LBNF Neutrino Flux Modeling

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ACE Workshop

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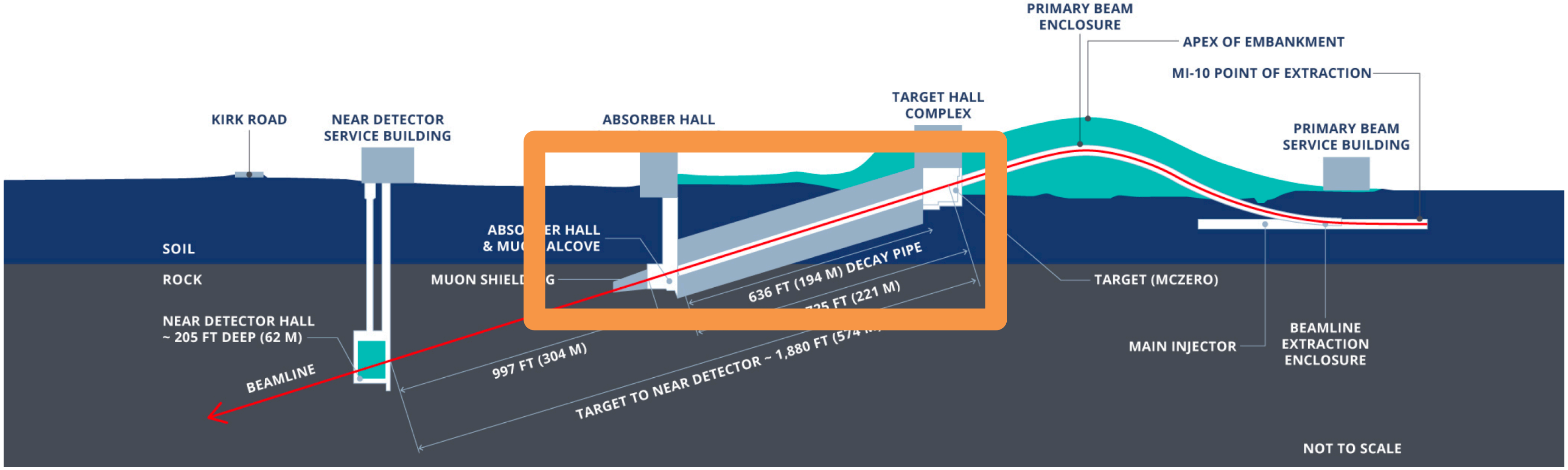
Fermilab

Outline

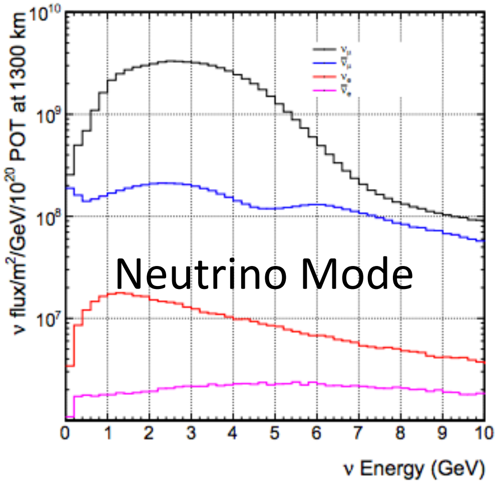
- Overview of DUNE **Beam Simulation**
- Reminder of **Optimization of the 1.2 MW** Beam
- Most **important beam parameters**
- What **proton energy?**
- Preliminary **studies for 2.4 MW**
- **Path to full optimization** for 2.4 MW

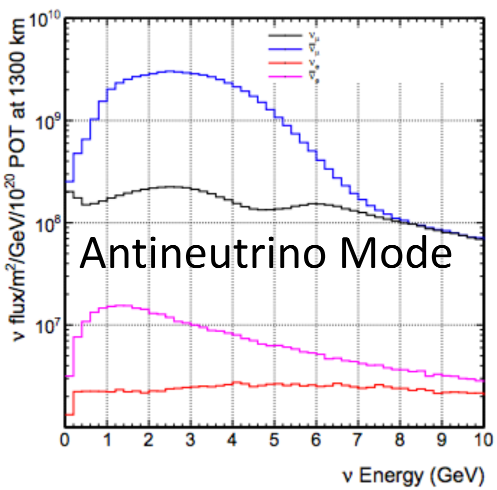
The DUNE Beam Simulation



- The DUNE neutrino flux is estimated with a **Geant4-based simulation** of the LBNF beam line
  - Starting with neutrino beam target and ending with muon shielding
- Implemented **natively in C++**, except the hadron absorber + muon monitors/shielding, which use gdml exported from MARS
- Basic output is **a list of all neutrinos produced along the beam line**, along with extensive information about their kinematics, parentage, etc

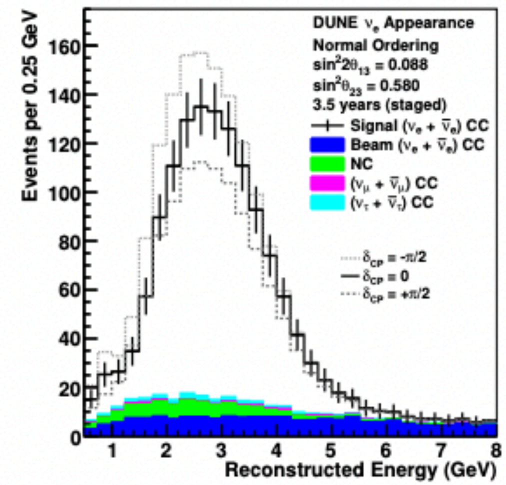
The DUNE Beam Simulation

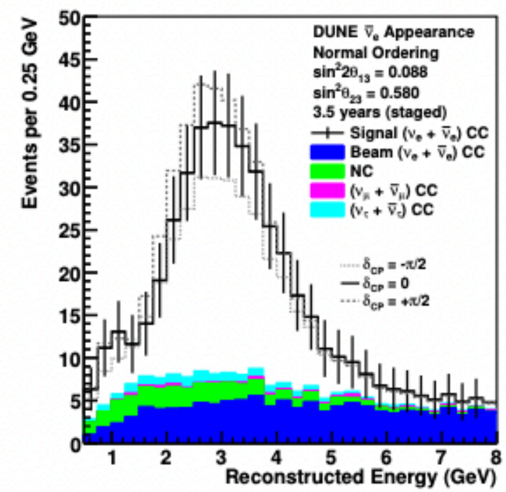




Initial neutrino energy spectra are the first step in simulations that produce predicted distributions at the DUNE detectors

(And cross sections and detector efficiencies)

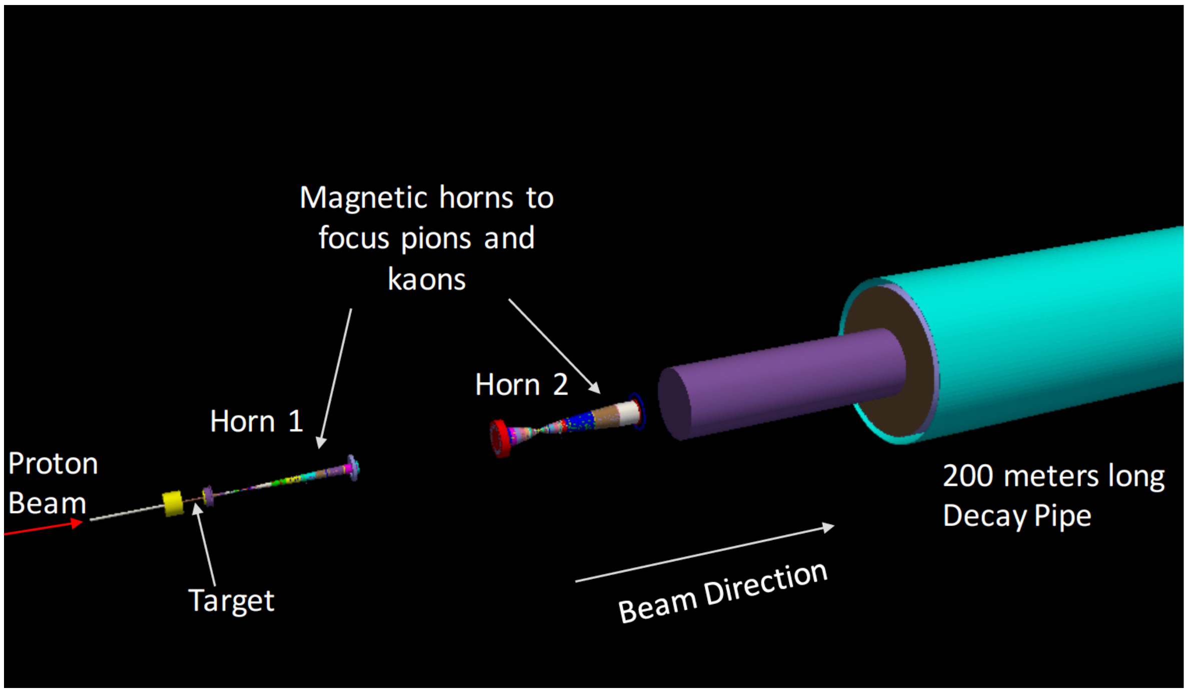




Figures from DUNE TDR

LBNF Beamline

- When I joined the experiment in ~2012, LBNF was planning a **NuMI-based beamline design:**



Reference Design

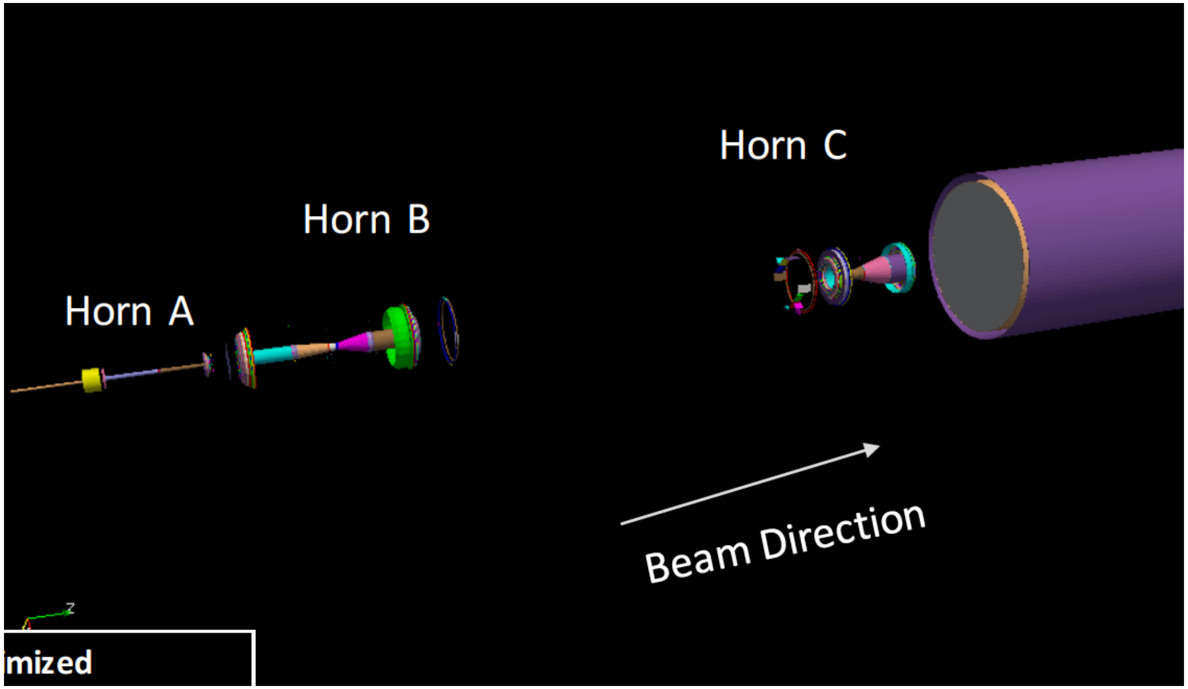
Two horns, nearly identical to those used in NuMI, run at slightly **higher current** (230 kA)

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

Figures courtesy Amit Bashyal

LBNF Optimized Beamline

- I, with the help of lots of others, helped identify an optimized design that used three horns:



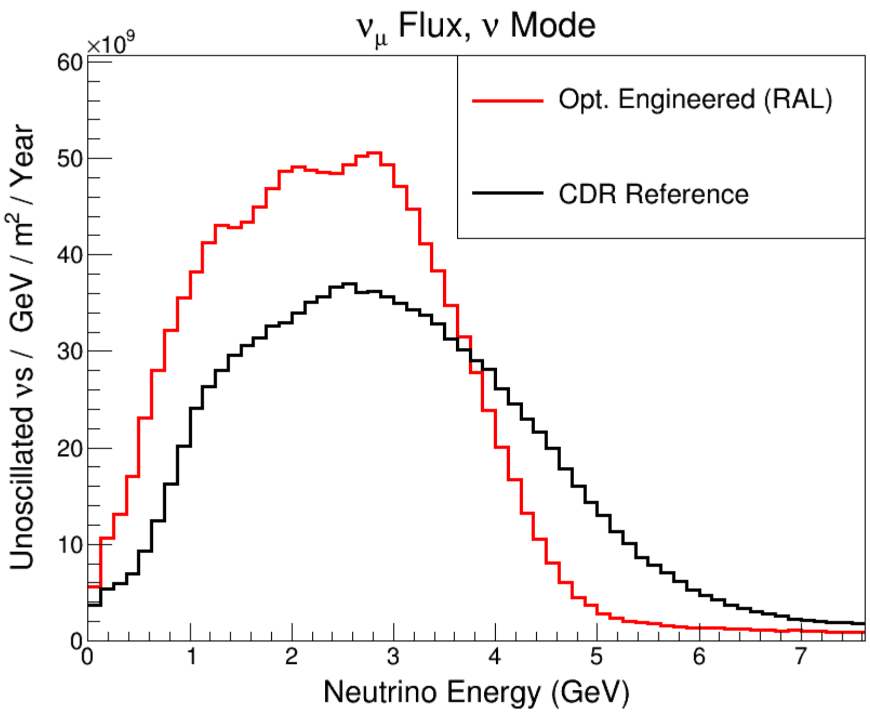
Optimized Design

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

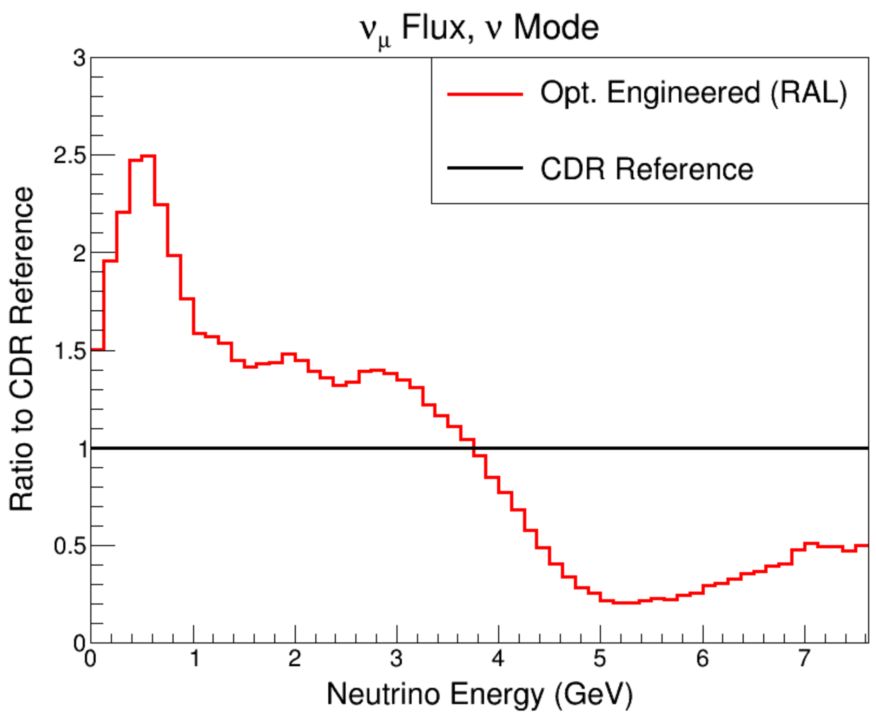
3-4 interaction length carbon target

Figures courtesy Amit Bashyal

Physics Performance of Beam Options

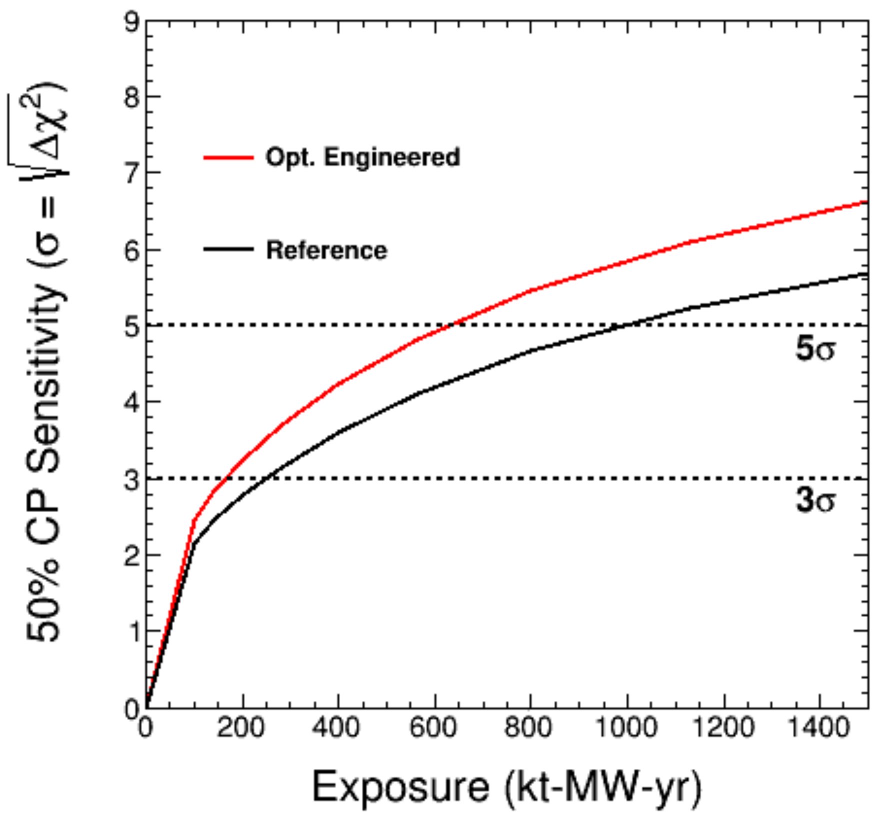


- Muon neutrino **flux is significantly improved in the optimized design** over the reference



