The LBNF Beam Optimization

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The LBNF Beam Optimization

- US/Fermilab program context
- LBNF and the DUNE experiment
- Goals of the LBNF beam
- Overview of the planned facility
- Beam optimization efforts
- Conclusions

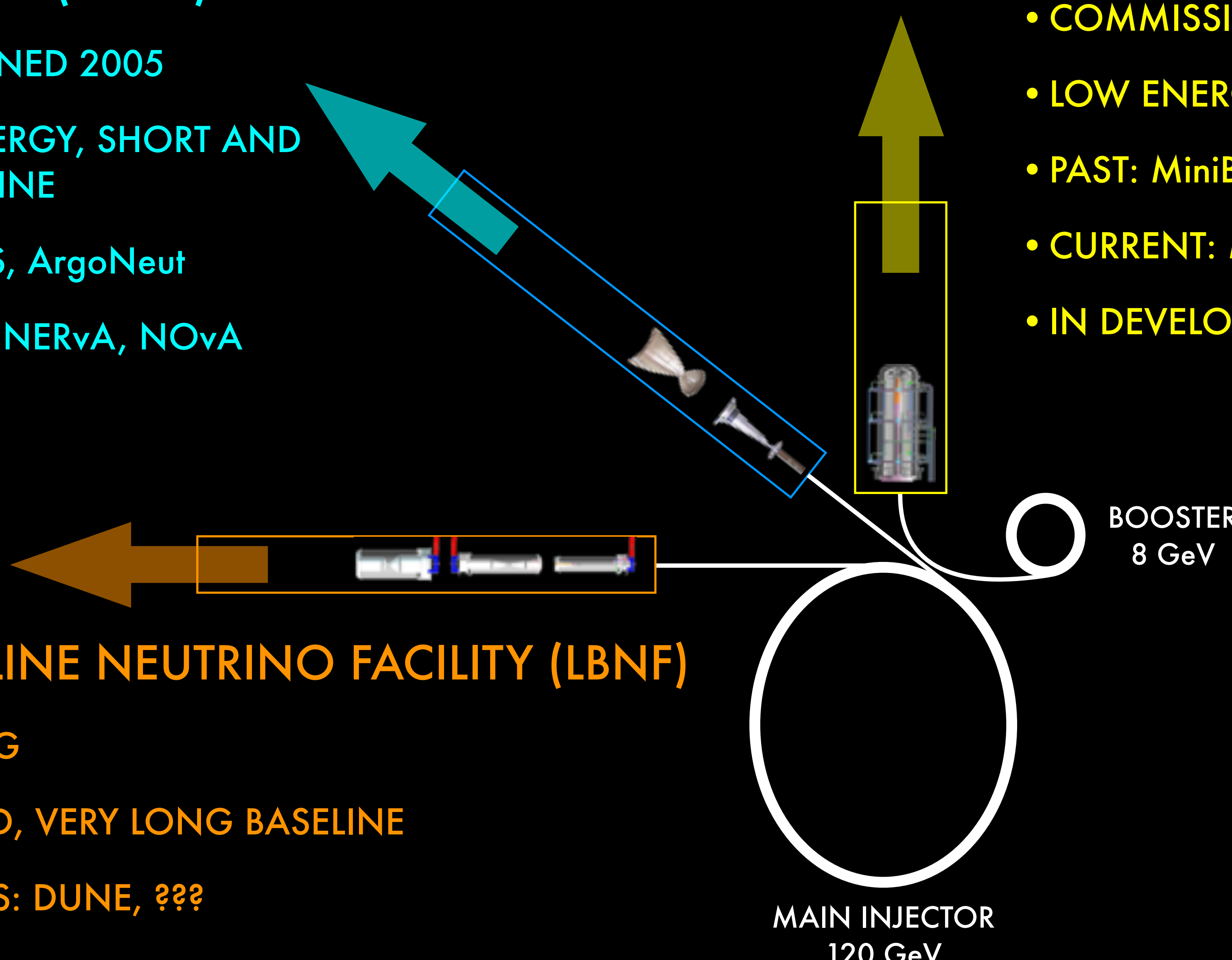
Fermilab neutrino beam facilities

NEUTRINOS AT THE MAIN INJECTOR (NuMI)

- COMMISSIONED 2005
- MEDIUM ENERGY, SHORT AND LONG BASELINE
- PAST: MINOS, ArgoNeut
- CURRENT: MINERvA, NOvA

BOOSTER NEUTRINO BEAM (BNB)

- COMMISSIONED 2002
- LOW ENERGY, SHORT BASELINE
- PAST: MiniBooNE, SciBooNE
- CURRENT: MicroBooNE
- IN DEVELOPMENT: SBND, ICARUS



LONG-BASELINE NEUTRINO FACILITY (LBNF)

- IN PLANNING
- BROAD BAND, VERY LONG BASELINE
- EXPERIMENTS: DUNE, ???

LBNF and the DUNE experiment

- DUNE experiment, and potentially others, will use Fermilab's Long Baseline Neutrino Facility (LBNF)

- US DOE project LBNF consists of:
  - Neutrino beam at Fermilab
  - Near detector hall at Fermilab
  - Underground infrastructure at Homestake lab
- Major partners include CERN, Sanford Underground Research Facility, Rutherford Appleton Lab/STFC

Goals of the LBNF beam

- Provide a very intense broad-band ν_μ ($\overline{\nu}_\mu$) beam between ~0.5 and ~4 GeV with minimal ν_e ($\overline{\nu}_e$) contamination. This energy range should span the first and second oscillation maxima associated with Δm^2_{23}.
- Accommodate primary beam power up to 1.2 MW, energy 60-120 GeV, at first
- Make sure non-replaceable parts are designed to handle a maximum eventual power of 2.4 MW

