Optimization of the LBNF Neutrino Beam

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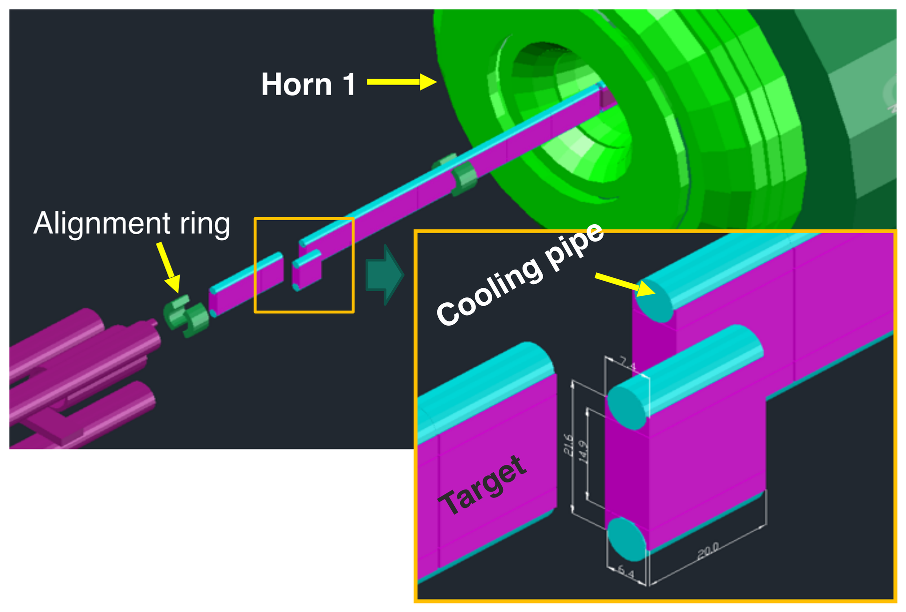
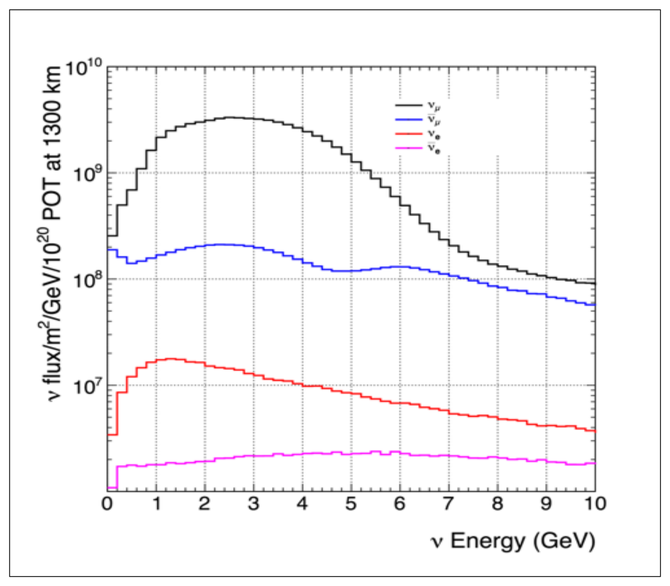
Reference Design

The LBNF neutrino beam will send neutrinos from Fermilab in Illinois to the DUNE detectors in the Stanford Underground Research Facility (SURF) in South Dakota. The current reference design is based heavily on the very successful NuMI beamline at Fermilab. It will use 60-120 GeV protons from the Main Injector that will impinge in a graphite target similar to the NuMI target but modified to accommodate a 1.2 MW proton beam. Resulting pions and kaons will be focused through a pair of focusing horns identical to those used in NuMI and allowed to decay in a 194 m long, 4 m diameter decay pipe.