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

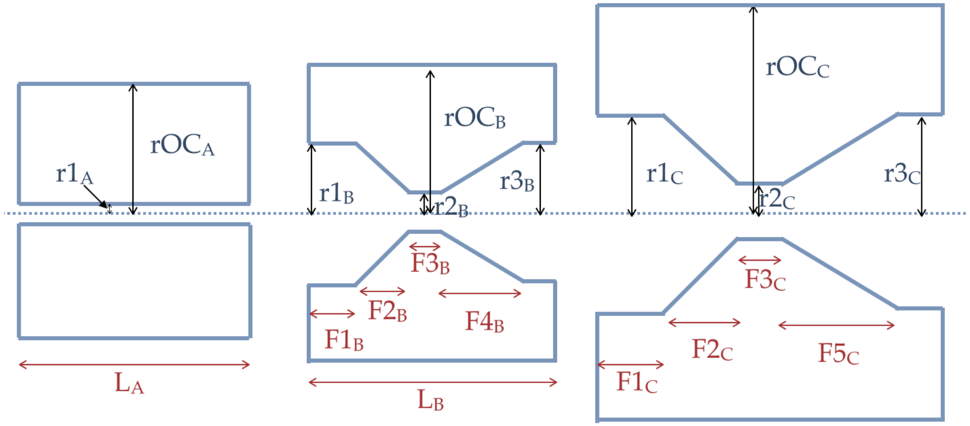
Physics Performance of Beam Options



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

Beam Optimization

- A first step in beam optimization is identify parameters of the beam that could be changed
  - These are what we eventually settled on:



Parameters Varied:

- Horn A/B/C shape parameters (see figure)
- Width/length of carbon fin-style target
- Horn current
- Horn positions
- Proton beam momentum & radius

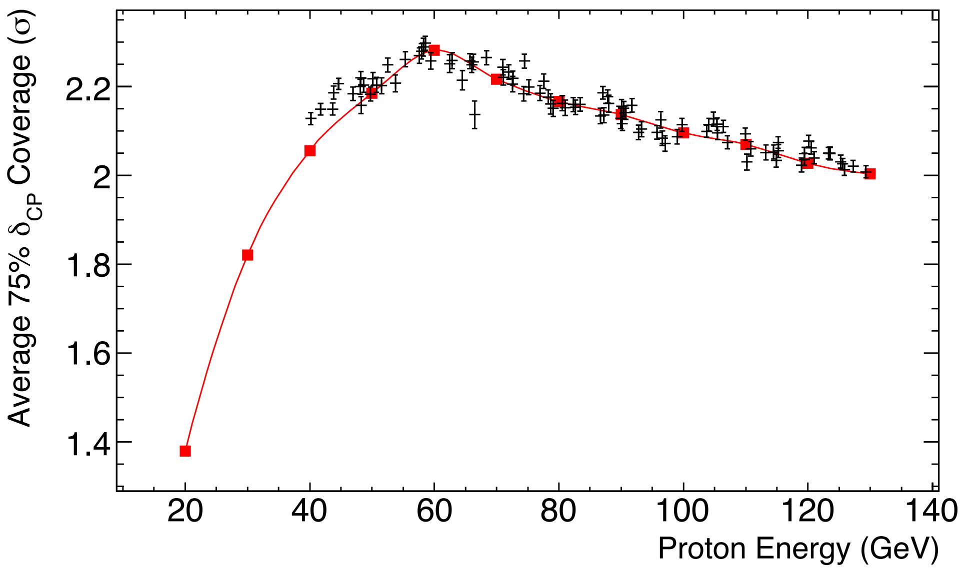
Beam Optimization

- First step in optimizing the beam to pick a quantity to optimize
- For LBNF/DUNE, the choice was pretty clear

> , we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δCP

Genetic Algorithms

- We developed a fast estimator of CP sensitivity that ran in 2 seconds (after the 1-2 hour simulation of the neutrino beam)

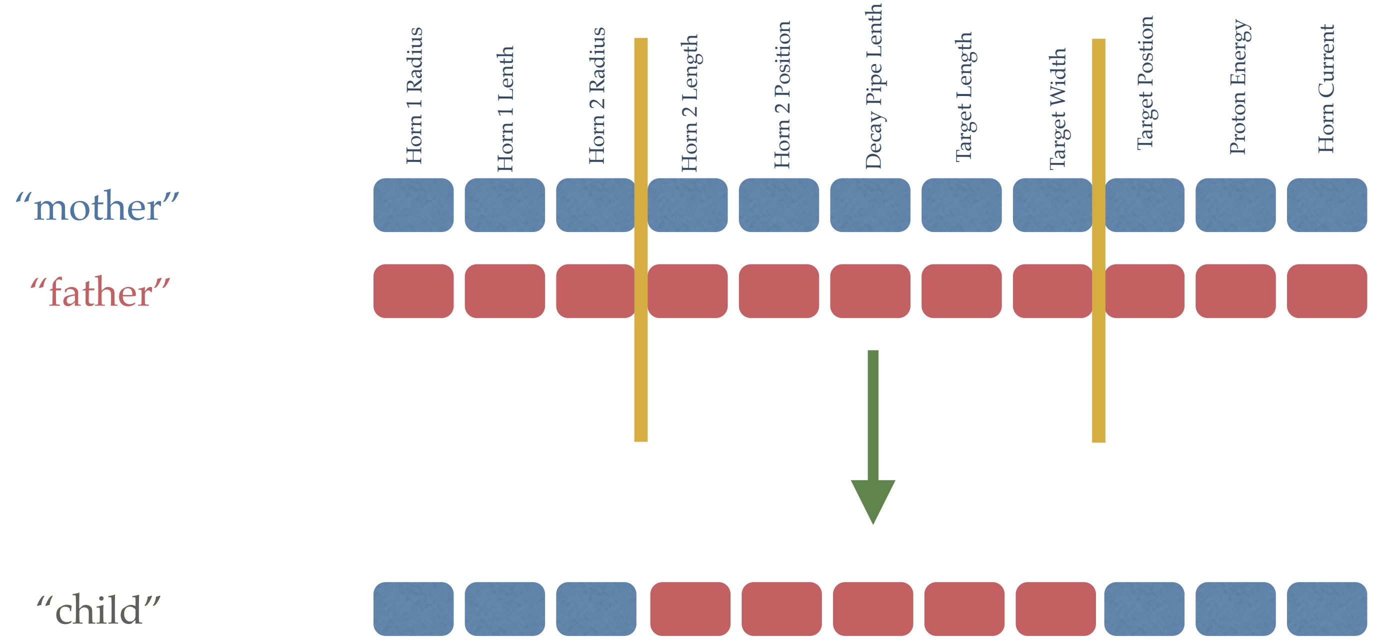


A comparison of an approximation with the actual CP sensitivity for different proton beam energies

But considering e.g. just 20 parameters, each with 20 possible values, scanning over the available phase space would take much **longer than the lifetime of the universe**, even with very fast simulations.

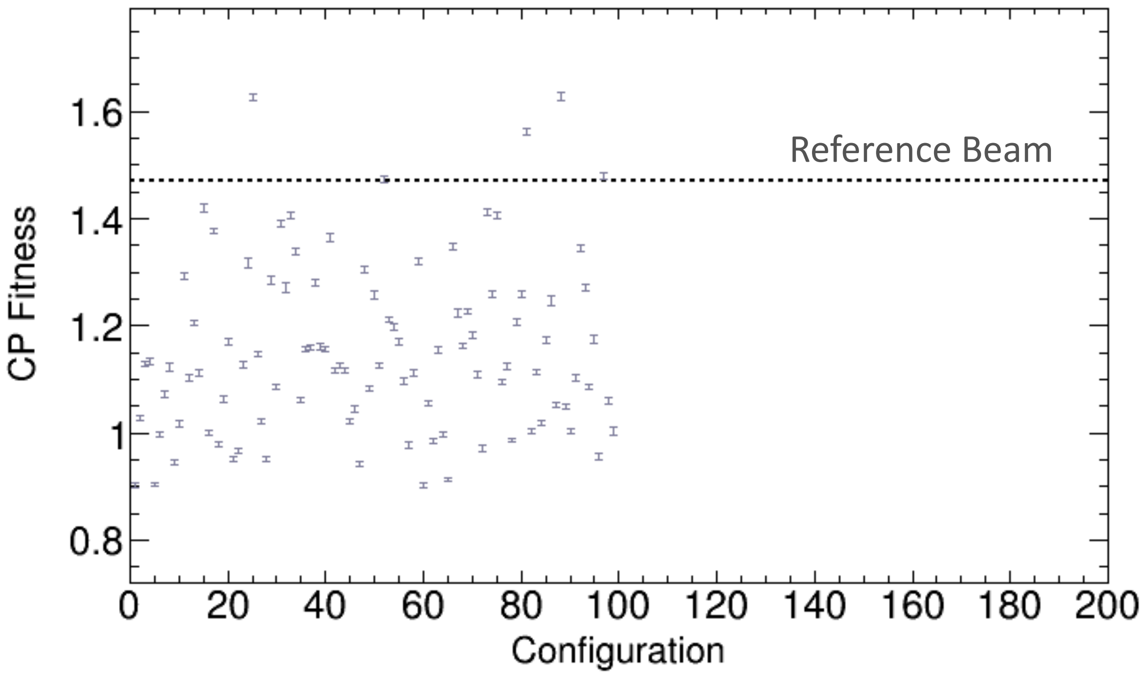
Genetic Algorithms

- 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

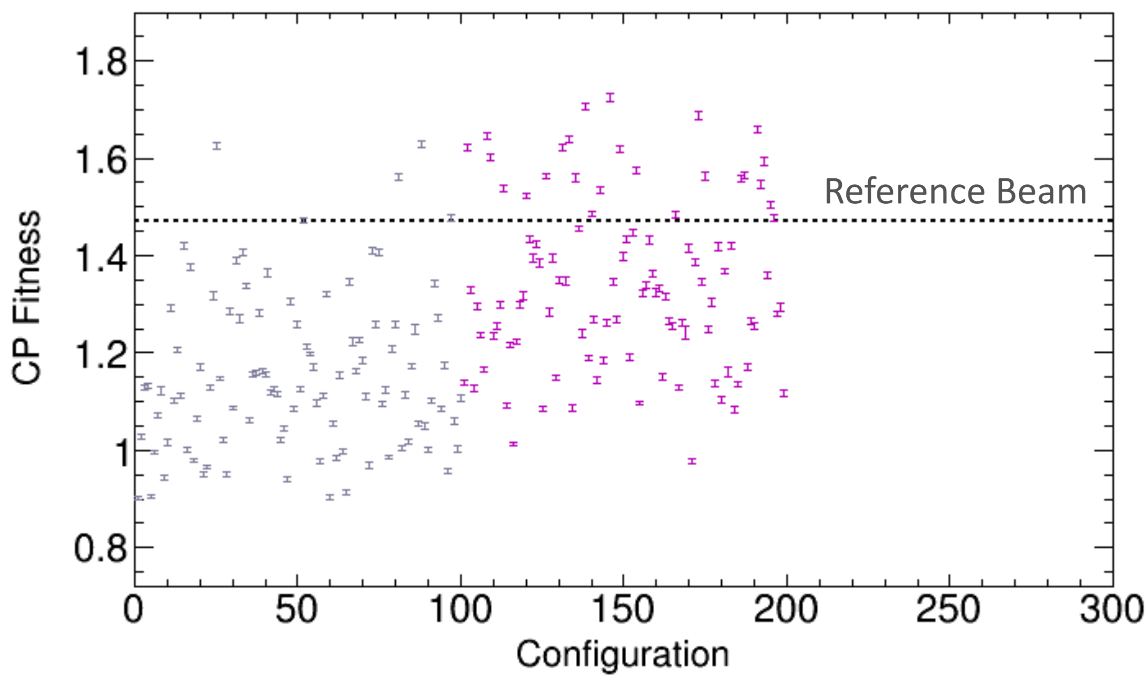
- The initial set of randomly chosen beams is generally pretty poor:



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

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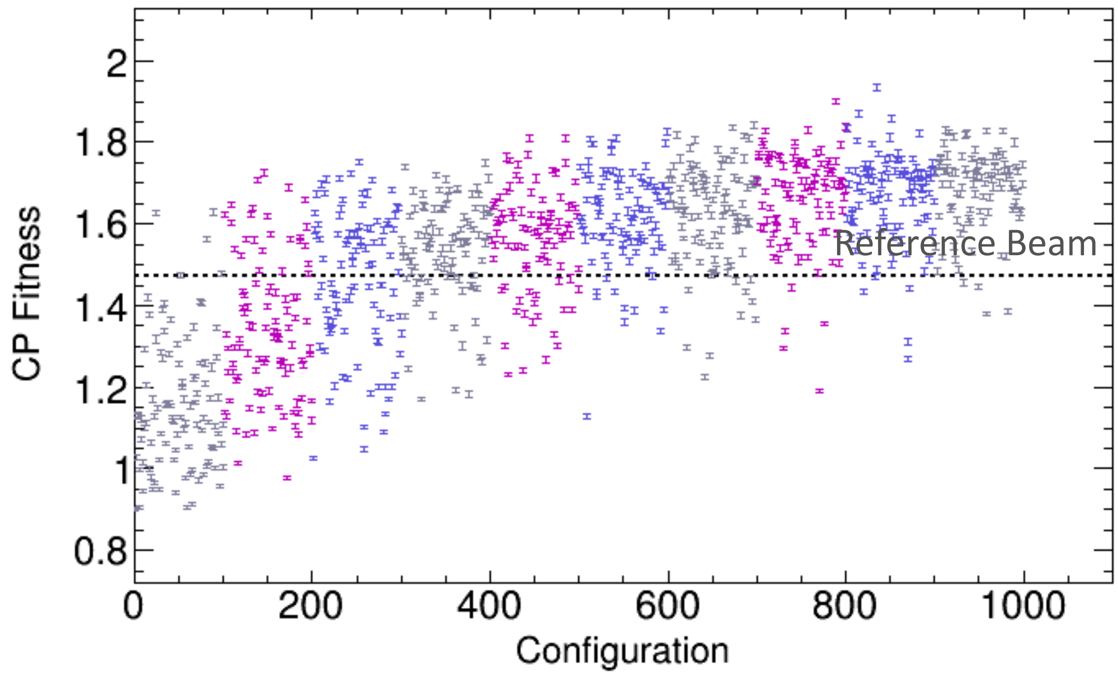

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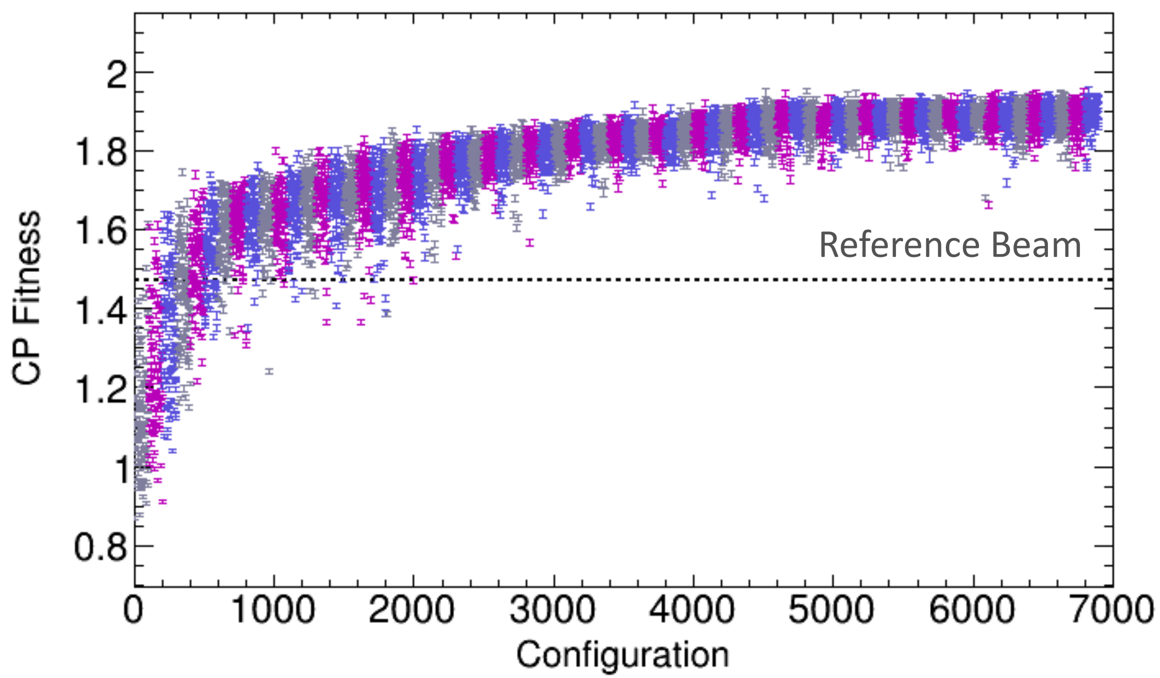
Genetic Algorithms

- 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

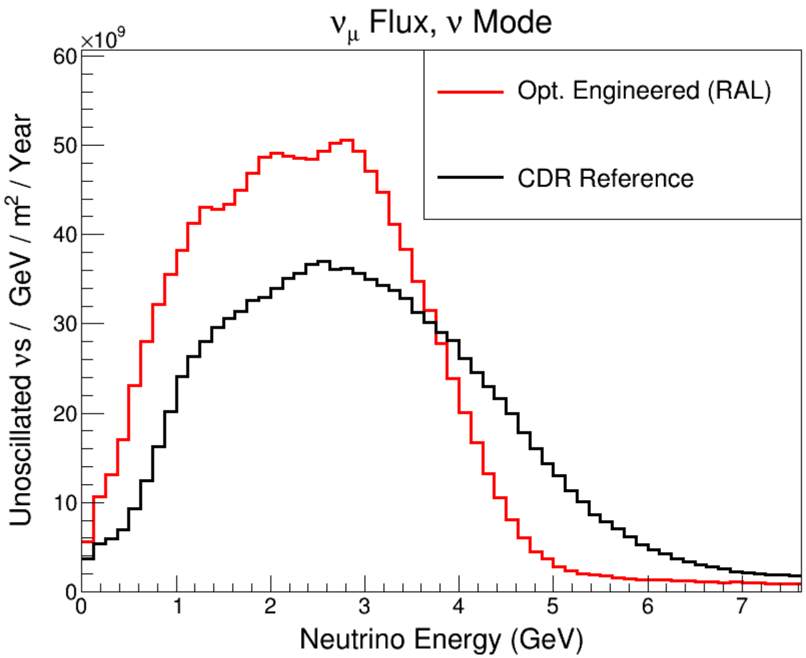


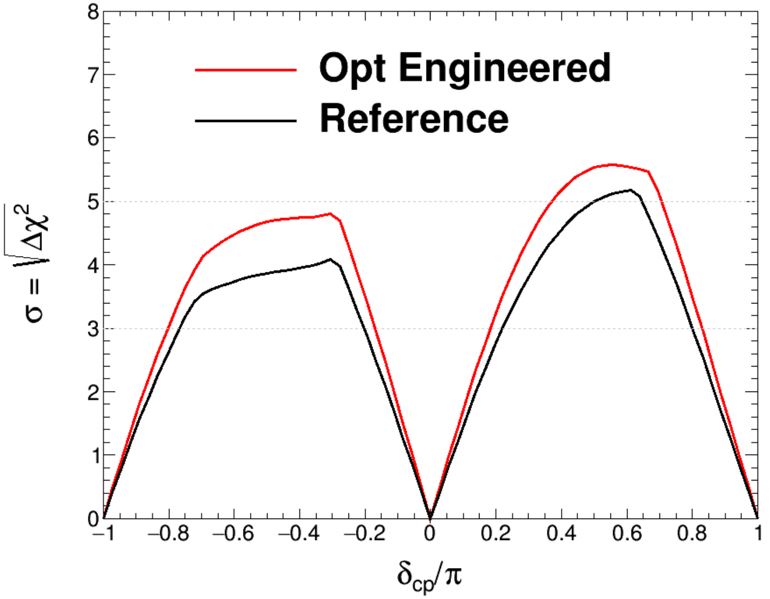
We know that this algorithm produces good beam designs.

