The LBNF Neutrino Beam

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For the DUNE/LBNF collaboration

Oregon State University

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

NSF

U.S. DEPARTMENT OF ENERGY

Office of Science

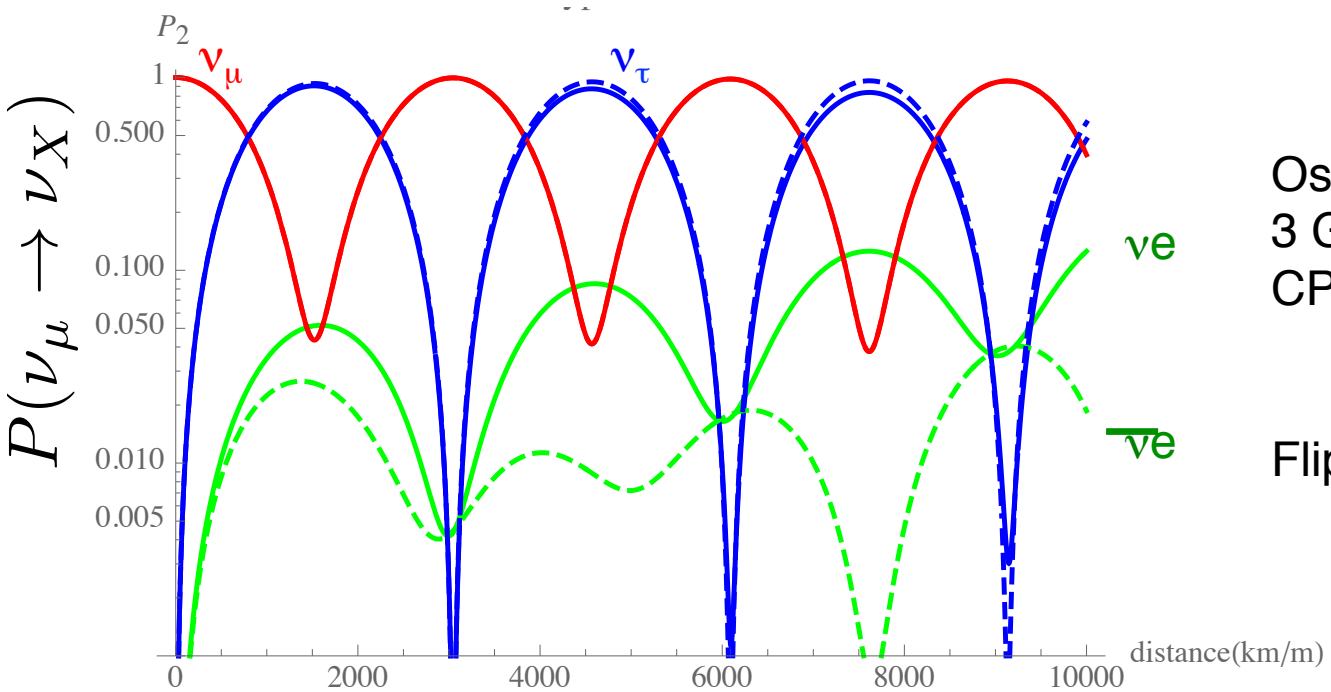
LBNF/DUNE Science Program

- Neutrino Oscillation Physics
  - Search for leptonic (neutrino) **CP violation**
  - Resolve the **mass hierarchy**
  - **Precision oscillation** physics
- **Nucleon Decay**
- **Supernova** physics and astrophysics
  - 3000 ve events in 10 sec from SN at 10 kpc
- Plus **many other** topics
  - neutrino interaction physics, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.

Neutrino CP violation

$$P_{i\to j} \sim F(\theta)\sin^2[\frac{\Delta m_{ij}L}{E}] \pm \sin\delta\ J(\theta)\prod_{k<\ell}\sin[\frac{\Delta m_{kl}L}{E}]$$

Start with muon neutrinos ν_μ, look for electron neutrinos ν_e



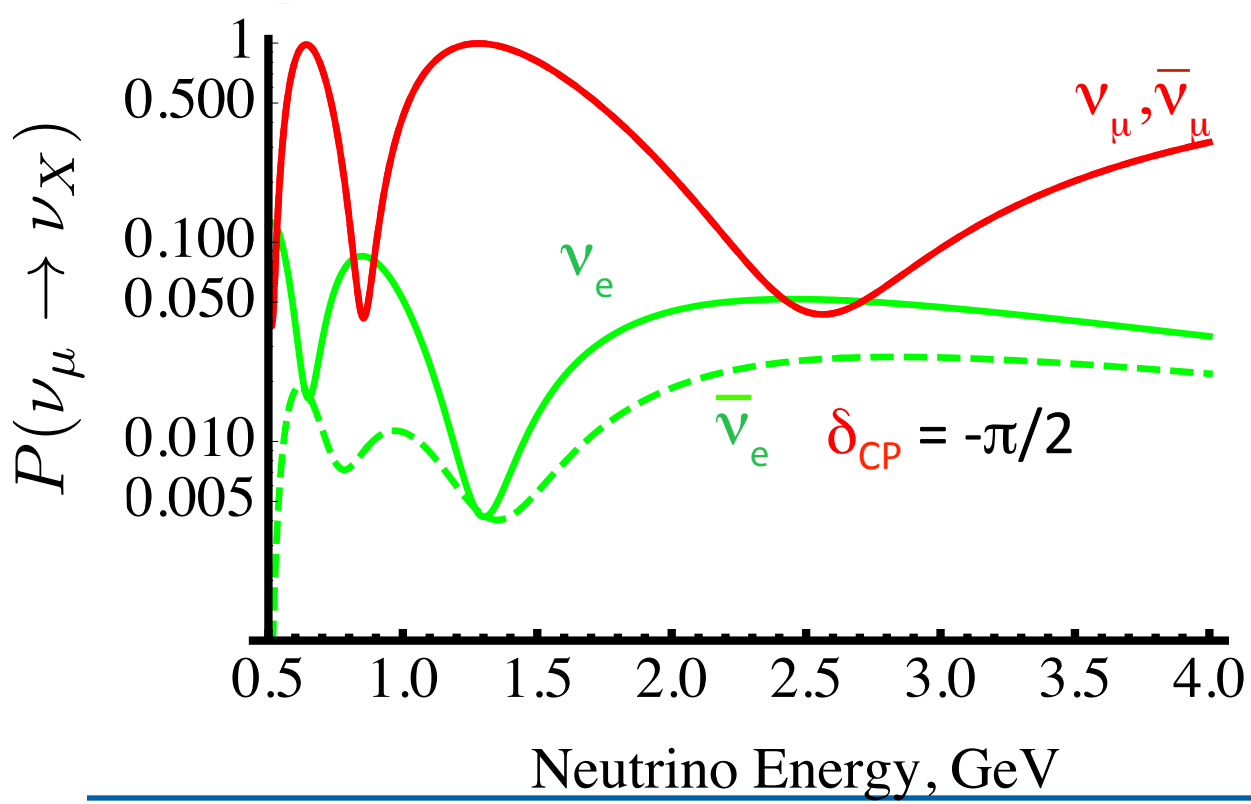
Oscillations for
3 GeV ν_μ
CP phase $\delta = -\pi/2$

Flips for $\delta = \pi/2$

Distance in km

LBNF/DUNE CP violation Physics at 1300 km baseline

$$P_{i\to j} \sim F(\theta)\sin^2[\frac{\Delta m_{ij}L}{E}] \pm \sin\delta\ J(\theta)\prod_{k<\ell}\sin[\frac{\Delta m_{kl}L}{E}]$$



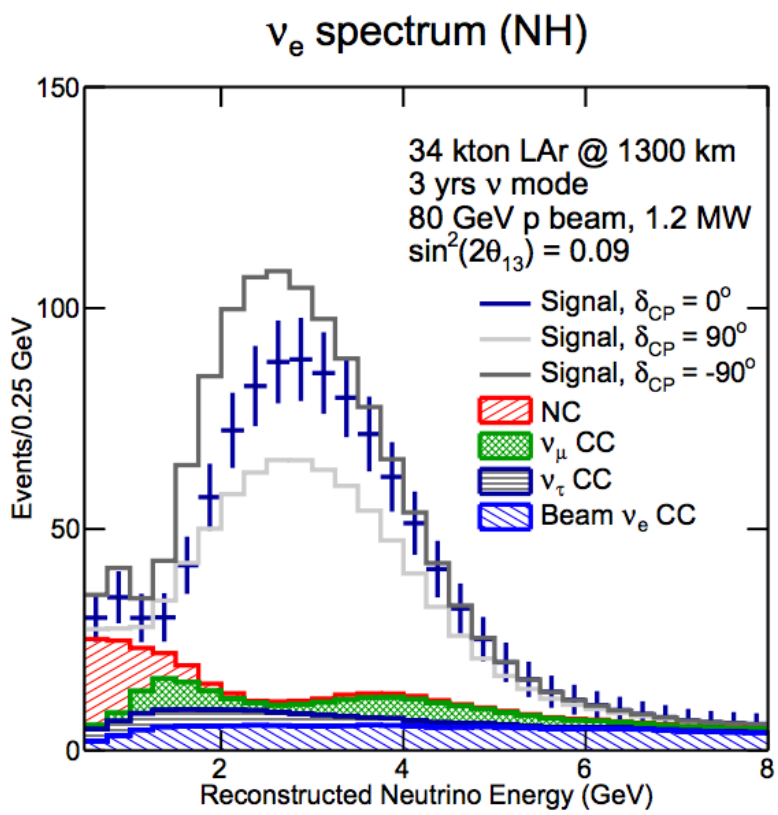
Sin[1/E] dependence

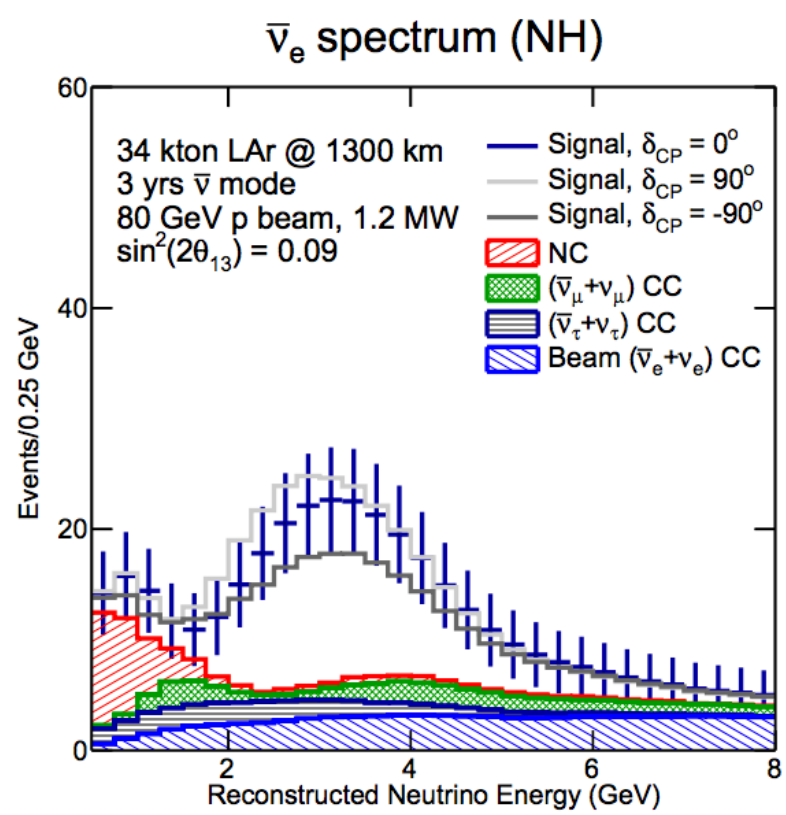
CP violation (and matter effects) show up as differences in

$\nu_\mu \to \nu_e$

LBNF/DUNE Long Baseline Physics

- We'll be trying to detect **very subtle differences** in predicted event spectra expected for different oscillation parameters:





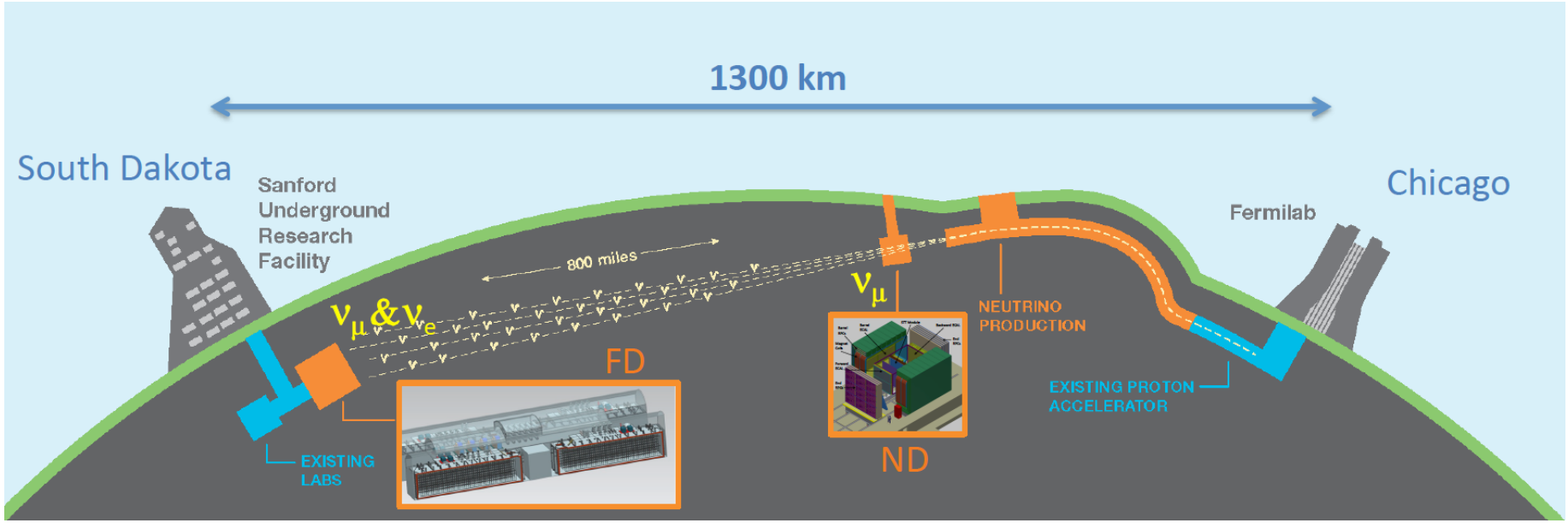
Older plots to illustrate the δ dependence

Physics requirements for a neutrino beam

- High neutrino fluxes in the right energy range
  - Emphasize 0.5-4 GeV at 1300 km
  - Deemphasize higher energies to avoid feed-down backgrounds
- Low intrinsic electron neutrino content
- Good sign separation (neutrino vs. anti-neutrino)
- Reproducible and simulatable

LBNF/DUNE Overview

- LBNF (Long Baseline Neutrino Facility) and DUNE (Deep Underground Neutrino Experiment):
  - Neutrinos from high-power proton beam
    - **1.2 MW from day one**; upgradeable to 2.4 MW
  - **Near detector** to characterize the beam
  - Massive underground Liquid Argon Time Projection Chambers
    - **4 x 17 kton** (fiducial mass of more than 40 kton)

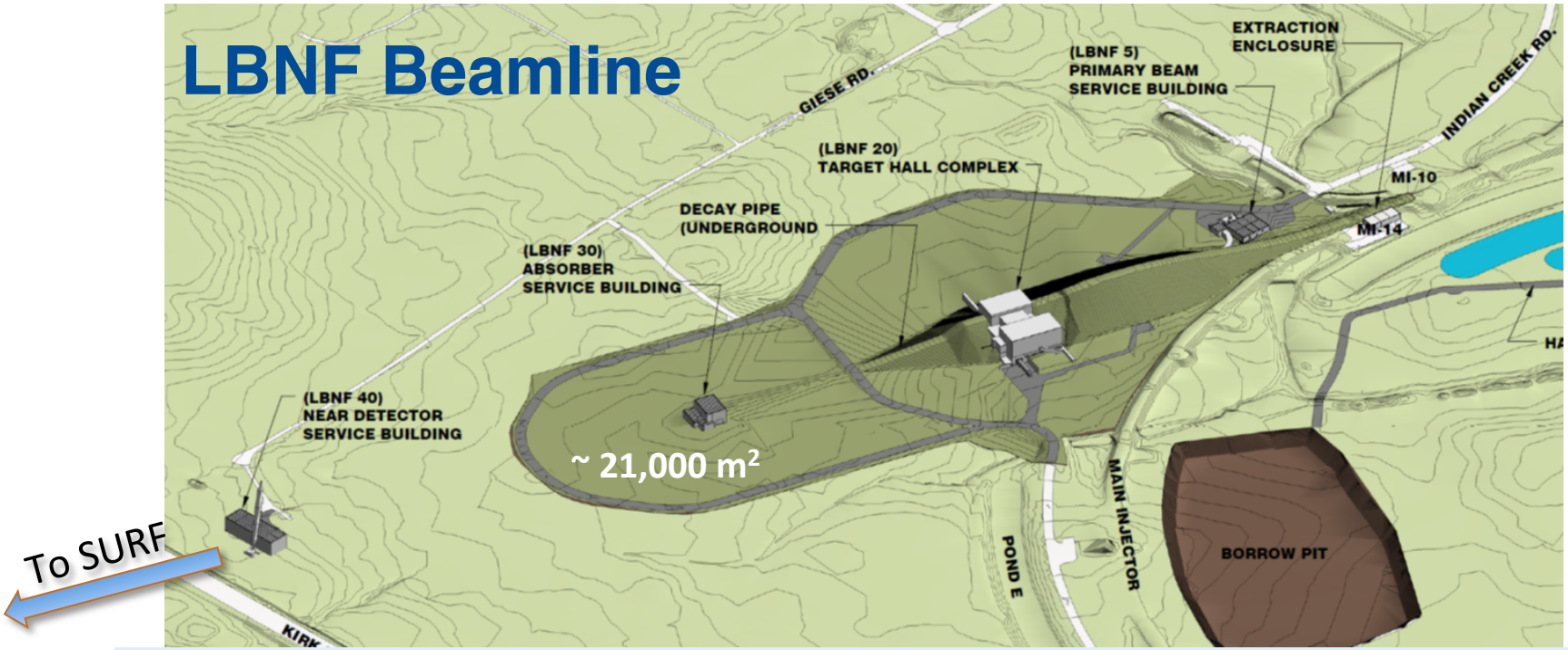


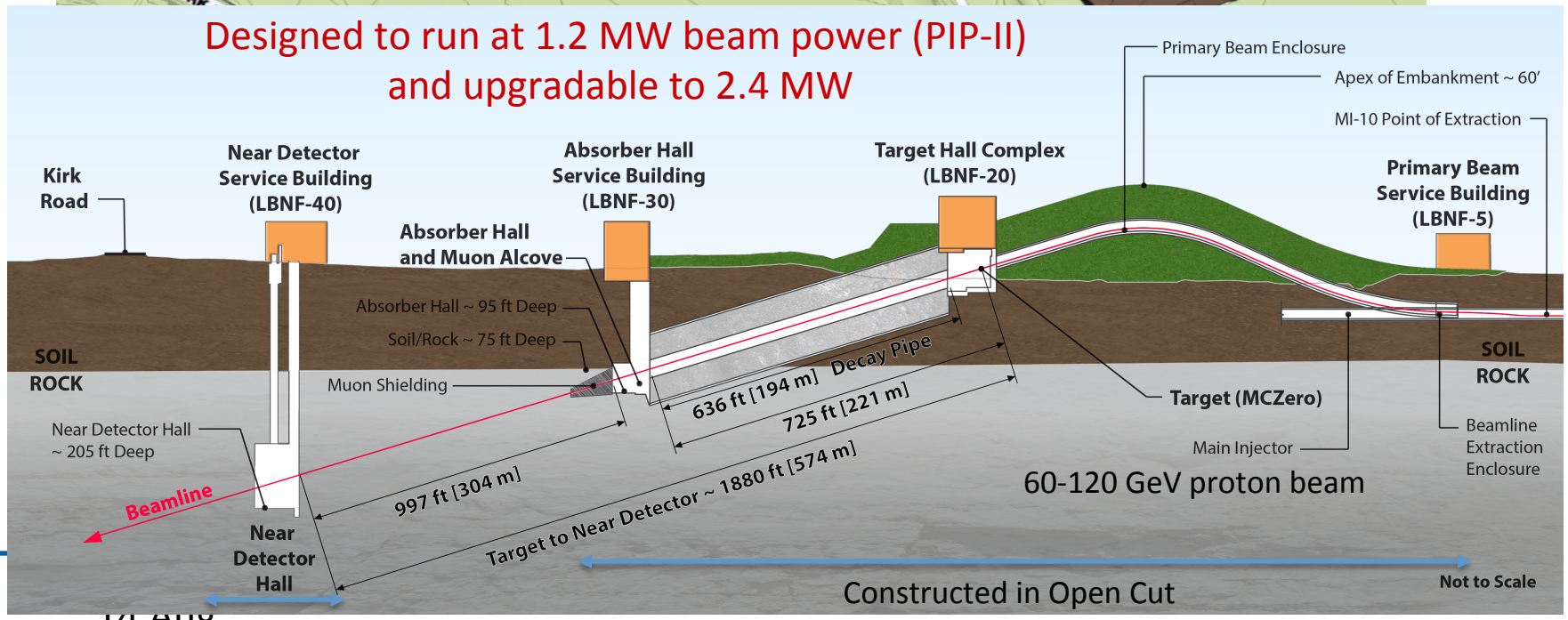
LBNF Beamline

- LBNF will use protons from the Main Injector, which will operate at 1.2 MW to start and will be upgradeable to 2.4 MW

Proton beam will be tunable between 60 and 120 GeV

LBNF Beamline





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Beamline Requirements and Assumptions

- Currently assuming 20 year operation of the Beamline Facility within a 30 year span.
- Operating Parameters:

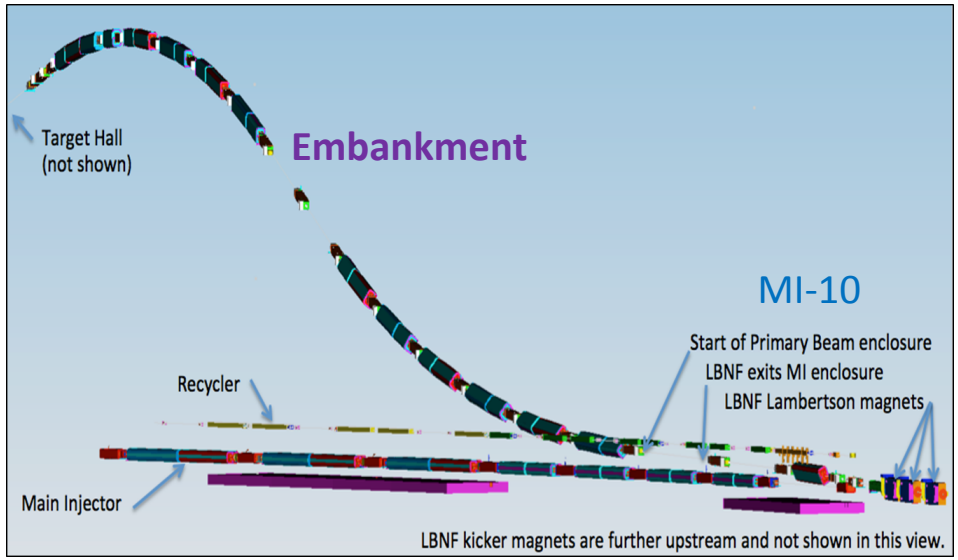
(1.1 – 1.9)x10^{21} POT/yr

Pulse duration: 10 μs
Beam size at target: tunable 1.0-4.0 mm. Current size ~2.7 mm.

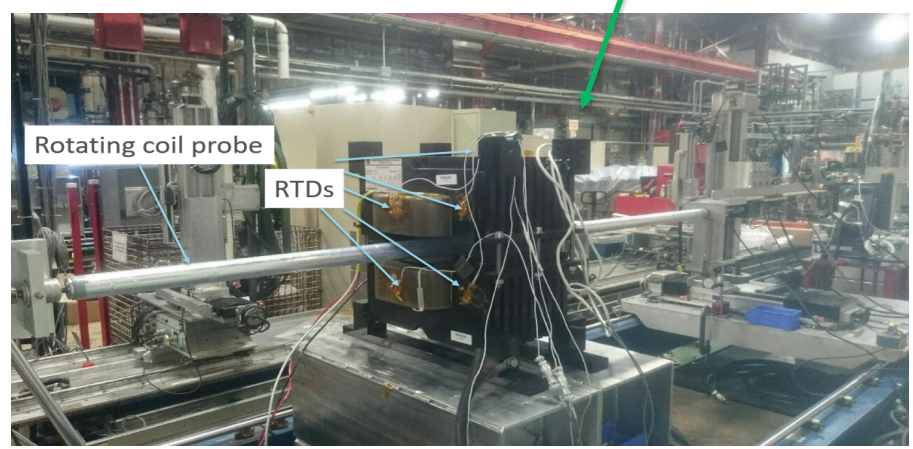
Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

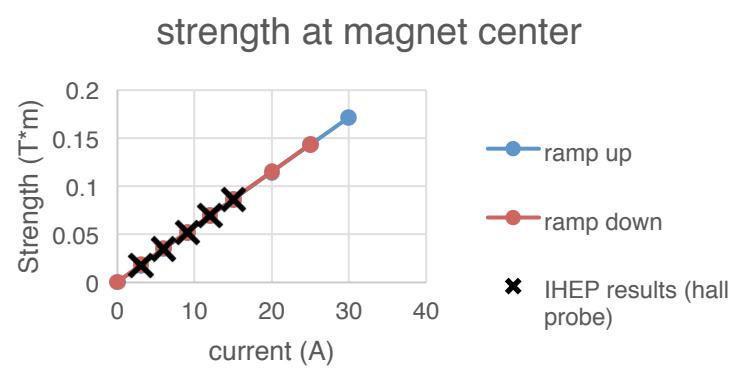
Primary Beamline

Beam optics point to 79 conventional magnets of well understood designs: 25 dipoles, 21 quads, 23 correctors, 6 kickers, 3 Lambertsons, 1 C magnet.