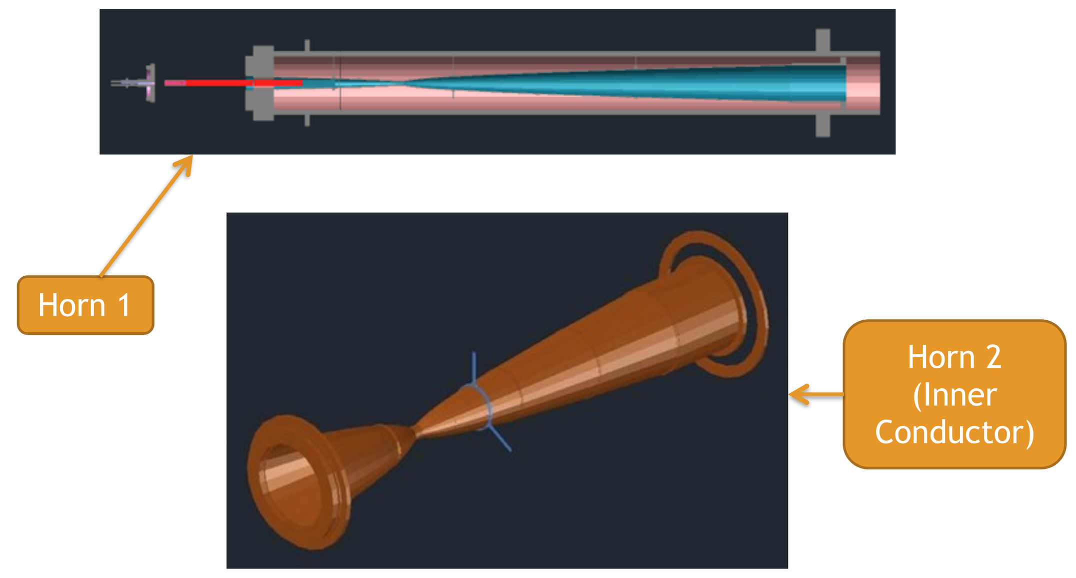
Target





Estimated DUNE neutrino fluxes when horn currents are configured to focus positively charged hadrons

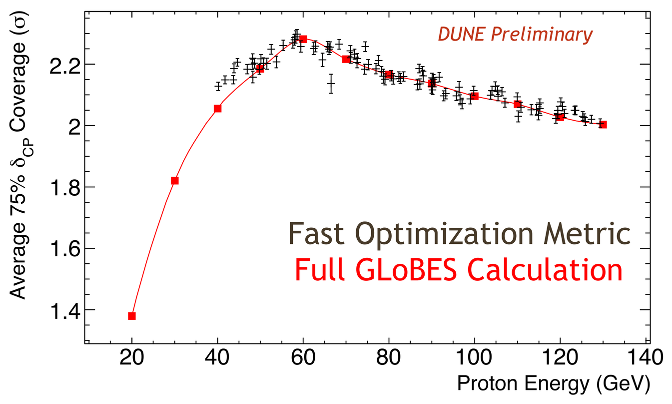
Focusing Horns



Optimization Algorithm

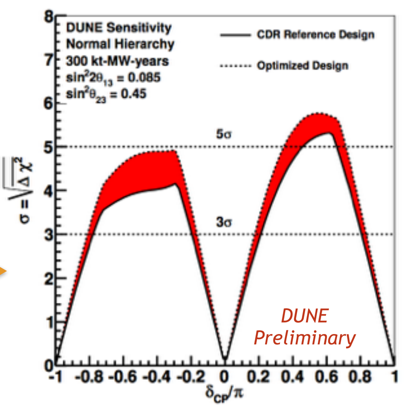
Goals and Criteria

Neutrino beams have historically been designed to produce maximal flux over a specified energy region; Modern computing techniques now allow optimization of beam designs for physics goals.



Optimization metric for the reference beam operated at a variety of primary proton beam momentum.

DUNE's sensitivity to CP violation as a function of δ_{CP} for an exposure of 300 kT•MW•years assuming a normal mass hierarchy

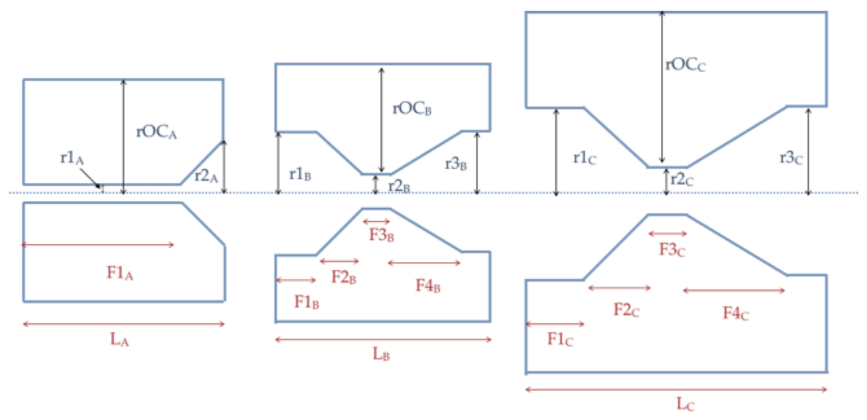


Our Optimization Metric: The value on the y axis that is below 75% of the curve for a particular beam.