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

Toward Reality

- Engineers transformed that idealized design into the engineered beam I described at the beginning of the talk

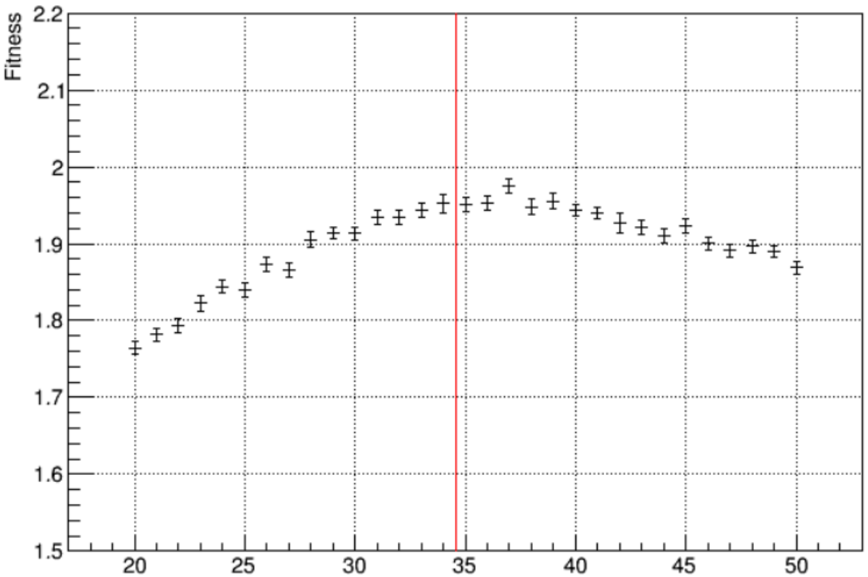




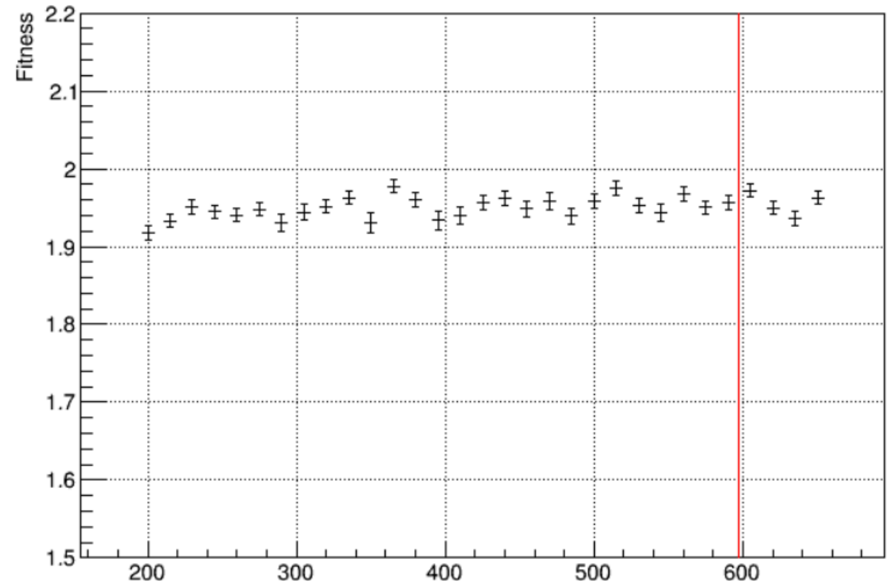
- Further engineering in the past few years has slightly reduced flux/ physics performance

Which Parameters are Most Important?

- Parameter scans were useful for understanding optimized systems:



Horn A Neck Radius in mm



Horn A OC Radius in mm

Lots more in DUNE Docdb 1151

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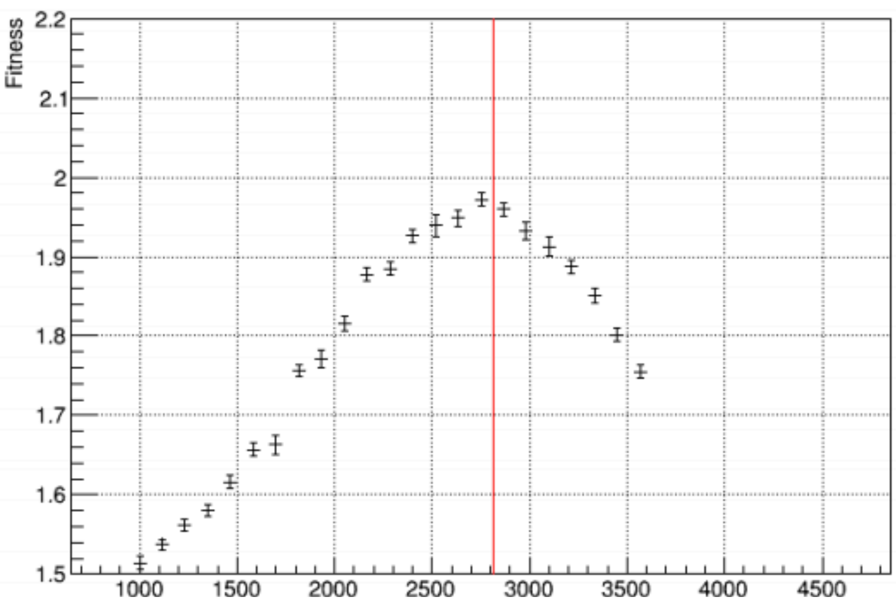
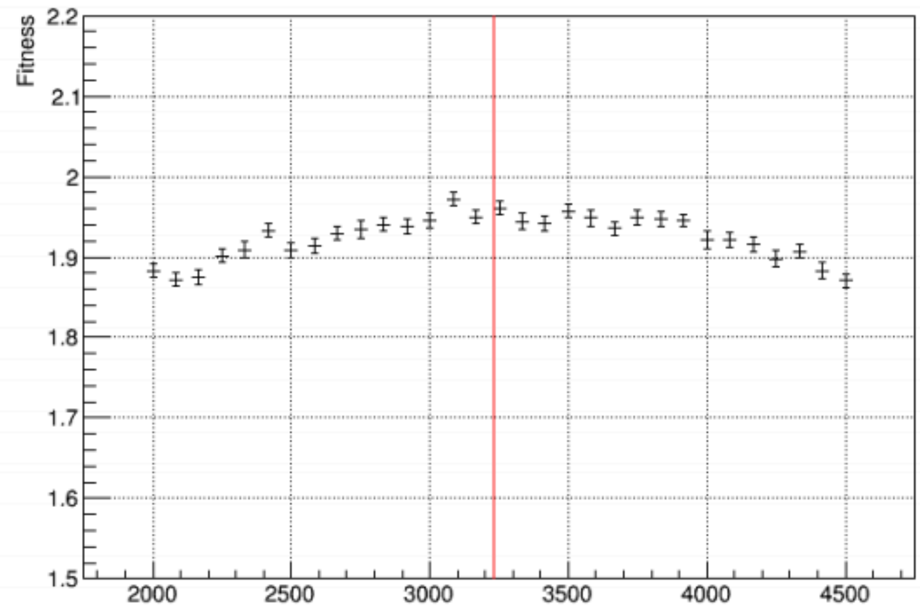


Horn A Length in mm



Horn B Length in mm

Lots more in DUNE Docdb 1151

Which Parameters are Most Important?

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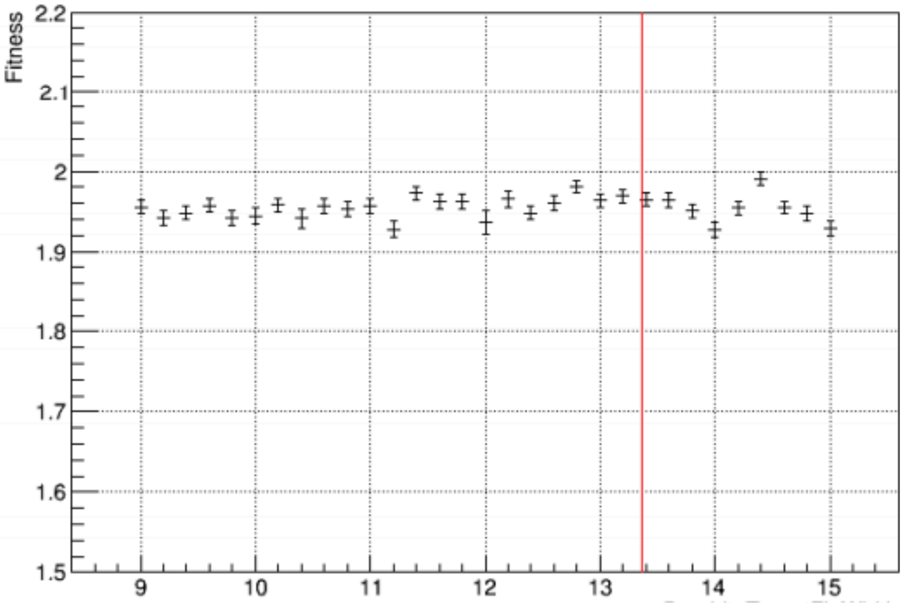
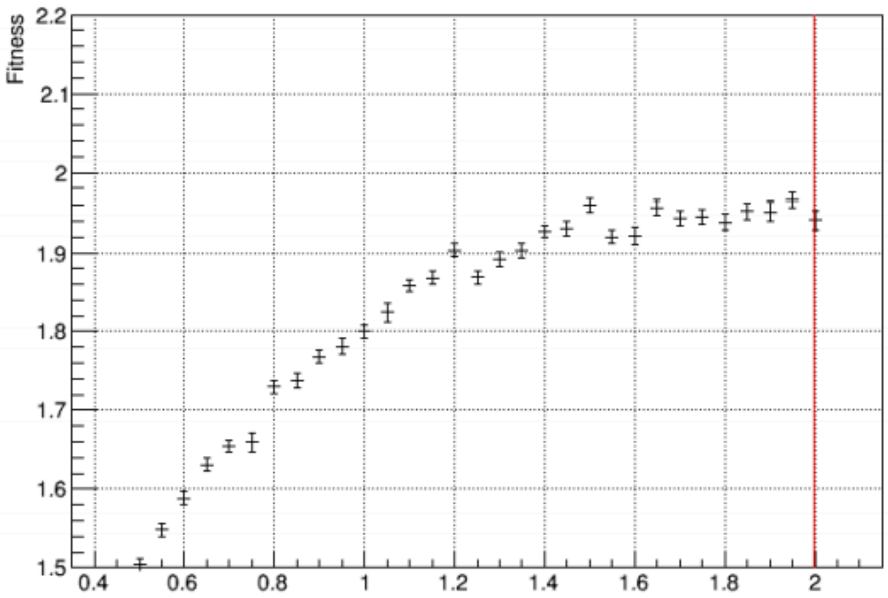


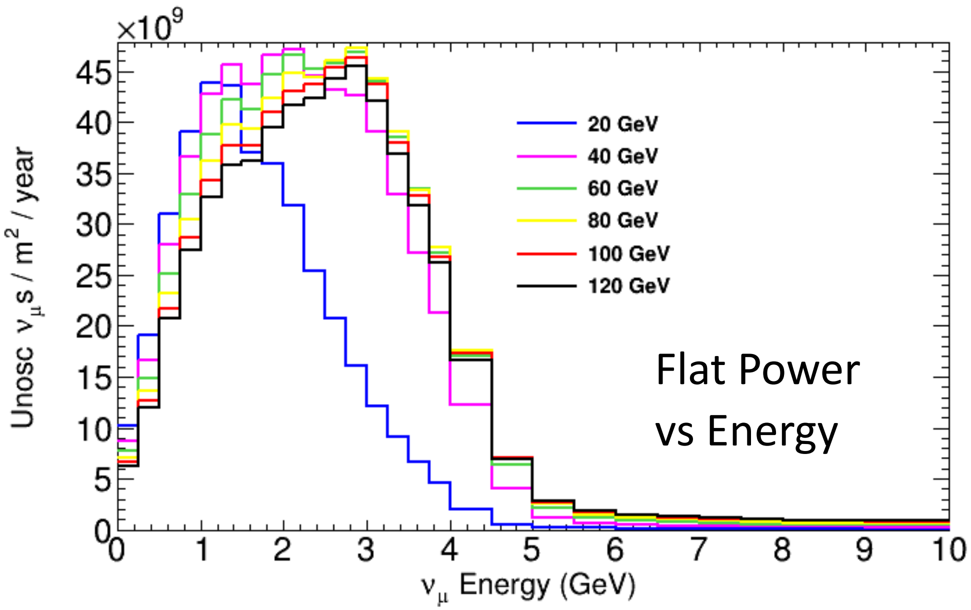
Target Fin Width in mm

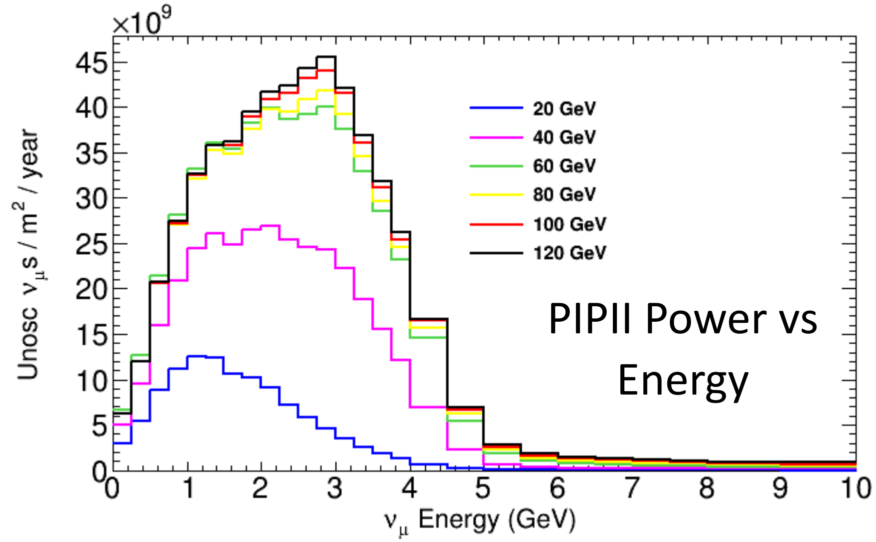


Target Length in m

Proton Energy

- I got a flurry of emails in my inbox yesterday asking about how flux/physics performance change with proton energy:



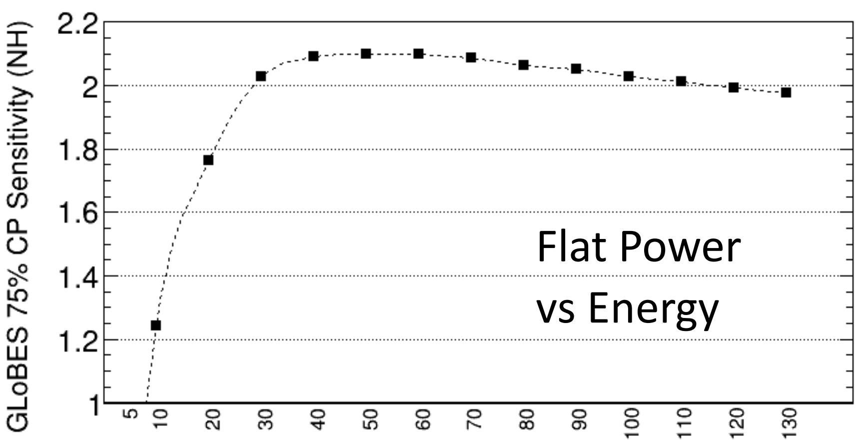


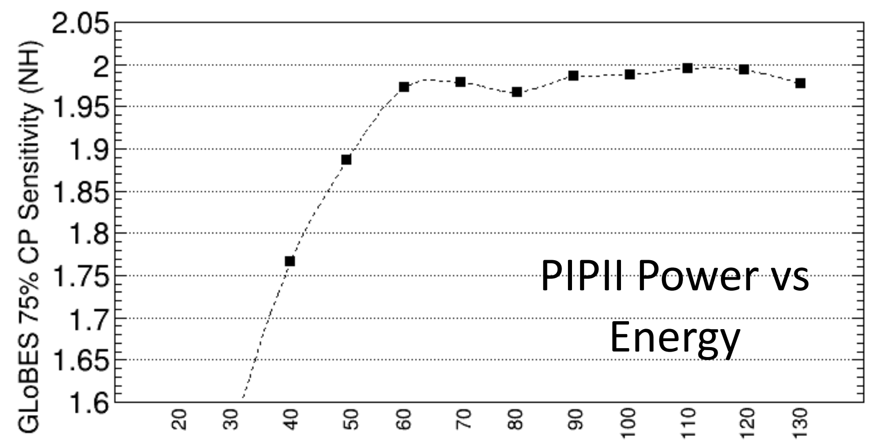
Proton Momentum (GeV/c)	Expected Beam Power (MW)	Expected POT/year
120	1.2	1.1E+21
80	1.2	1.65E+21
60	1.2	2.2E+21