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

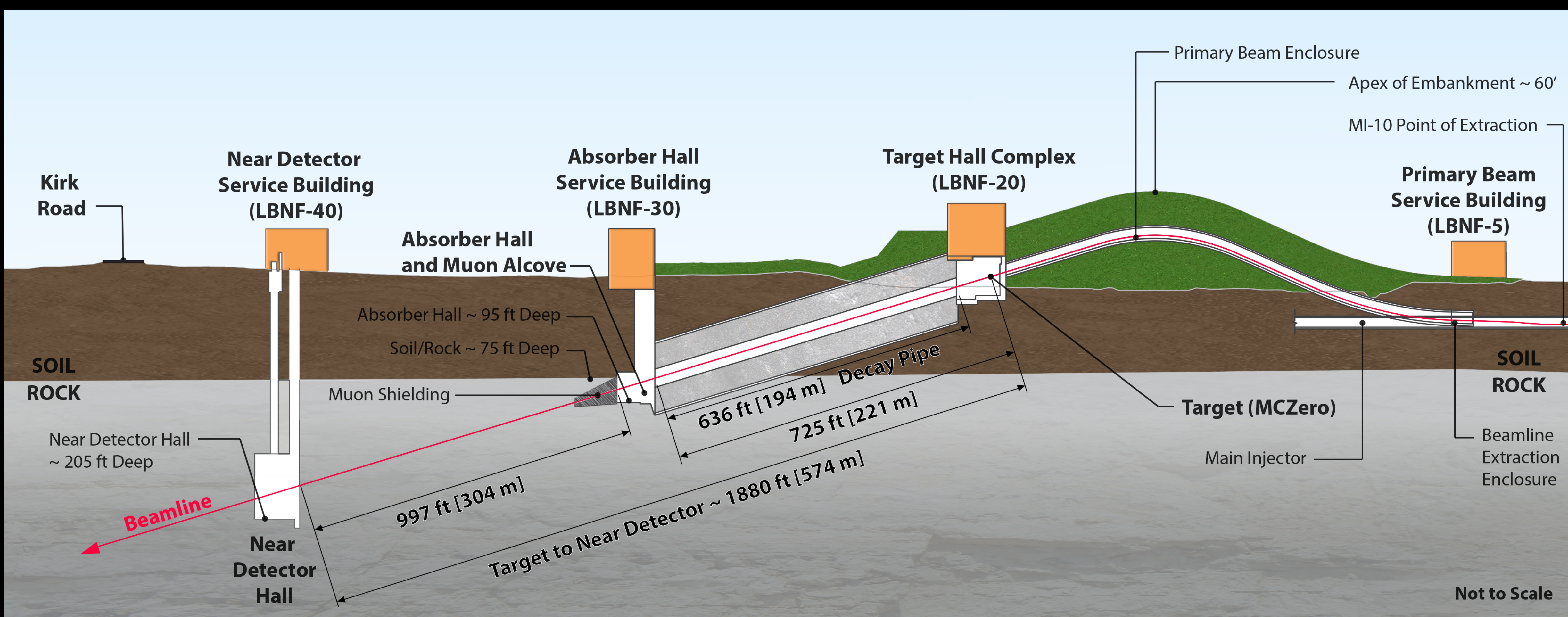
Goals of the LBNF beam

Parts being designed for 2.4 MW (good proxy for "parts that are very hard to replace once installed"):

- Size of enclosures (primary proton beamline, target chase, target hall, decay pipe, absorber hall)
- Radiological shielding of enclosures (except for the roof of the target hall, which can be upgraded when needed)
- Primary beamline components
- The water cooled target chase cooling panels
- The decay pipe, its cooling, and the decay pipe downstream window
- Beam absorber
- Remote handling equipment
- Radioactive water system piping
- Horn support structures designed for lifetime of facility

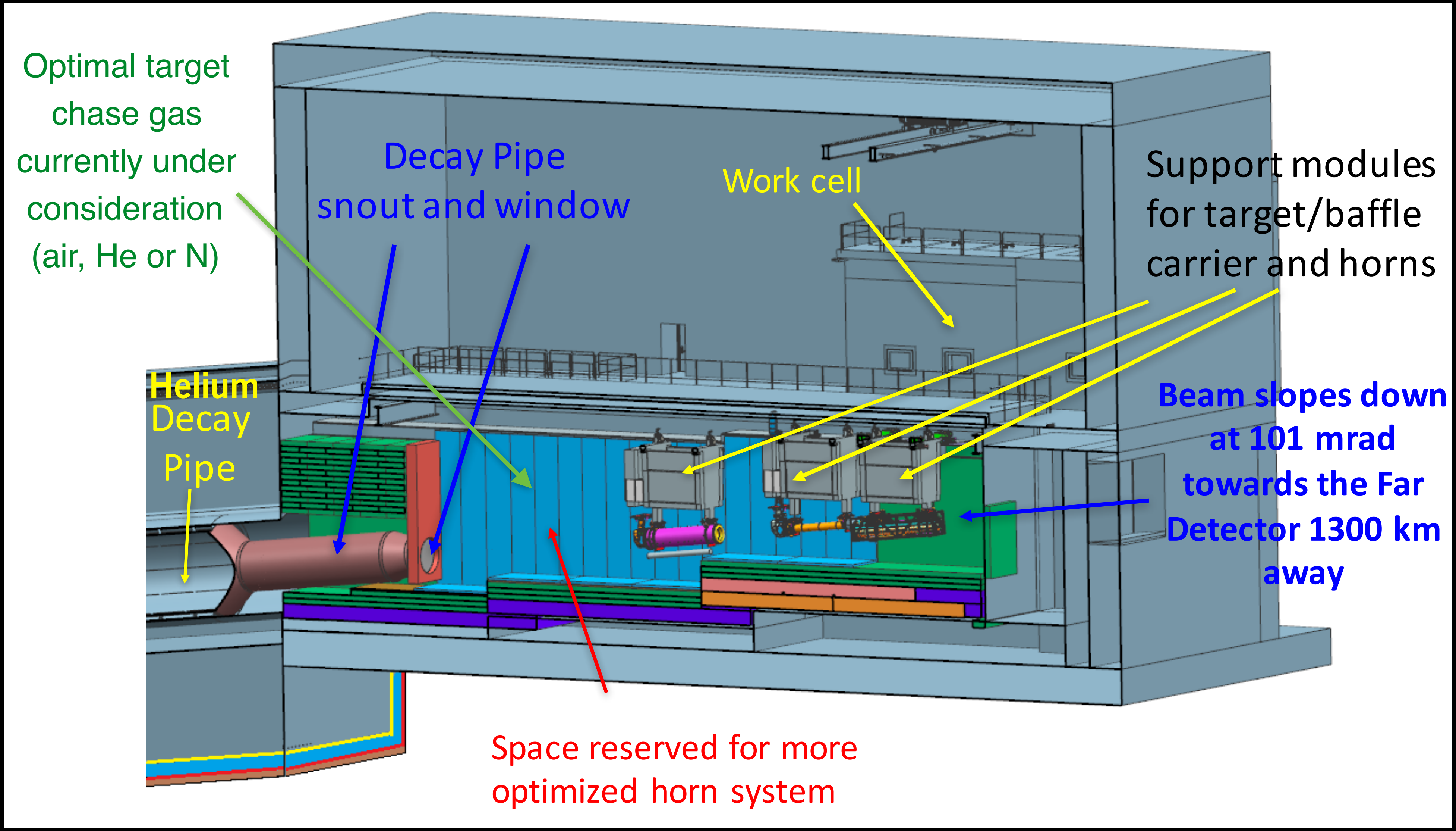
LBNF beam “Reference Design”

- “Hill” design of civil construction
- Avoids excessive excavation in rock, radiation in ground water (tritium)



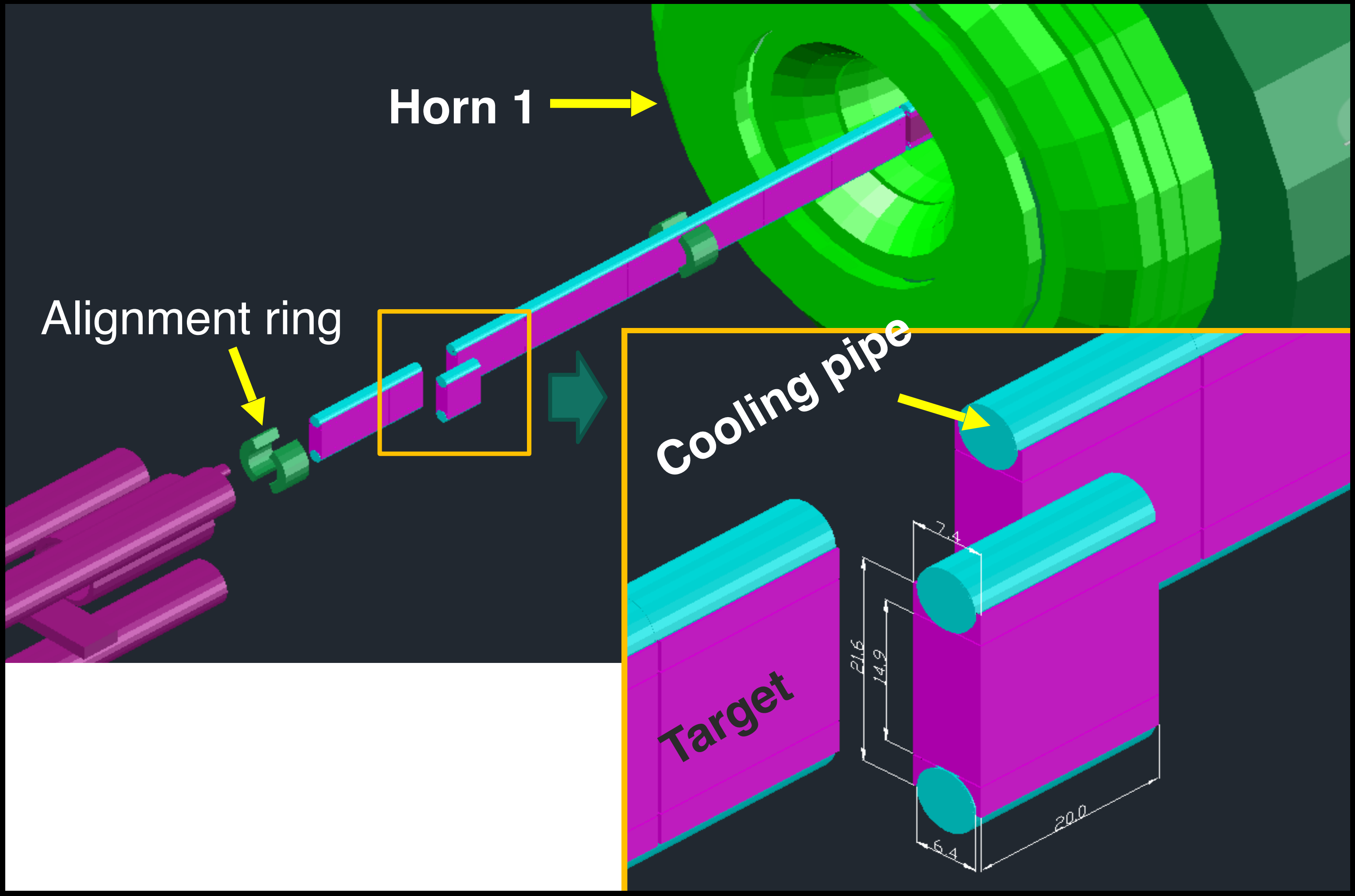
LBNF beam "Reference Design"