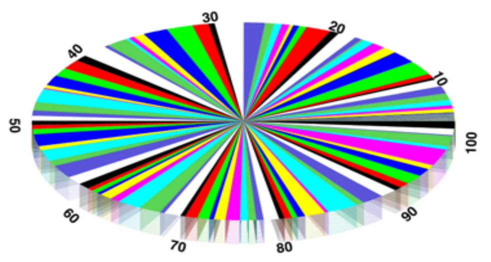
One of DUNE's most important physics goals is searching for CP violation in the lepton sector by measuring neutrino mixing parameter δ_{CP}. We have developed a fast estimator for δ_{CP} sensitivity that transforms flux to estimated sensitivity in a few seconds.

Genetic Algorithm

We have identified optimal beam designs using a genetic algorithm, which begins by simulating a sample of beams with randomly chosen parameters



Parameters varied in the optimization include horn size and shape, target dimensions, horn currents and primary proton beam size and momentum

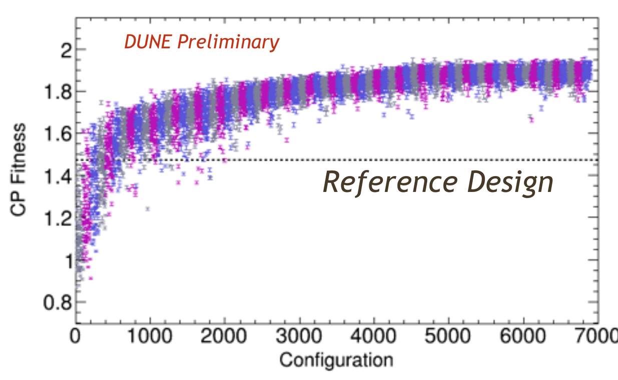


The best of the random beams are identified via a roulette wheel with the area of a beam proportional to the optimization metric (CP sensitivity) of that beam

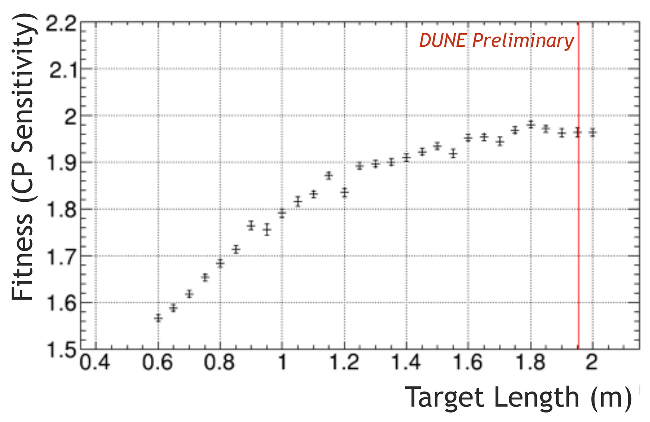
The best beams are "mated" together to form new beam designs

Evolution of Optimization Metric

The physics performance of the first "generation" of beams is generally poor, but as the mating process is repeated, the beam designs rapidly improve



Eventually, the parameters of the optimization stop changing, and the optimization converges to an optimal beam design

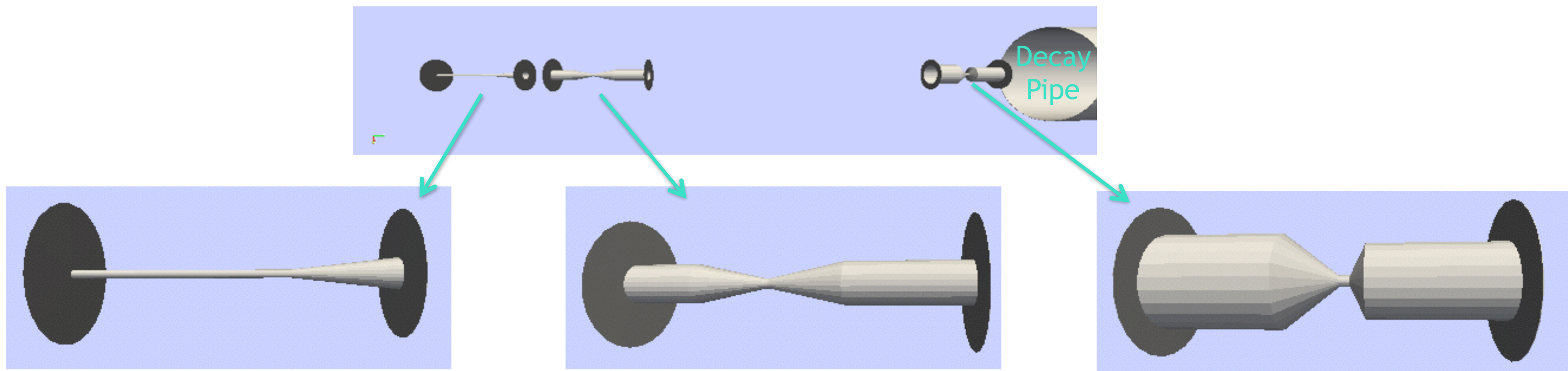


Parameter scans around the optimal design help us understand which parameters of the optimization are most important. Here we see that a long target (> 1.7 m) maximizes CP sensitivity.