Proton Momentum (GeV/c)	Expected Beam Power (MW)	Expected POT/year
120	1.2	1.1E+21
80	1.07	1.47E+21
60	1.03	1.89E+21

Proton Energy

- With PIP-II power profile, performance is roughly flat between 60-120 GeV
- With flat power profile, optimal proton energy is ~40-60 GeV





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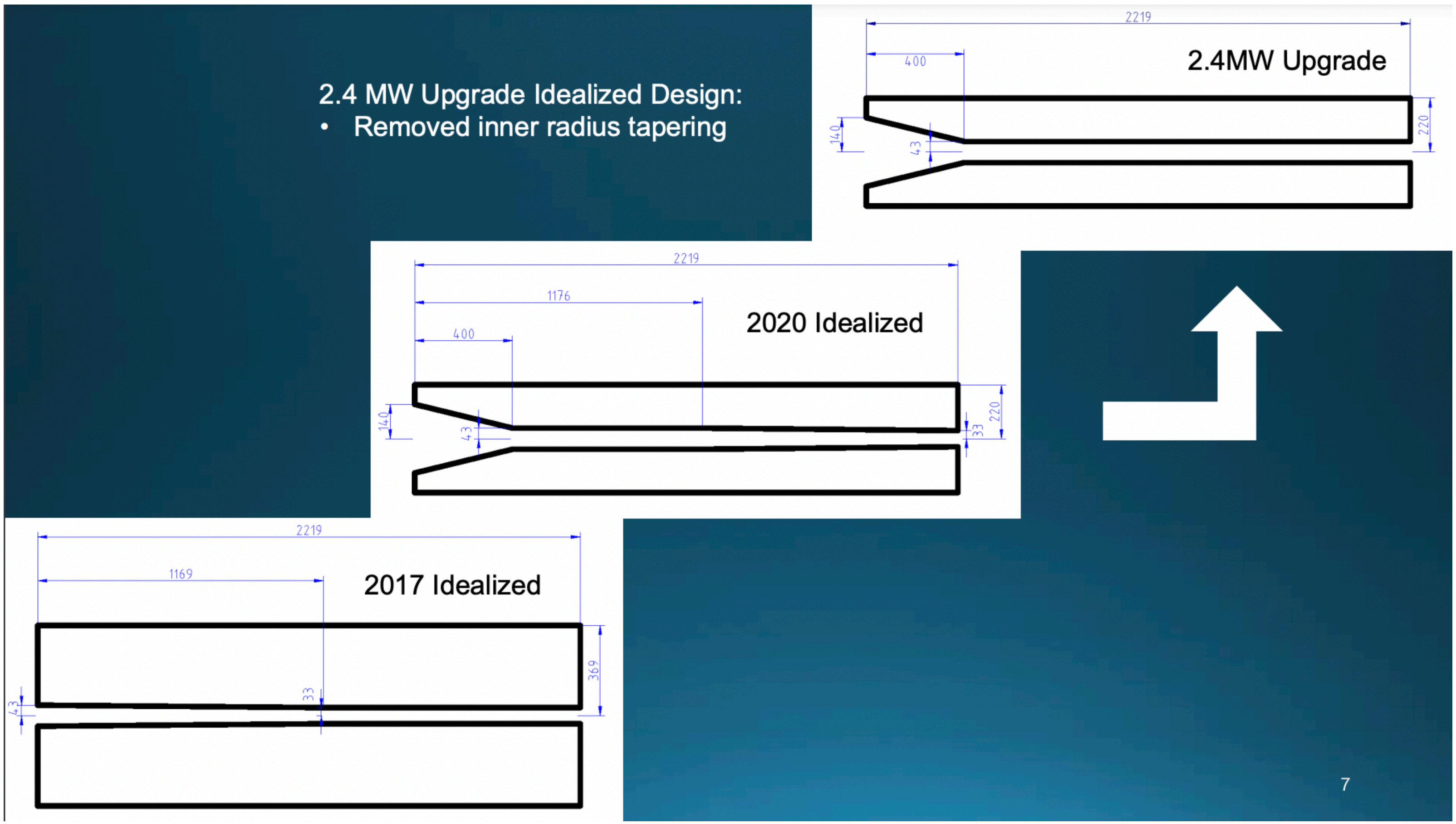
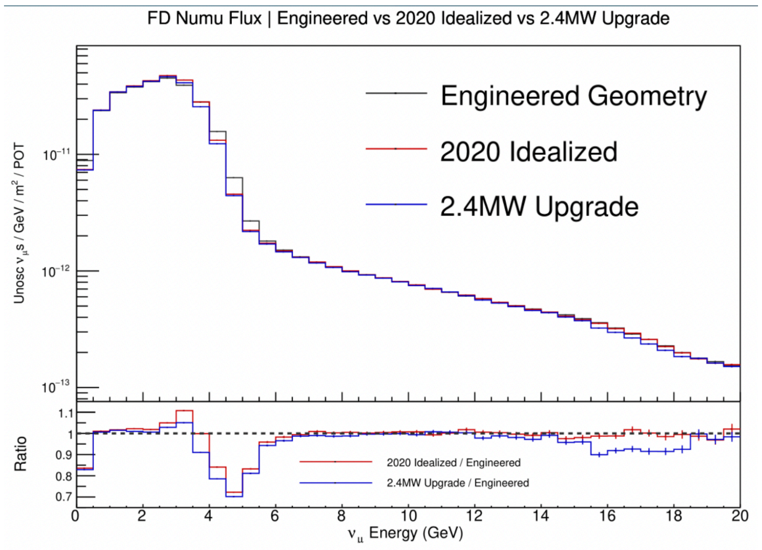
Preliminary Studies for 2.4 MW

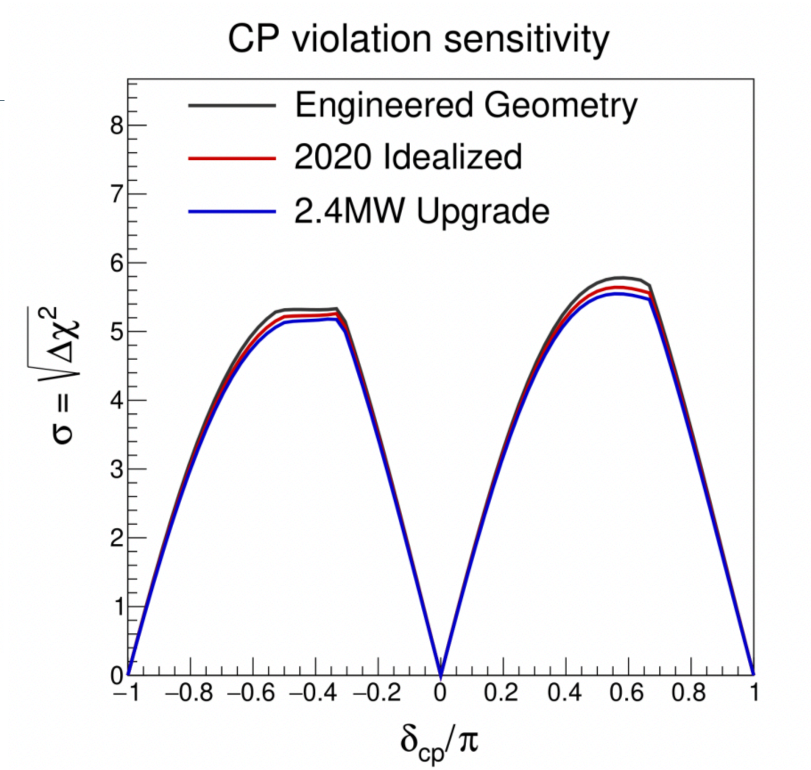
- Drexel undergrad Zev Imani recently looked at some minor modifications proposed by Cory Crowley for 2.4 MW upgrade:



Preliminary Studies for 2.4 MW

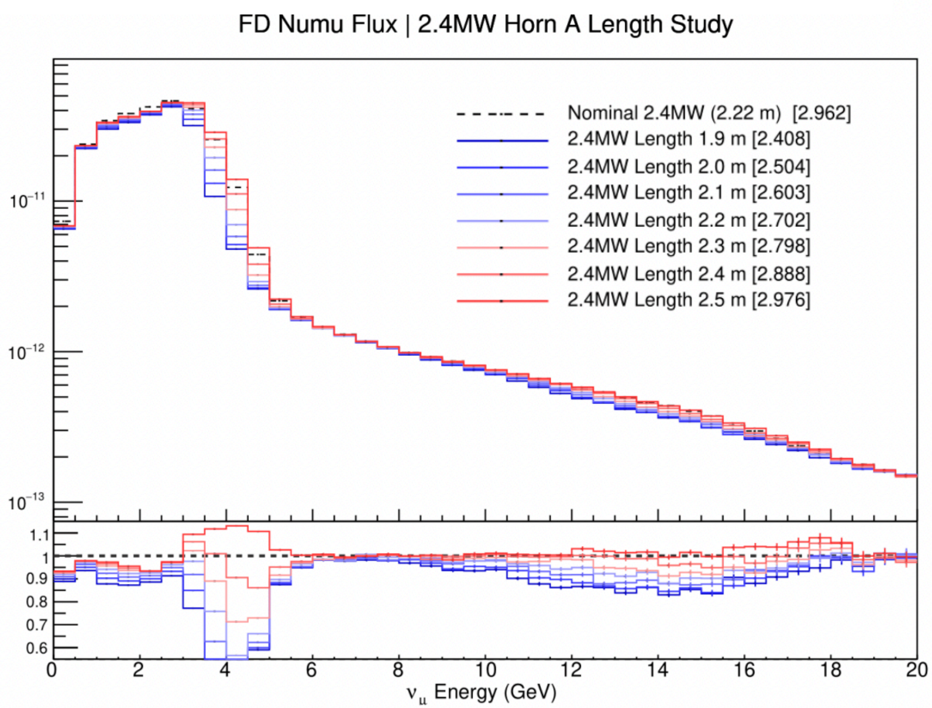
- Changes resulted in a small loss in flux / physics sensitivity:

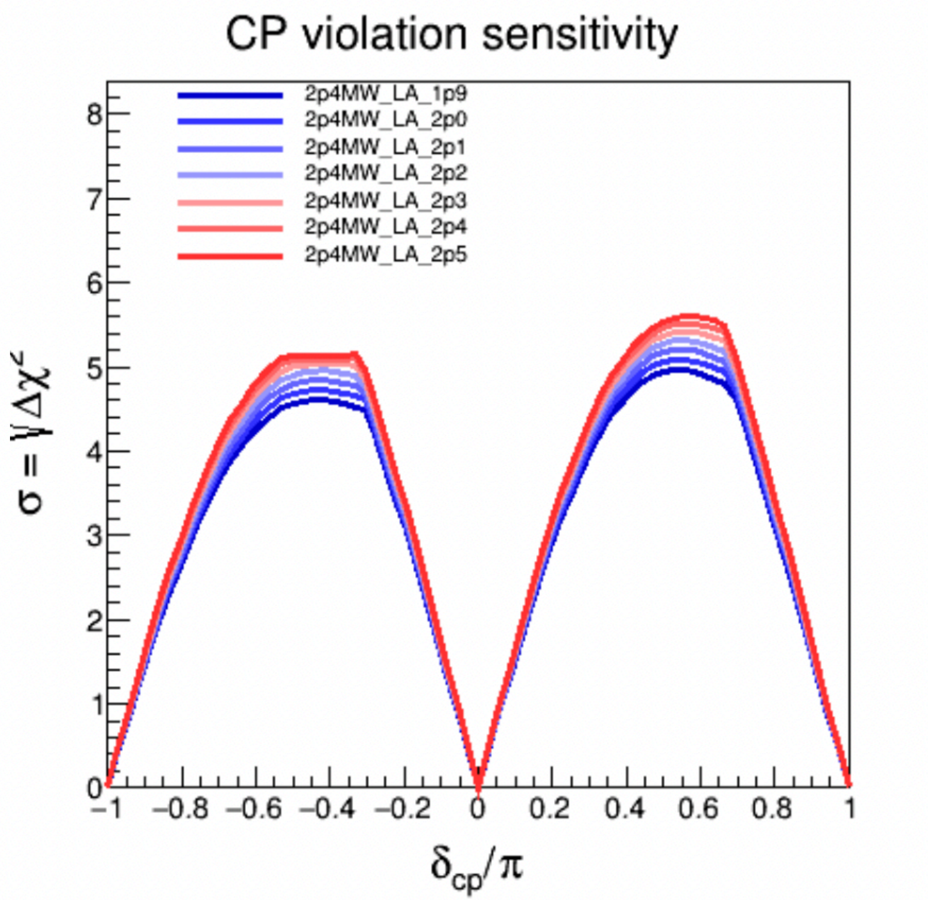




Preliminary Studies for 2.4 MW

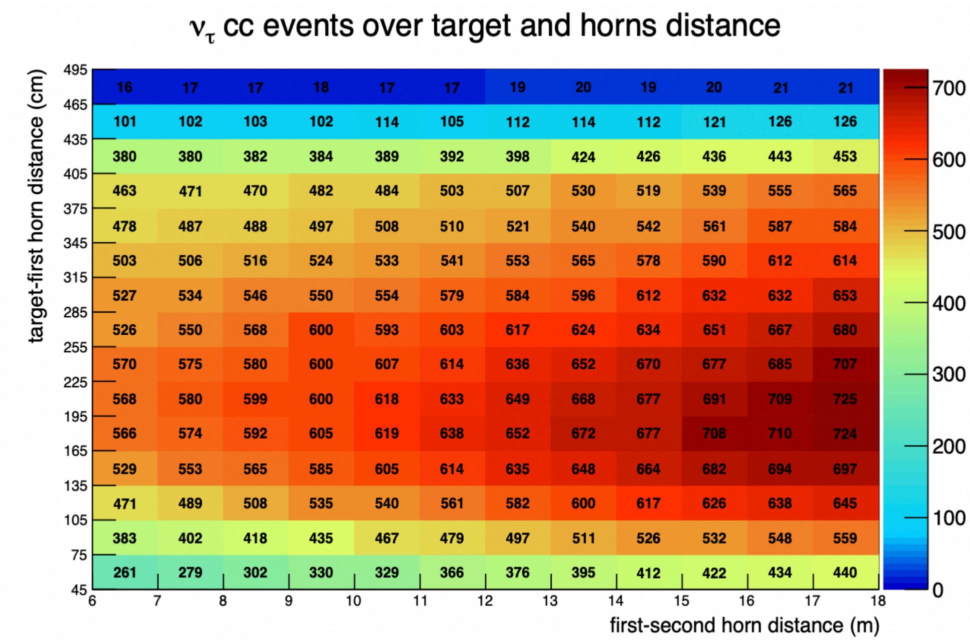
- Zev also showed that loss could be regained by making Horn 1 longer:

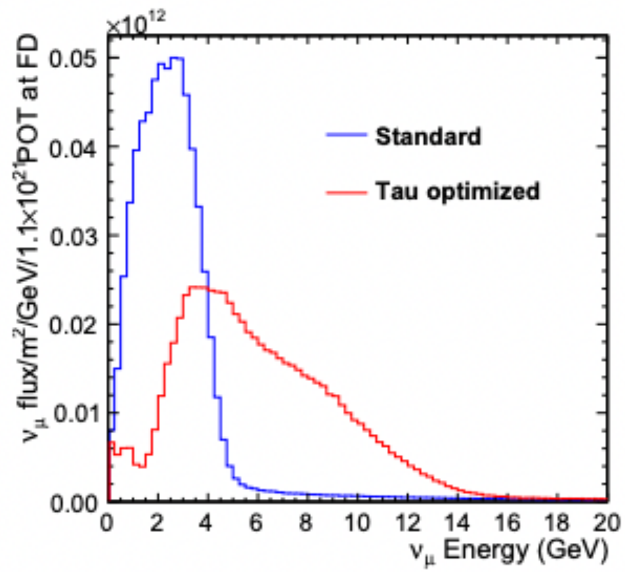




Preliminary Studies for 2.4 MW

- Letizia Parato also did a simple optimization for tau neutrino appearance (a potential future physics goal):





Next Steps

- If we want to do a full **re-optimization for 2.4 MW**, it is going to take some significant manpower
  - It took **several years of my effort** when I was a postdoc / associate scientist
  - As a faculty member, I no longer have the amount of time required to do this sort of thing, but my postdoc, Andrew Olivier is planning to work on resurrecting the optimization machinery
    - He’s in the audience at FNAL today
- The **functionality necessary in the beam simulation mostly still exists**
  - But will require some mucking with Geant4 geometries
  - Optimization algorithm is relatively simple; could reuse my scripts or re-implement
  - Will need **help from beam experts on constraints** / space to explore

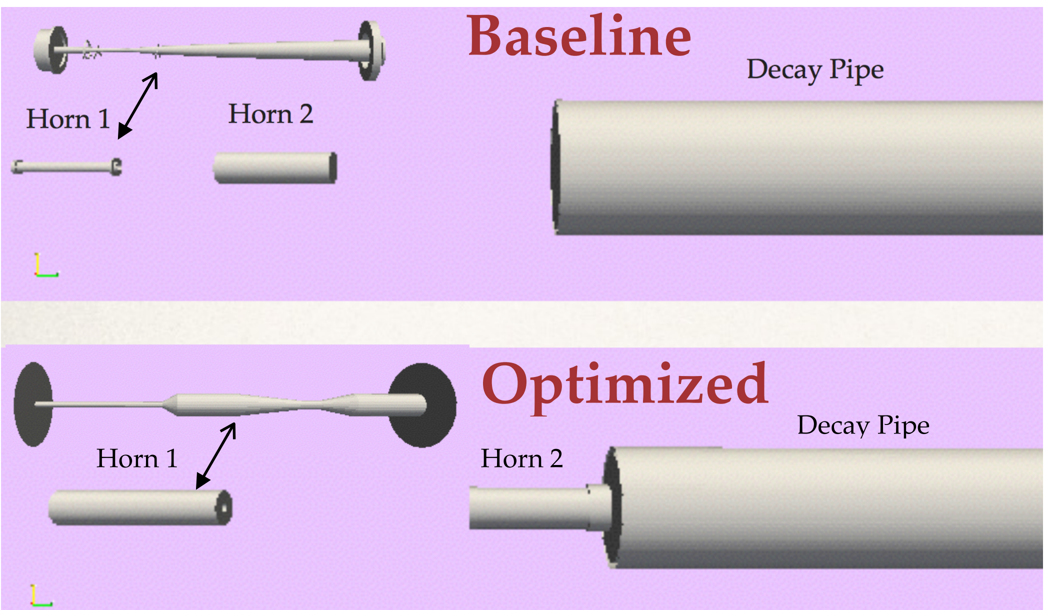
Conclusion

- 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
- **Preliminary studies** have been done for 2.4 MW
- **Full re-optimization for 2.4 MW** and tau neutrinos can be done, but will take quite a bit of time
  - And we will need **help from engineers**

Thank You!

