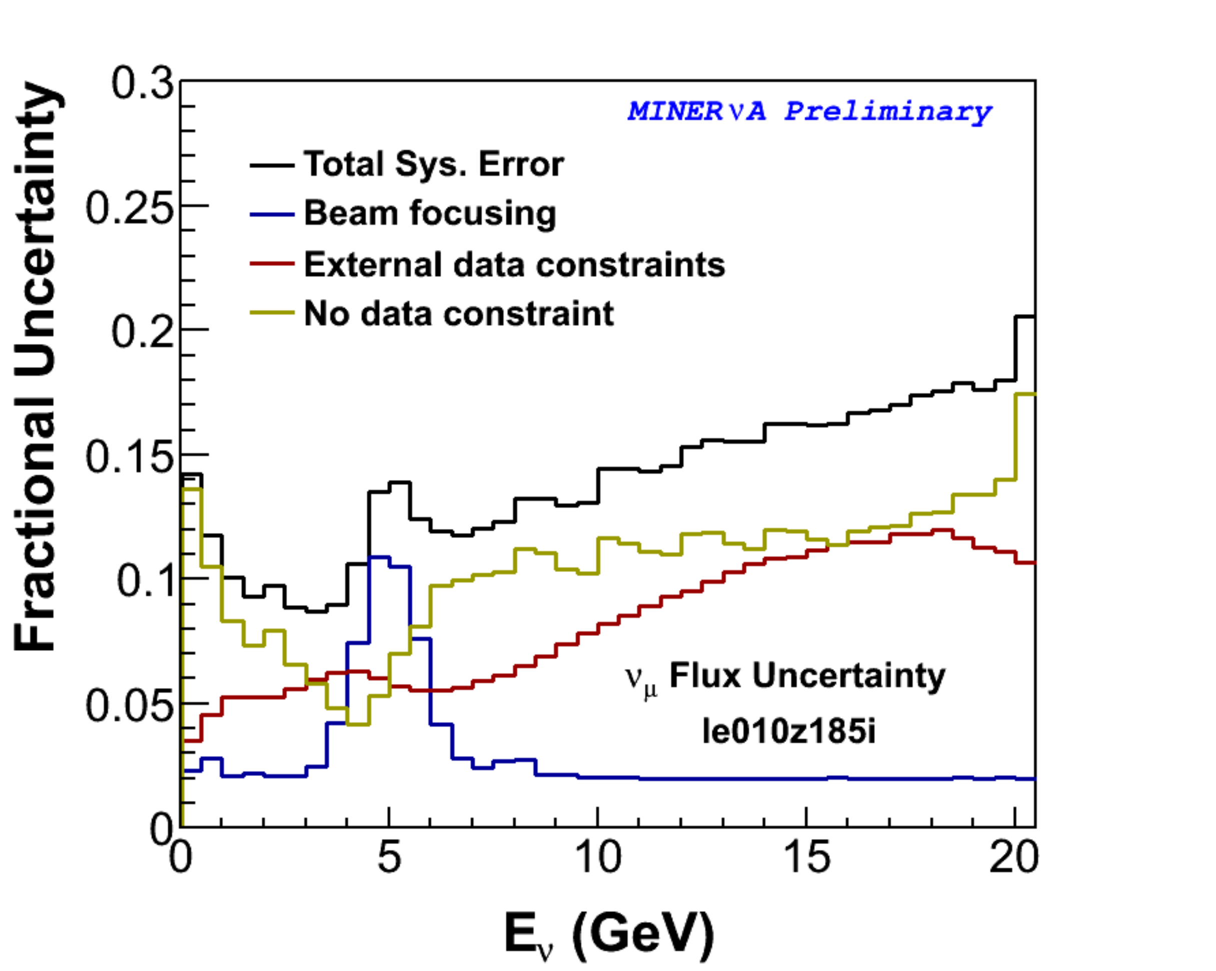


Figure 10: Summary of alignment systematic uncertainties on the flux at the near detector.



Hadron production systematics are not well understood for any beamline option. Have borrowed flux uncertainties and correlations from NuMI for preliminary studies, also working to follow procedures pioneered by T2K and MINERvA

Conclusion

- The LBNF modeling program aims to make the LBNF beam the best-modeled neutrino beam ever built
- Current focus is on beamline optimization; also very important: characterization of the beam for physics and detector design studies
- Nearly all aspects of modeling would welcome new collaborators. Particular areas of need are:
    - Engineering and simulation work to simulate realistic optimized designs
    - Physics studies of optimized beam options
    - Develop simulation and requirements of muon detectors
    - Evaluation of systematic uncertainties and correlations for reference and optimized beam designs

Thank You!

Optimized Parameters

Table 2: Parameters of focusing system optimization

Parameter	Allowed Range	Preferred Value FHC	Preferred Value RHC
Horn 1 r_1	20 - 50	40 mm	25 mm
Horn 1 r_2	35 - 200	166 mm	125 mm
Horn 1 r_3	20 - 75	65 mm	22 mm
Horn 1 r_4	20 - 200	167 mm	148 mm
Horn 1 r_{OC}	200 - 800	632 mm	660 mm
Horn 1 l_1	800 - 2500	1906 mm	1252 mm
Horn 1 l_2	50 - 1000	218 mm	713 mm
Horn 1 l_3	50 - 1000	911 mm	834 mm
Horn 1 l_4	50 - 1000	969 mm	466 mm
Horn 1 l_5	50 - 1000	281 mm	150 mm
Horn 1 l_6	50 - 1000	487 mm	890 mm
Horn 1 l_7	50 - 1000	979 mm	990 mm
Horn 2 Longitudinal Scale	0.5 - 2	1.39	1.84
Horn 2 Radial Scale	0.5 - 2	1.63	1.64
Horn 2 Radial Offset	-78 - 100	54.6 mm	46 mm
Horn 2 Longitudinal Position	3000 - 15000	14503 mm	13181 mm
Target Length	500 - 2500	2463 mm	2473 mm
Target Width	9 - 15	10.5 mm	10.0 mm
Proton Energy	40 - 130	109 GeV	116
Horn Current	150 - 300	297 kA	297 kA