- Initial engineering work on LBNF beam has been based on an evolution of the 2-horn NuMI design: this has resulted in the "reference design" for LBNF



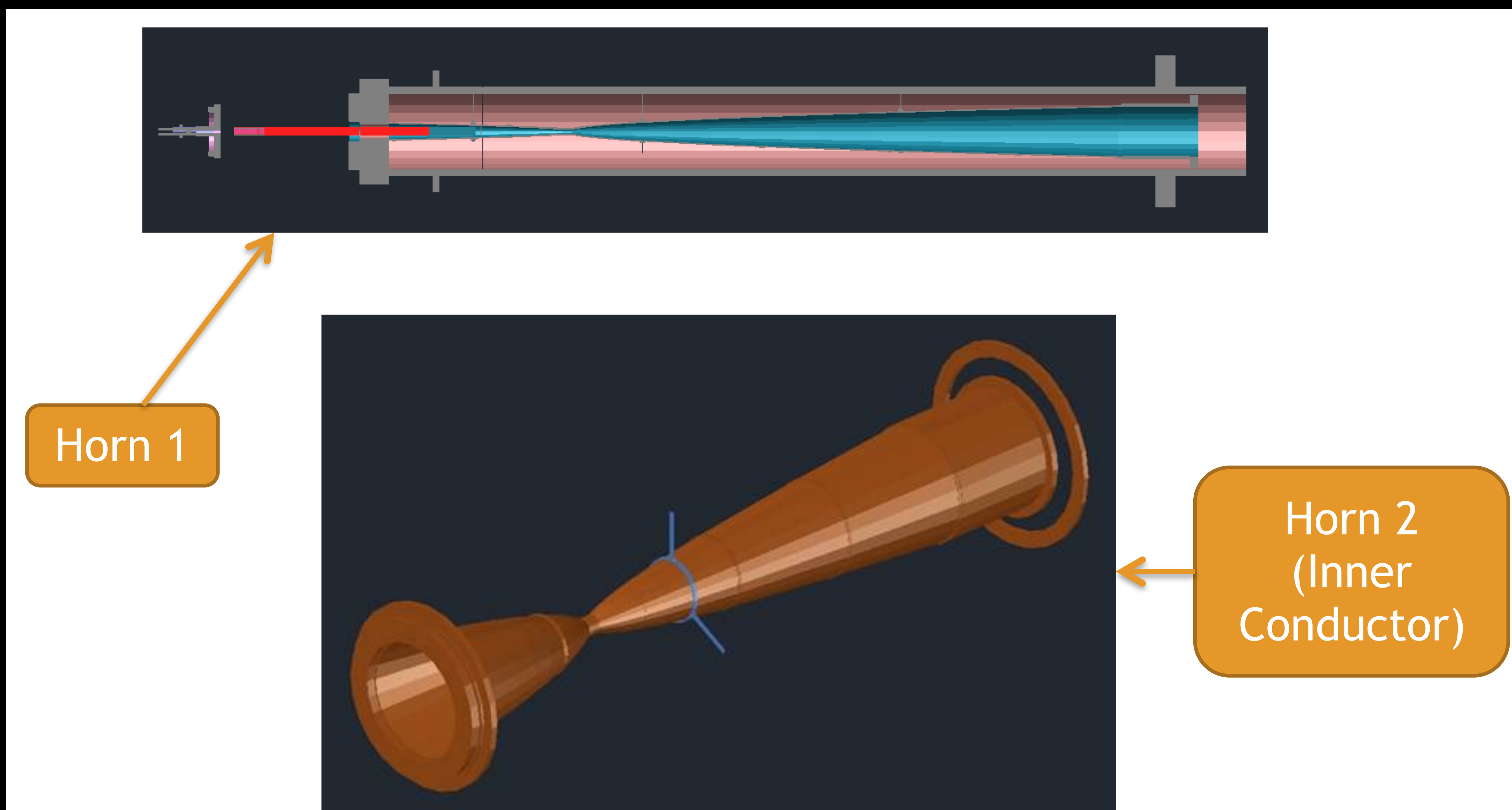
LBNF beam "Reference Design"

- Target design is NuMI-inspired: "flat" with water cooling tubes, partially inserted into Horn 1
- Material: segmented graphite, 950mm total length



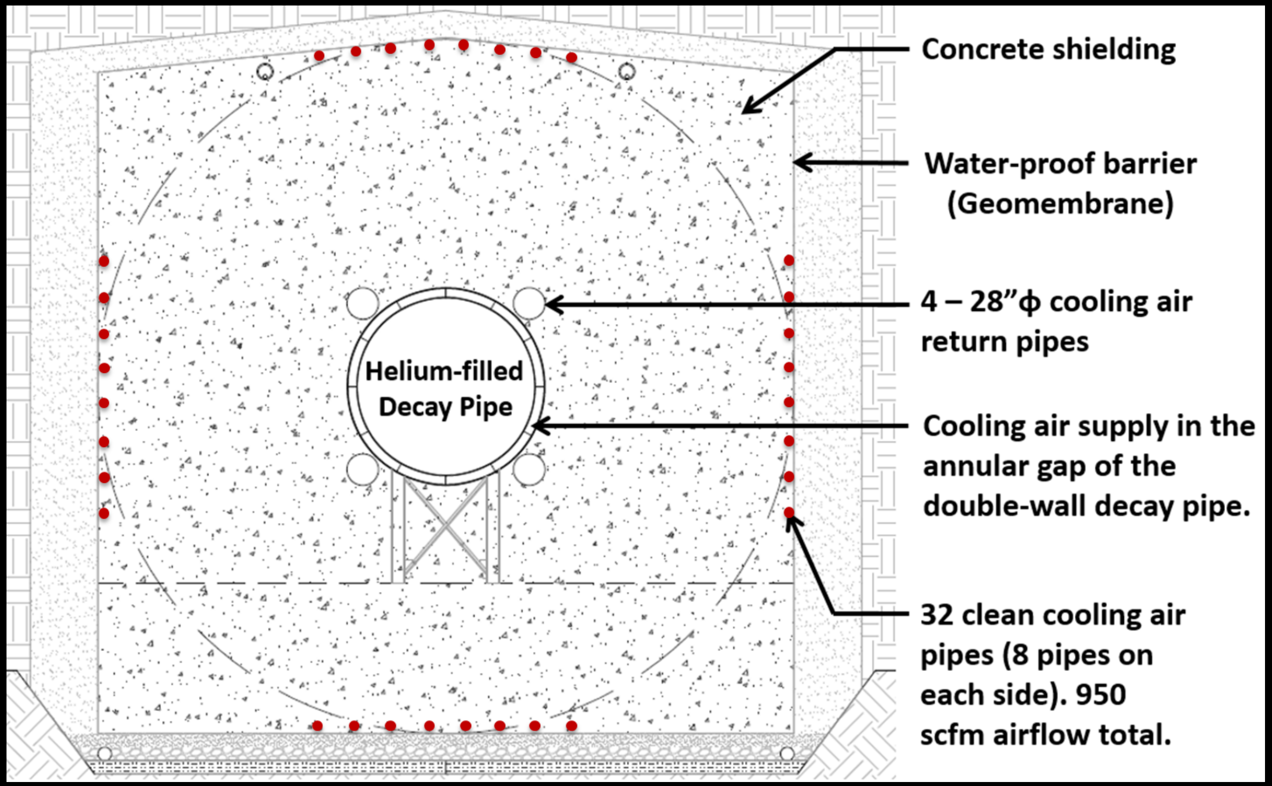
LBNF beam "Reference Design"