- Prototype Corrector Magnet, fabricated at IHEP/China, on the test stand at Fermilab in October 2017

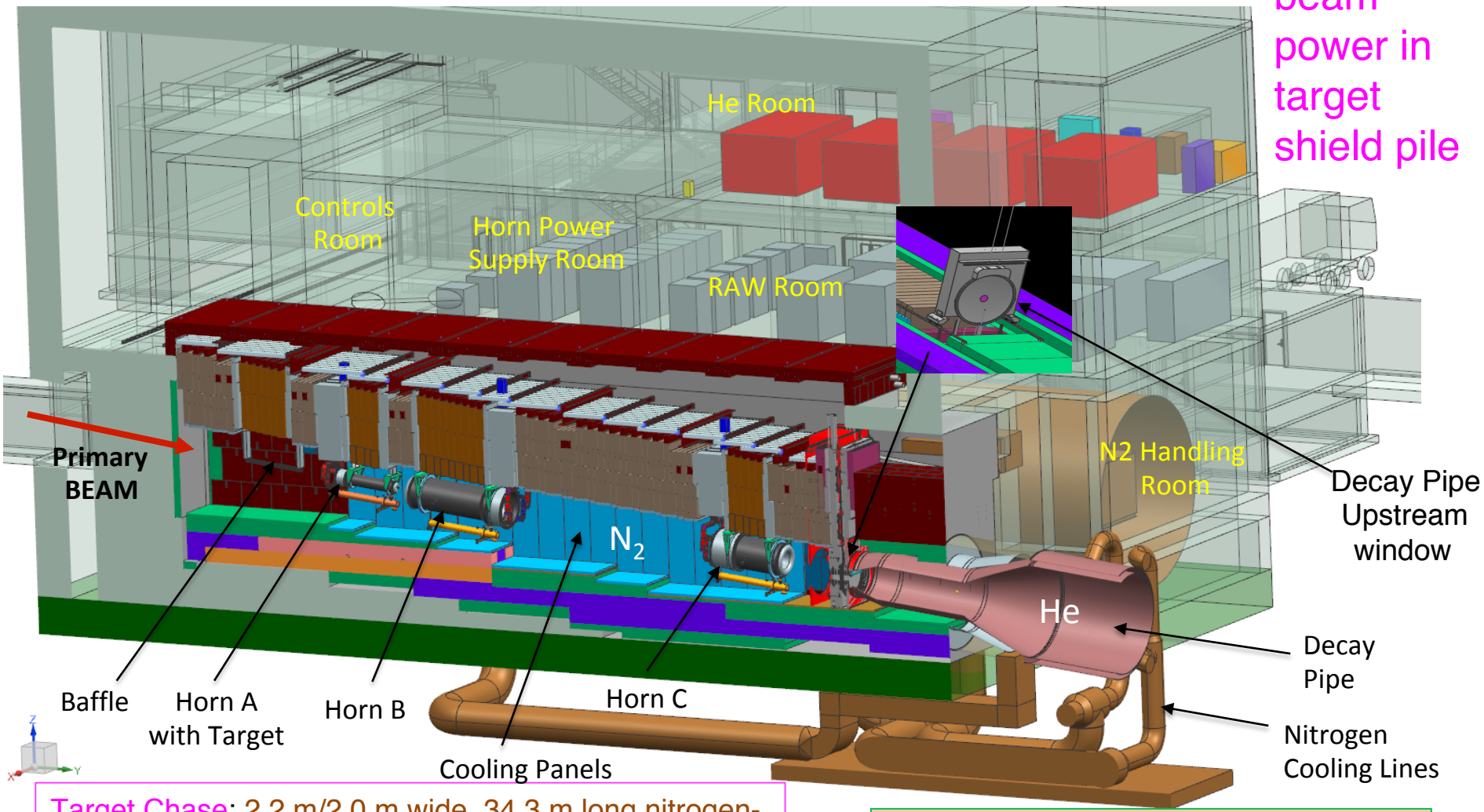




- Kicker magnet prototype constructed at Fermilab and being tested now

Target Hall Shield Pile Layout – Optimized Design

~ 52% of beam power in target shield pile



Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (cooling panels).

Preliminary design work started for the Target Shield Pile in FY18.

3 year program of optimizations (2015-2018)

- Start with a “NuMI” design similar to MINOS/NOvA

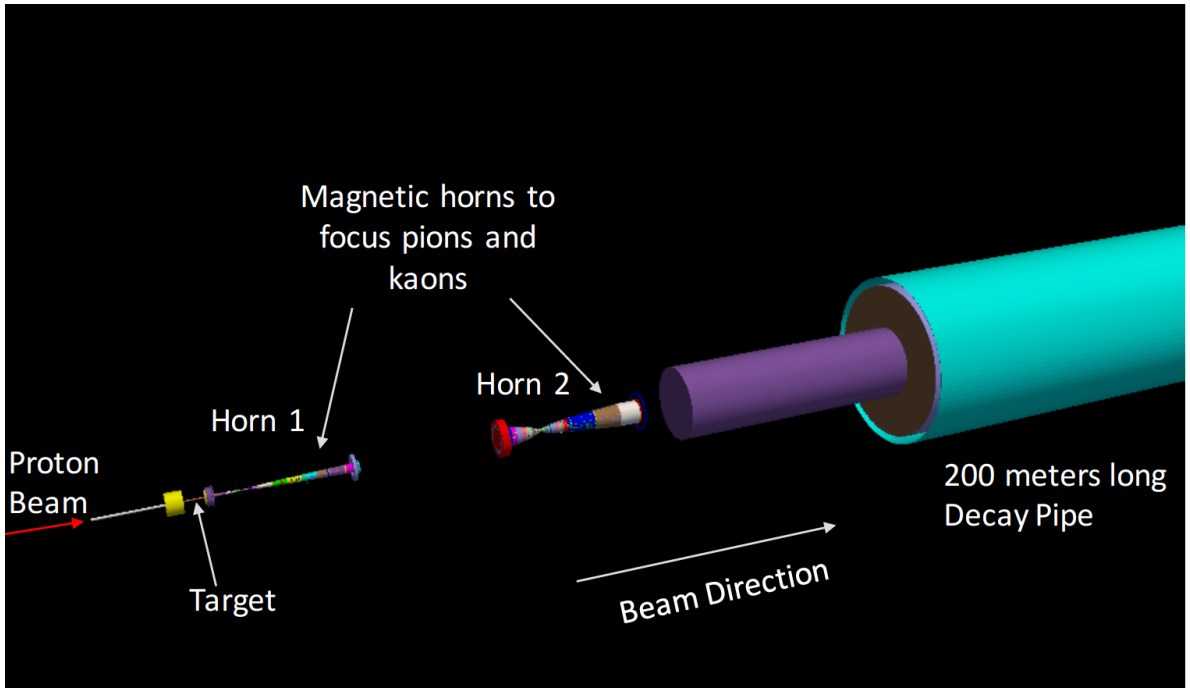
- Adapt g4lbne and ppfx simulation tools
  - Geant simulations of beamline elements
  - Reweighting of geant interaction probabilities to reflect real data from hadro-production measurements

- Explore beamline designs and optimize

- Bottom line ~ 30% improvement in physics reach/proton

LBNF Beamline

- Starting point for optimization



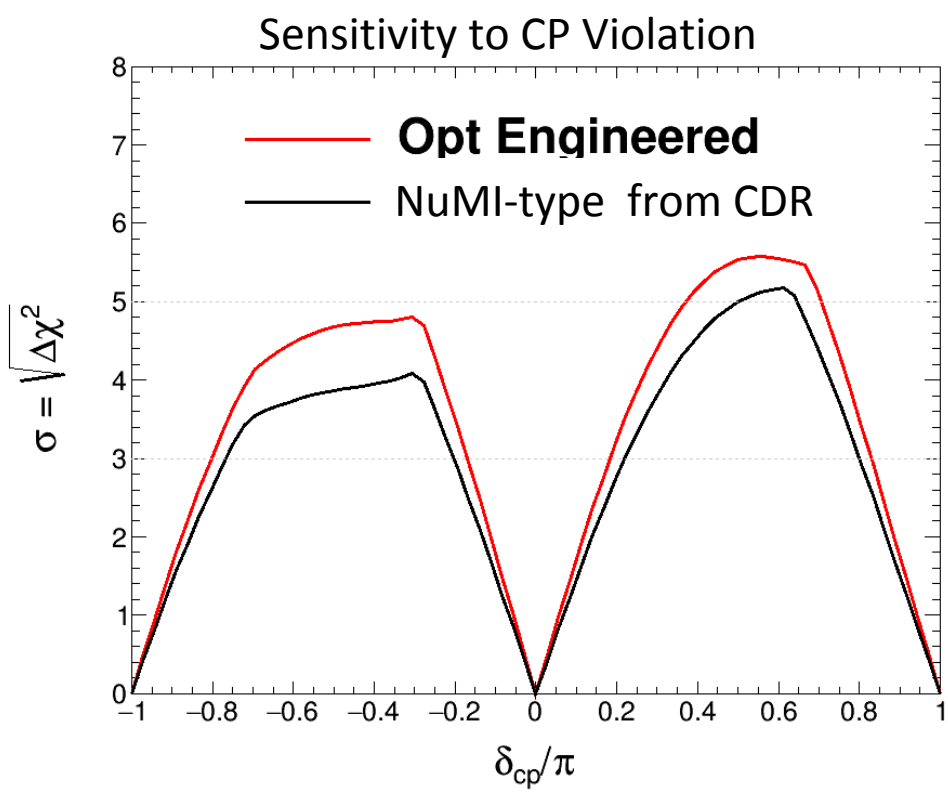
Reference Design

Two horns, nearly identical to those used in NuMI, run at slightly higher current (230 kA)

1 m long graphite fin target, similar to but not identical to NuMI target

Figures courtesy Amit Bashyal

Physics Performance of Beam Options

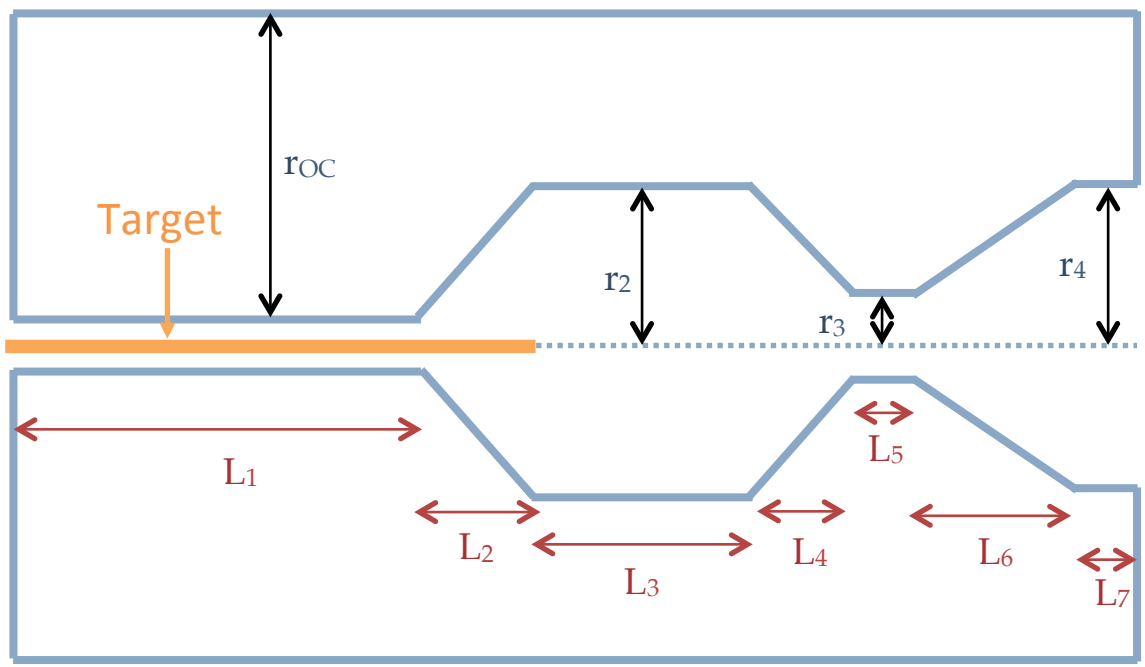


- Sensitivity after 6 years of running
- If there is a lot of CP violation (δ_{CP} near π/2 and -π/2), DUNE will be able to clearly see it
- For smaller amounts of CP violation, the situation will be less clear

Sensitivities use CDR GLoBES setup and default parameters, and exposure of 300 kT MW years; CP sensitivity assumes a normal mass hierarchy