Results

Optimized Design

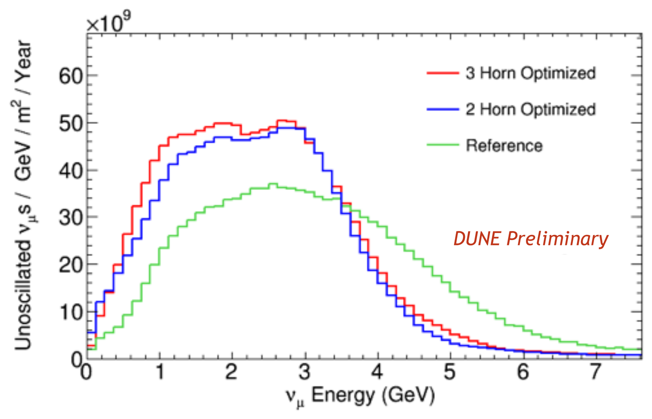
The best beam design identified to date includes three focusing horns that are substantially different than the NuMI horns, with higher horn currents. The optimized target is 2m (~2 times the length of the reference target).

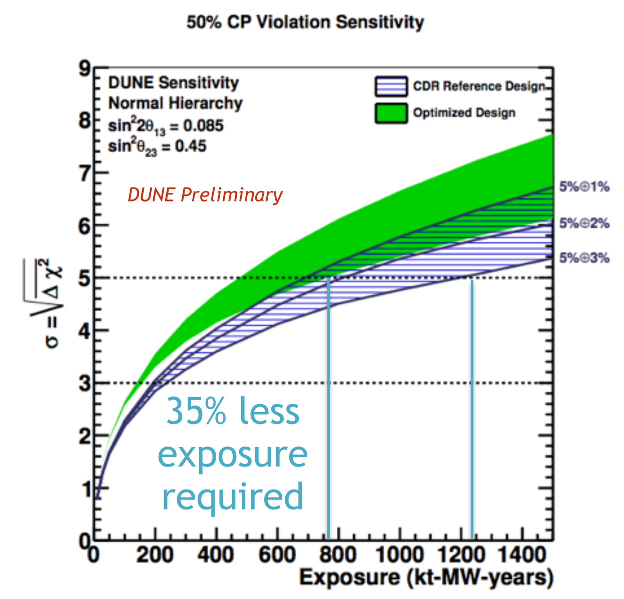


Physics Capabilities

Simulations show that the optimized beam design produces 44% more muon neutrino flux between 0.5 and 4 GeV while also decreasing wrong-sign neutrino contamination. These changes lead to substantial improvements in sensitivity to CP violation, and other physics deliverables such as the mass hierarchy.

Muon neutrino flux in the reference and in two versions of the optimized beam

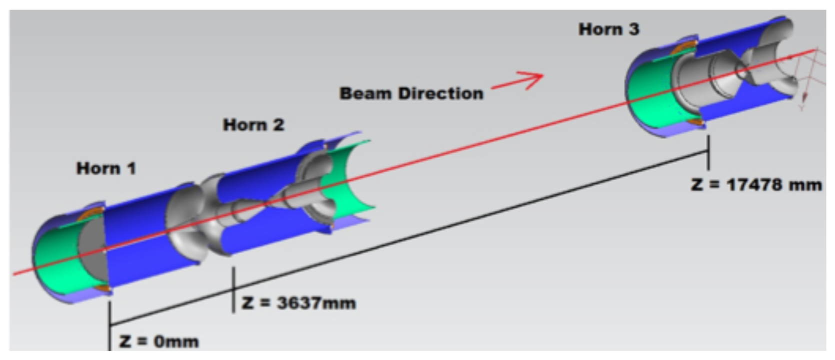




CP sensitivity for 50% of the values of as a function of exposure for the reference and 2-horn optimized design)

Future Plans

Mechanical design of the three-horn optimized design Figure courtesy Cory Crowley (FNAL).



LBNF Optimization work is shifting from development of optimization algorithms to engineering studies of optimized options. New optimization algorithms, such as "particle swarm" algorithms are also being developed to speed up iteration with engineers

The effect of target design on physics performance is also being studied. In addition to the graphite-fin style target of NuMI, other targets under consideration include Helium-cooled cylinders and sphere arrays, as well as targets that incorporate high-z materials at the downstream end.