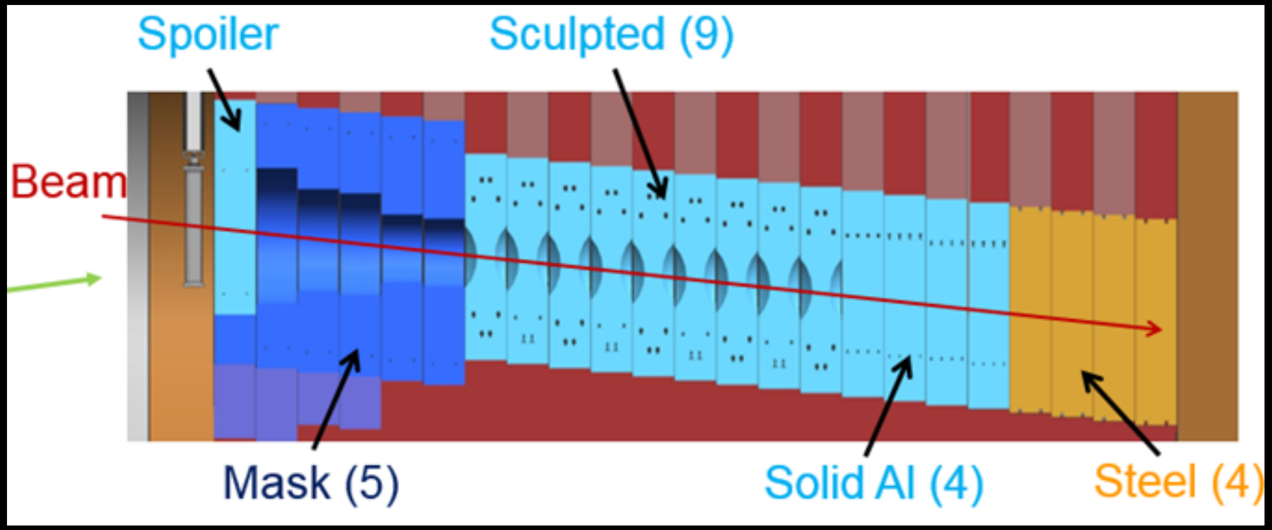
- Horns are basically NuMI's design, with slight modifications to operate at 230 kA and with a reduced pulse width of 0.8 ms



LBNF beam "Reference Design"

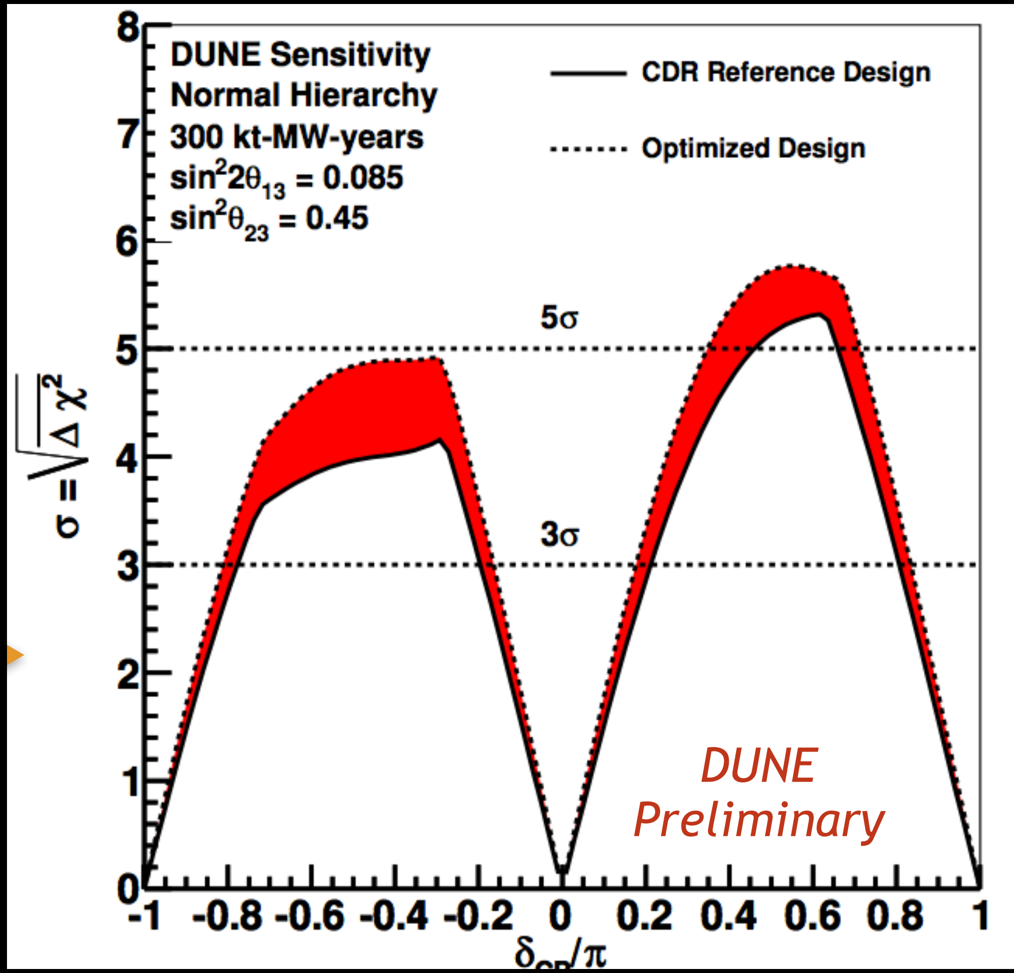
- **Downstream of horns, design differs greatly from NuMI!**
- Decay pipe:
  - 194 m long, 4 m diameter
  - Helium-filled
  - Air-cooled
- Absorber:
  - Receives 30% of primary beam energy
  - "Spoiler" scatters, spreads out energy deposition
  - Core of replaceable water-cooled aluminum blocks 12 inches thick
  - Surrounded by air-cooled steel and concrete shielding
  - Designed to handle steady-state operations and accident conditions at 2.4 MW beam power, 60-120 GeV primary proton energy