Beam Optimization

- Define parameters to optimize
- Initial set of 20 expanded later

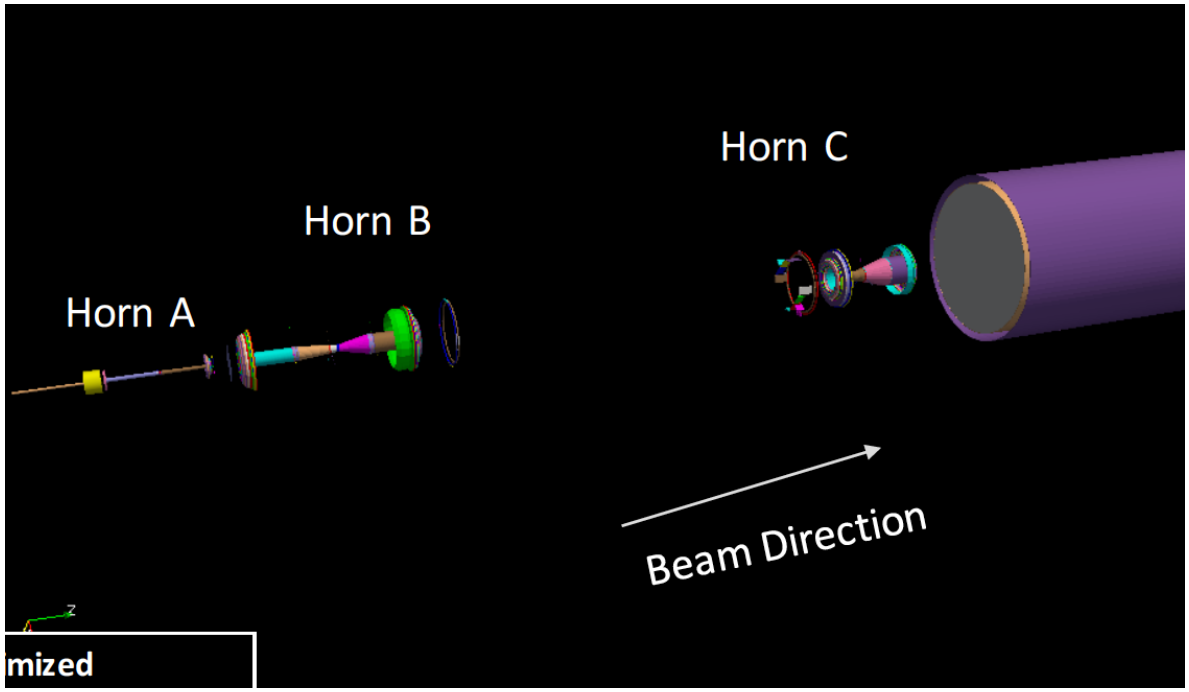


Parameters Varied:

- Horn 1 shape parameters (see figure)
- Width/length of carbon fin-style target
- Horn current
- Horn 2 radial and longitudinal scales
- Horn separation
- Proton beam momentum & radius

LBNF Optimized Beamline

- After optimization



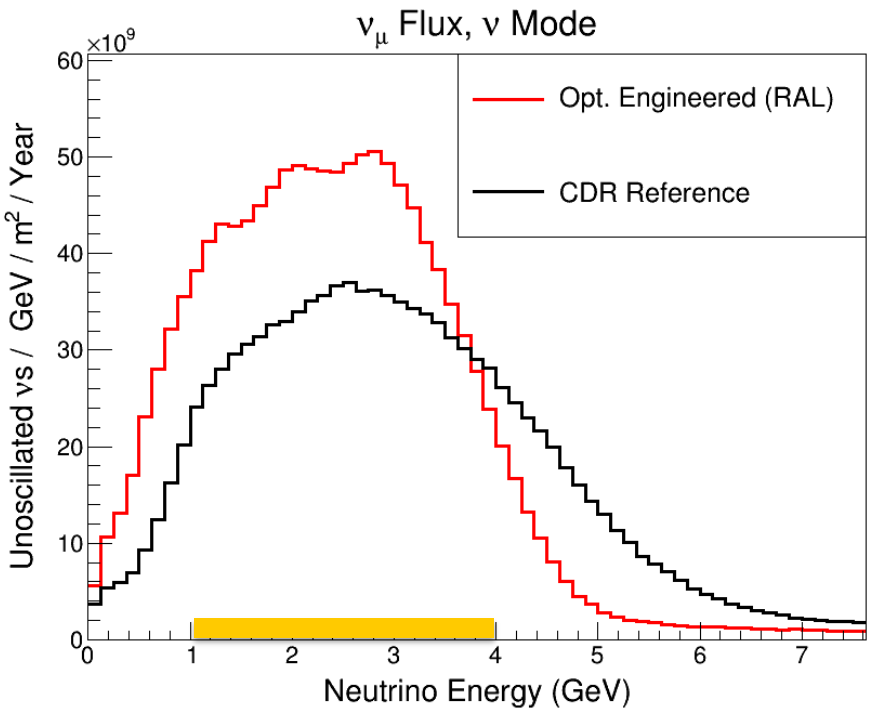
Optimized Design

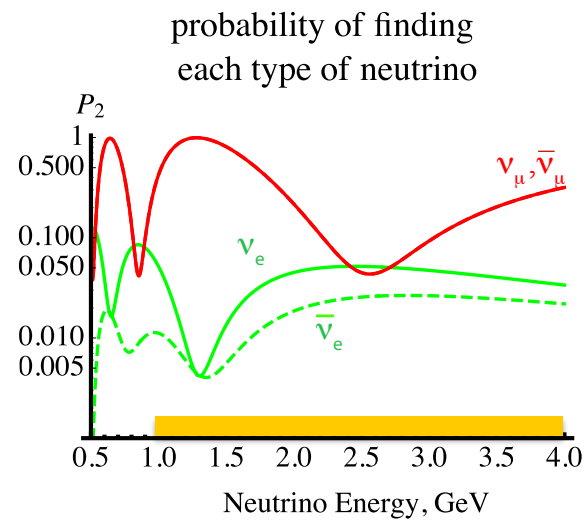
Three horns, not similar to NuMI, run at **300 kA**

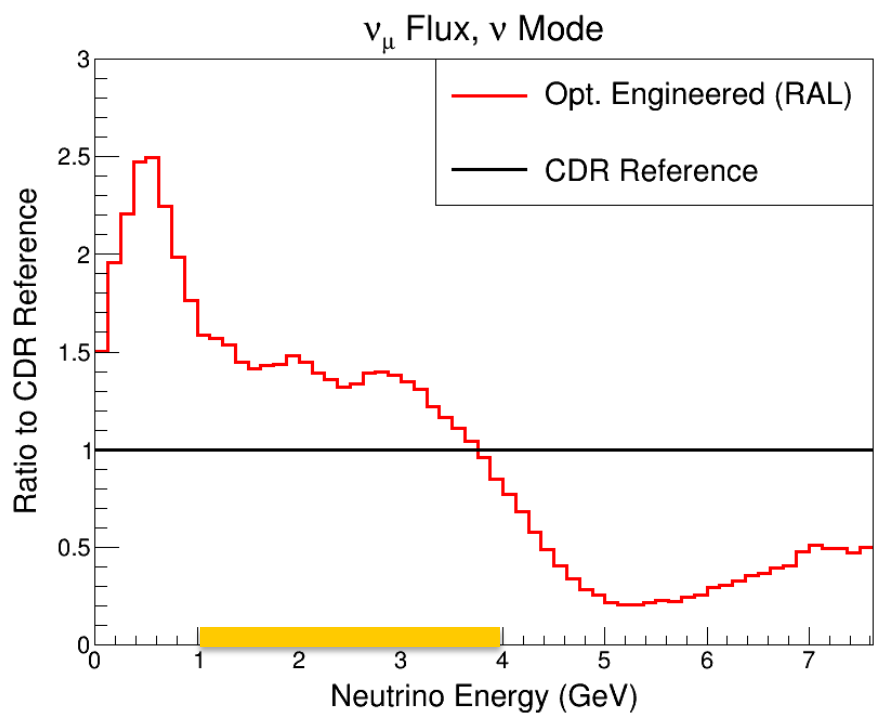
2.2 m long carbon target

Figures courtesy Amit Bashyal

Physics Performance of Beam Options

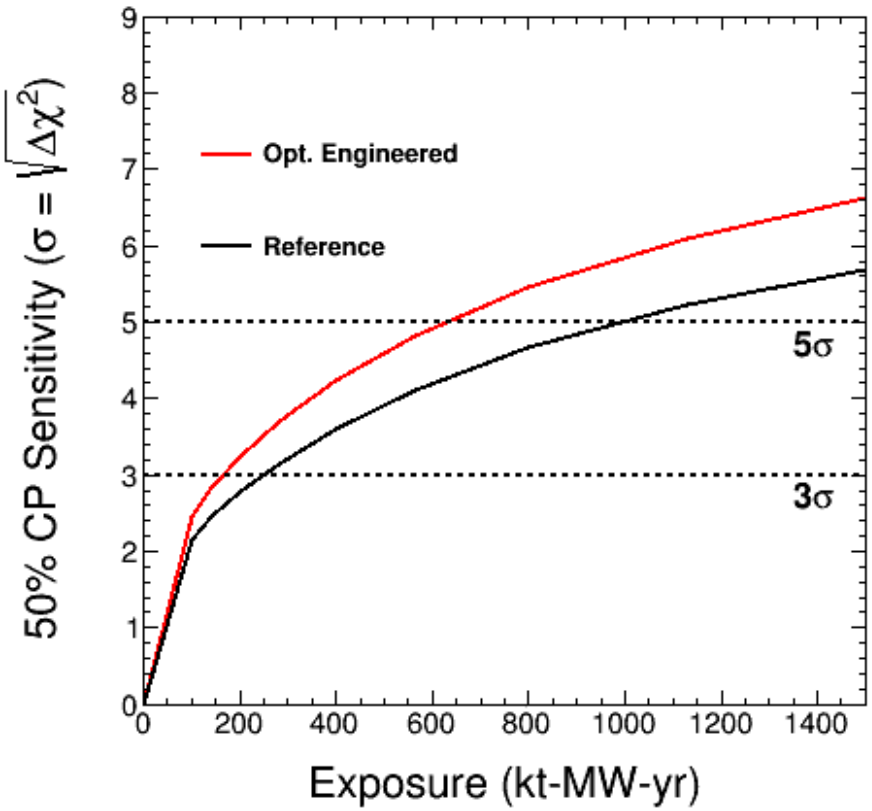






- Flux increases by 36% in the critical 1-4 GeV region
- Increase is more than a factor of two below 1 GeV

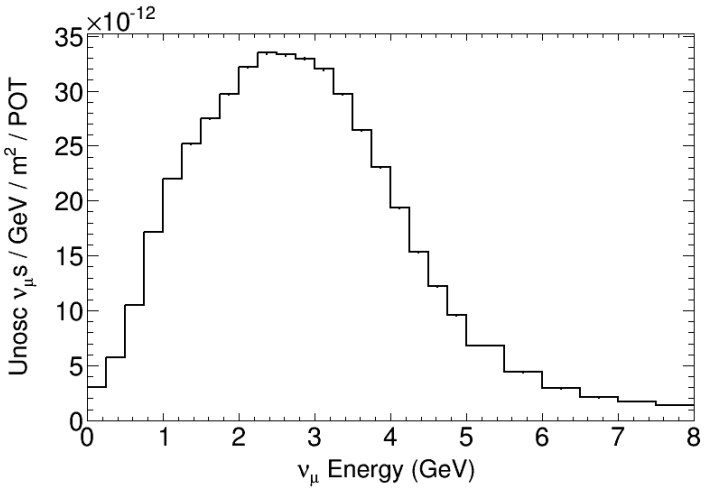
Physics Performance of Beam Options

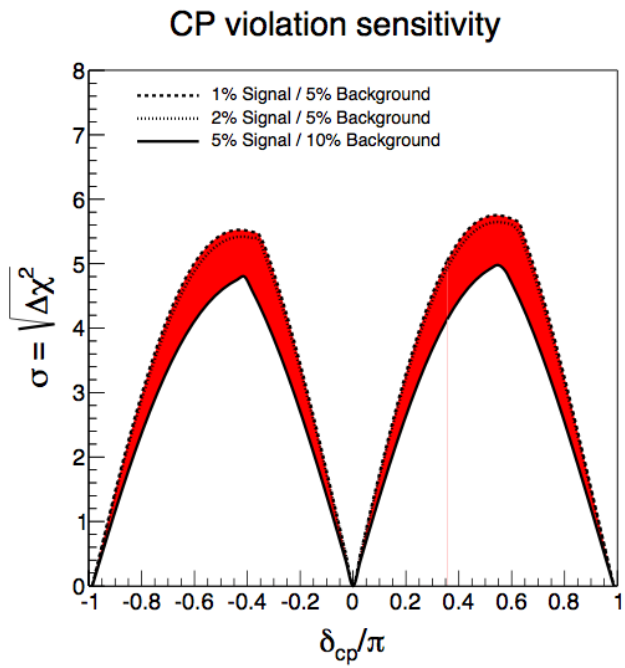


- For CP violation, the improvements in time to reach physics milestones **corresponds to increasing the far detector mass by 70%** — 28 kTons of liquid Argon
- Last fall, LBNF/DUNE **made the decision to go forward** with the optimized beam design
  - Physics argument was clear
- The rest of this talk:
  - **How we redesigned the beam** to get a physics improvement equivalent to 28 kTon of additional liquid Argon

Optimization

- Simulate beam configurations
- estimate the physics performance
- pick the best one:



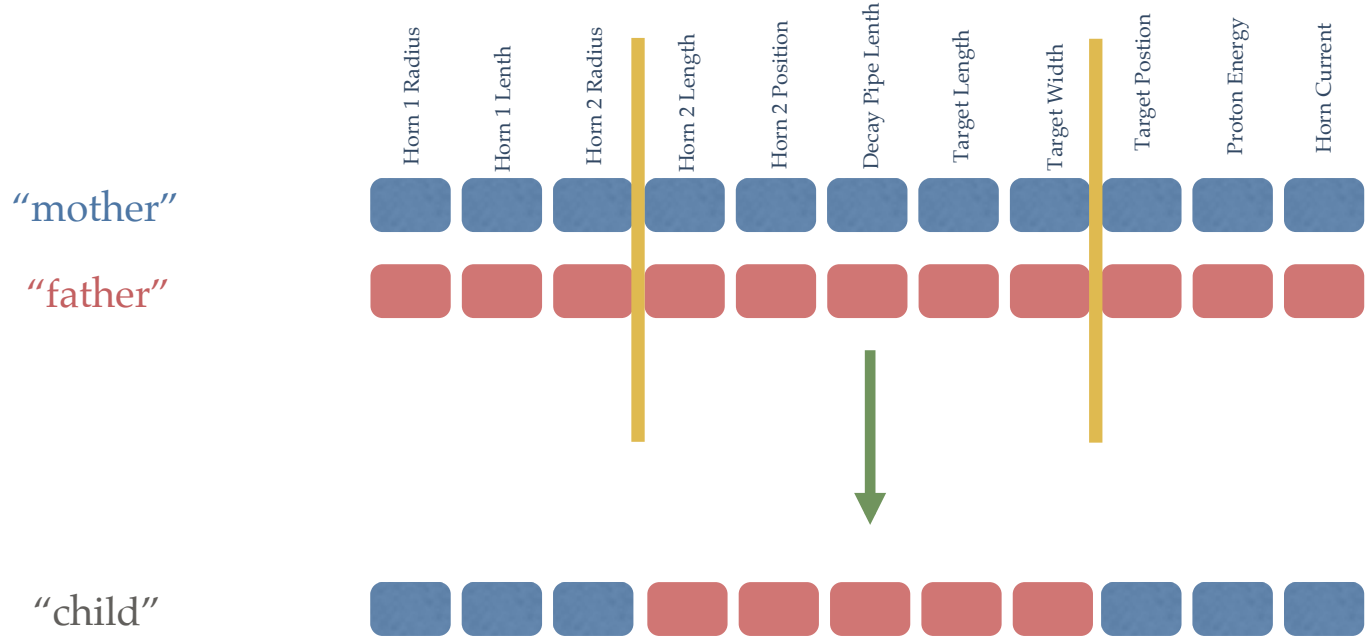


Brute force takes a very long time to optimize!

Genetic Algorithms

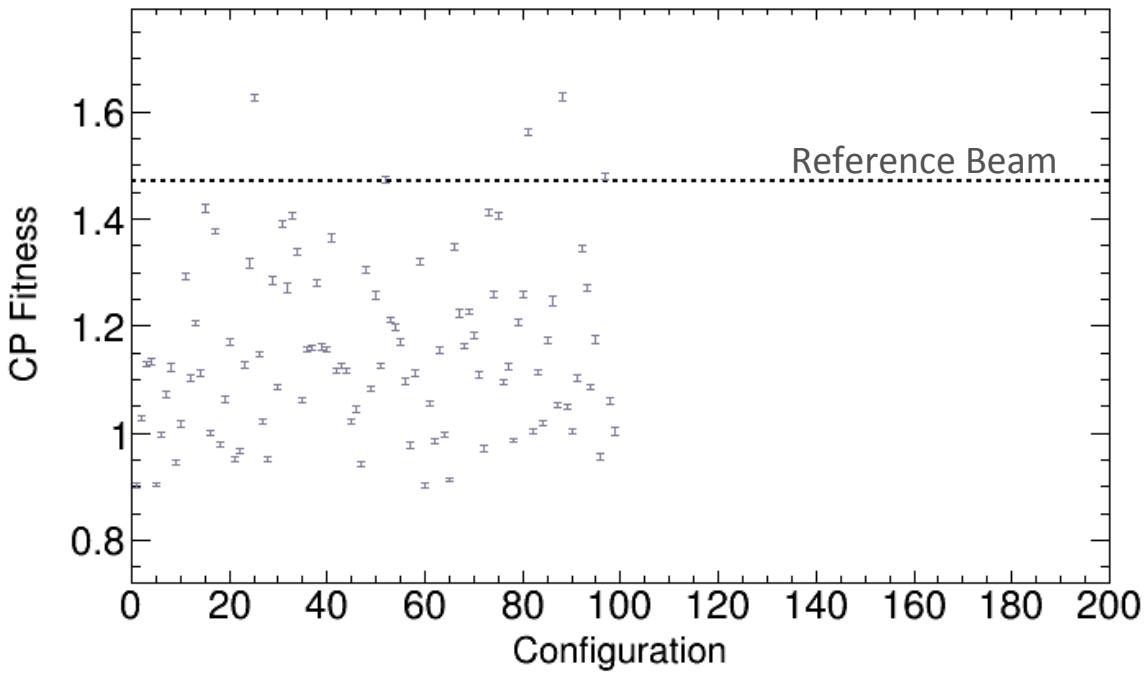
M.~Calviani, S.~Di Luise, V.~Galymov and P.~Velten, ``Optimization of neutrino fluxes for future long baseline neutrino oscillation experiments, arXiv:1411.2418

- Since we wanted to build the beam sometime in our lifetimes, we developed a genetic algorithm
  - A beam configuration is viewed as an organism; you start with a sample of randomly chosen organisms
  - Configurations are judged based on "fitness" (CP sensitivity) and best configurations are mated together to form new (and better) designs



Genetic Algorithms

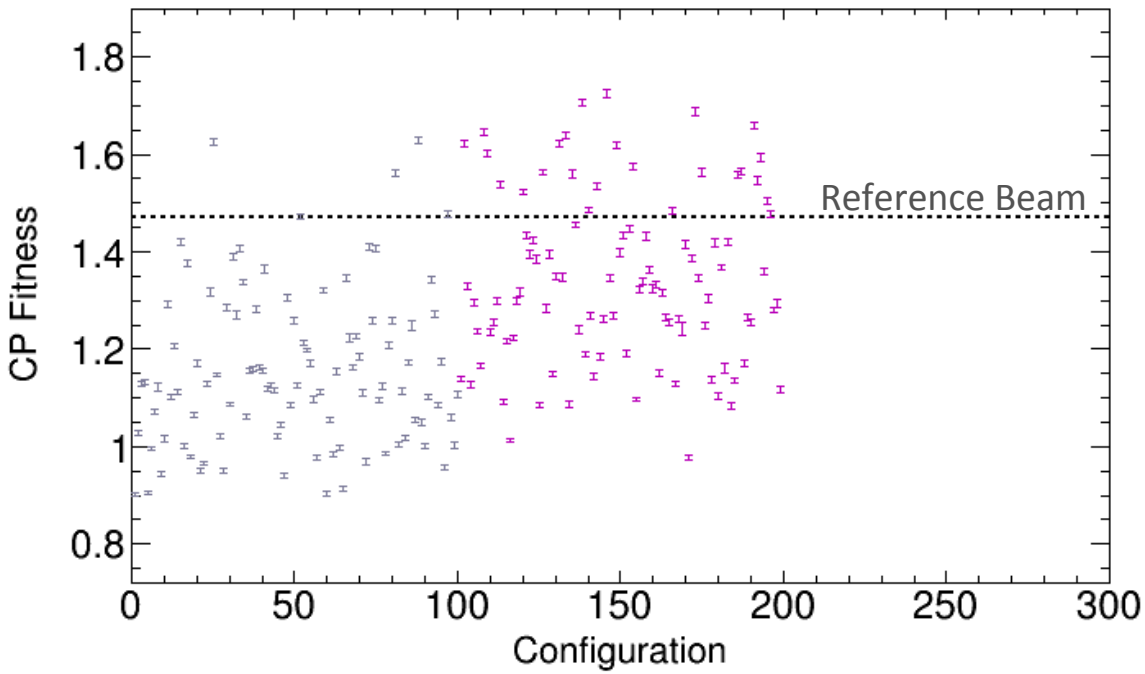
- The initial set of randomly chosen beams is generally pretty poor:



But when you take the best ones, and mix them together…

Genetic Algorithms

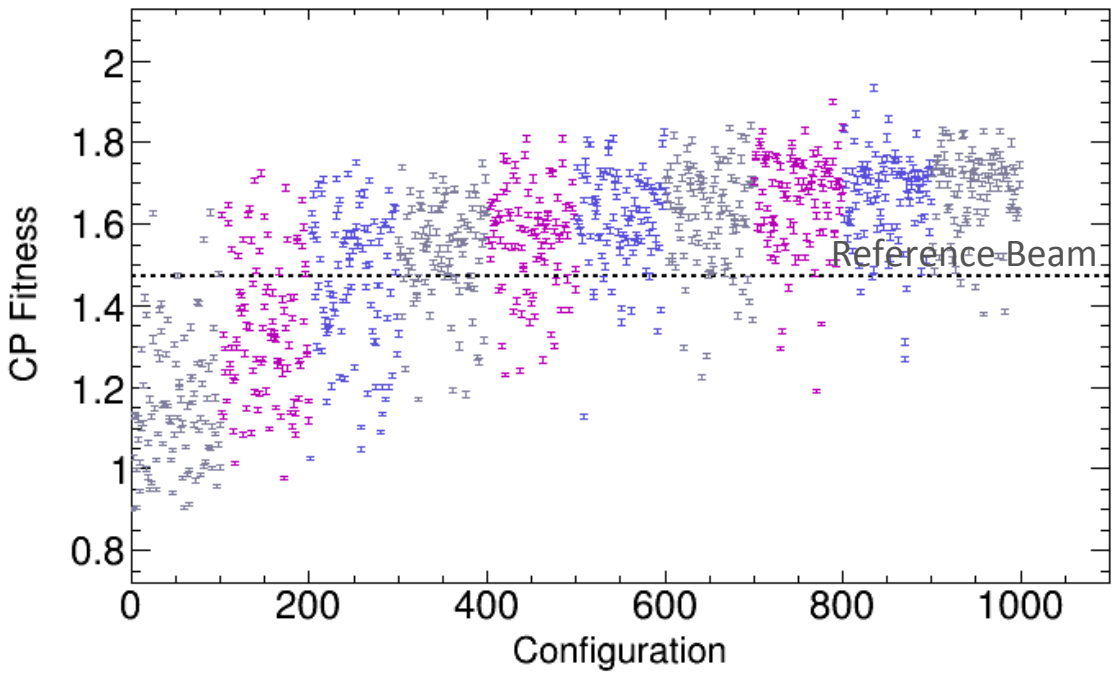
- Pretty much immediately, you start to do a lot better:



And then you repeat this survival of the fittest procedure over and over again

Genetic Algorithms

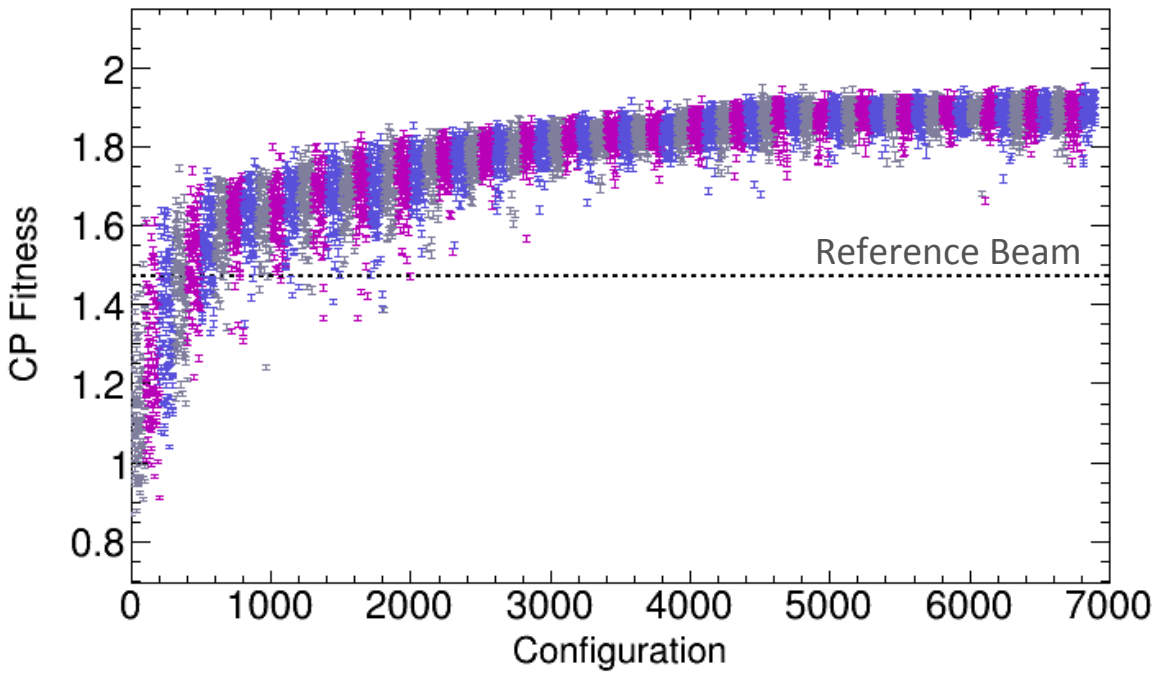
- Pretty much immediately, you start to do a lot better:



And then you repeat this survival of the fittest procedure over and over again

Genetic Algorithms

- Eventually, the algorithm converges on an optimal beam design
  - Each generation runs in parallel on the Fermigrid and takes ~ 2 hours; convergence takes a few weeks



We know that this algorithm produces good beam designs.