Initial Results

- Our first attempts at optimization considered a two-horn system



Features of optimized focusing system:

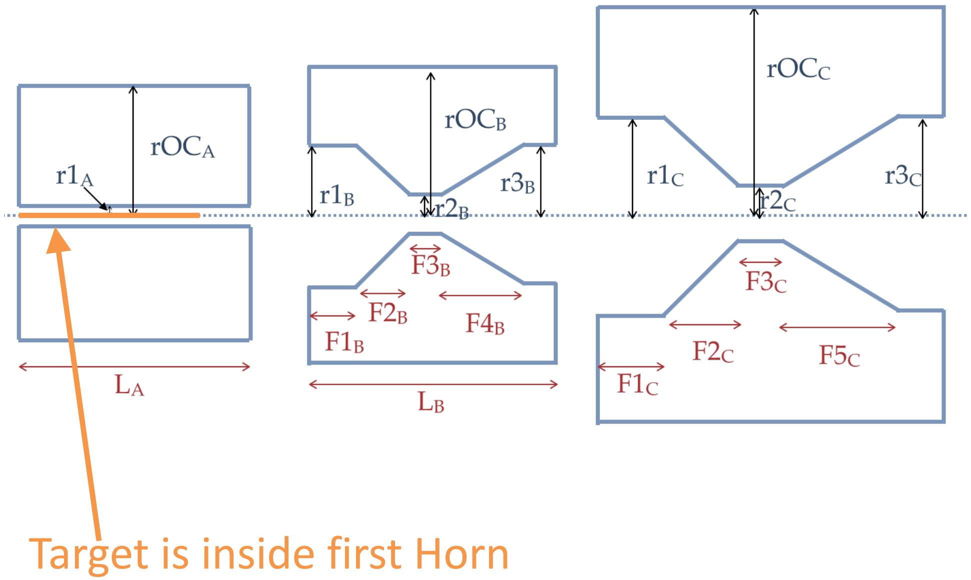
- Very long first horn
- Long (2.5 m) target
- Larger second horn
- Greater horn separation
- As much horn current as possible

Iteration with Engineers

- We embarked on many more rounds of optimization, incorporating realistic engineering constraints

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

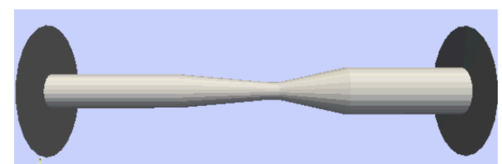


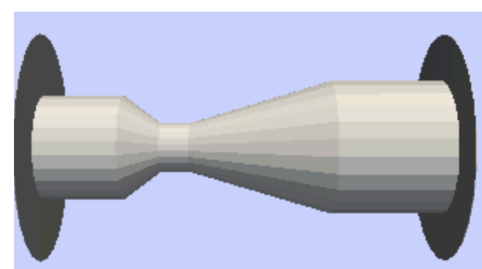
Final Idealized Design

- We ultimately chose to pursue the focusing system with the best CP sensitivity of all of our optimized beams:

Features of final idealized design

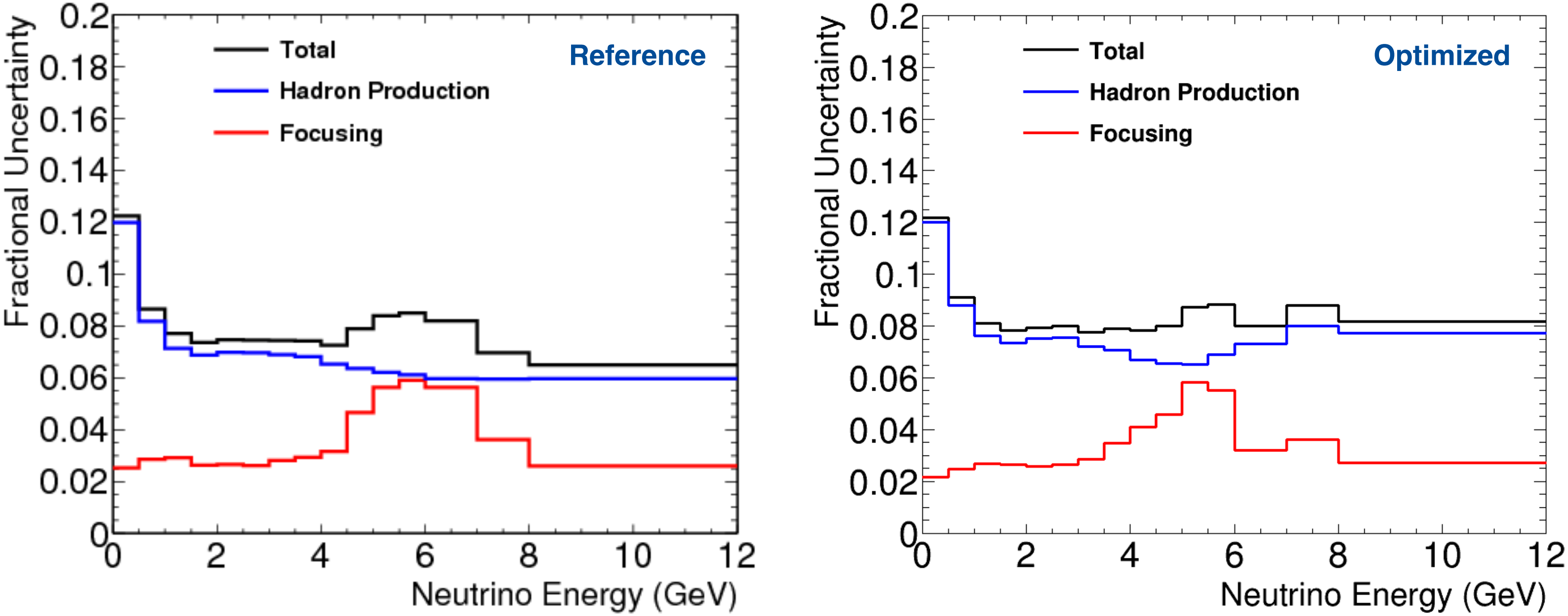
- Short first horn, slightly tapered
- Long (nearly 4 m) second horn
- Wide third horn
- 2 m long target
- 300 kA horn currents
- 110 GeV proton beam





Systematic Uncertainties of Optimized Beam

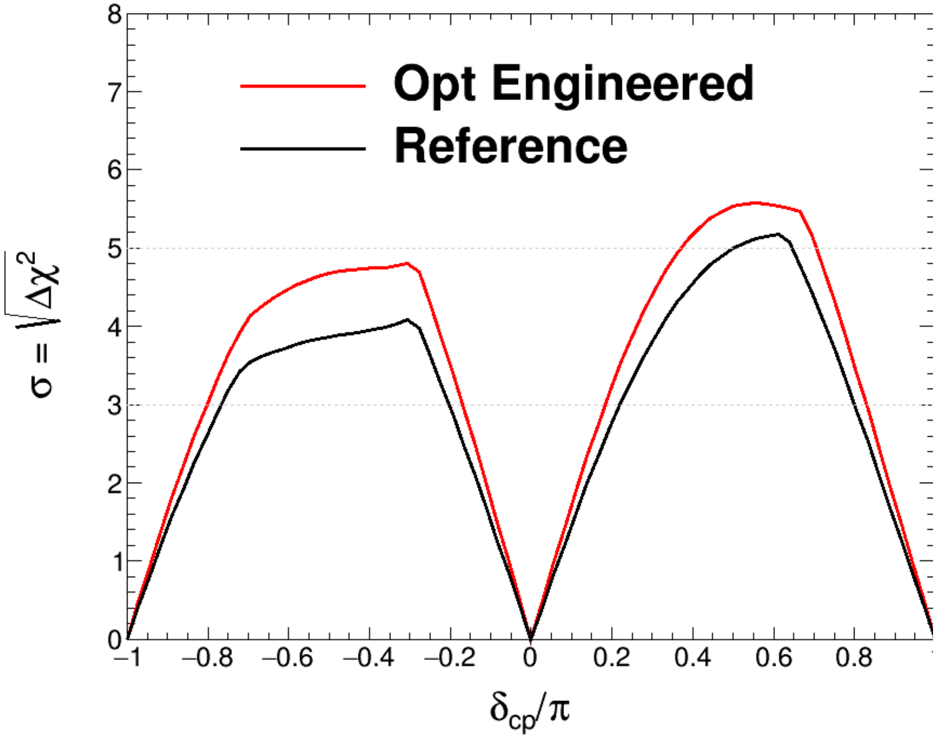
- Also studying uncertainties on neutrino flux with optimized beam
  - Estimated using infrastructure developed by MINERvA



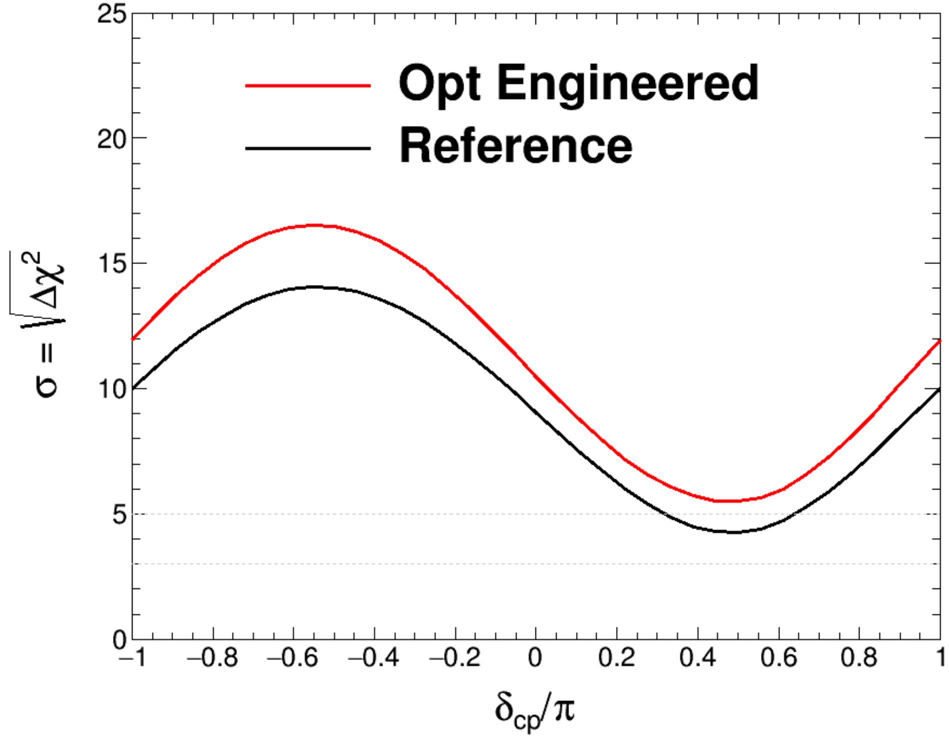
Physics Performance of Beam Options

- This translates into improvements in physics sensitivities

Sensitivity to CP Violation



Sensitivity to Mass Hierarchy

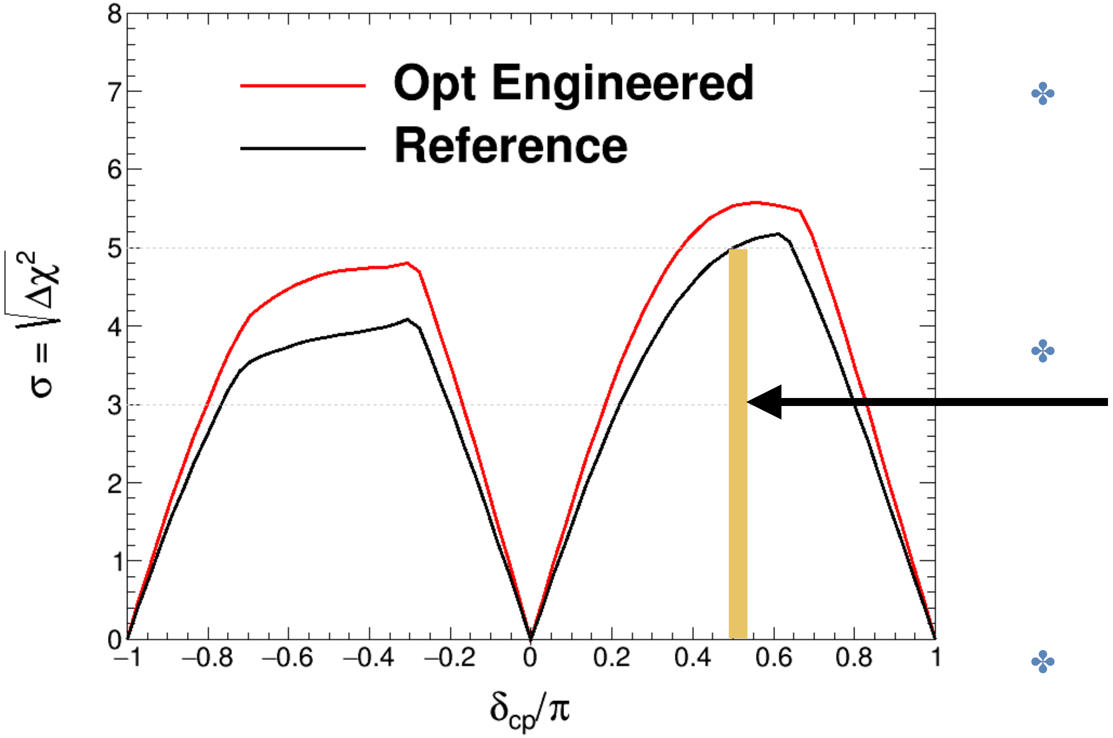


Sensitivities use CDR GLoBES setup and default parameters, and exposure of 300 kT MW years; CP sensitivity assumes a normal mass hierarchy

Physics Performance of Beam Options

- You're going to see a lot of this plot, so let's go over it briefly:

Sensitivity to CP Violation



- It shows how sensitive DUNE will be to CP violation after about 6 years
- 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

Physics Performance of Beam Options

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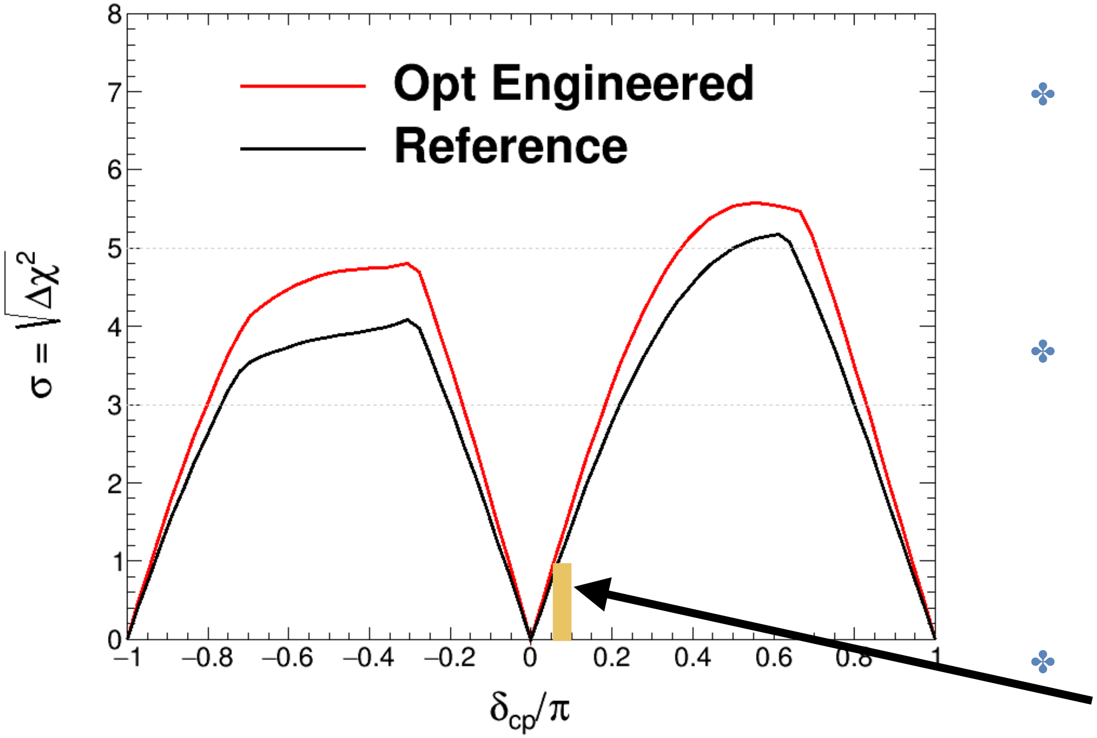