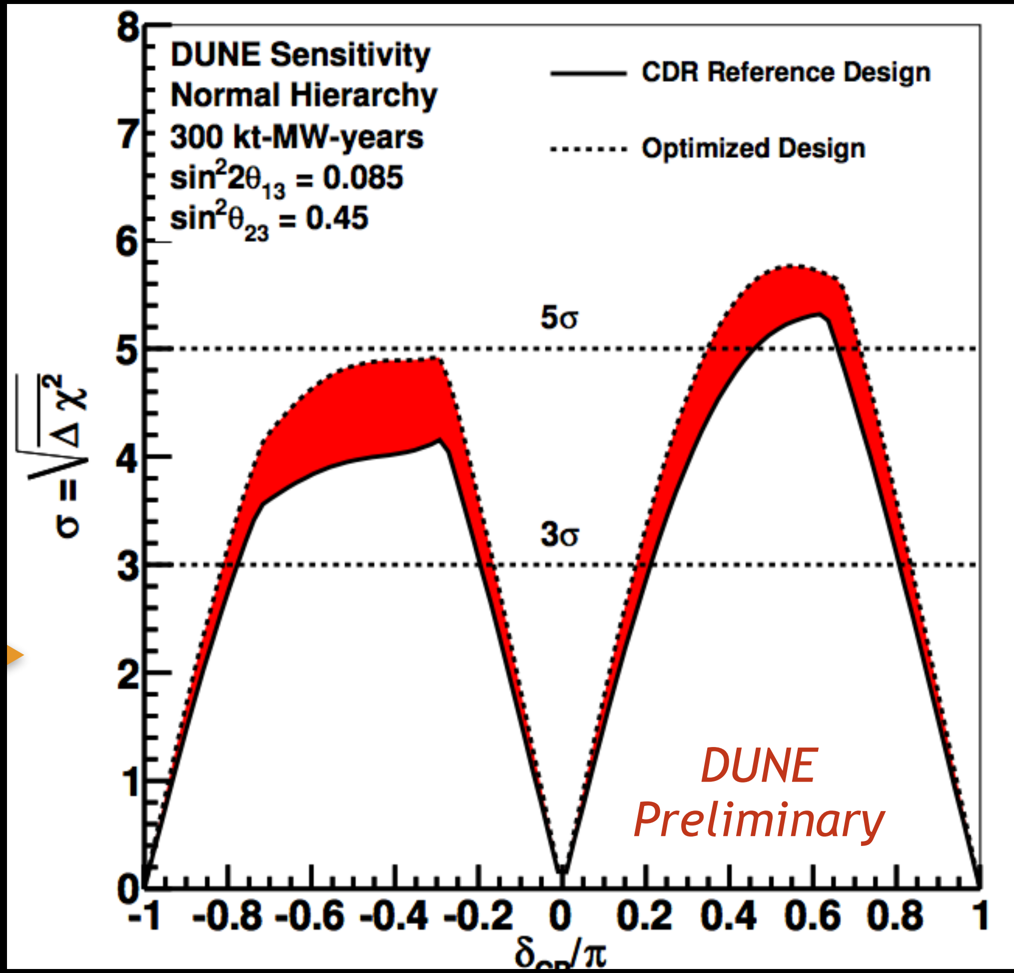
Optimizing for better physics

- Modern computing resources allow optimization of beam geometry based on physics-derived figures of merit
- New effort to redesign beam based directly on sensitivity to CP violation
- Figure of merit is the sensitivity (in σ) reached over 75% of the range of δ_{CP} with 300 kt·MW·yr operation



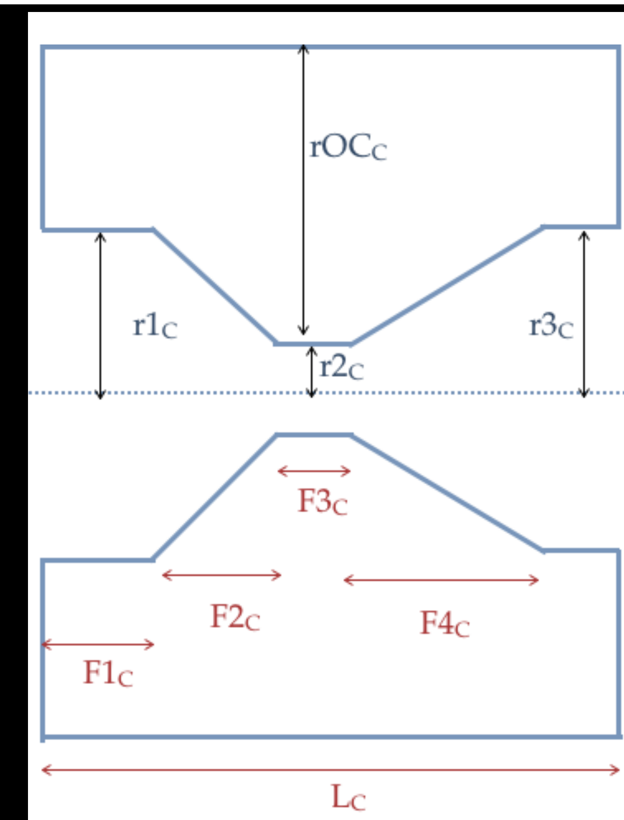
Optimizing for better physics

- Allows us to optimize beam based on physics sensitivity, simultaneously considering all aspects of the flux, including:
  - Relative importance of flux at first and second oscillation maxima
  - Wrong-flavor backgrounds (ν_e)
  - Wrong-sign backgrounds
  - Feed-down background from high-energy flux