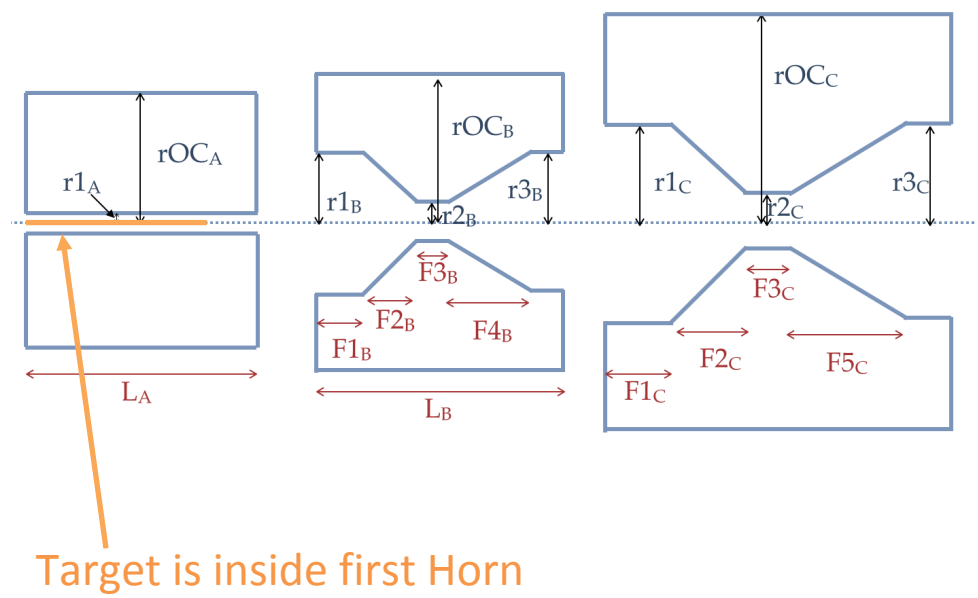
We can never know that it gave us the best possible design

Iteration with Engineers

- After a preliminary test, talk to the engineers

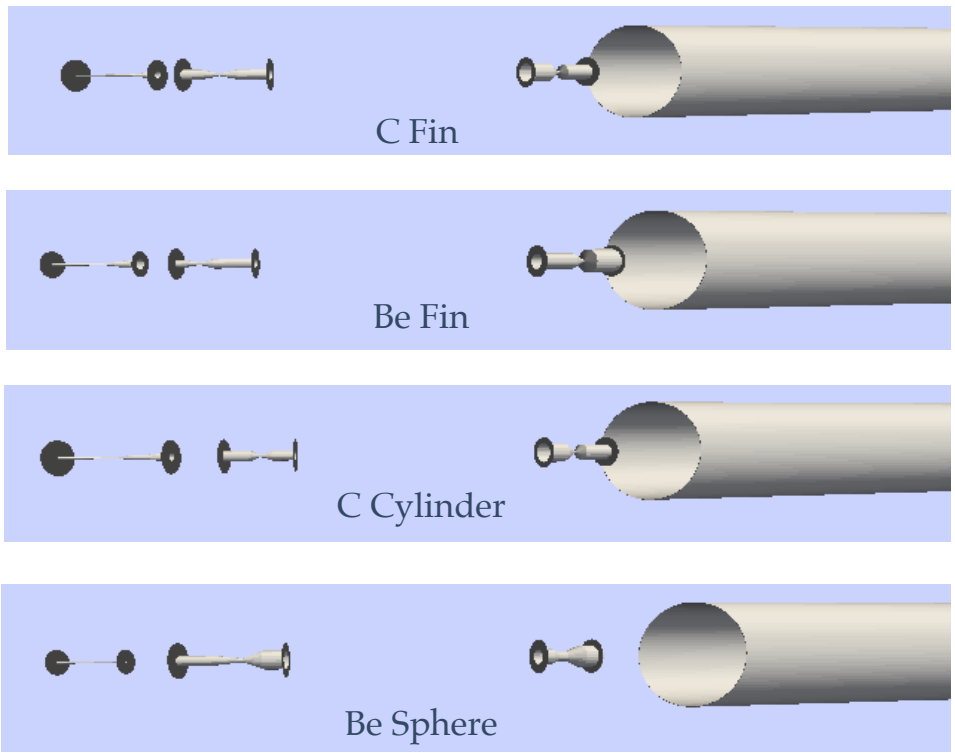
Engineering constraints considered

- Split first horn into two horns
- Target length limited to 2 m
- Horn size limited
- Horn system constrained to fit into ~21 m target chase
- Realistic inner conductor thicknesses

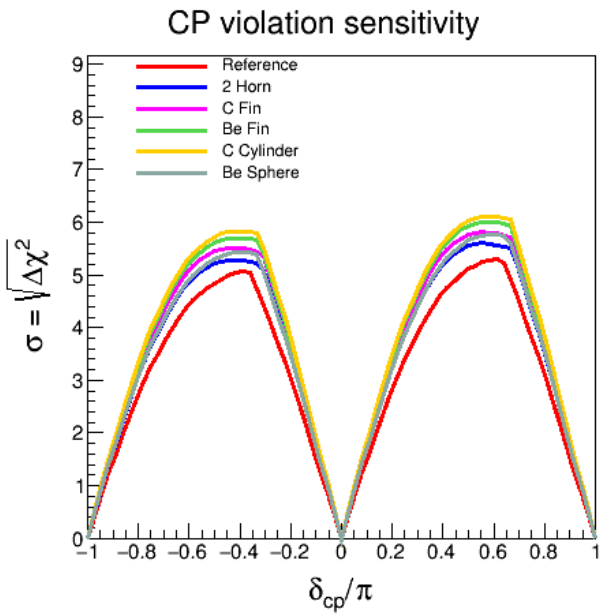


Iteration with Engineers

- Run optimizations with a several different target options:

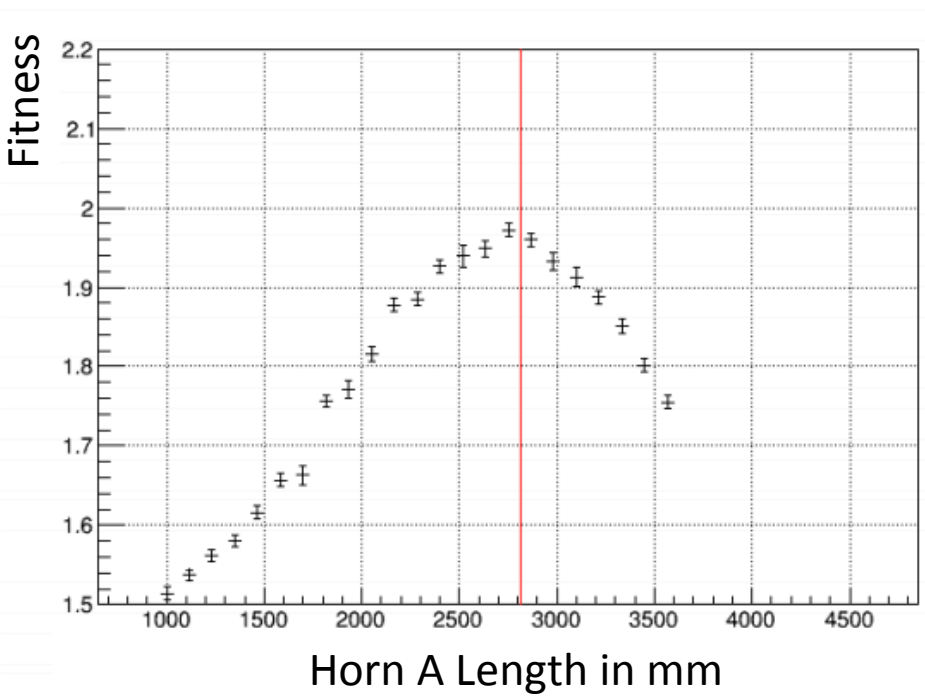


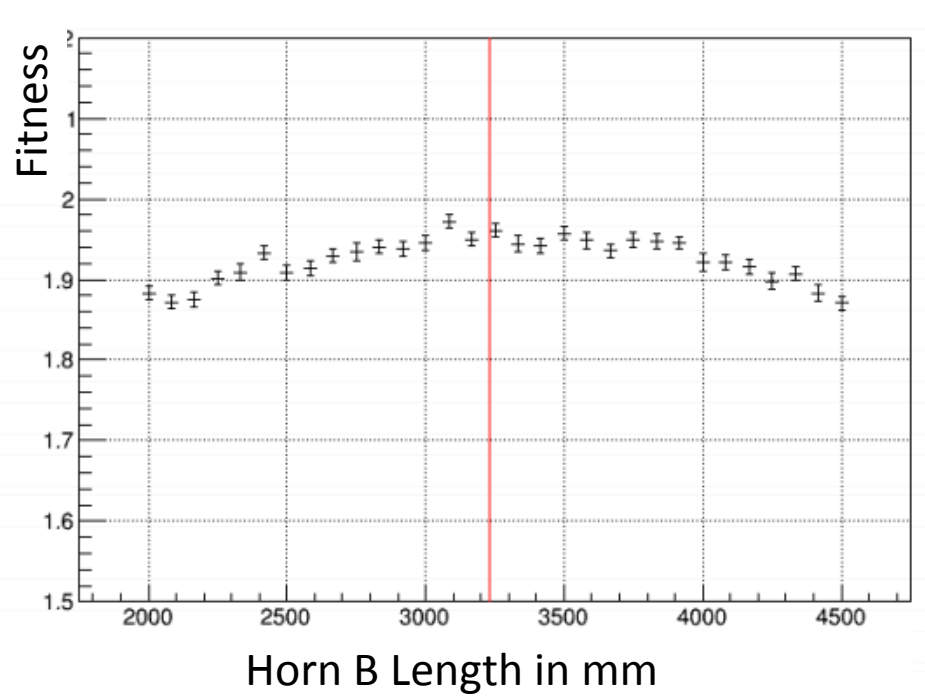
Different targets caused the optimization to find slightly different focusing systems. Some combinations are better than others, physics-wise



Iteration with Engineers

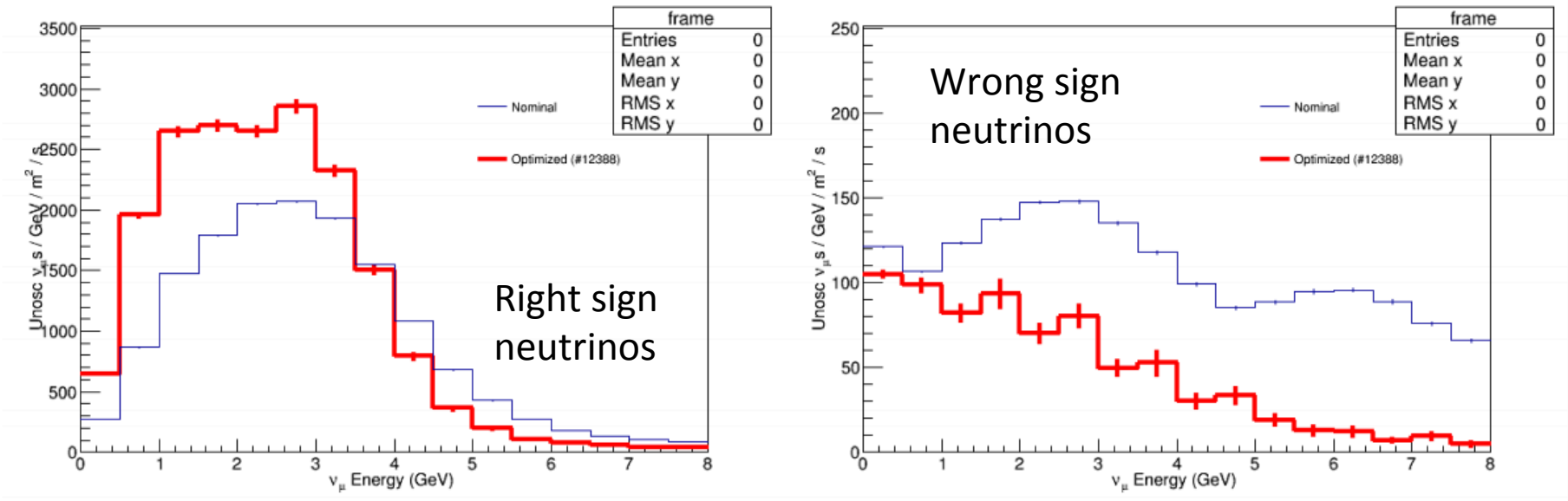
- Parameter scans help us understand





Understand what's happening

- Subdominant neutrinos matter too!