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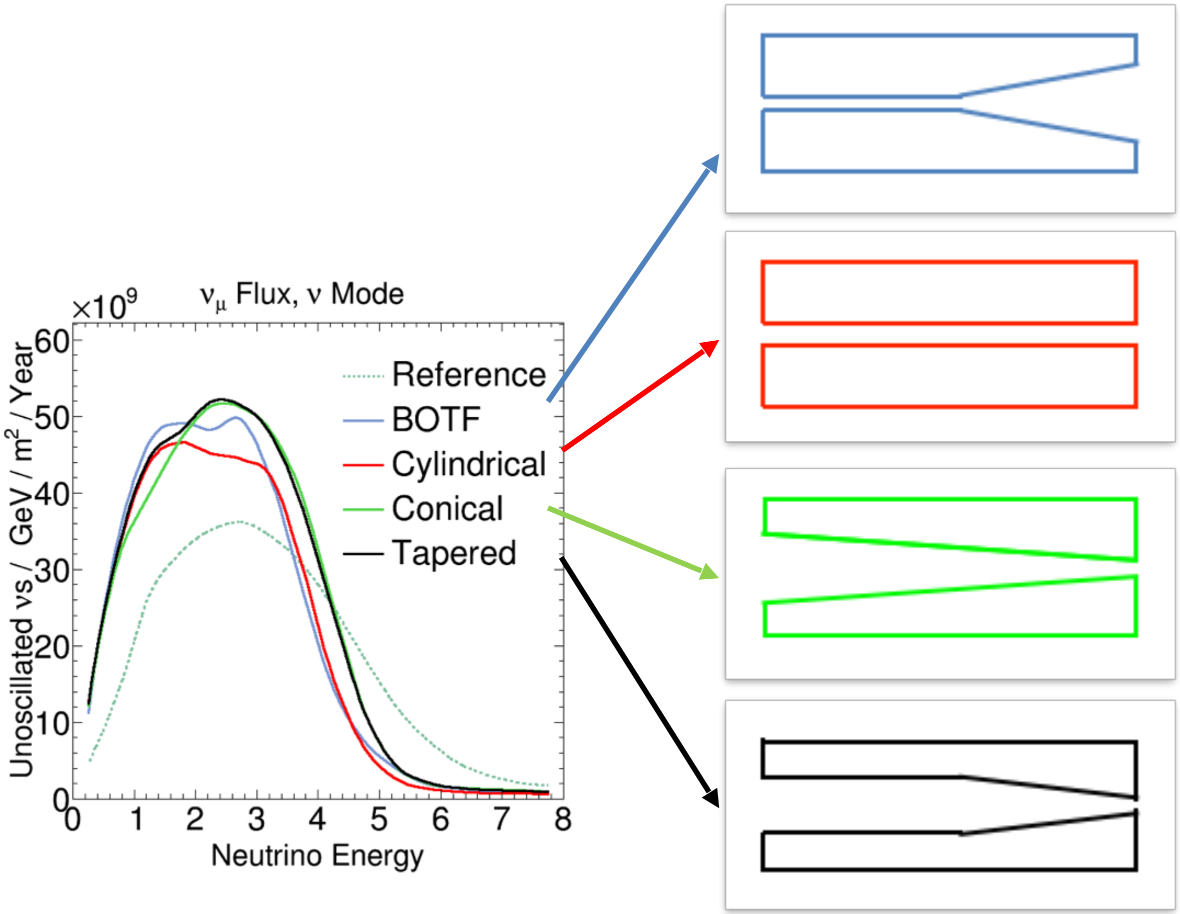
Iteration with Engineers

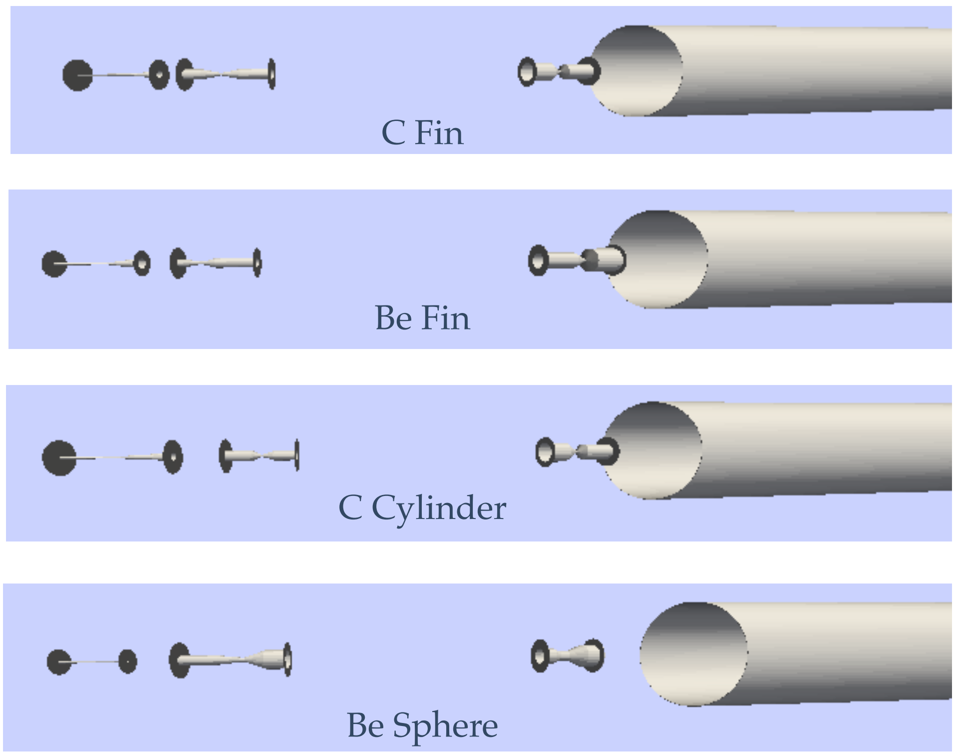
- We also considered a bunch of options for the shape of the first horn



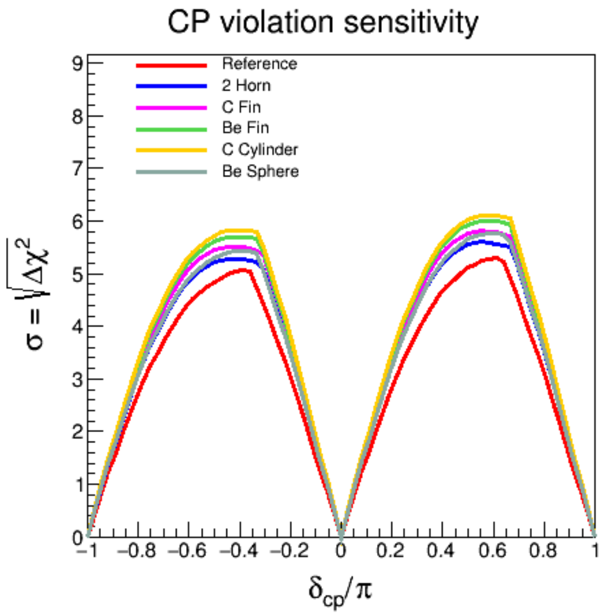
- Engineers expressed preference for more simple inner conductor
- See slightly better performance with more complex shapes — flared or tapered shapes vs cylindrical or conical inner conductor

Iteration with Engineers

- And ran optimizations with a several different target options:

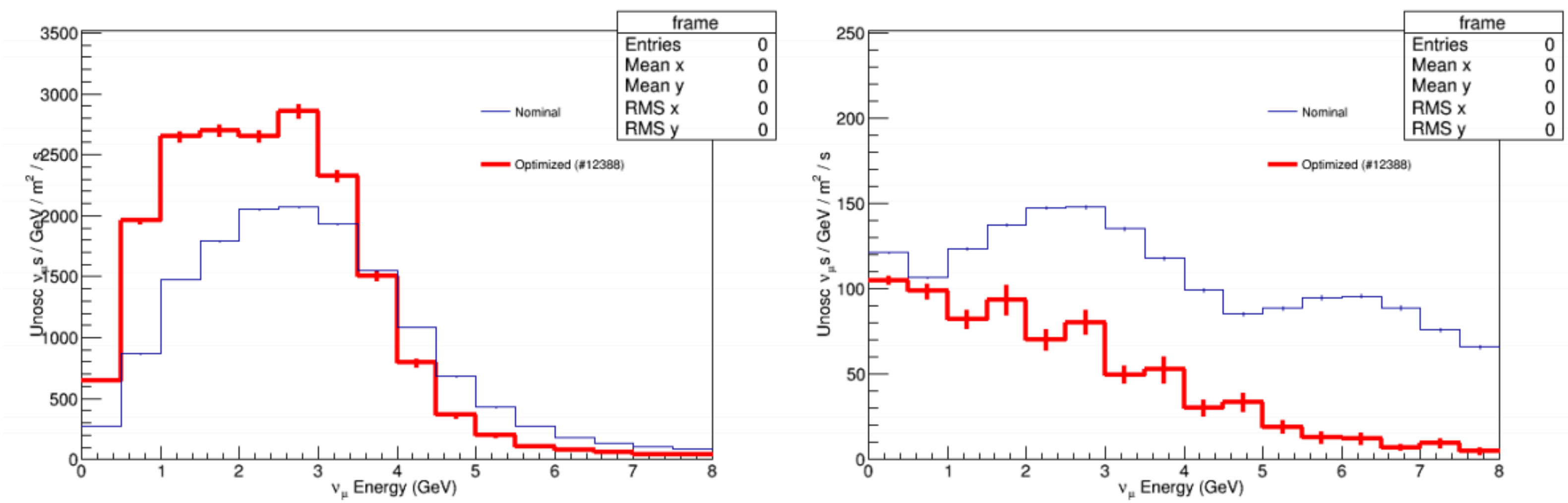


Different targets caused the optimization to find slightly different focusing systems. Some combinations are better than others, physics-wise



Iteration with Engineers

- Subdominant neutrinos matter too



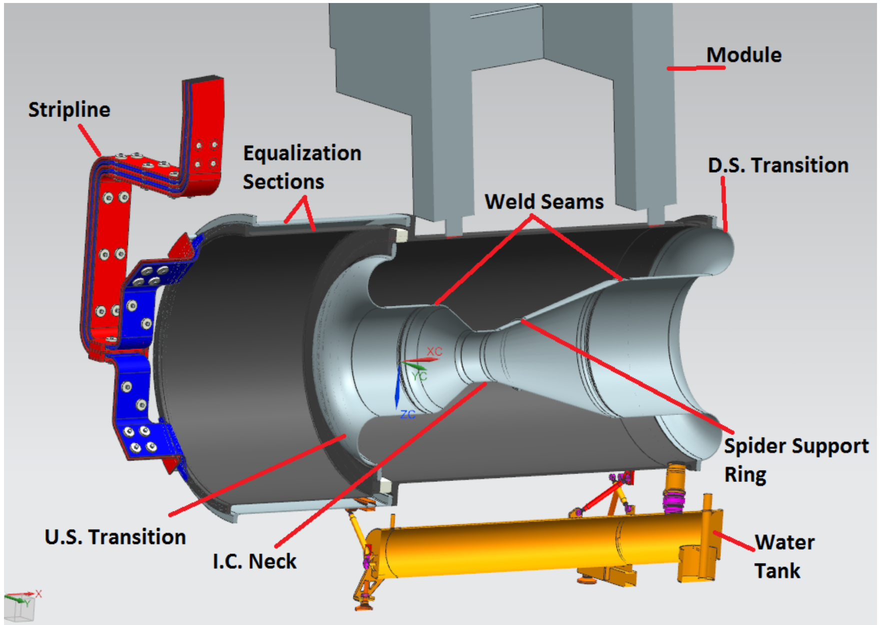
In many cases, improvements to CP-sensitivity is due not only to increases muon neutrino flux (and muon antineutrino flux in antineutrino mode), but also reductions in neutrino backgrounds in antineutrino mode ("wrong-sign" backgrounds")

Toward Reality

- The optimized horns at this point were basically sheets of aluminum with 300 kA but no cooling or supports
  - We turned the design over to engineers to add necessary details of real horns

It wasn't possible to include details like full support/cooling systems in the simulation used for the optimization

These elements were expected to have a modest negative impact on the performance of the beam (more material = less neutrinos)



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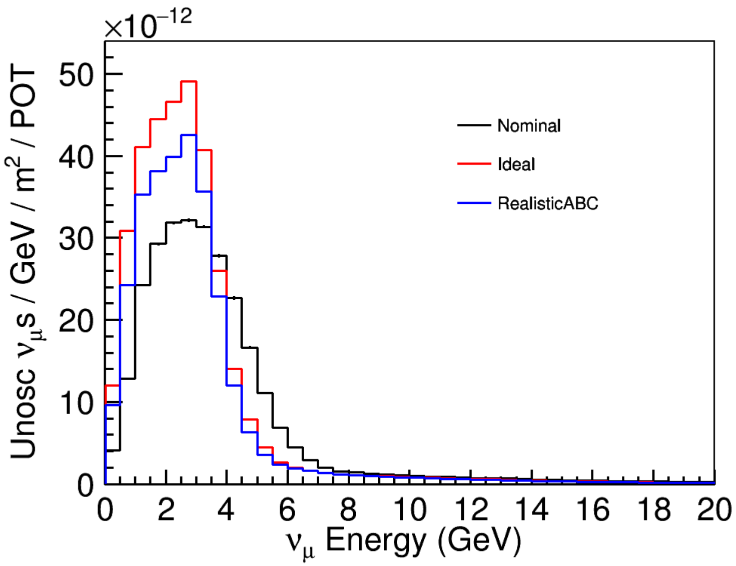
- The optimized horns at this point were basically sheets of aluminum with 300 kA but no cooling or supports
  - We turned the design over to engineers to add necessary details of real horns

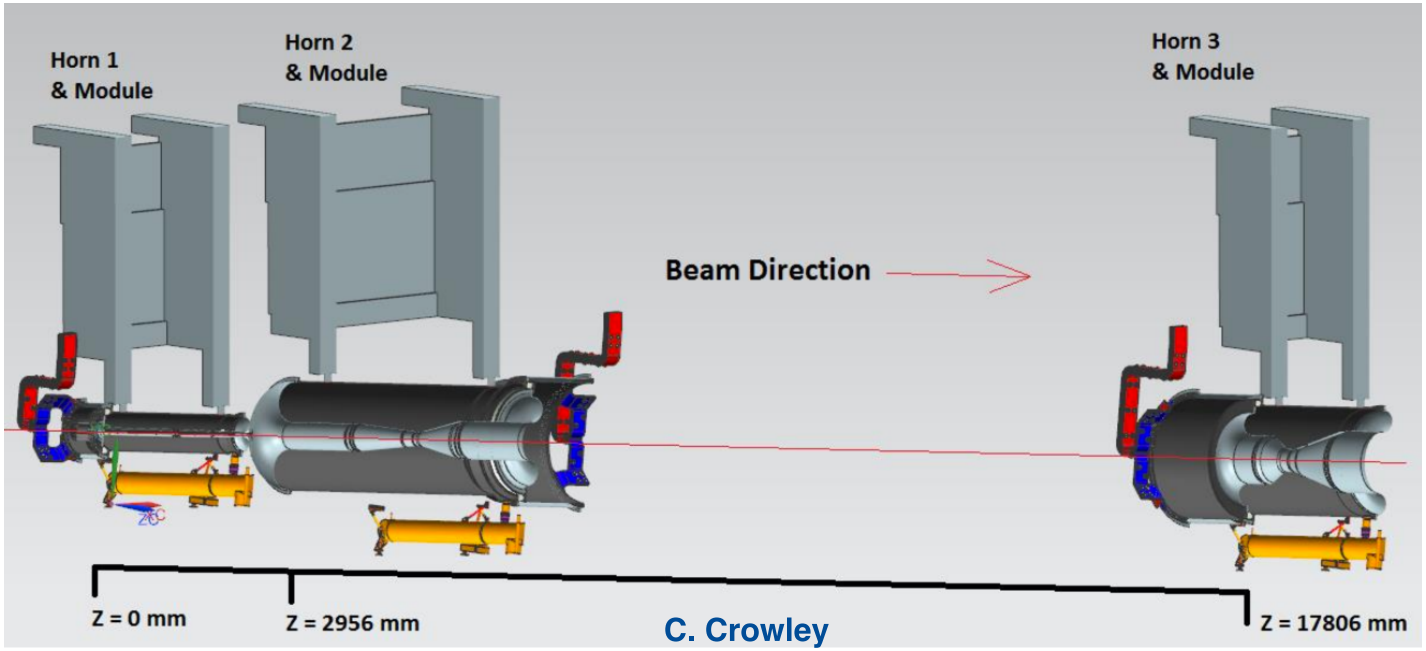


Initial results showed big losses in neutrino flux and physics performance

What we learned:
Most losses came from a “game of telephone” between engineers and physicists
Also, some came from extra material in the beamline — inner conductors and target supports

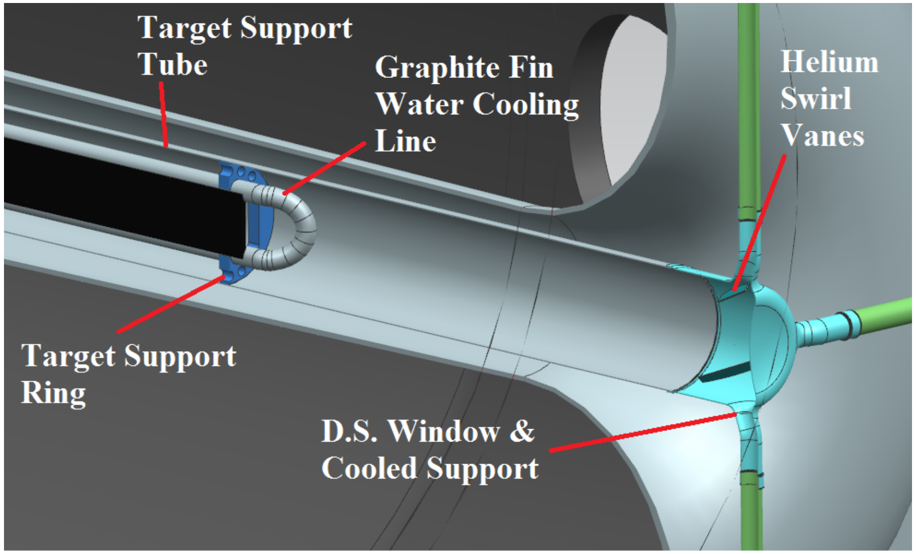
Toward Reality

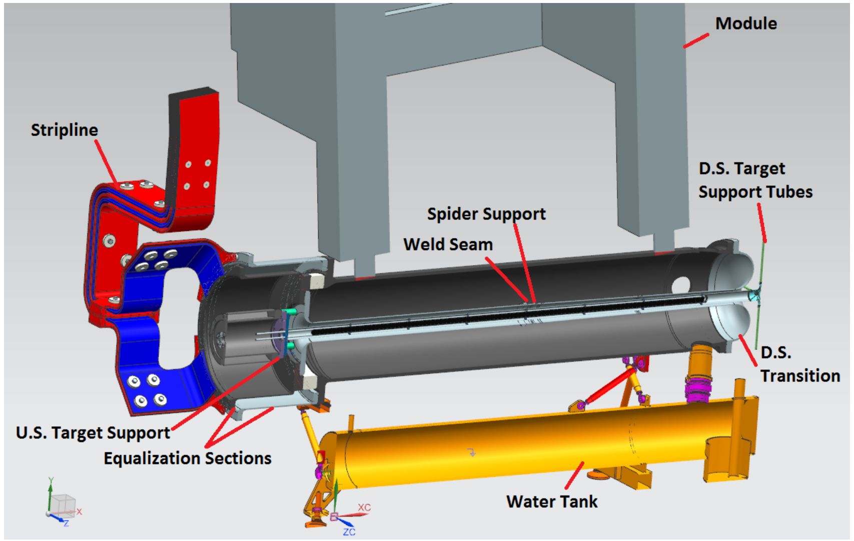
- Engineers then produced a second iteration, taking into account the lessons learned from the first round



Toward Reality

- Engineers then produced a second iteration, taking into account the lessons learned from the first round
  - 2 m target is fully integrated into Horn A
  - Target body & cooling lines are held by support rings inside a titanium tube.