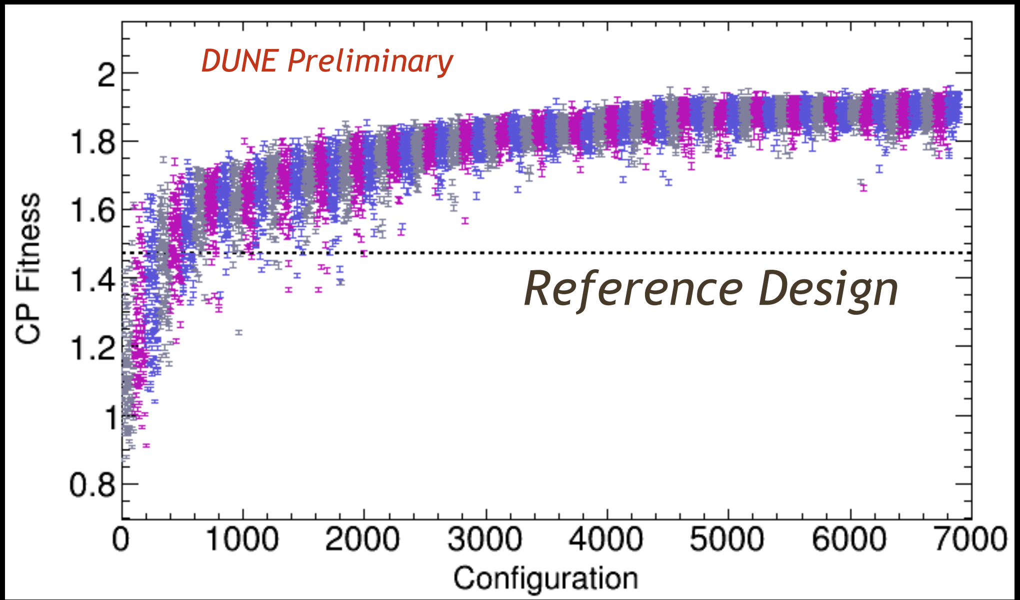
Optimizing for better physics

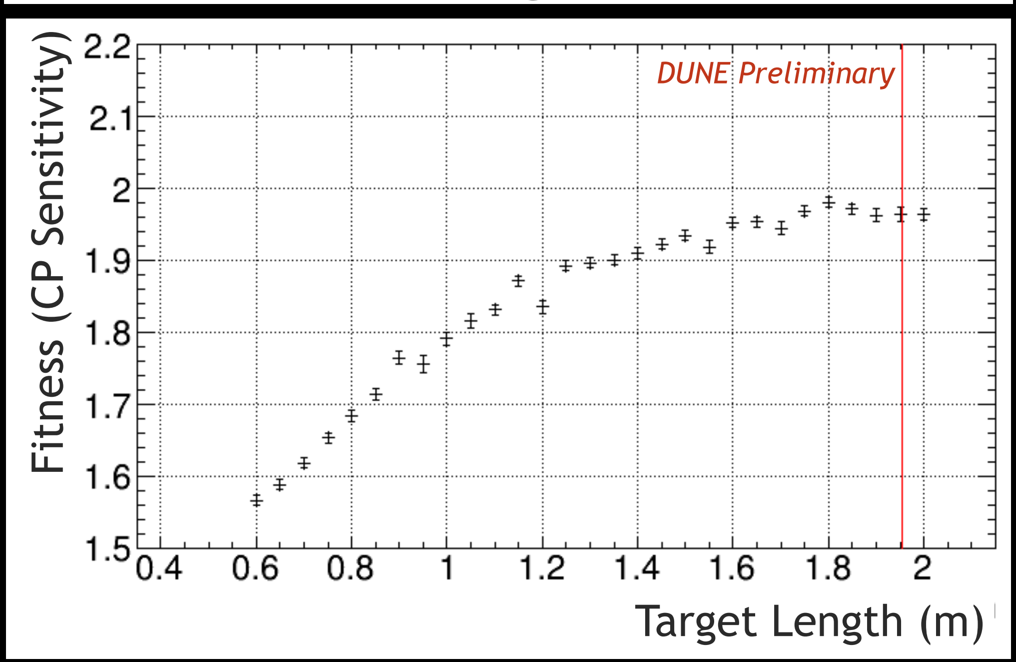
- Genetic algorithm varies (within limits imposed by assumed engineering constraints):
  - Target size and location
  - Horn size and shape parameters
  - Horn currents
  - Primary proton beam size and energy
- Individual design throws are evaluated, better ones “mated” to form new beam designs



Optimizing for better physics

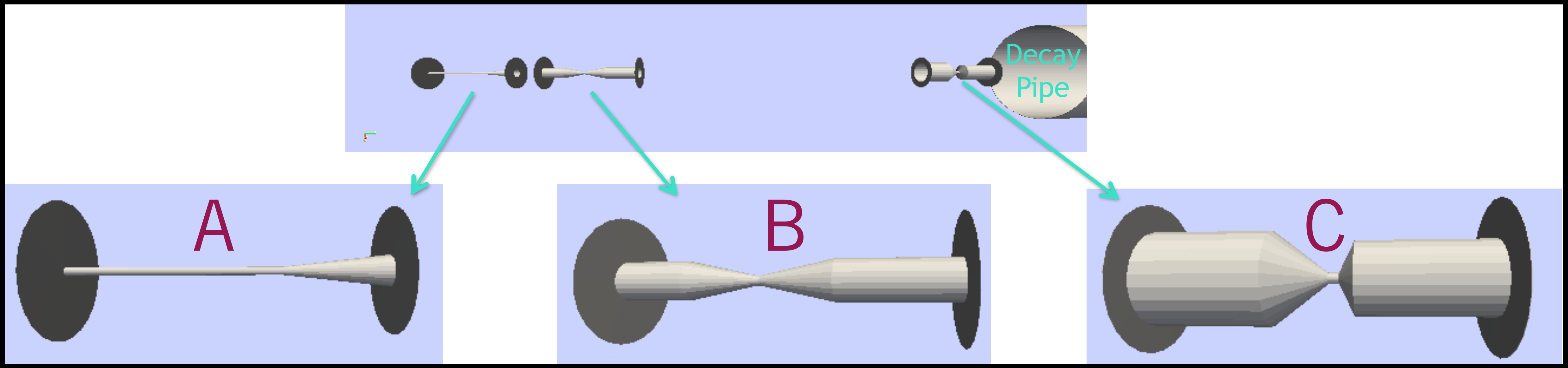
- The physics performance of the first “generation” of beams is generally poor, but as the mating process is repeated, designs improve
- Eventually, the parameters of the optimization stop changing, and the optimization converges to an optimal beam design
- 1-D parameter scans around the optimal design help us understand the importance of parameters and our degree of sensitivity to them.





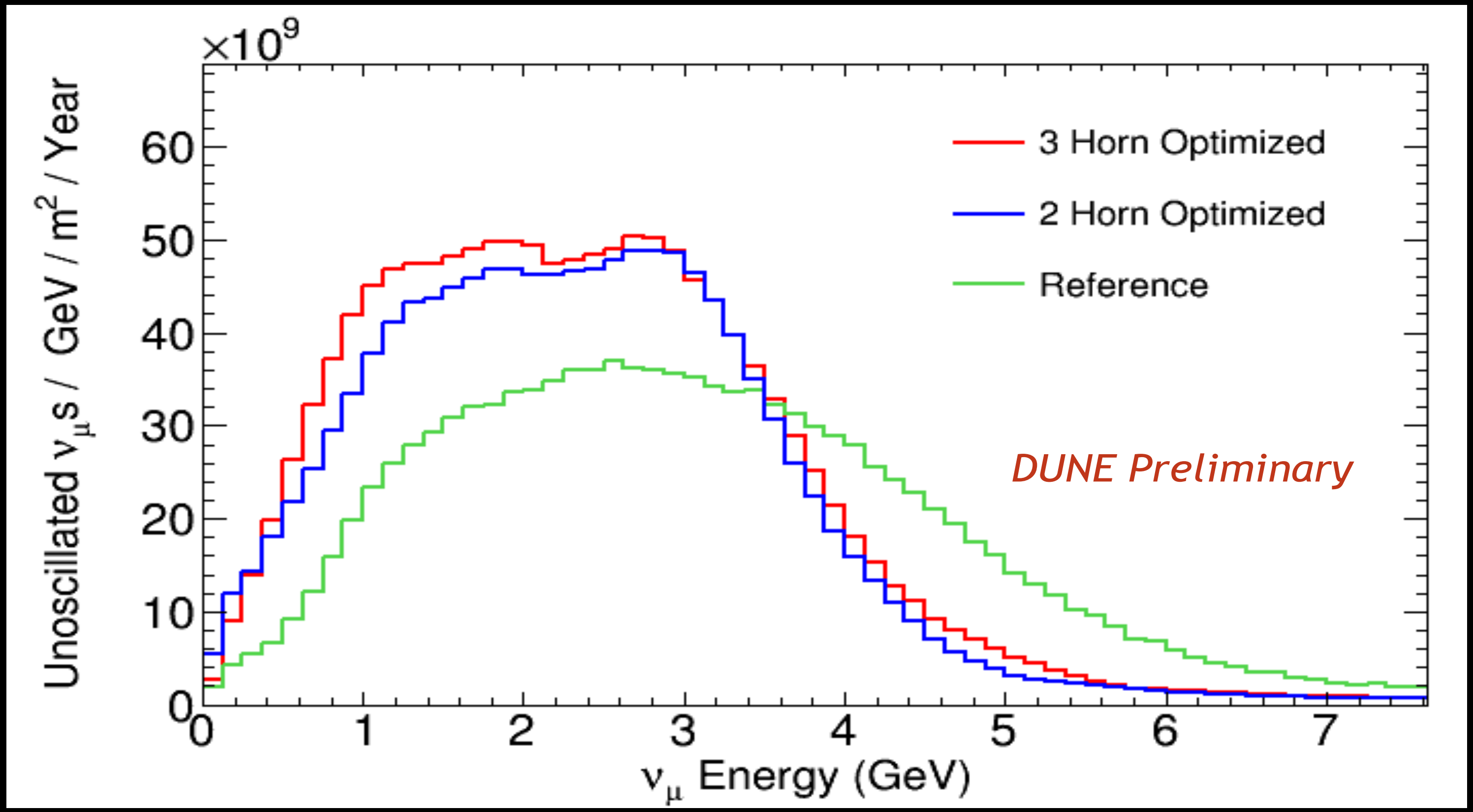
The optimized beam

- Optimized beam is very different from the reference design or NuMI
- Much longer target length of 2m (limit of range that was considered)
- Three horns rather than two
  - Each horn length about 3 m
  - Larger outer-conductor diameters
  - Current 300 kA