Improvements to CP-sensitivity due to both:

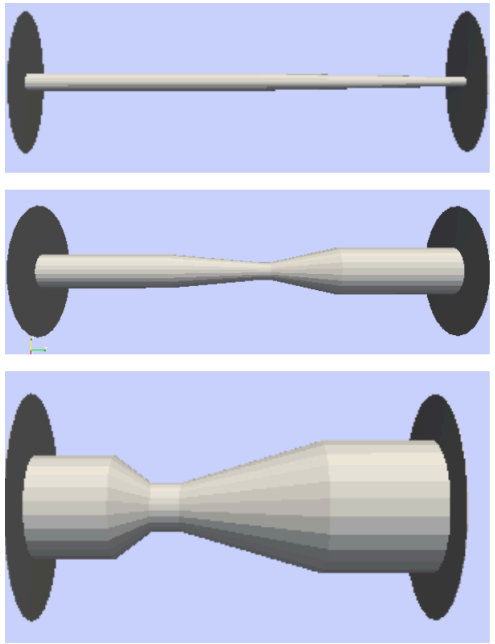
- increases muon neutrino flux
- reductions in neutrino backgrounds in antineutrino mode ("wrong-sign" backgrounds")

Final Idealized Design

- Optimized design that maximizes physics sensitivity for CP violation

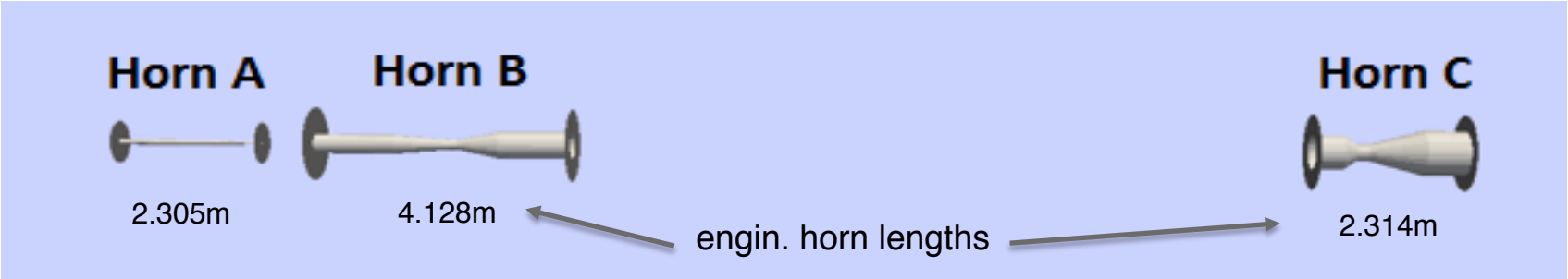
Features of final idealized design

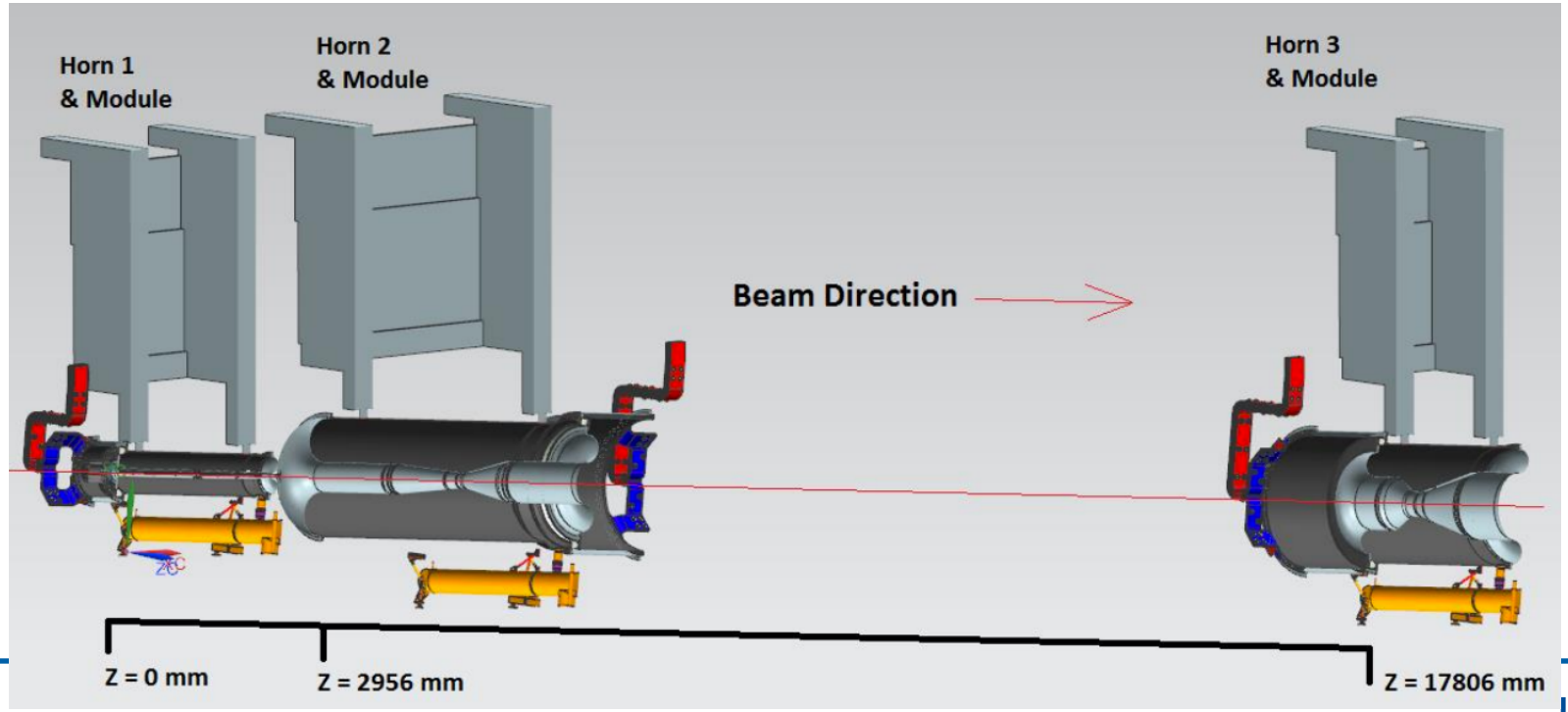
- Short first horn, slightly tapered
- Long (nearly 4 m) second horn
- Wide third horn
- 2 m long target
- 300 kA horn currents
- 120 GeV proton beam



Optimized → Engineered - Spring 2018

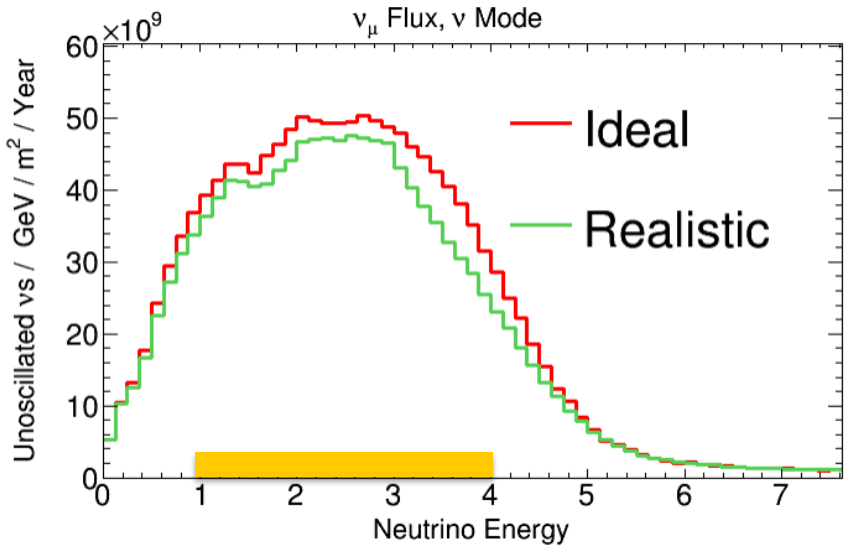
Add in the bells and whistles and flanges and pipes and supports of a real beamline
Lots of geant coding

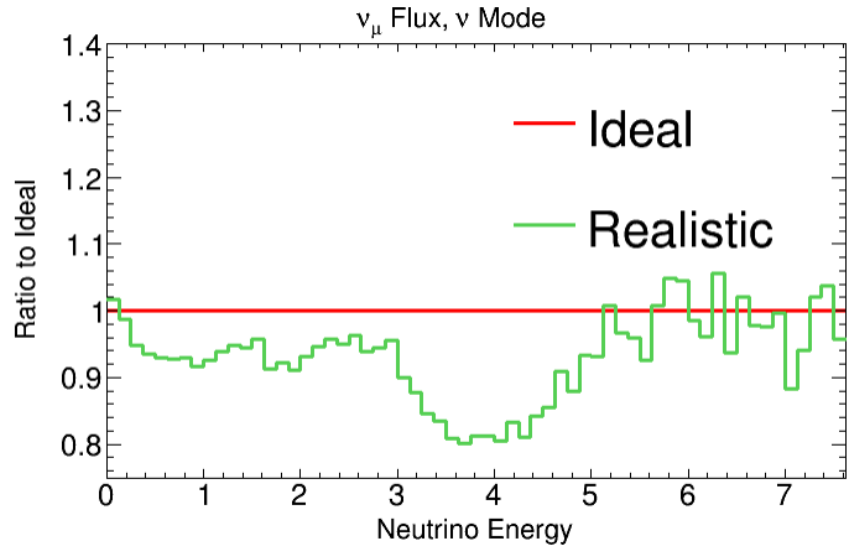




Toward Reality

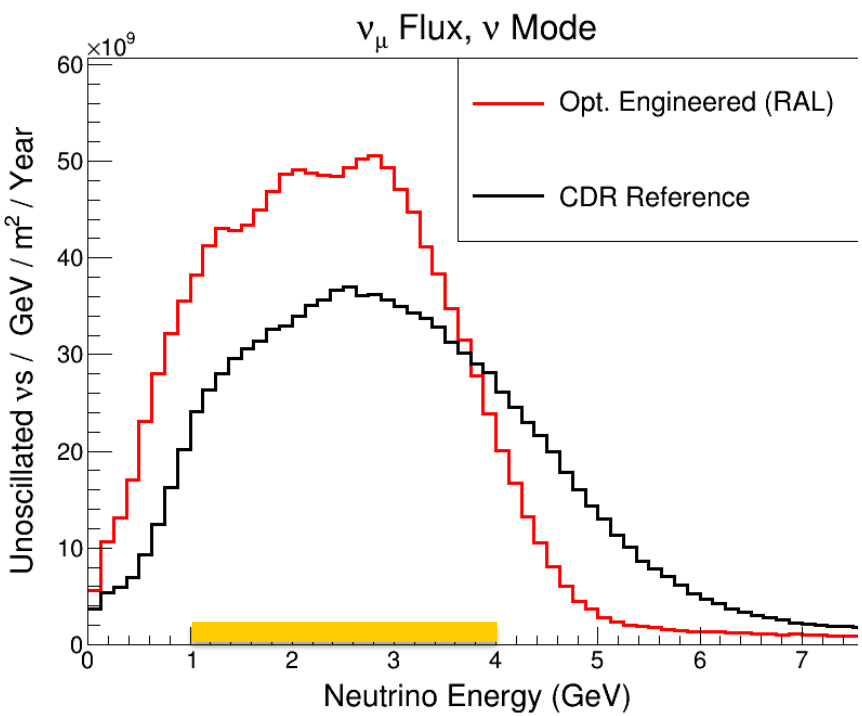
- Flux/physics changes are quite modest relative to the idealized design !

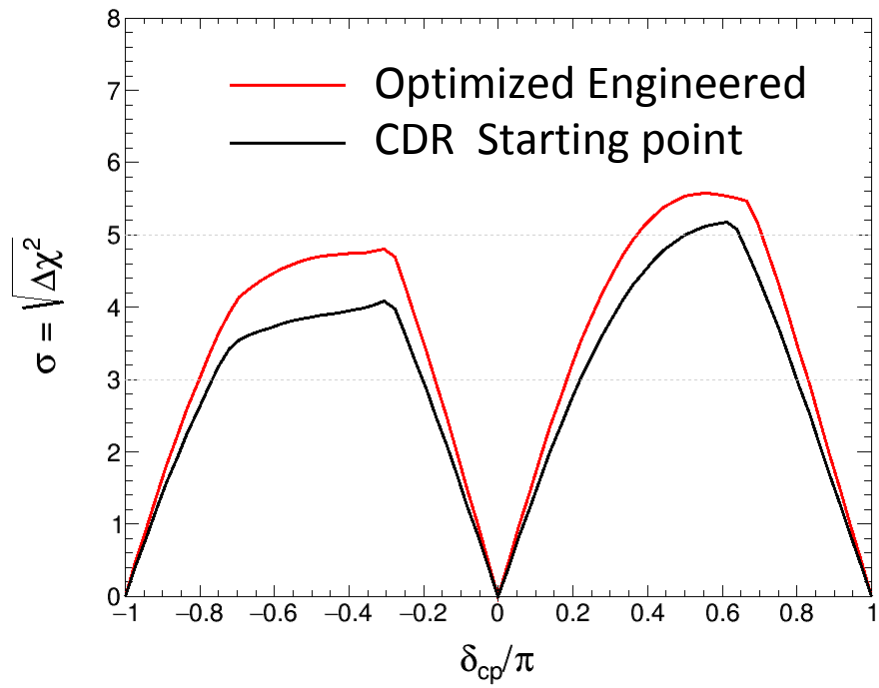




Toward Reality

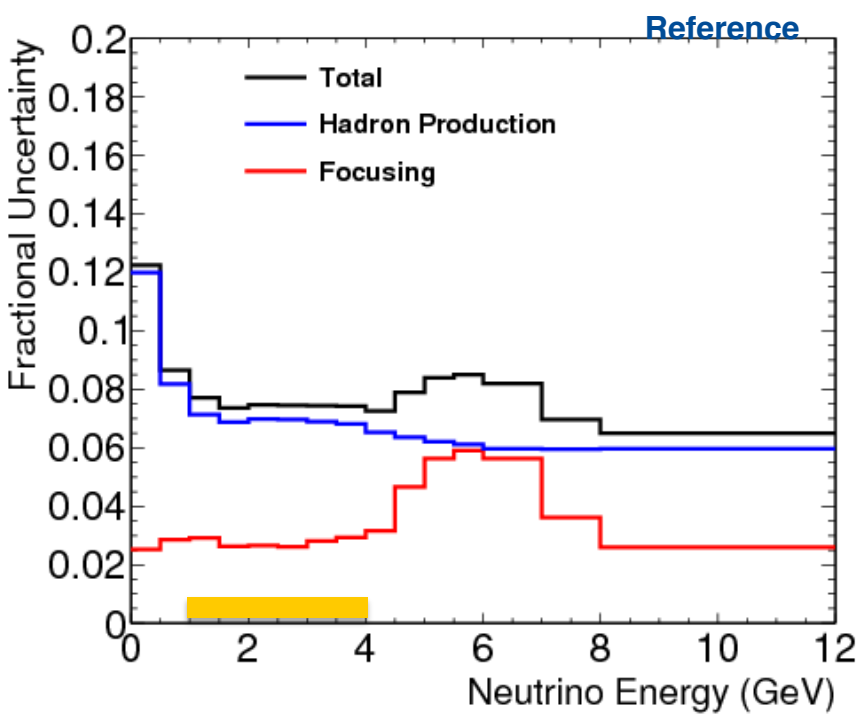
- The result of all of these iterations

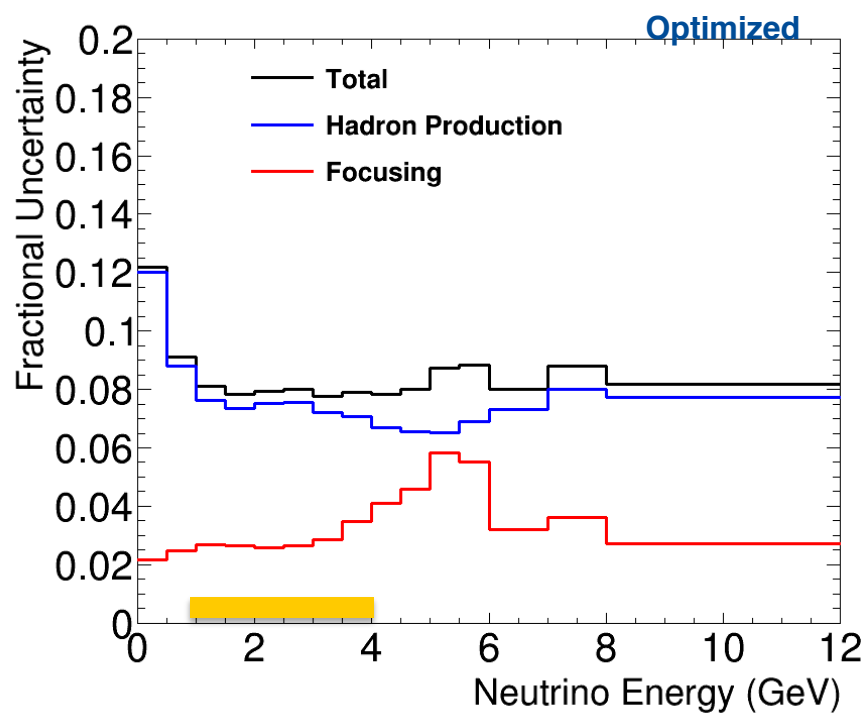




Systematic Uncertainties of Optimized Beam

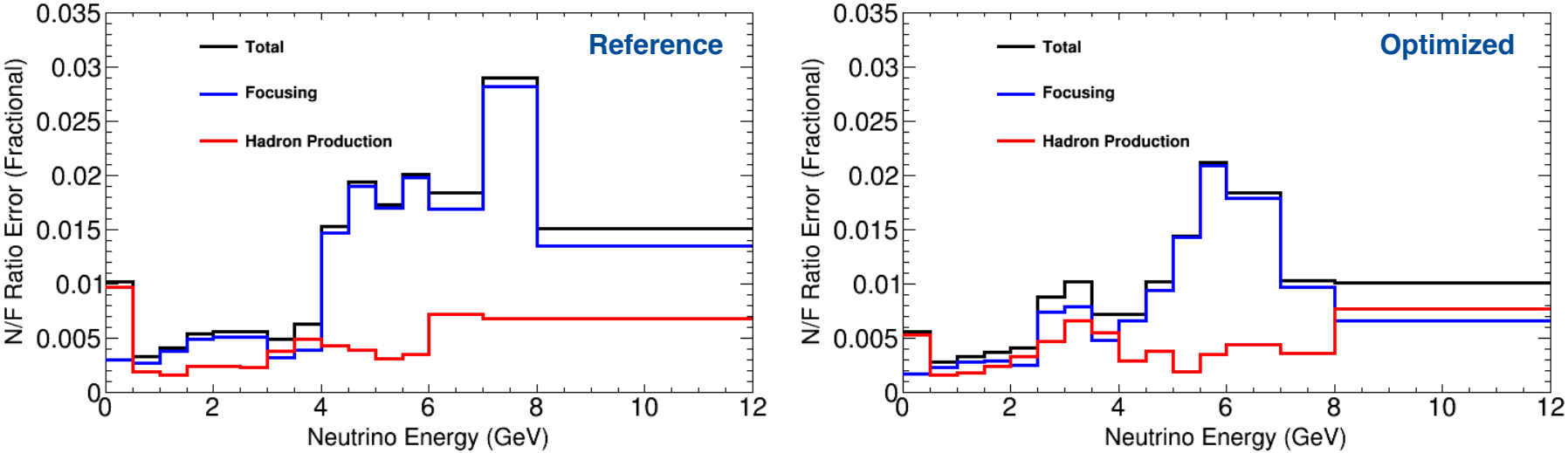
- Does a longer target make us more sensitive to systematics in hadron production models?
- Study input uncertainties on neutrino flux with optimized beam.
- Estimated using infrastructure developed by MINERvA (geant4+ppfx constraints)





Systematic Uncertainties

- Uncertainty on near/far ratio (critical to oscillation measurements) is also similar:



Next Steps

- The optimized target/horn system is currently at the level of Conceptual Design
- Proceeding to a full Preliminary Design
- Simulation needs to keep up as our final results depend on understanding the beamline as it is finally built.

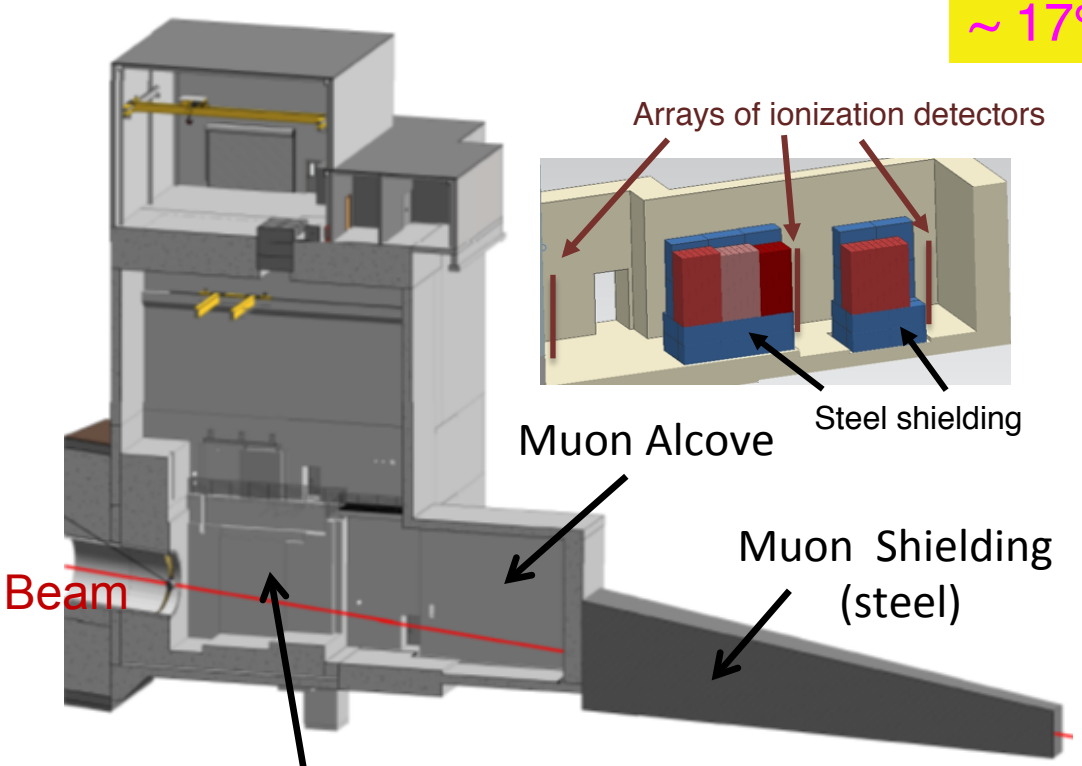
Conclusion

- The LBNF optimized design is the result of **several years of optimization and iteration** with engineers
- Final design yields **significantly better flux and sensitivity** to oscillation parameters than the Reference design
- Optimized beam is current **progressing to Preliminary design**
- **Optimization continues** for potential long term DUNE physics goals

Backups

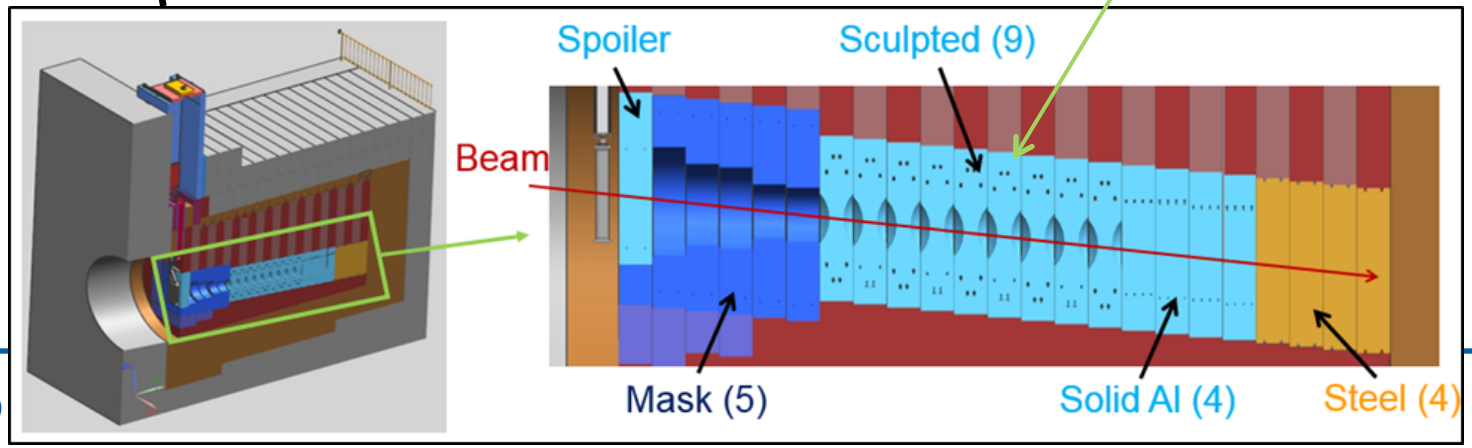
Absorber Hall Complex

The Absorber is designed for 2.4 MW
~ 17% of beam power in Absorber



Absorber Cooling
Core: water-cooled
Shielding: forced air-cooled

- Flexible, modular design with replaceable core blocks
- More uniform absorber design under study



Decay Pipe

- 194 m long, 4 m inside diameter
- Double-wall, carbon steel decay pipe, with 20 cm annular gap for cooling
- Helium filled
- Nitrogen cooled
- 5.6 m thick concrete shielding
- Geomembrane barrier system
- It collects ~23% of the beam power, removed by the nitrogen cooling system

Decay Pipe Cross Section