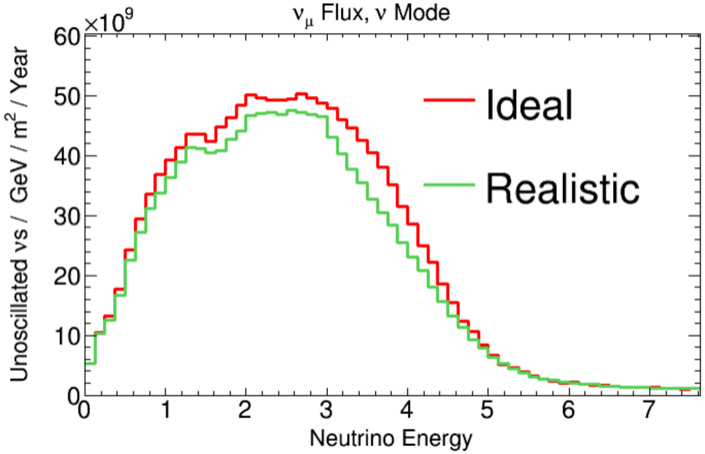


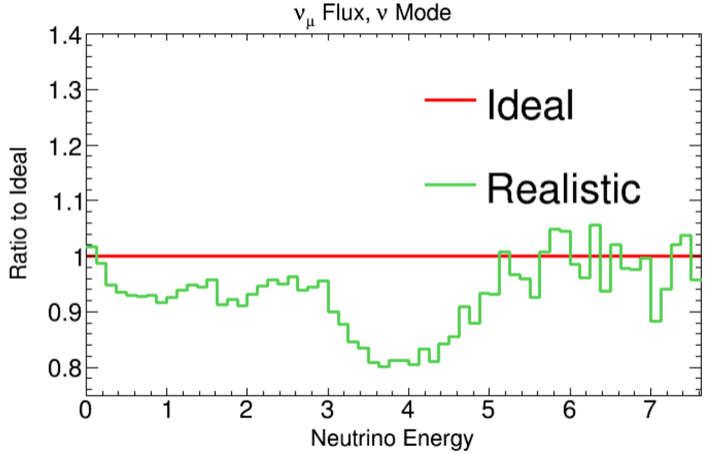


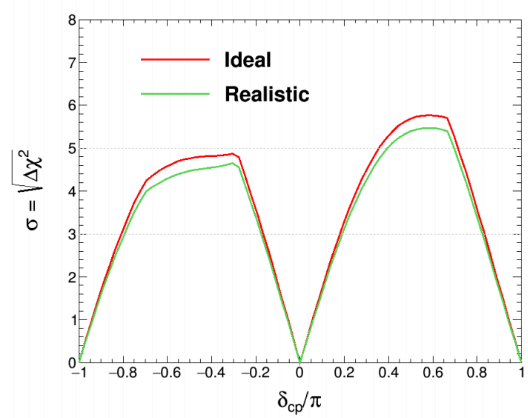
  - Helium flows through support tube from upstream end for heat removal.

Toward Reality

- Flux/physics losses this time were quite modest:

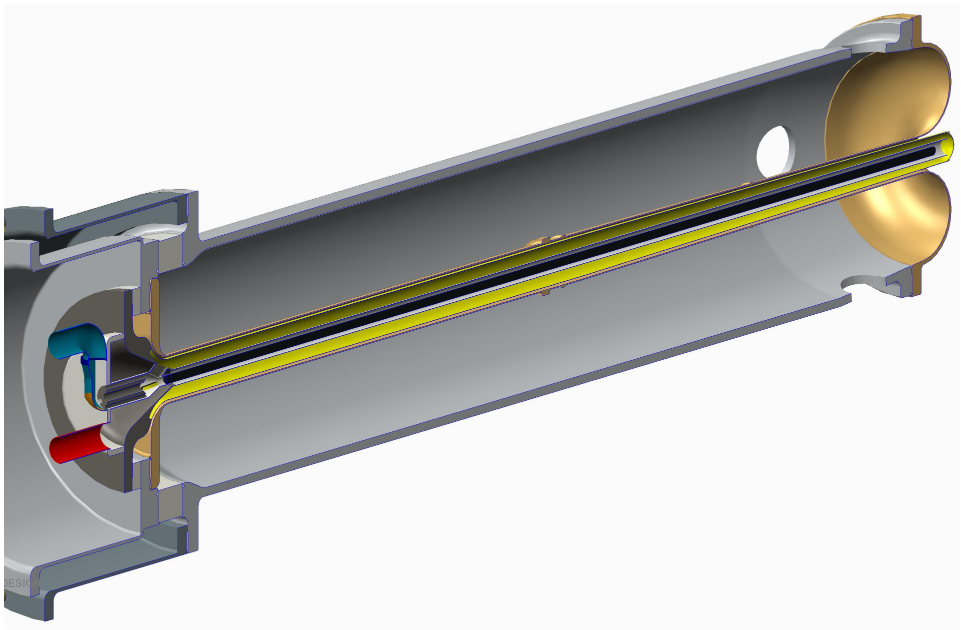


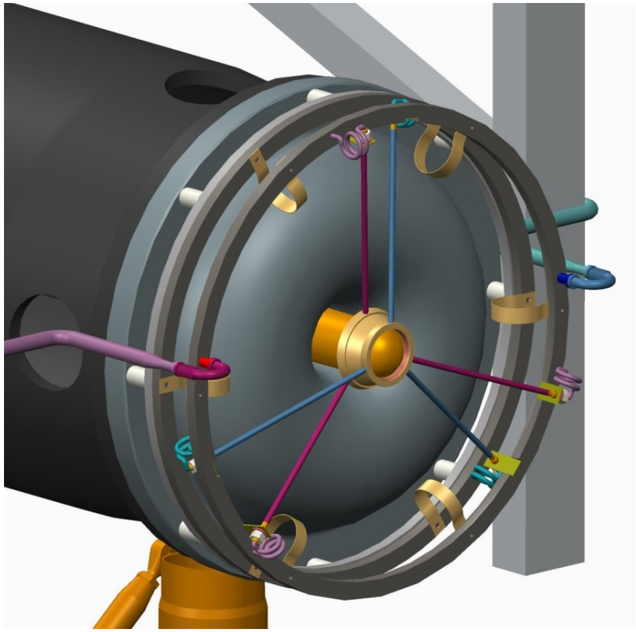




Toward Reality

- And those losses were mitigated by a new target design:

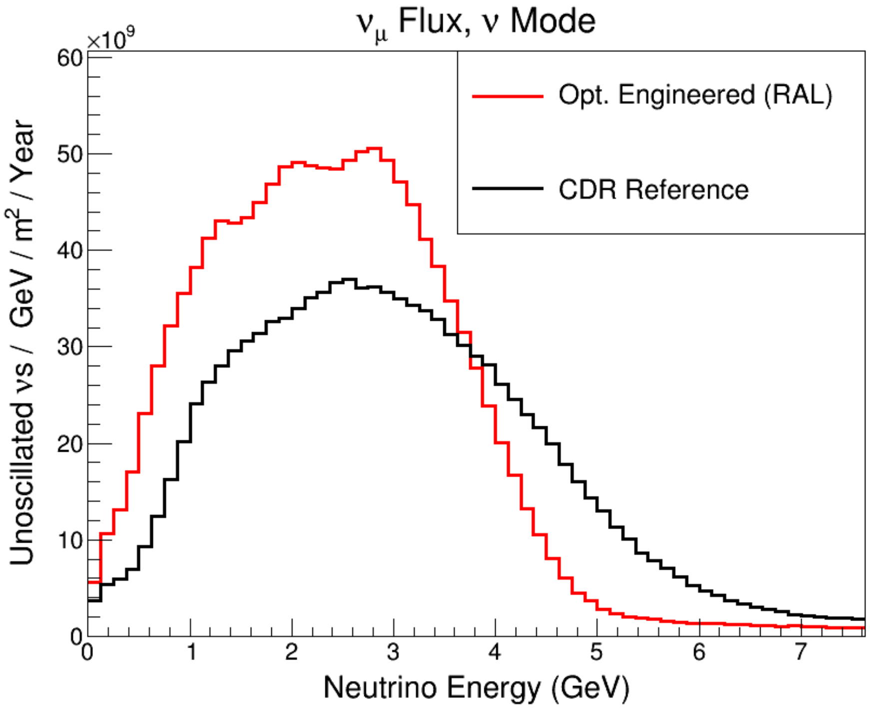


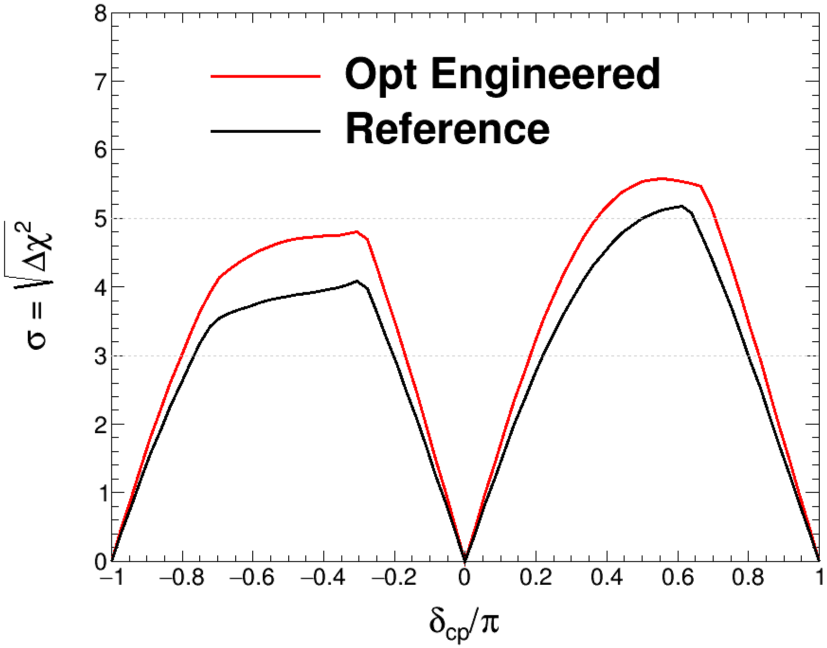


  - After optimization, a carbon cylindrical design was developed at RAL
  - Have studied two options — 2.2 m long cylinder w/ cooled support (current nominal design), and 1.5 m without support

Toward Reality

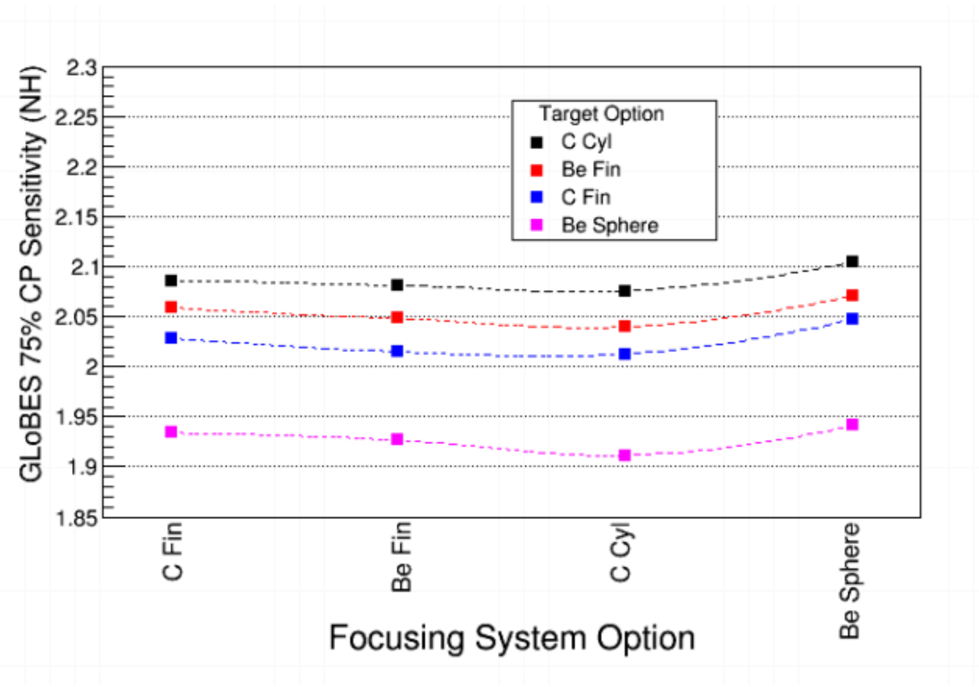
- And that brings us back to the optimized beam I described at the beginning of the talk:





Iteration with Engineers

- Further investigation of optimizations performed with different options:

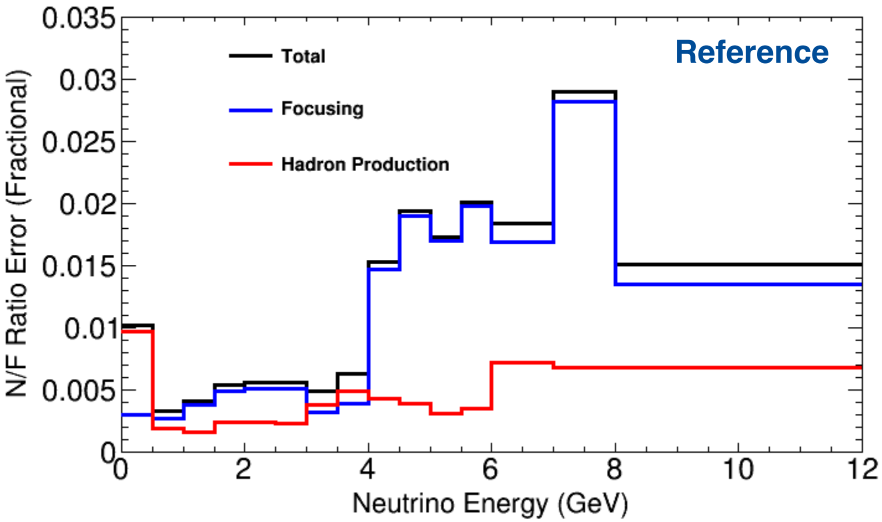


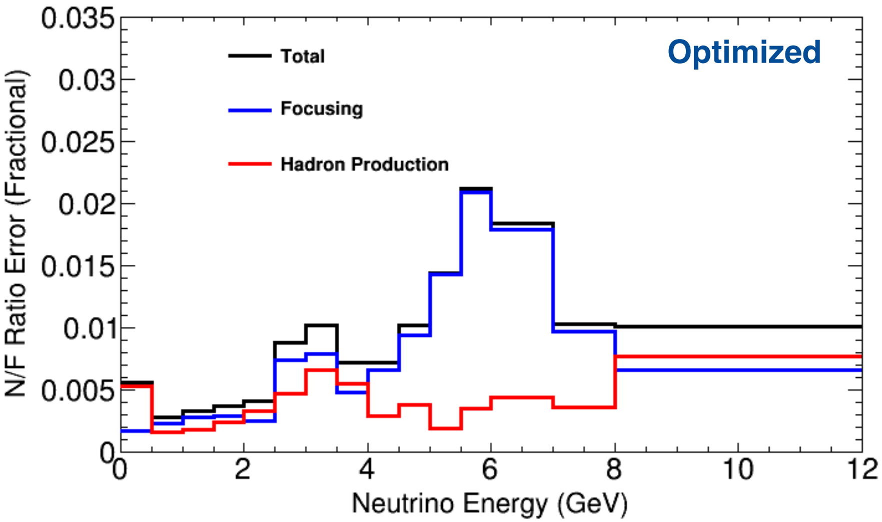
Difference in physics performance was primarily due to the target itself, not focusing system.