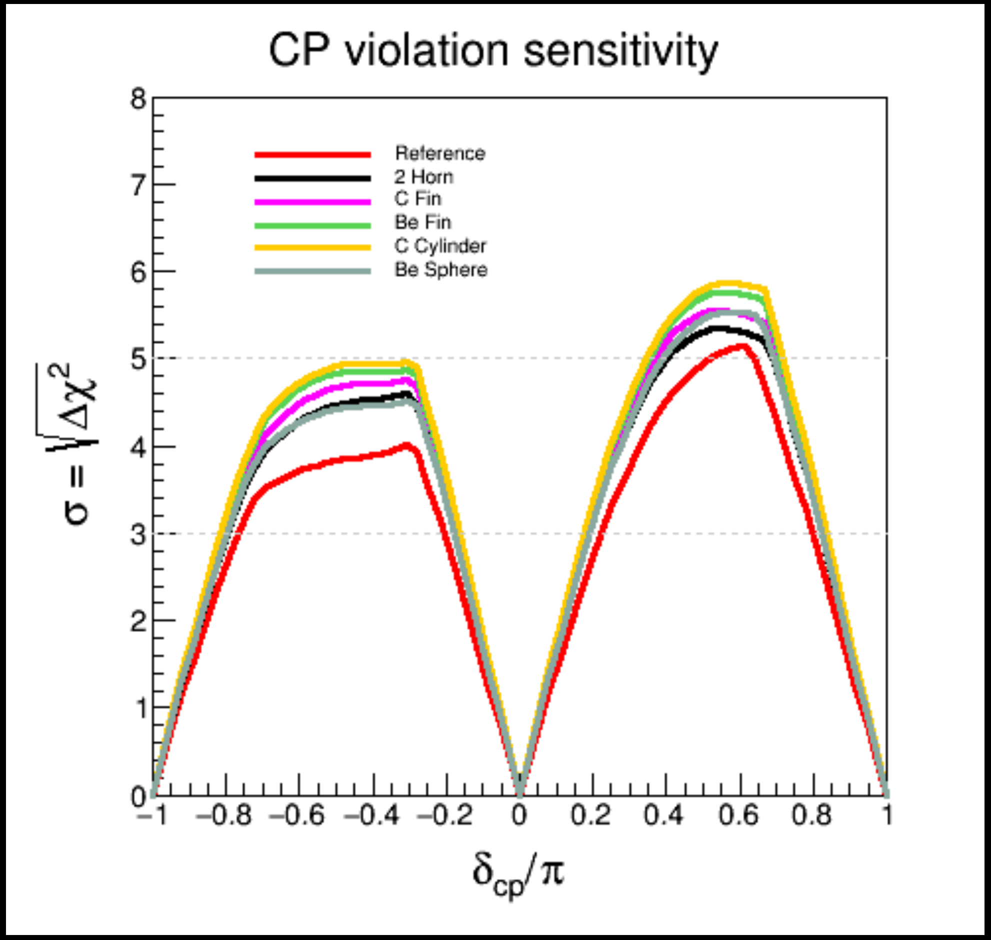
The optimized beam

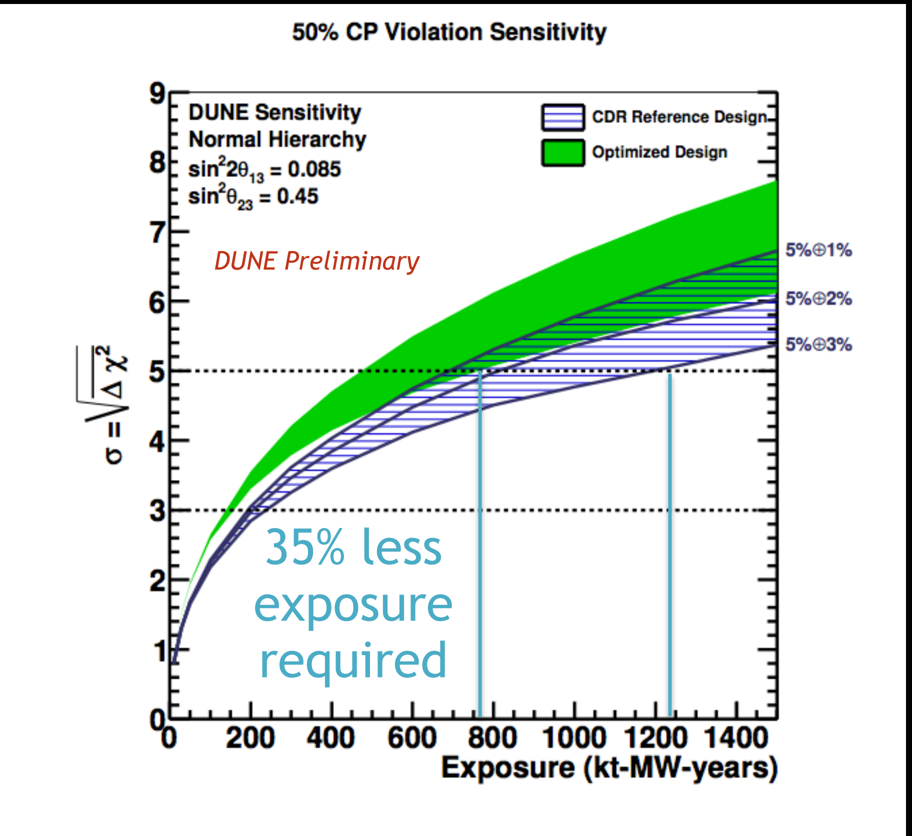
- Simulations show that the optimized beam design produces 44% more muon neutrino flux between 0.5 and 4 GeV while also decreasing wrong-sign neutrino contamination.
- Flatter beam spectrum in desired range with reduced high-energy tail



The optimized beam

- These changes lead to substantial improvements in sensitivity to CP violation, and other physics deliverables such as the mass hierarchy.
- Useful sensitivity to CPV could be achieved significantly earlier

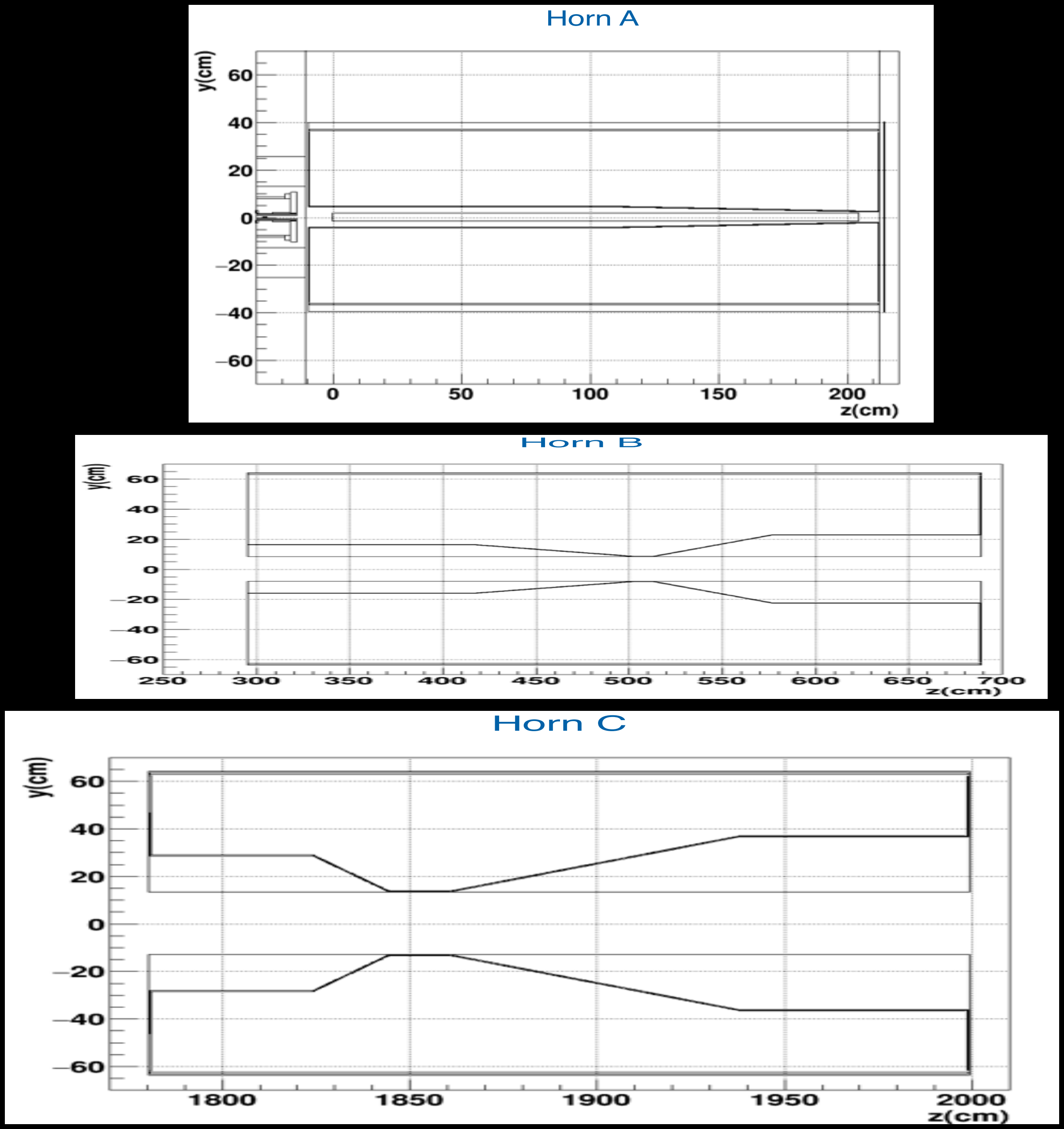




CP sensitivity for 50% of the values of as a function of exposure for the reference and 2-horn optimized design)

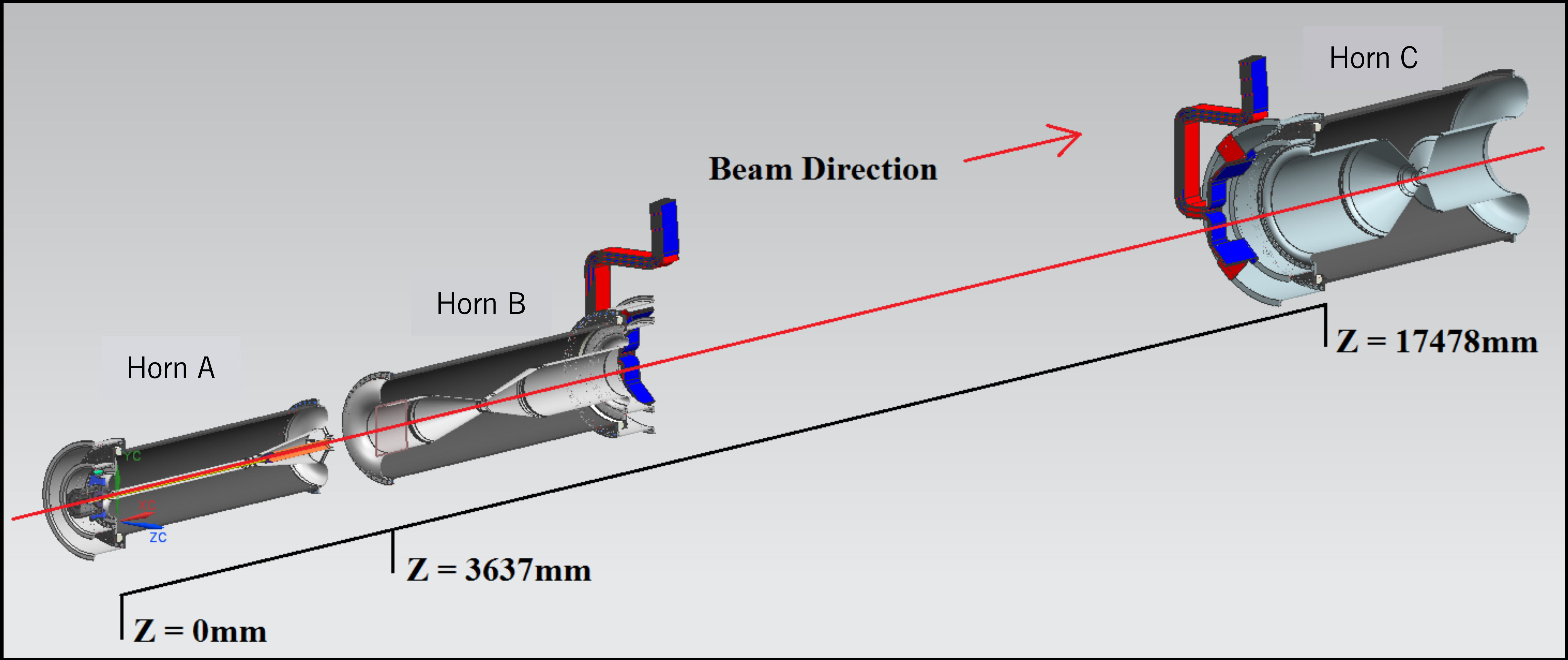
Engineering-informed re-optimization of horns

- New optimization algorithms are being developed to speed up iteration with engineers.
- Initial revision of horn parameters:
  - Horn A
    - Becomes a shorter horn with tapered IC.
  - Horn B
    - Length added to make up for shorter Horn A; Horn B becomes slightly more expensive
  - Horn C
    - Changes shape, but keeps large IC scale



Note: horns not to scale

Initial mechanical designs of horns



Next steps in optimization

- 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.
- Longer target with halo-scattering "wings" reduces peak energy deposition at absorber by over an order of magnitude.
    - Thinner/simpler absorber design may be possible with this target
    - This would make muon monitoring more feasible by decreasing energy threshold to reach monitors and making material distribution easier to model
    - Also reduce backgrounds in muon monitor and near neutrino detector from decays of pions created in absorber

Next steps in optimization

- Engineering efforts on the optimized design and iteration of the design parameters are proceeding
- Some studies of higher-energy tunes for ν_τ appearance
- Aiming for review of the optimized beam, decisions end of summer 2017

Flux systematic errors: NA61

- NA61 is measuring pion and kaon production at various energies and targets
  - 2016 run: completed several data sets. These will be used to model both primary and secondary production in the LBNF targets.
  - Plan additional runs in 2017 and 2018 to complete cross-section tables

beam	target	beam momentum
p	Pb	80 GeV/c
p	C	60 GeV/c
π^+	C	60 GeV/c
p	C	120 GeV/c
p	Al	60 GeV/c
p	Be	60 GeV/c
π^+	Be	60 GeV/c
p	Be	120 GeV/c

NEUTRINO BEAMS

LBNF timeline

- September 2017: Optimized beamline conceptual design ready for review
- March 2020: Start of construction
- August 2026 : Beamline installation and checkout complete
- Operations begin December 2026 at 1.2 MW

Conclusions

- A feasible reference design has been established for the LBNF beam
- Optimization efforts appear to allow significant improvement
- Engineering toward the optimized design is progressing

Conclusions

- Decisions on optimized design expected mid-2017
- Many basic parameters of the beam will be hard or impossible to change once construction is underway
- Now is the time for input (or, better, participation) in the beam design