Cylindrical and Sphere targets here do not have complete material description, so this is not an apples-to-apples comparison

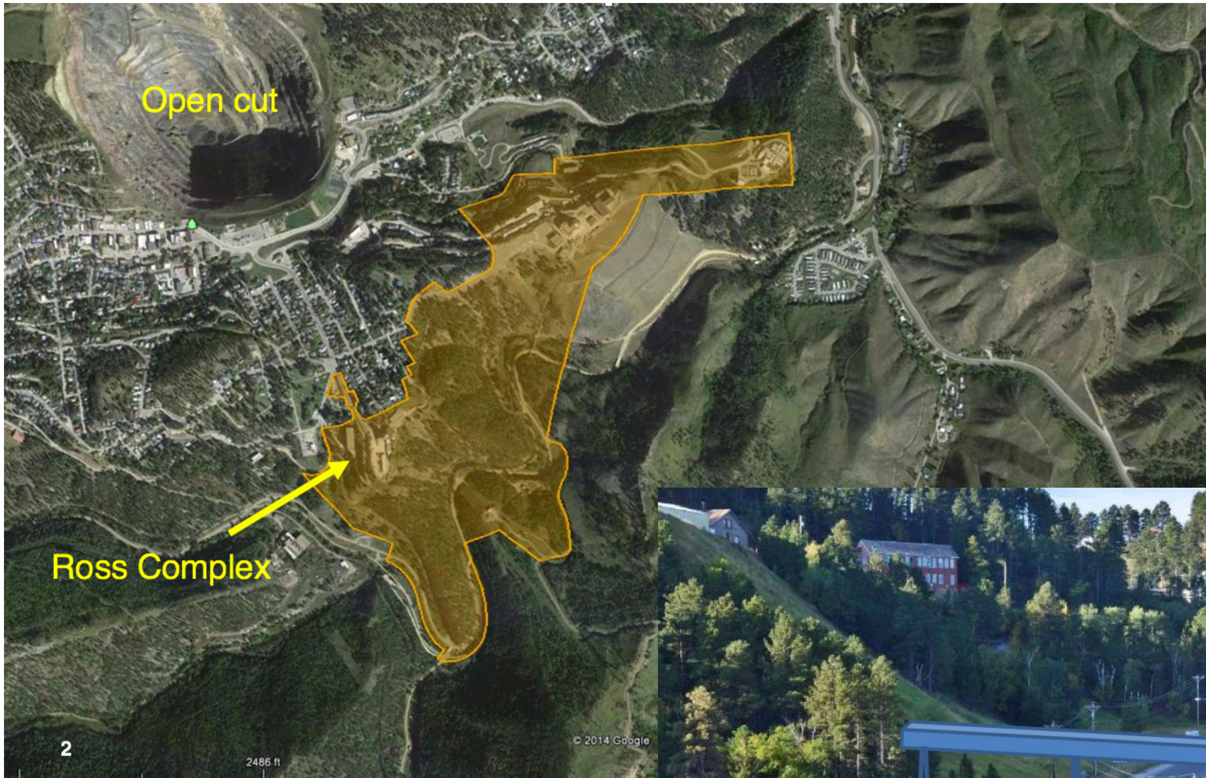
Systematic Uncertainties

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





LBNF/DUNE: Overview



875,000 tons of rock will be moved from shaft to open cut

Conceptual illustration of rock conveyer. Construction begins this year; ~3 years of rock-moving expected

LBNF/DUNE: Overview

Construction has begun!

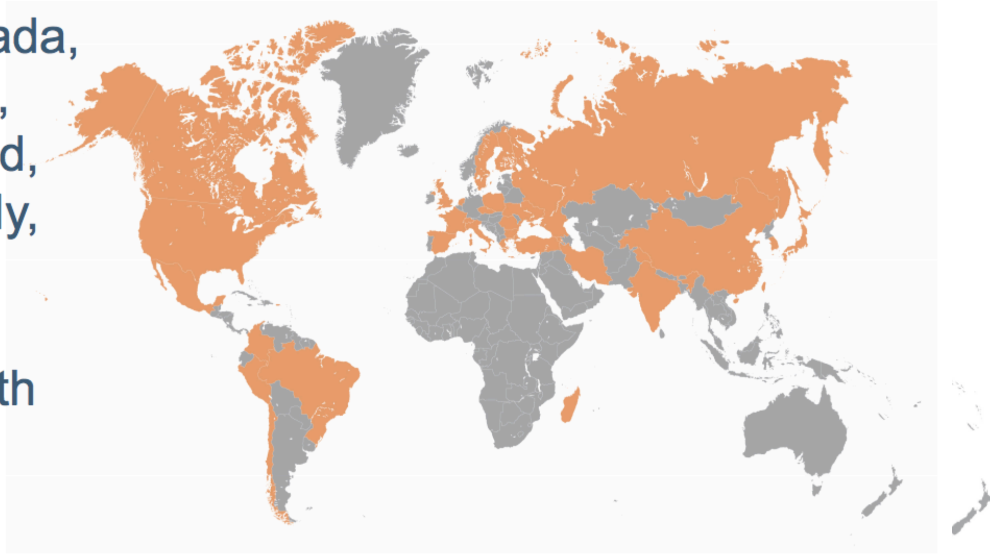
LBNF/DUNE: Overview

As of today:

60 % non-US

1095 collaborators from 175 institutions in 31 nations

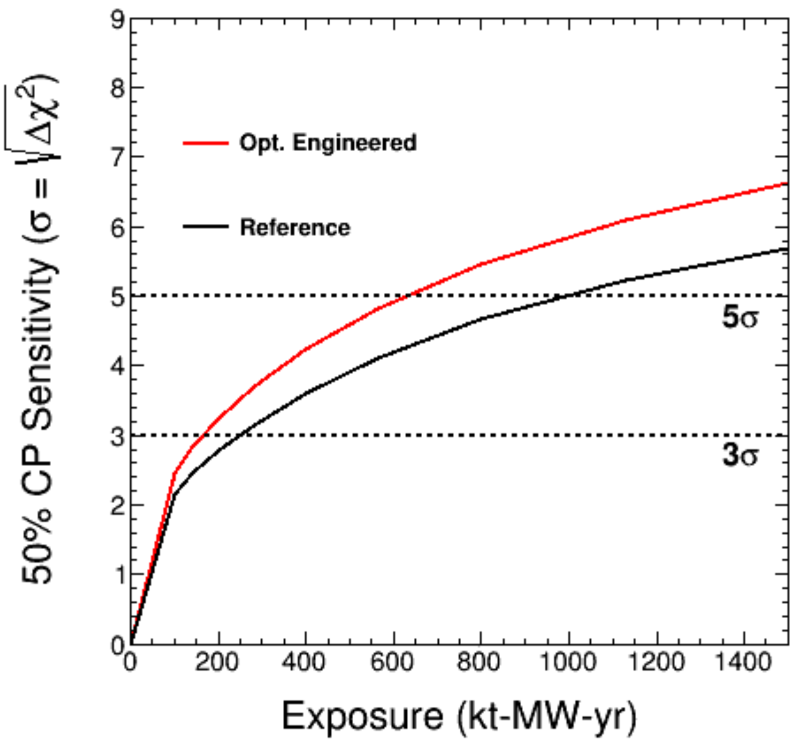
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

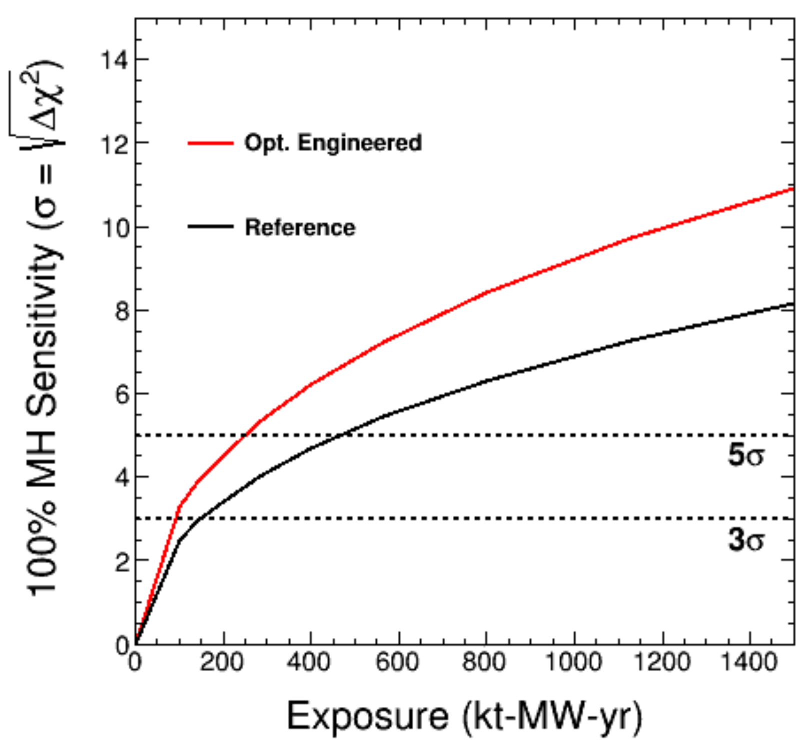


DUNE: a fully international science collaboration
LBNF (Long Baseline Neutrino Facility): US(DOE)-hosted project with international contributions

Physics Performance of Beam Options

- Improvements are present for all exposures:





Sensitivities use CDR GLoBES setup and default parameters; CP sensitivity assumes a normal mass hierarchy

Physics Performance of Beam Options

- Comparison of a few milestones

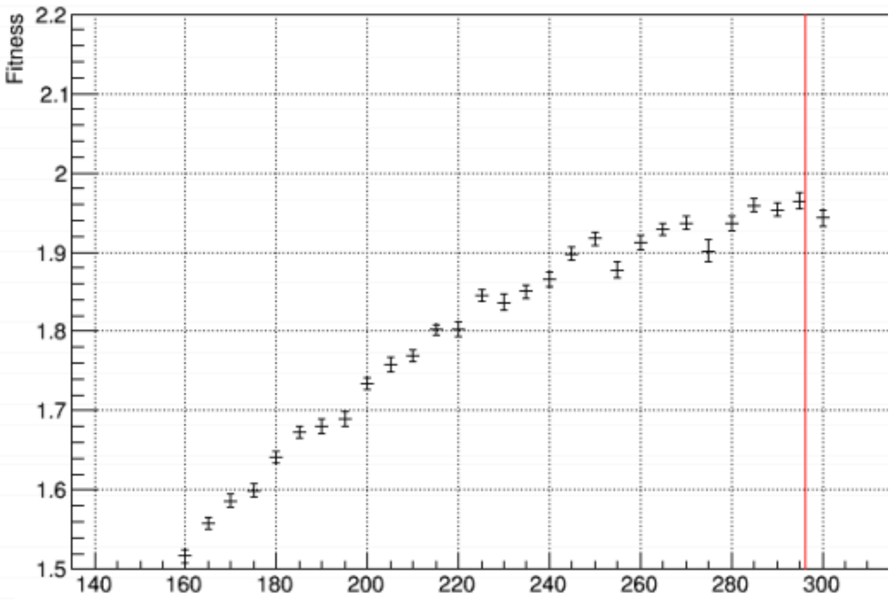
	Optimized	Reference	Improvement vs Reference
Time to 3 sigma 75% CP sensitivity (kT MW y)	921	1577	42%
Time to 5 sigma 25% CP sensitivity (kT MW y)	293	419	30%
100 % MH coverage @ 400 kT MW y (# sigma)	6.21	4.69	33%
$\sin^2 2\theta_{13}$ resolution @ 1000 kT MW y	0.0036	0.0043	18%
$\sin^2 \theta_{23}$ resolution @ 1000 kT MW y	0.0027	0.0031	12%

Equivalent to increasing mass of far detector by 70%, or 28 kTon

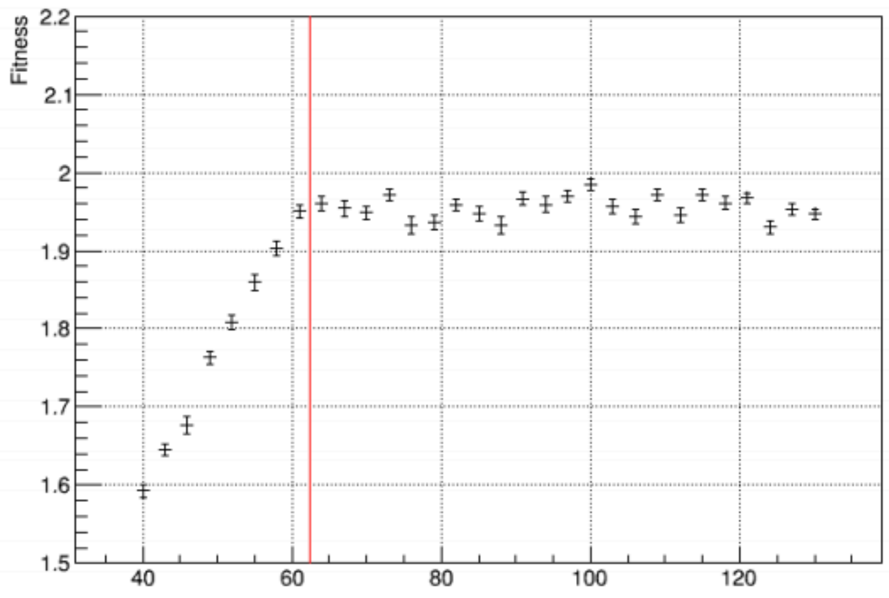
17 kTon of Argon

Beam Optimization

- Parameter scans were useful for understanding optimized systems:

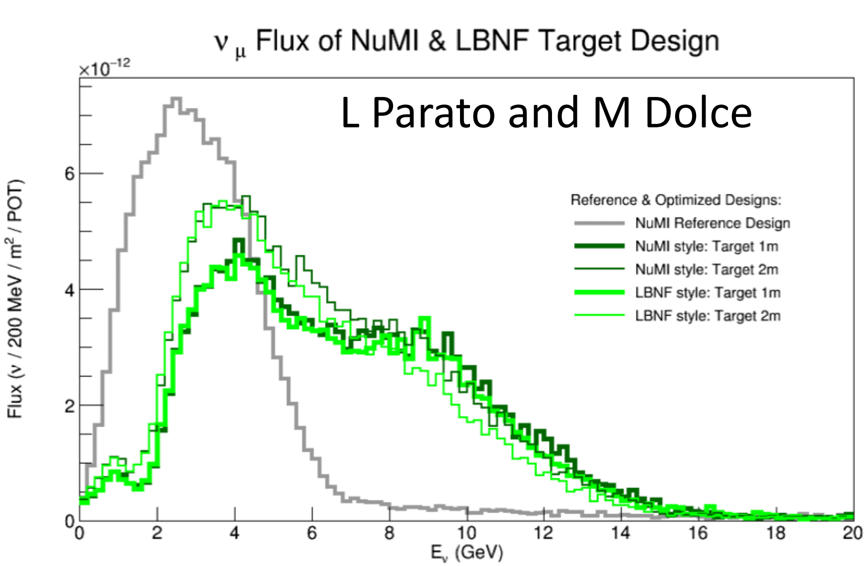


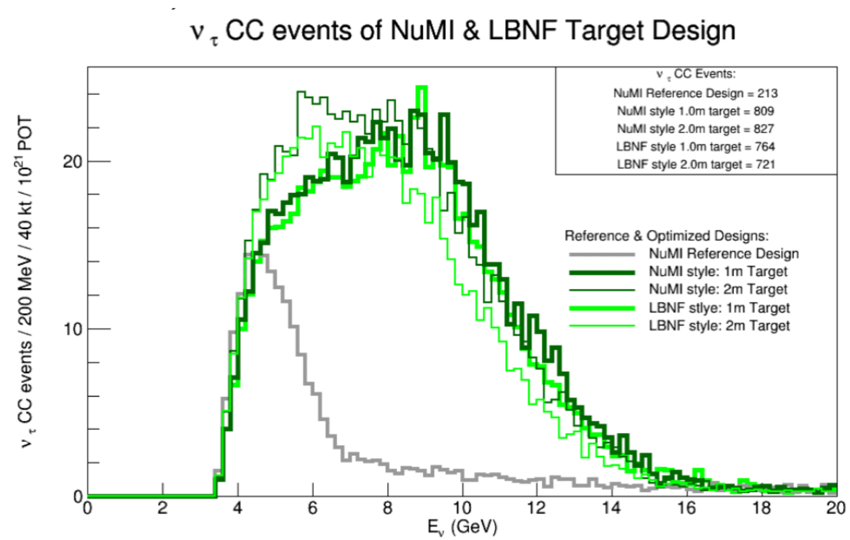
Horn Current (kA)



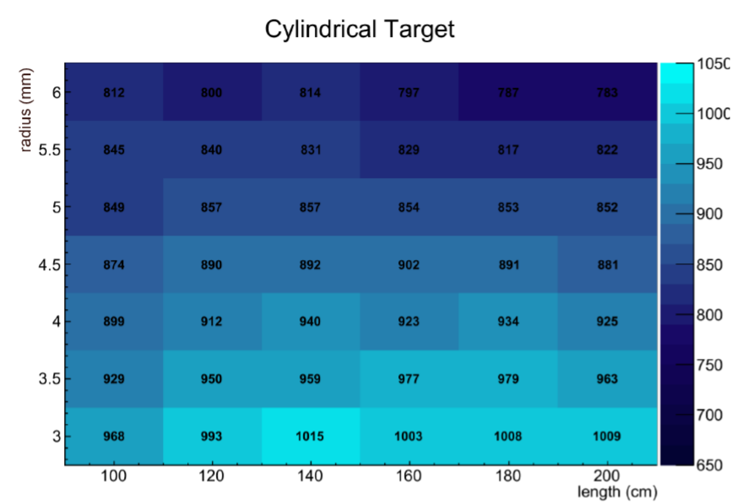
Proton Momentum (GeV)

High Energy Optimization





$$\sigma_{\text{beam}} = \text{target width}/3$$



- Have done optimizations for **tau neutrino** appearance
- **~1000 events / year** possible with NuMI parabolic horns
- Slightly less with optimized horns
- Also beneficial for separating **CP/NSI**

Toward Reality

- Cylindrical target gives modest improvements to flux/CP sensitivity: