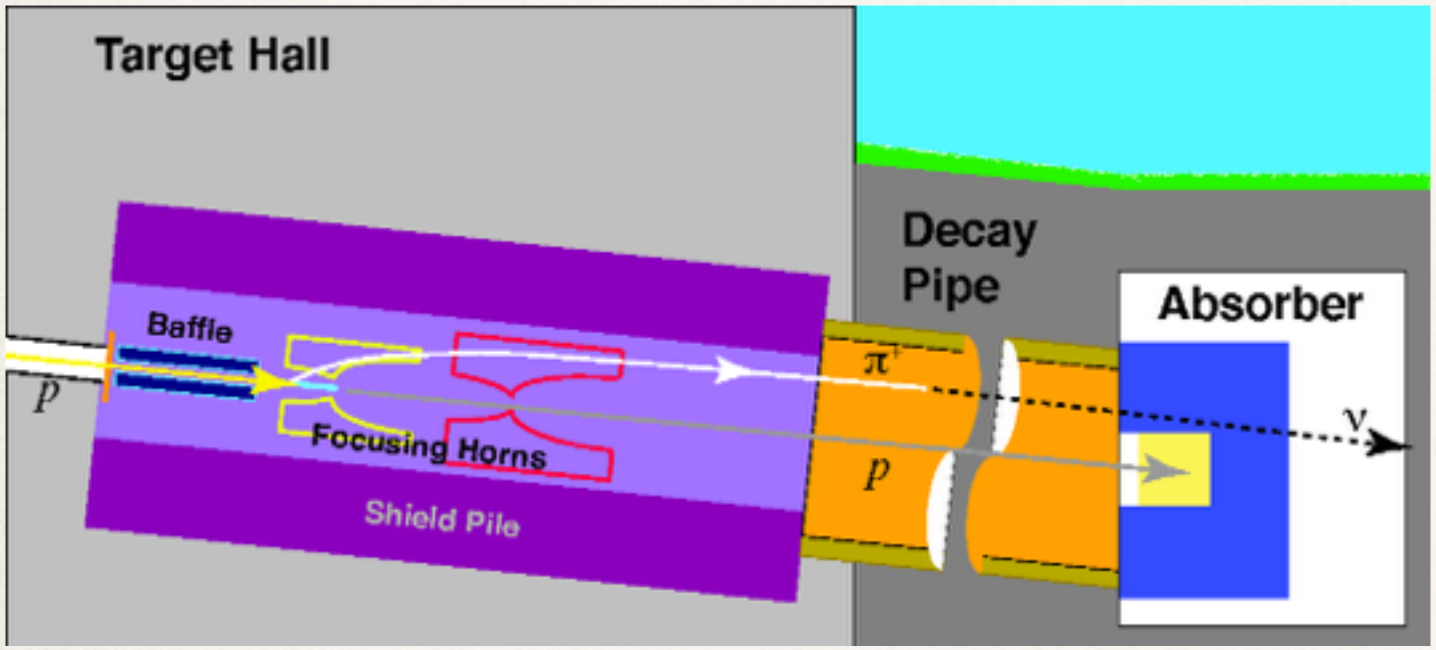
Beamline Optimization

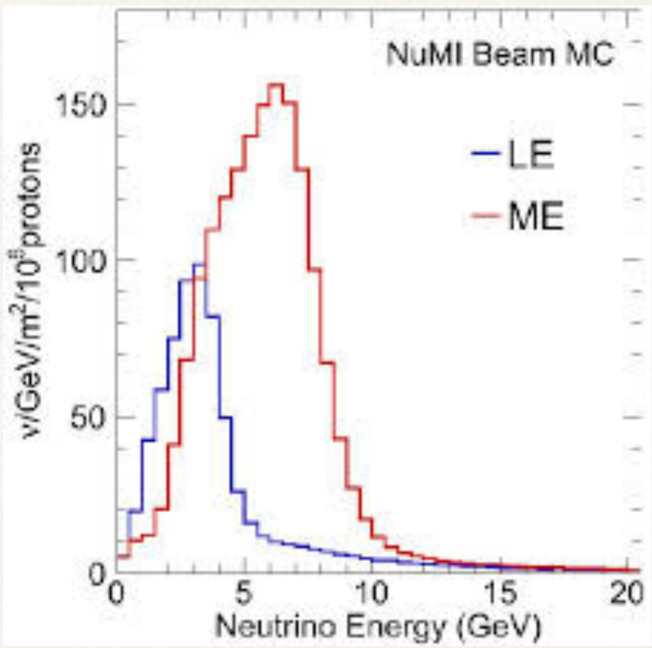
Laura Fields
Northwestern University

22 January 2015

Introduction

- Neutrino beamlines have a lot of configurable parameters:





- Primary beam energy, target size/shape, horn shapes/current/spacing, decay pipe dimensions

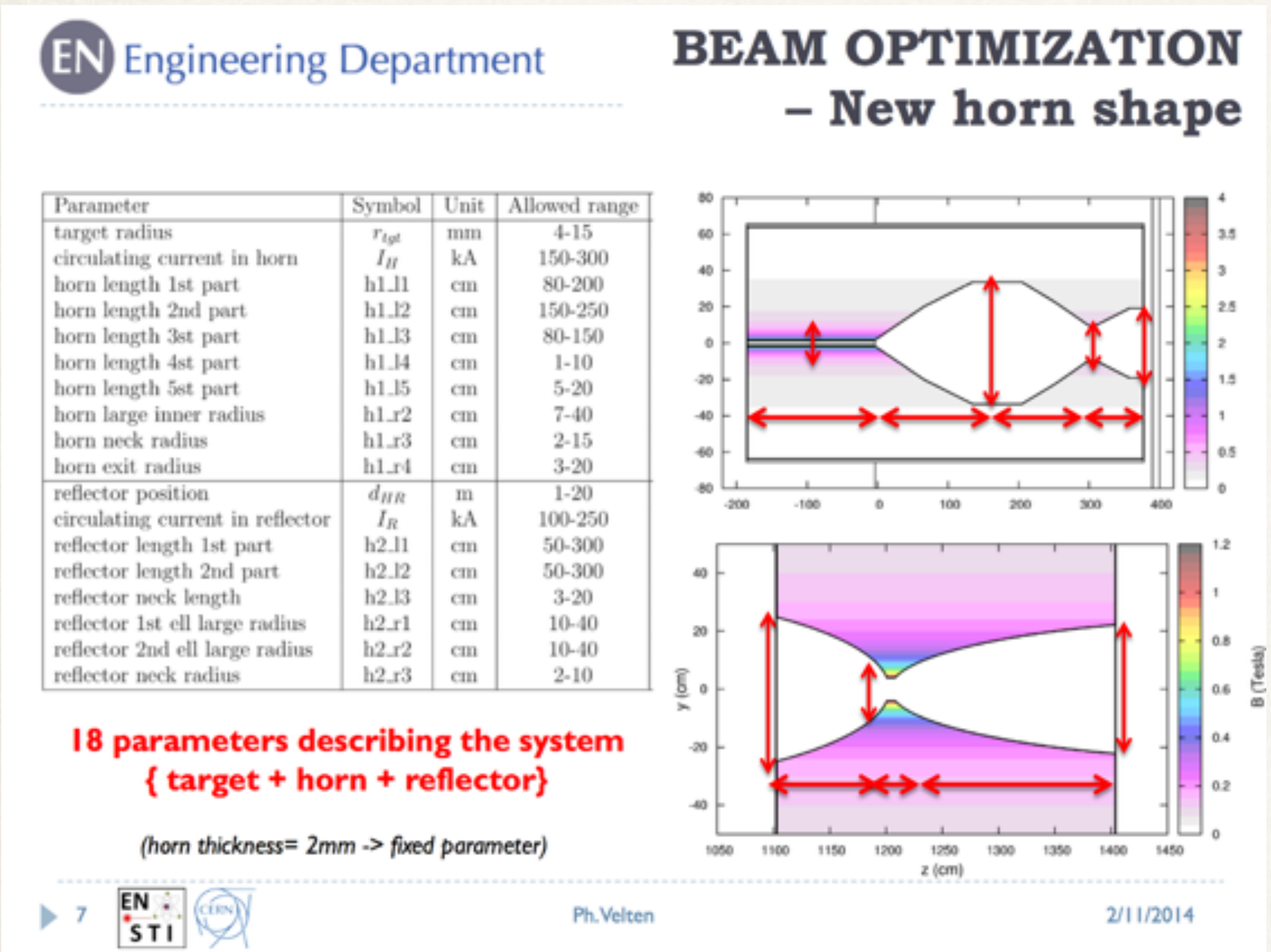
- The different NuMI beam tunes are an excellent demonstration of this

- My goal: to find the best configuration for ELBNF physics

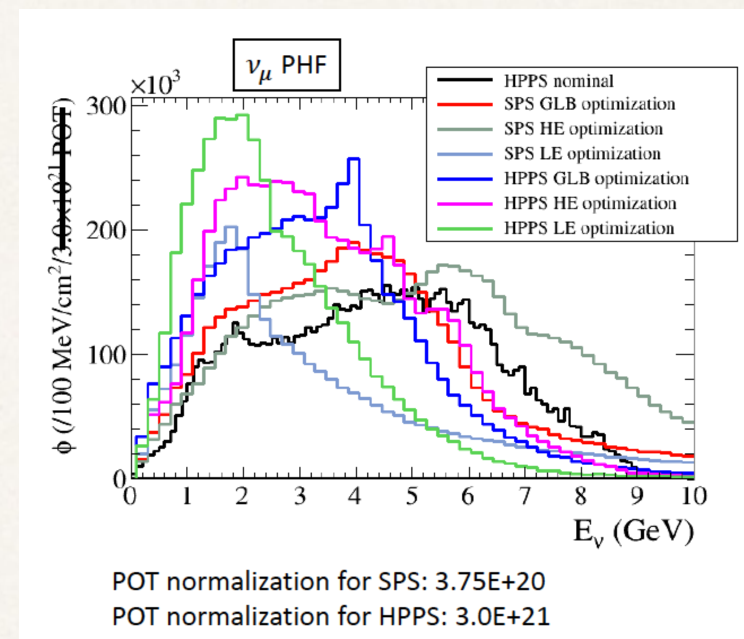
Introduction

- LBNO has had success optimizing their beam configuration:

Ph. Velten and M. Calviani



Parameter	Symbol	Unit	Allowed range
target radius	r_{tgt}	mm	4-15
circulating current in horn	I_H	kA	150-300
horn length 1st part	h1_l1	cm	80-200
horn length 2nd part	h1_l2	cm	150-250
horn length 3st part	h1_l3	cm	80-150
horn length 4st part	h1_l4	cm	1-10
horn length 5st part	h1_l5	cm	5-20
horn large inner radius	h1_r2	cm	7-40
horn neck radius	h1_r3	cm	2-15
horn exit radius	h1_r4	cm	3-20
reflector position	d_{HR}	m	1-20
circulating current in reflector	I_R	kA	100-250
reflector length 1st part	h2_l1	cm	50-300
reflector length 2nd part	h2_l2	cm	50-300
reflector neck length	h2_l3	cm	3-20
reflector 1st ell large radius	h2_r1	cm	10-40
reflector 2nd ell large radius	h2_r2	cm	10-40
reflector neck radius	h2_r3	cm	2-10

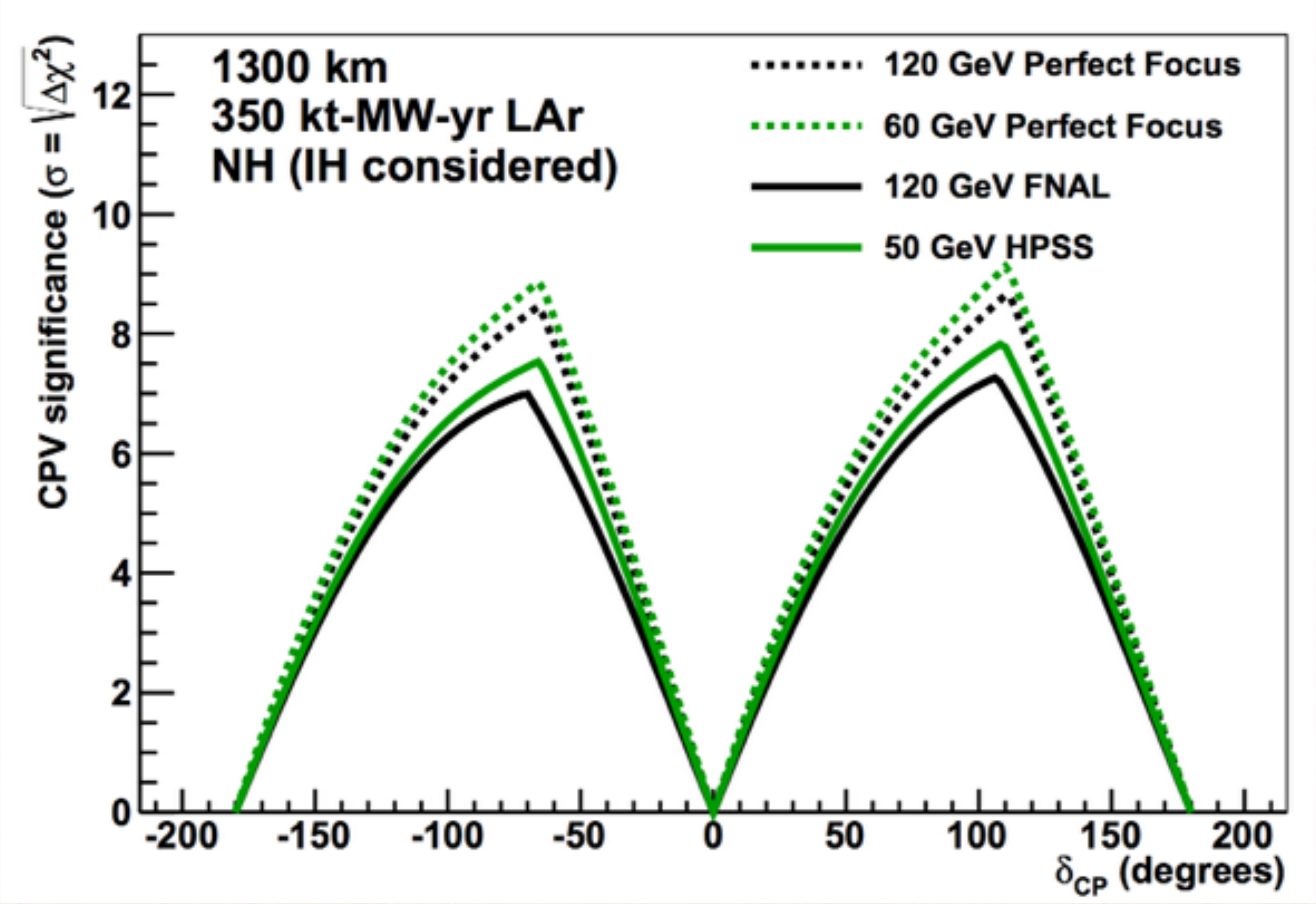


F. Sanchez Galan
NBI 2014

- Used a genetic algorithm, considered two different proton beams, and optimized to several quantities; the most successful optimized ν_μ flux from 1 to 2 GeV

Introduction

- Replacing the standard LBNE flux with the LBNO optimized flux in LBNE sensitivity studies modestly improves CP sensitivity:

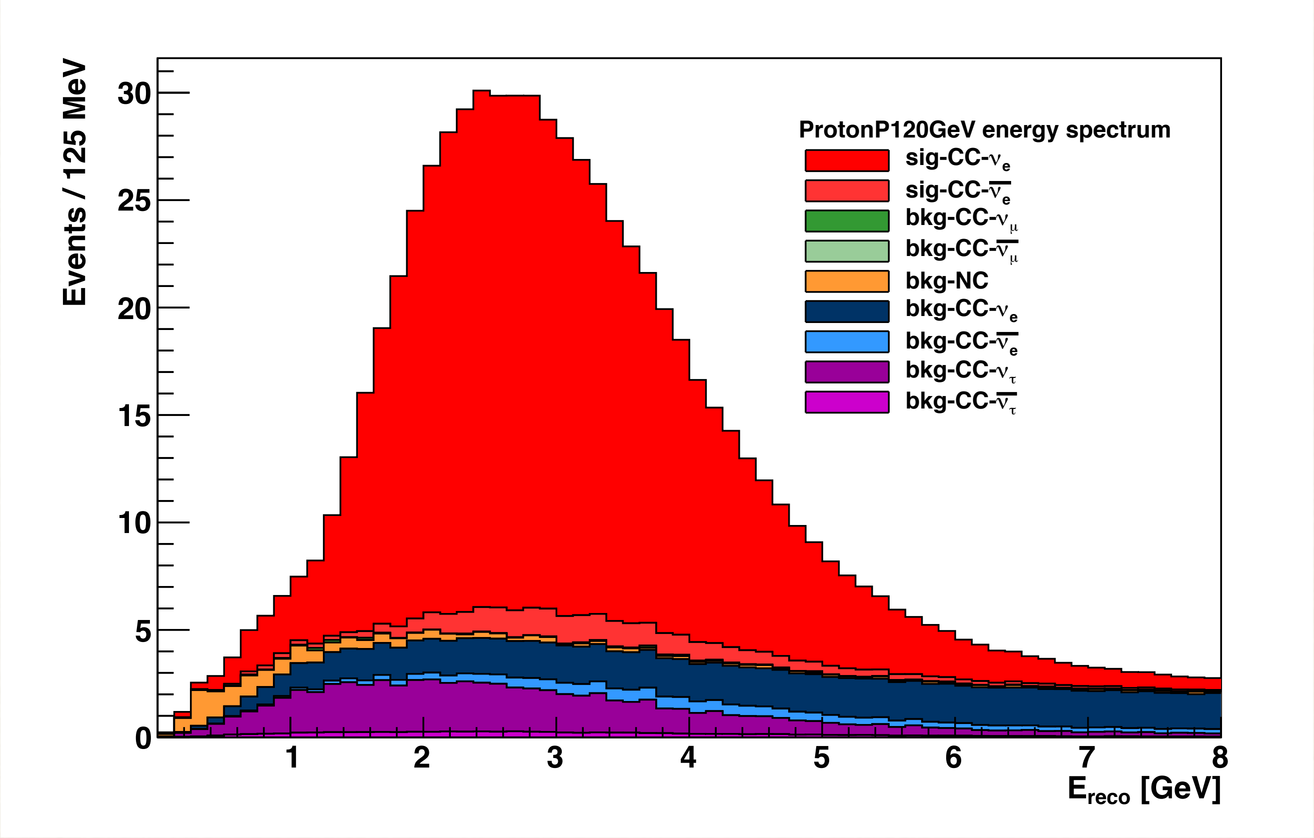


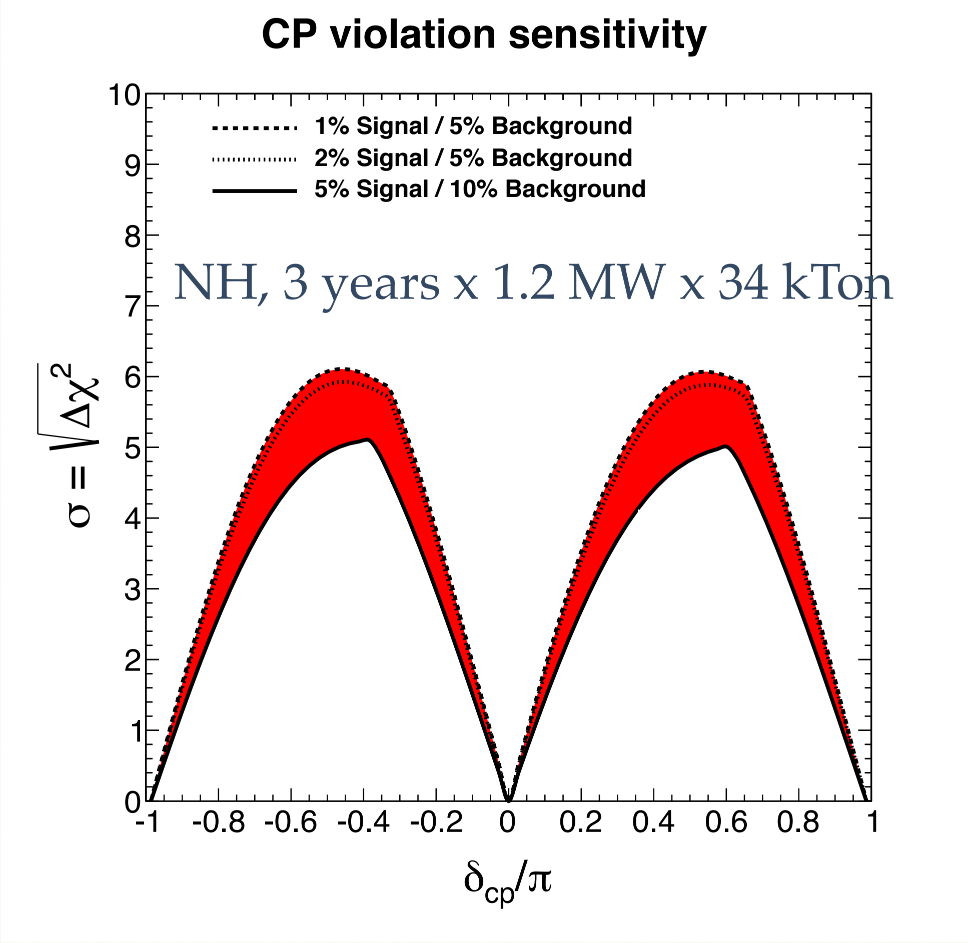
L. Whitehead

- But we can likely do better by doing a similar optimization of the ELBNF beamline. This talk is about my attempt to do that.

Optimization Procedure

- First, we need something to optimize. I wanted to move beyond simply maximizing flux in certain region — CP sensitivity is a complicated function of signal & background fluxes, cross sections, efficiencies, fake rates, resolution, etc

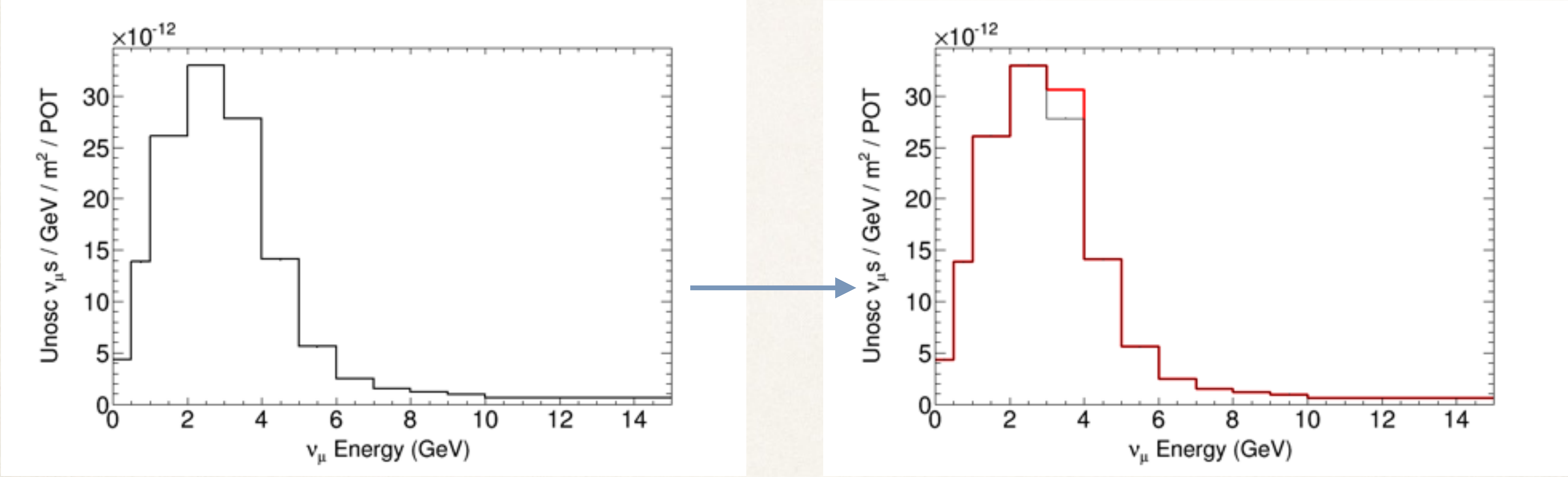




- Ideally, we would use the Fast MC, which incorporates our current best estimates of all of these. Unfortunately, flux -> sensitivities takes ~ a week, so a full Fast MC based oscillation would take years

Optimization Procedure

- Instead, I used the Fast MC to do something we've been wanting to do in the beam simulation group for years: to quantify the relative merit of different flux energy bins:

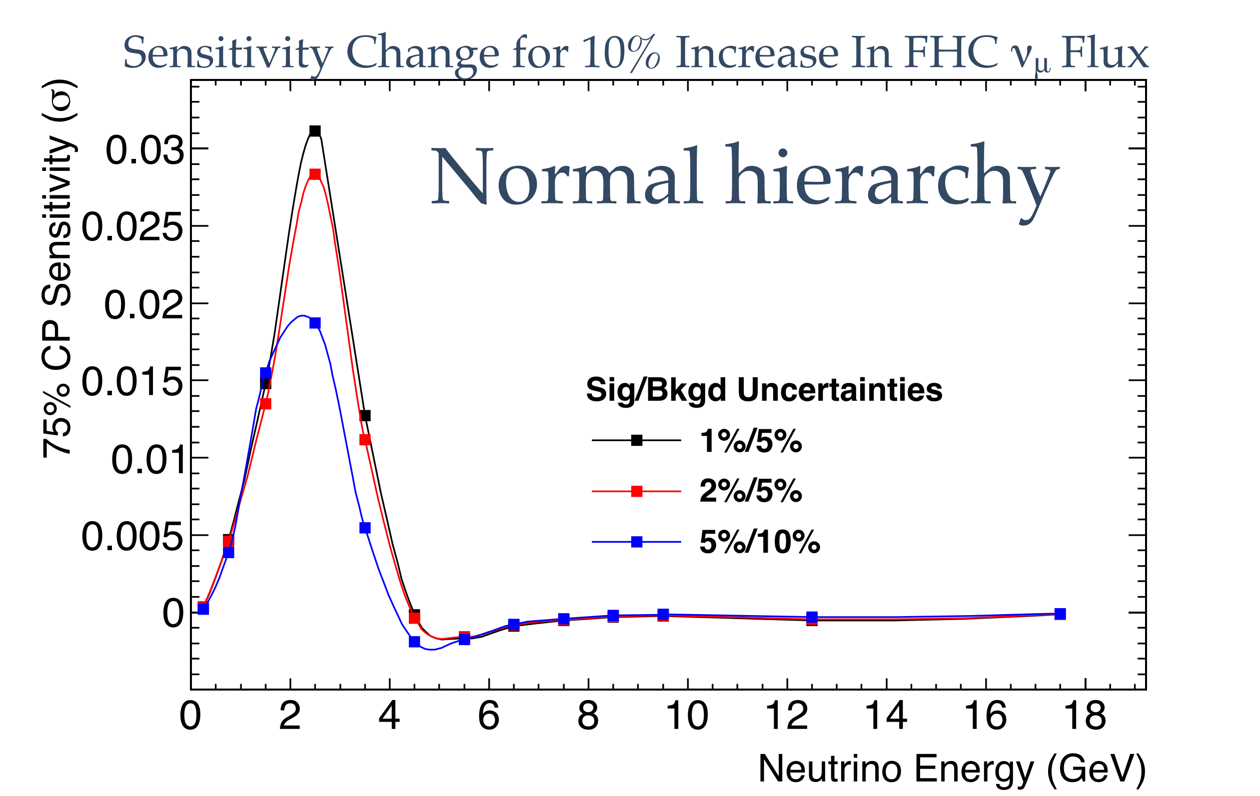


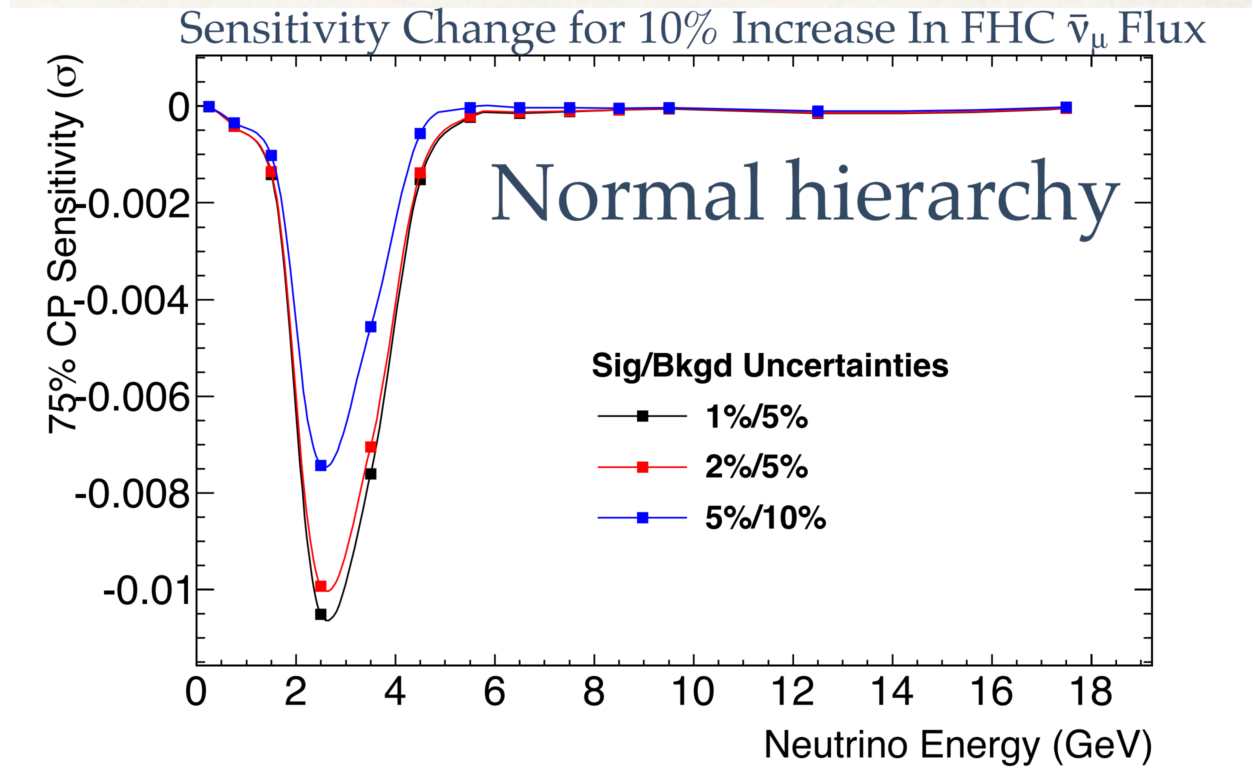
- I used the fast MC to study the change in CP sensitivity given variations to individual bins of flux

- This was done for 672 configurations (3 fluxes (ν_μ,$\bar{\nu}_\mu$,ν_e), 2 running modes (neutrino and anti-neutrino),14 energy bins, 8 fractional changes in flux)

Optimization Procedure

- How the 75% CP Sensitivity changes with changes to individual flux energy bins:





- This shows that, for 10% changes in neutrino-mode fluxes, the most important bins by far are between 2 and 4 GeV. Increasing ν_μ signal increases CP sensitivity, and increasing $\bar{\nu}_\mu$ wrong-sign contamination decreases sensitivity

- The Conventional wisdom that we need to minimize the high energy tail is not supported here — the size of the high energy tail has very little effect on CP sensitivity (and neither does ν_e contamination — not shown)

Optimization Procedure

- From this information about changes in CP sensitivities for changes in individual fluxes/energy bins, I construct a metric that approximates the CP sensitivity for any beam configuration:

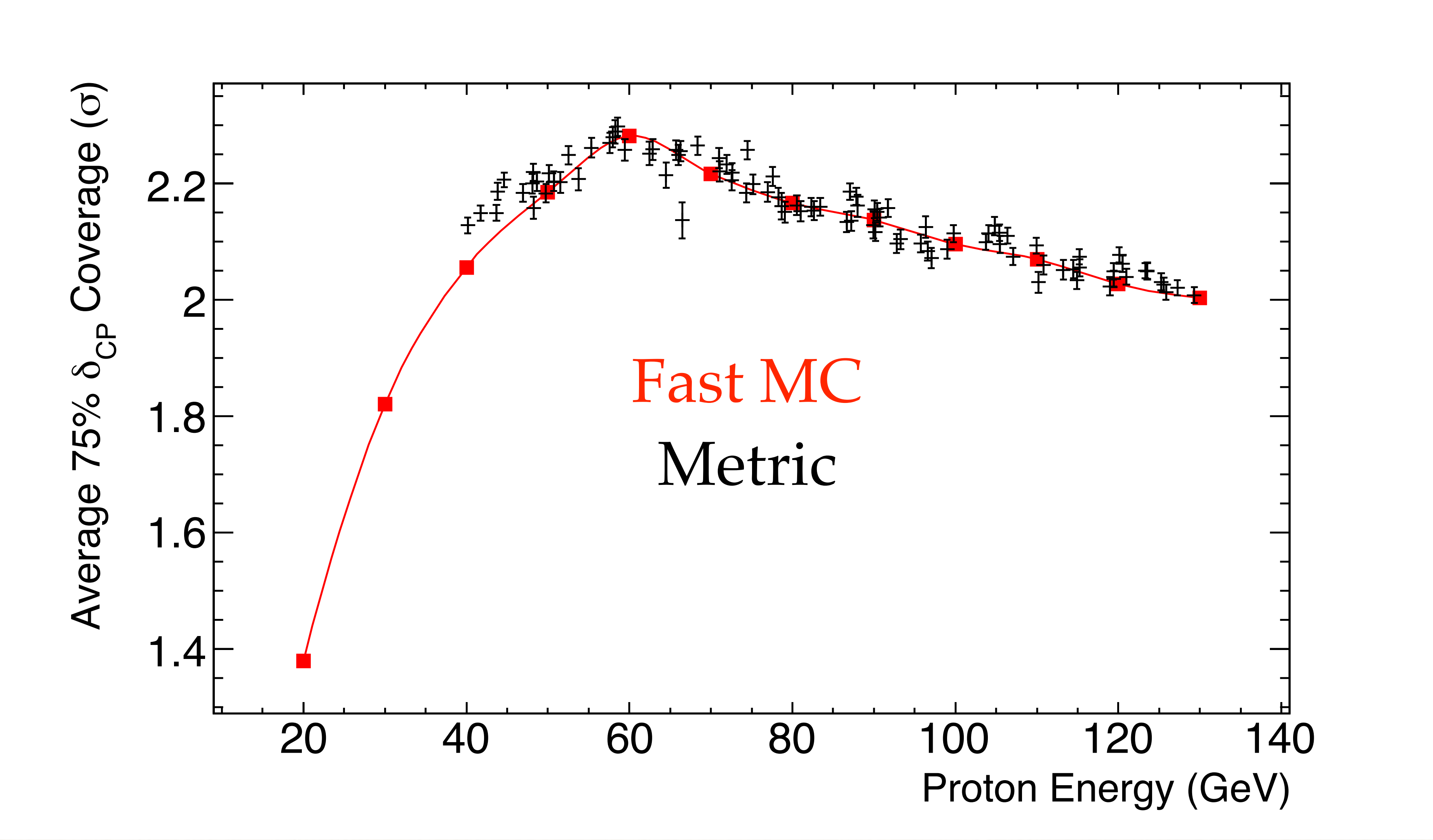
$$S = S_{\text{nominal}} + \sum_{\substack{\text{j} \\ \text{flavors}}} \sum_{\substack{j \\ \text{E bins}}} (\Delta S(\Delta \Phi))$$

A function that interpolates between the fast MC runs to estimate the change in sensitivity given some change in flux in one energy bin for one neutrino flavor

- I used the FMC sensitivities that assume 2% signal / 5% background systematic uncertainties, and average the NH and IH sensitivities

Optimization Procedure

- How well does this metric approximate the “real” sensitivities — i.e. those from the Fast MC?
- It does well at predicting the change in sensitivity as we change the primary proton energy (and assuming PIP II power estimates at different energies):

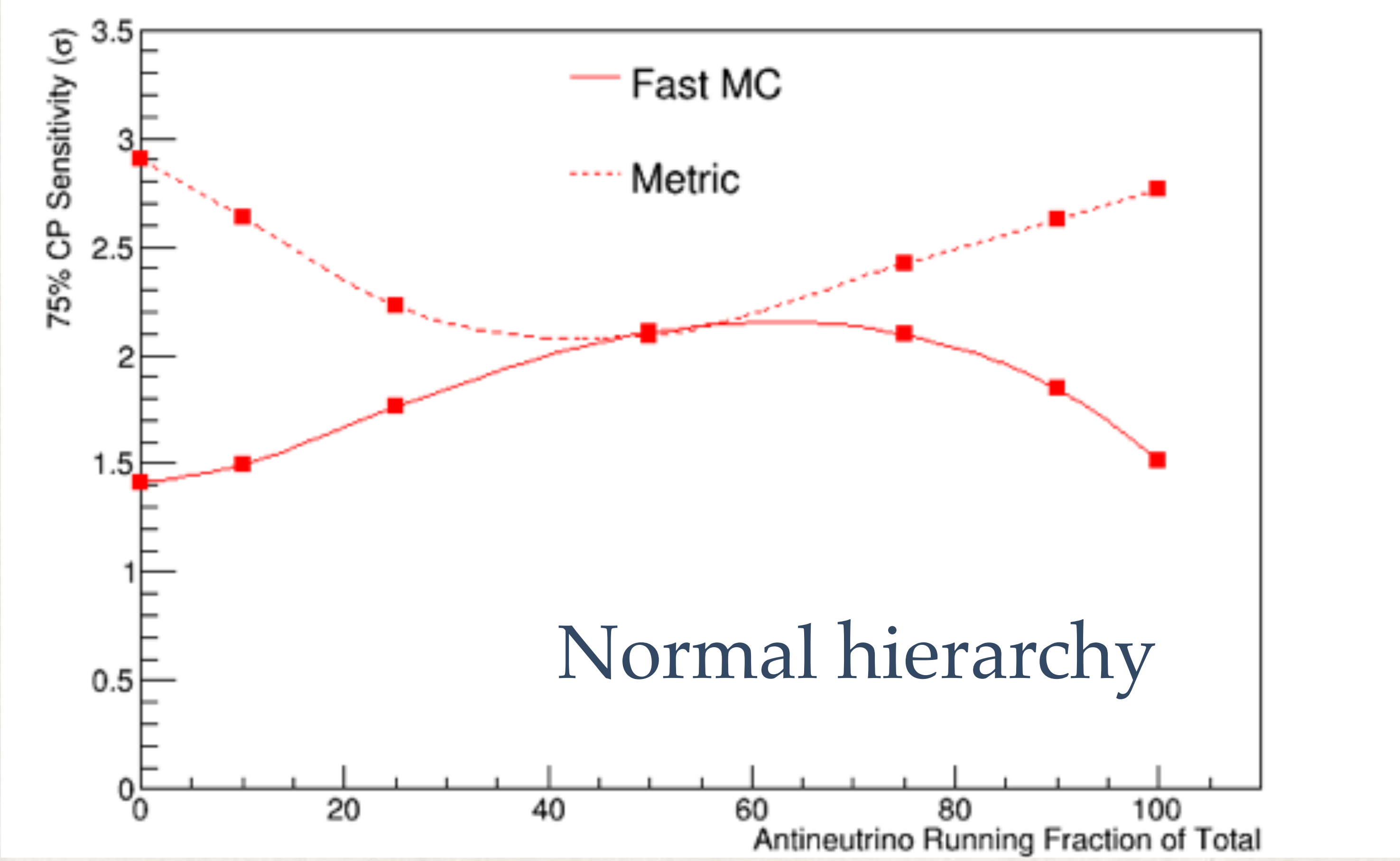


Red points take ~ a week; black points take ~ an hour

Optimization Procedure

- But it doesn't do as well when many different fluxes and energy bins are changing simultaneously, like when we change the antineutrino running fraction

- Performance of the metric has recently been improved, but for results reported in this talk do not optimize antineutrino running fraction



This illustrates that the metric is just an approximation of sensitivity (and a poor one in some cases); it will be important to cross check results of optimization with the Fast MC

Optimization Procedure

- Now we have something to optimize.
- I followed LBNO's example of using a genetic algorithm
- Overview of a genetic algorithm
  - Define a set of parameters you want to optimize (with boundaries)
  - Begin by generating a small sample (~100 configurations) of randomly chosen configurations — the first "generation"
  - Choose the configurations with the best "fitness" (in our case, the CP sensitivity metric) and "mate" them together to form a new generation
  - Continue until you no longer find configurations with improved fitness over previous generations

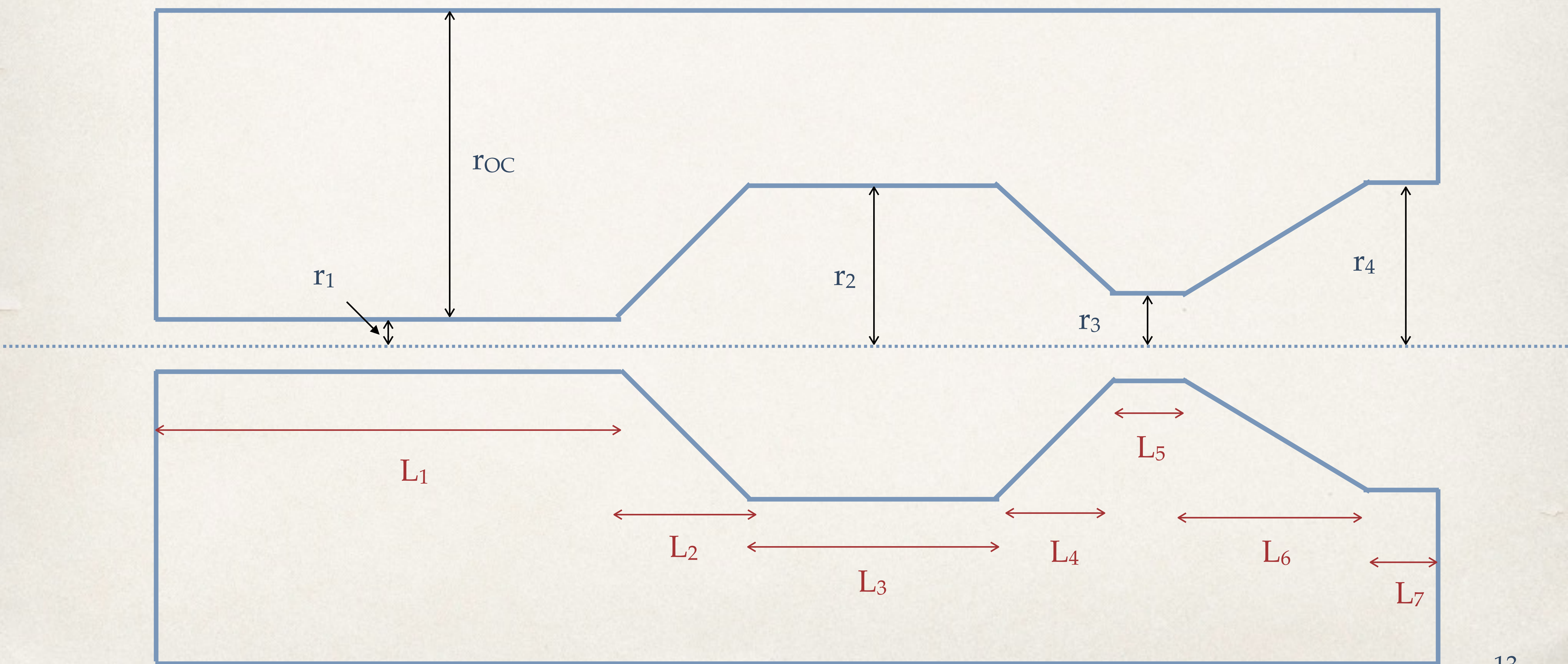
Optimization Procedure

- Parameters varied in the optimization:

Parameter	Lower Limit	Upper Limit	Unit
Horn 1 Shape: r1	20	50	mm
Horn 1 Shape: r2	35	200	mm
Horn 1 Shape: r3	20	75	mm
Horn 1 Shape: r4	20	100	mm
Horn 1 Shape: rOC	200	800	mm
Horn 1 Shape: l1	800	2500	mm
Horn 1 Shape: l2	50	1000	mm
Horn 1 Shape: l3	50	1000	mm
Horn 1 Shape: l4	50	1000	mm
Horn 1 Shape: l5	50	1000	mm
Horn 1 Shape: l6	50	1000	mm
Horn 1 Shape: l7	50	1000	mm
Horn 2 Longitudinal Scale	0.5	2	NA
Horn 2 Radial Scale	0.5	2	NA
Horn 2 Longitudinal Position	3.0	15.0	m from MCZERO
Target Length	0.5	2.0	m
Target Fin Width	5	15	mm
Proton Energy	40	130	GeV
Horn Current	150	300	kA

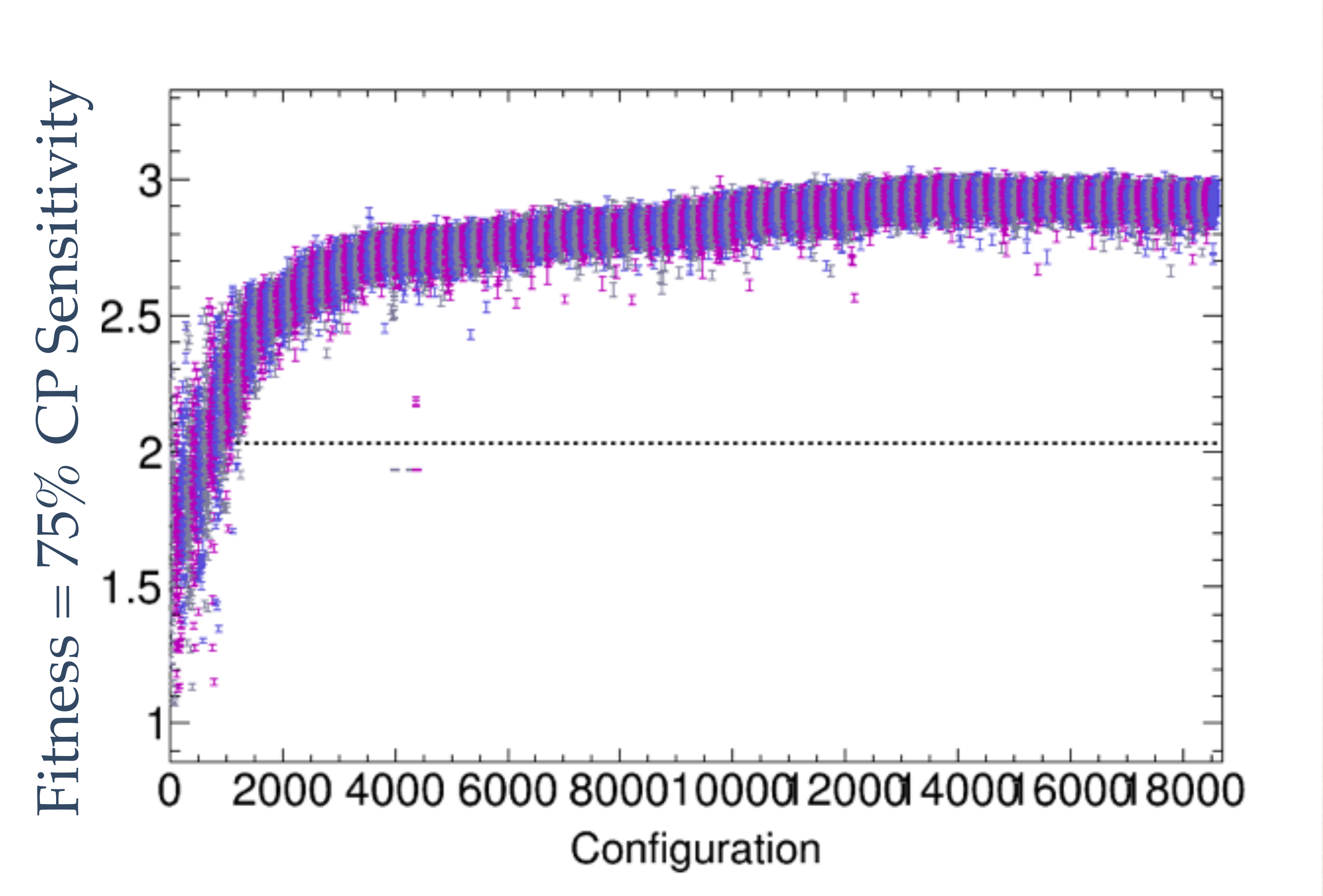
Optimization Procedure

- Horn 1 shape parameters
  - Inspired by LBNO optimization
  - Not constrained to have this shape — basically just a 7 segment horn with floating length and radii



Results: Fitness Evolution

- I ran approximately 18,000 beam configurations. The genetic algorithm converges by around 13000 configurations



Here the colors separate the ~150 "generations of the genetic algorithm"

Results: Fitness Evolution

- The fitness definitions allows breakdowns of what fluxes are contributing to the increase in fitness:
  - More than half of the increase comes from decreasing wrong sign backgrounds, particularly in antineutrino mode
  - The remainder is due to increasing signal neutrinos at first and second oscillation maximum
  - The size of the intrinsic electron neutrino contamination does not have substantial impact on fitness and doesn't change significantly in the optimization
  - Plots showing these effects are in the backup slides

Results: Best Configuration

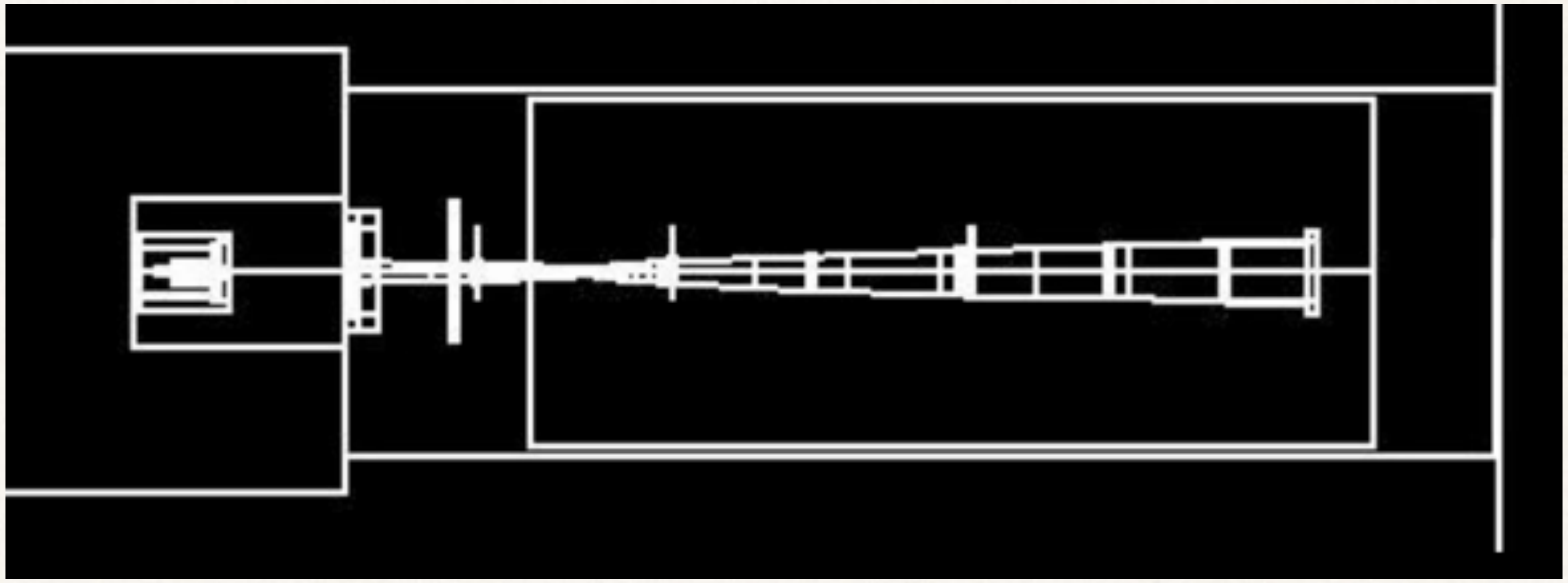
- Parameters of best configuration

Parameter	Nominal Value	Optimized Value	Unit
Horn 1 Shape: r1	-	26	mm
Horn 1 Shape: r2	-	156	mm
Horn 1 Shape: r3	-	21	mm
Horn 1 Shape: r4	-	92	mm
Horn 1 Shape: rOC	165	596	mm
Horn 1 Shape: l1	-	1528	mm
Horn 1 Shape: l2	-	789	mm
Horn 1 Shape: l3	-	941	mm
Horn 1 Shape: l4	-	589	mm
Horn 1 Shape: l5	-	155	mm
Horn 1 Shape: l6	-	58	mm
Horn 1 Shape: l7	-	635	mm
Horn 2 Longitudinal Scale	1	1.28	NA
Horn 2 Radial Scale	1	1.67	NA
Horn 2 Longitudinal Position	6.6	12.5	m from MCZERO
Target Length	0.95	1.9	m
Target Fin Width	10	11.6	mm
Proton Energy	120	65	GeV
Horn Current	200	298	kA

- Total Horn 1 length in nominal design is 3.36 m vs 4.70 m is optimized configuration
- Horn 2 length/outer radius are 3.63 m / 0.395 m in nominal configuration vs 4.65 / 0.66 m in optimized configuration

Results: Best Configuration

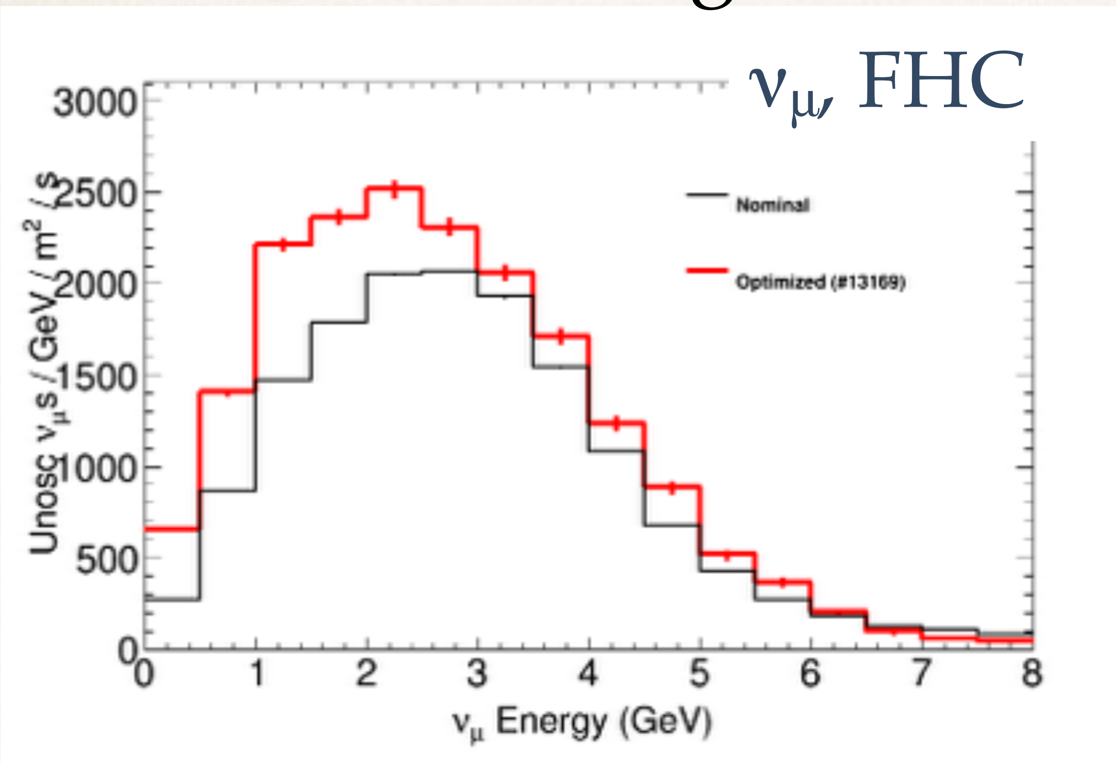
- Visualizations of horn 1 inner conductors:

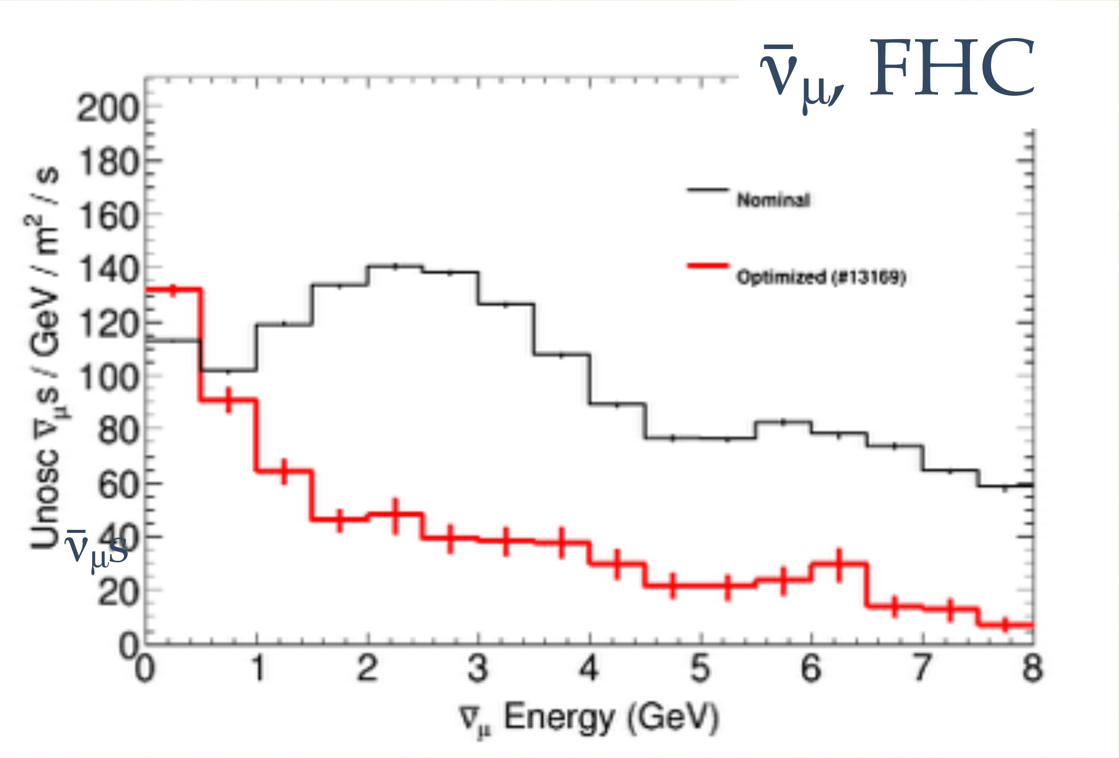


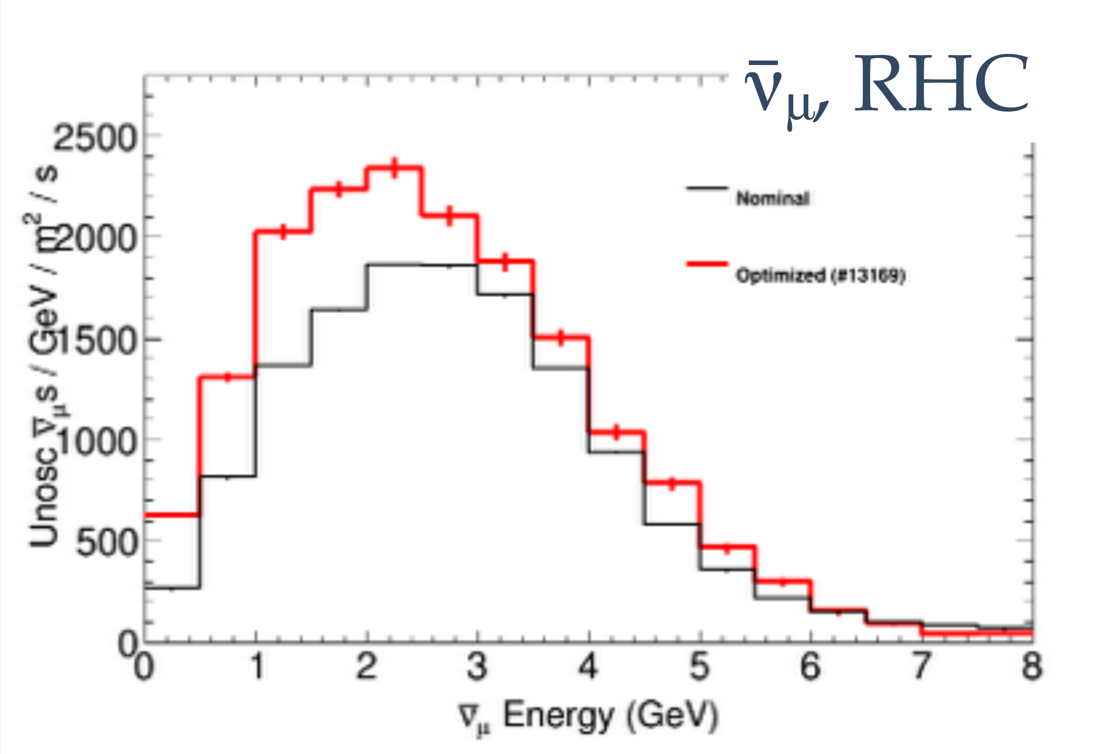
Figures courtesy Amit Bashyal

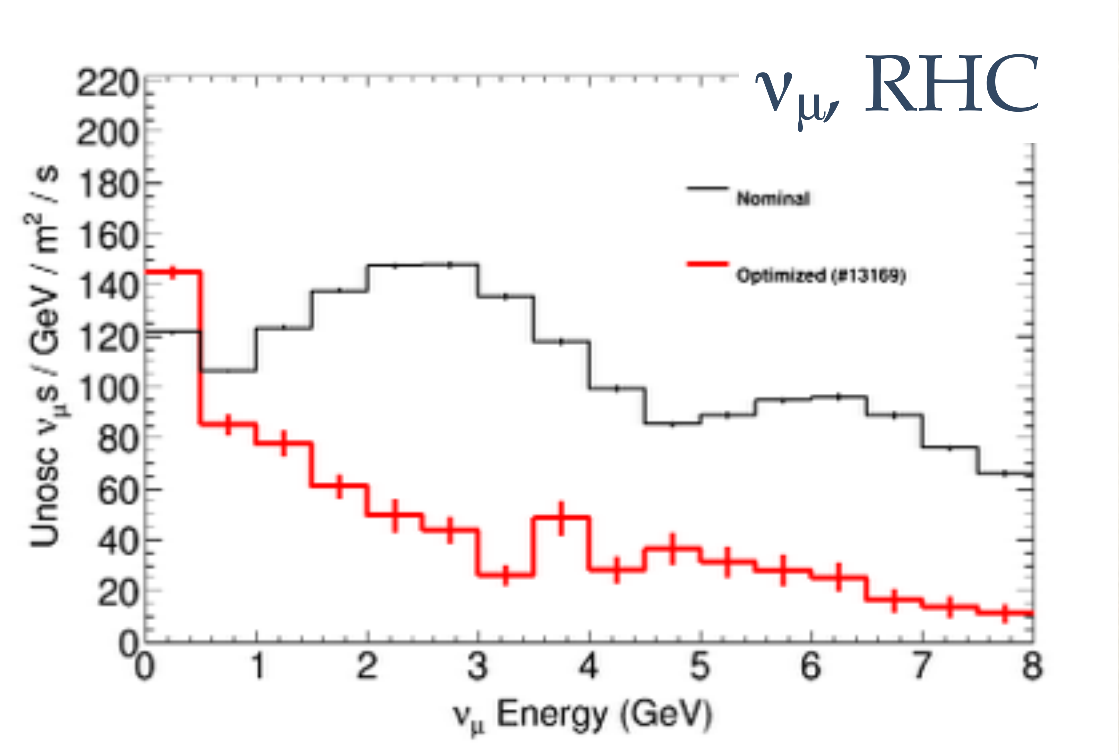
Results: Best Configuration

- Flux of best configuration, compared with nominal:



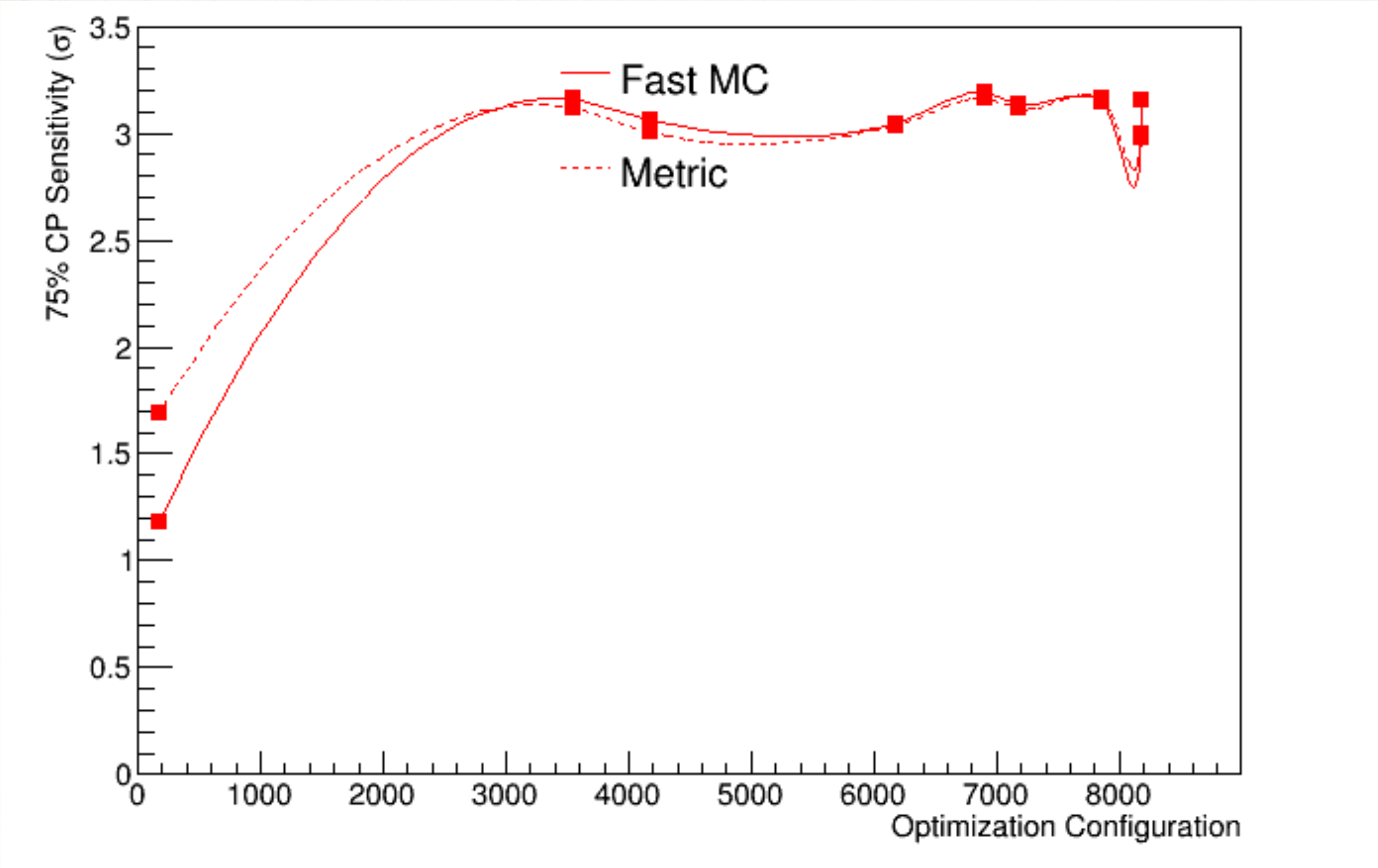






Results: Fast Monte Carlo

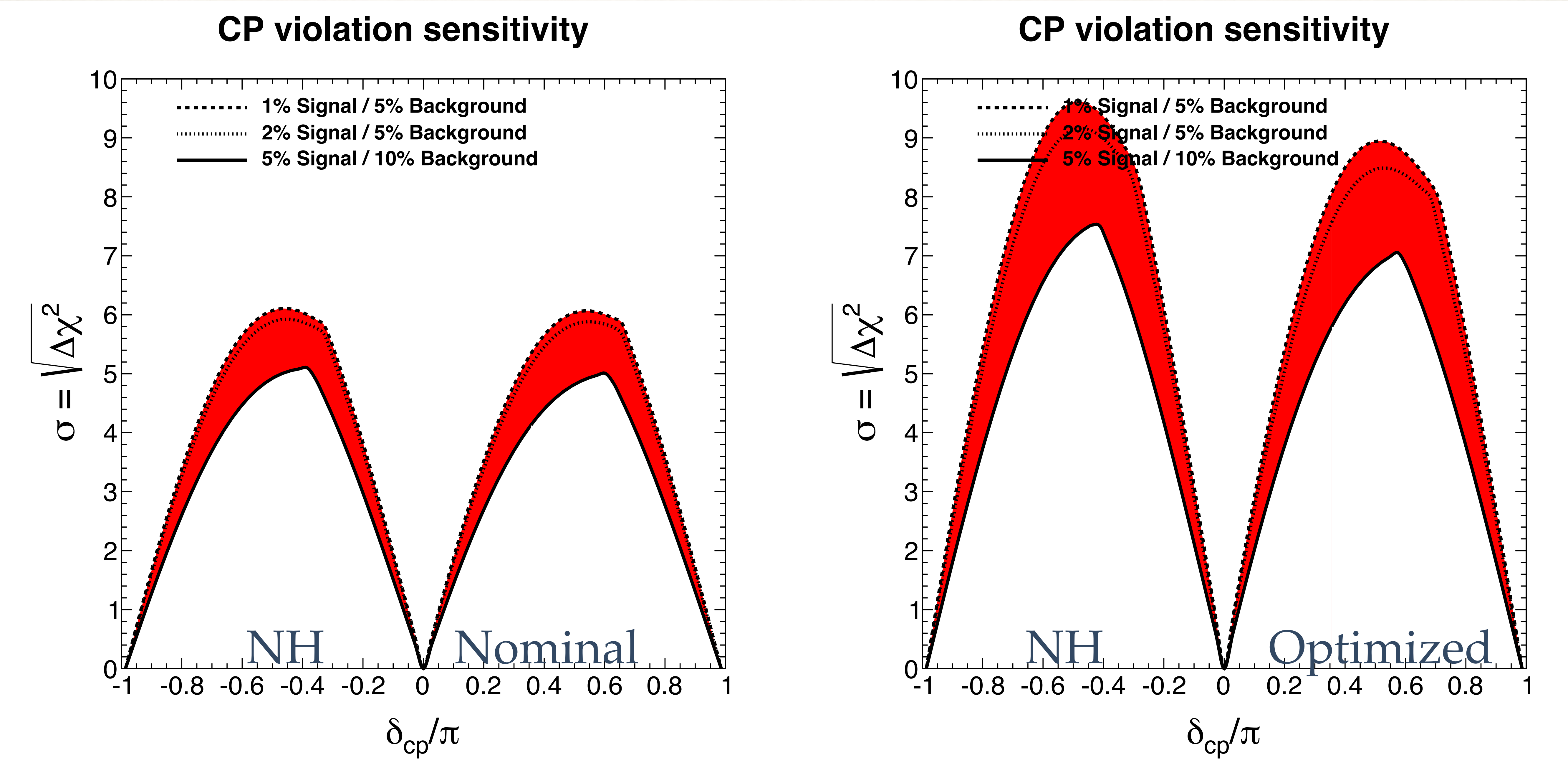
- I also chose a few of the best and a few randomly chosen configurations through the Fast MC to see how well the fitness reproduces the 'actual' CP sensitivity:



Sensitivities from FMC track the fitness metric quite nicely!

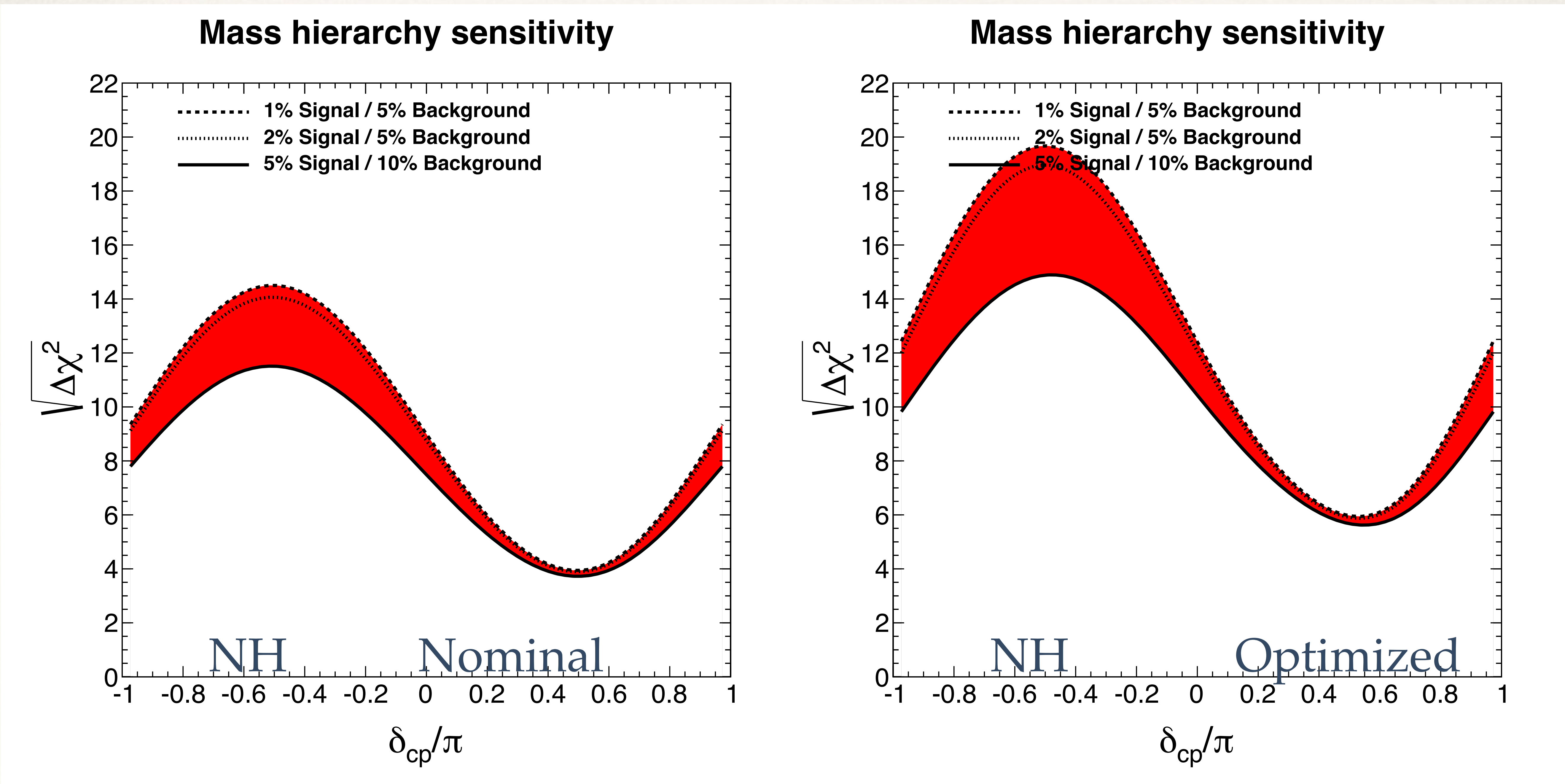
Results: Fast Monte Carlo

- FMC Sensitivities to CP Violation:



Results: Fast Monte Carlo

- FMC Sensitivities in Mass Hierarchy:



Results: Beyond Monte Carlo

- Others are currently cross-checking these results with non-FMC GLOBES setups
  - Currently see big differences between FMC and non-FMC sensitivity calculations
  - We are working to understand these
- We can conclusively say that this optimized beam configuration increases signal flux at the second oscillation maximum and substantially decreases wrong-sign flux
  - The impact of these changes on CP sensitivity depends on assumptions about cross-sections, efficiencies, fake rates, etc and is therefore much less certain

Next Steps

- Continue sensitivity studies outside of Fast MC
- A new optimization is running now that allows neutrino and antineutrino parameters to float separately
- This study uses an idealized horn design — with no spider supports and such; will have to study how the flux changes with a more realistic horn implementation

The End

Backup

Optimization Procedure

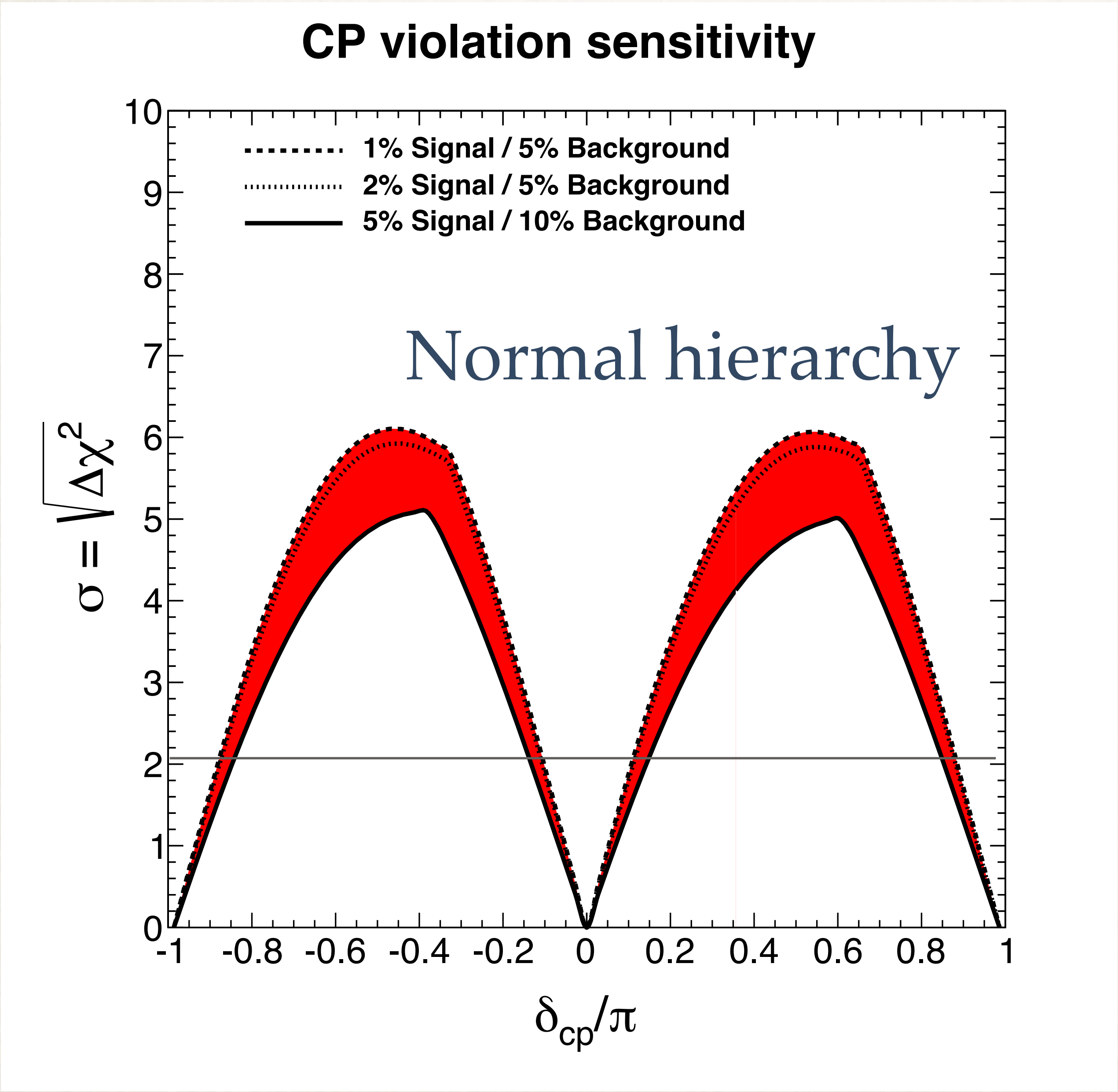
- "CP sensitivity" can mean one of several different quantities. For my optimization studies, I took the advice of P5 and used CP sensitivity for 75% of CP phase space:

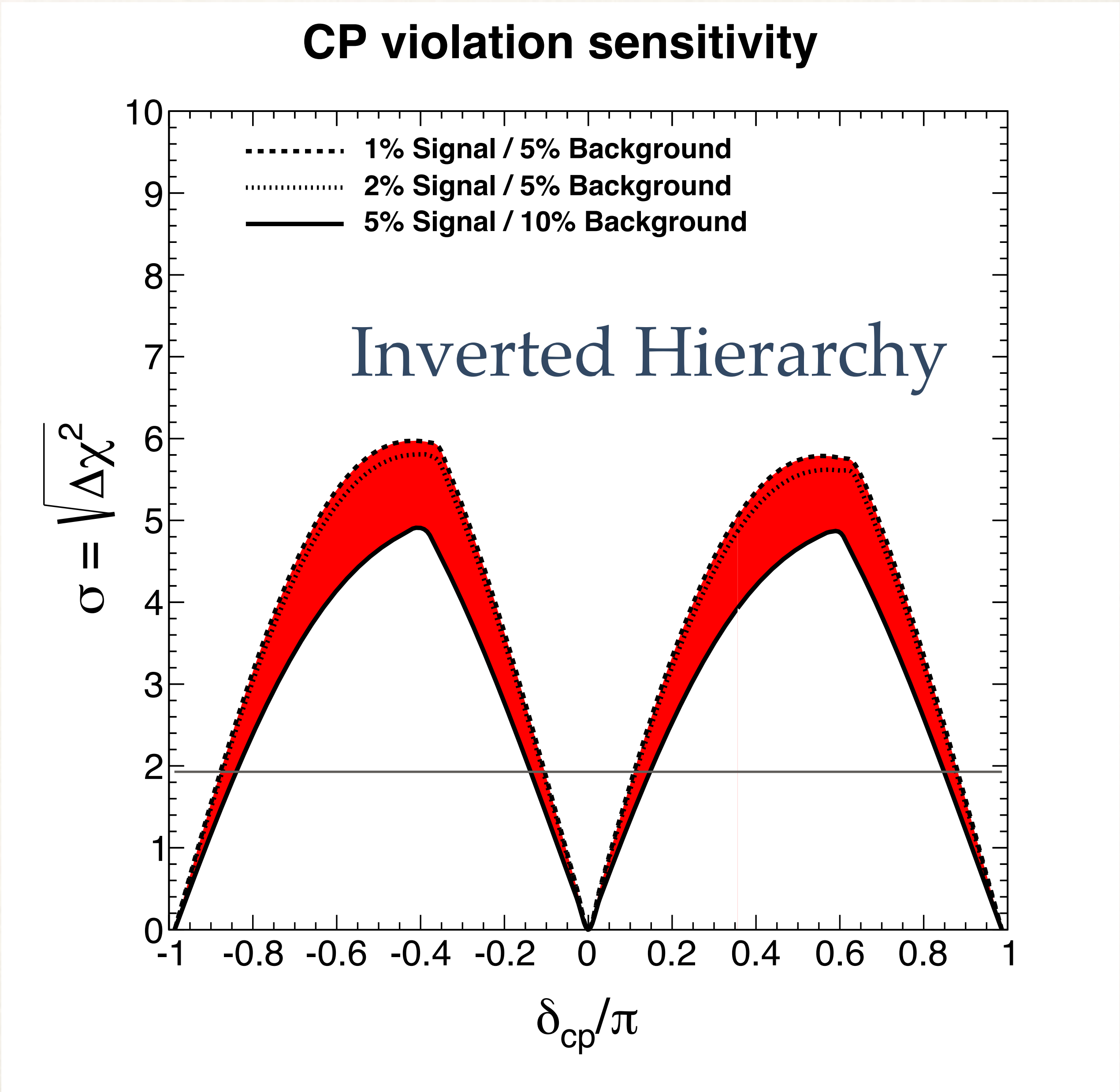
Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] 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 δ_{CP}. By current estimates, this goal corresponds to an exposure of 600 kt*MW*yr assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the**

Optimization Procedure

- According to the fast MC the sensitivity for 75% of the range of possible values of δCP is about 2.1/1.9 for NH/IH:

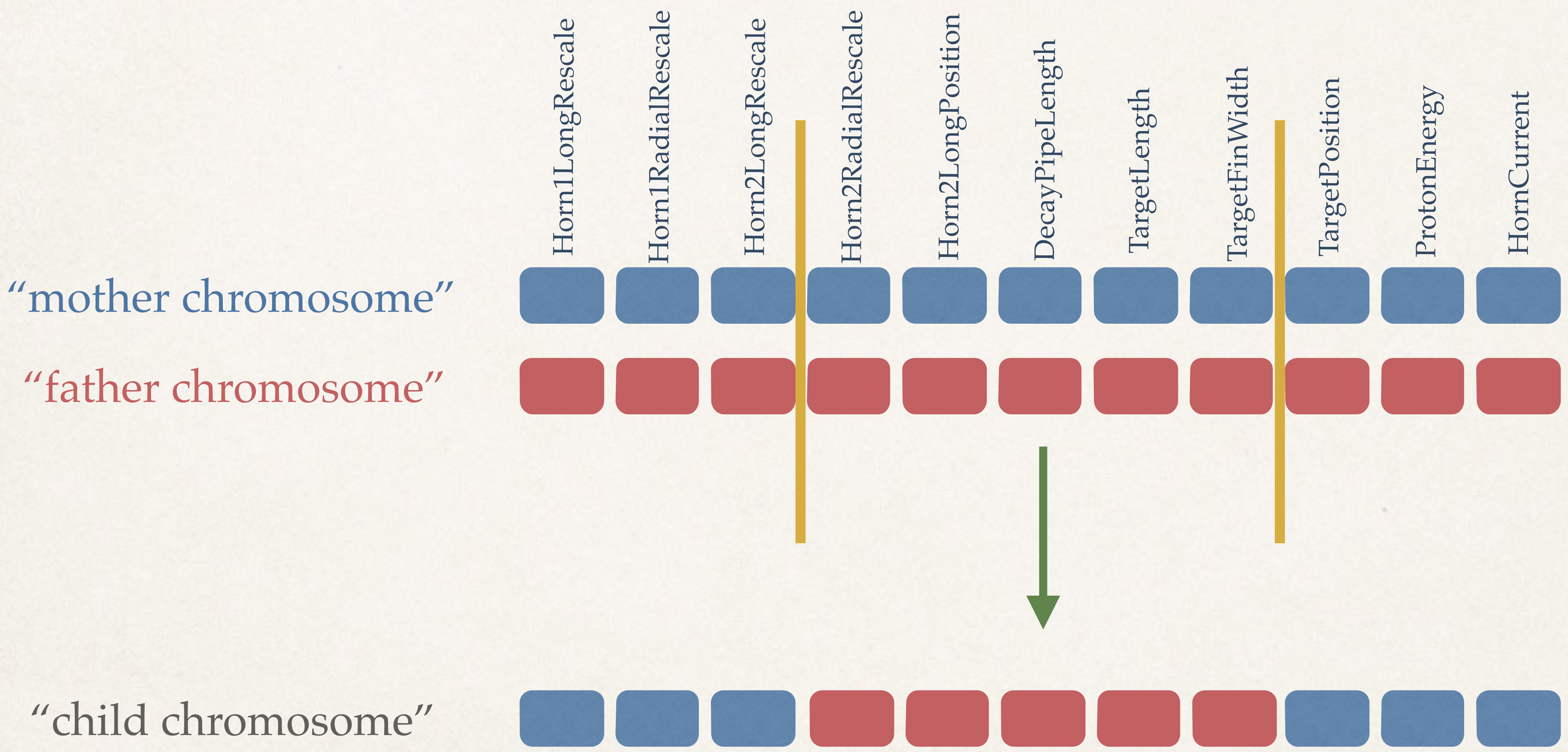




This is with the current 1.2 MW beam configuration

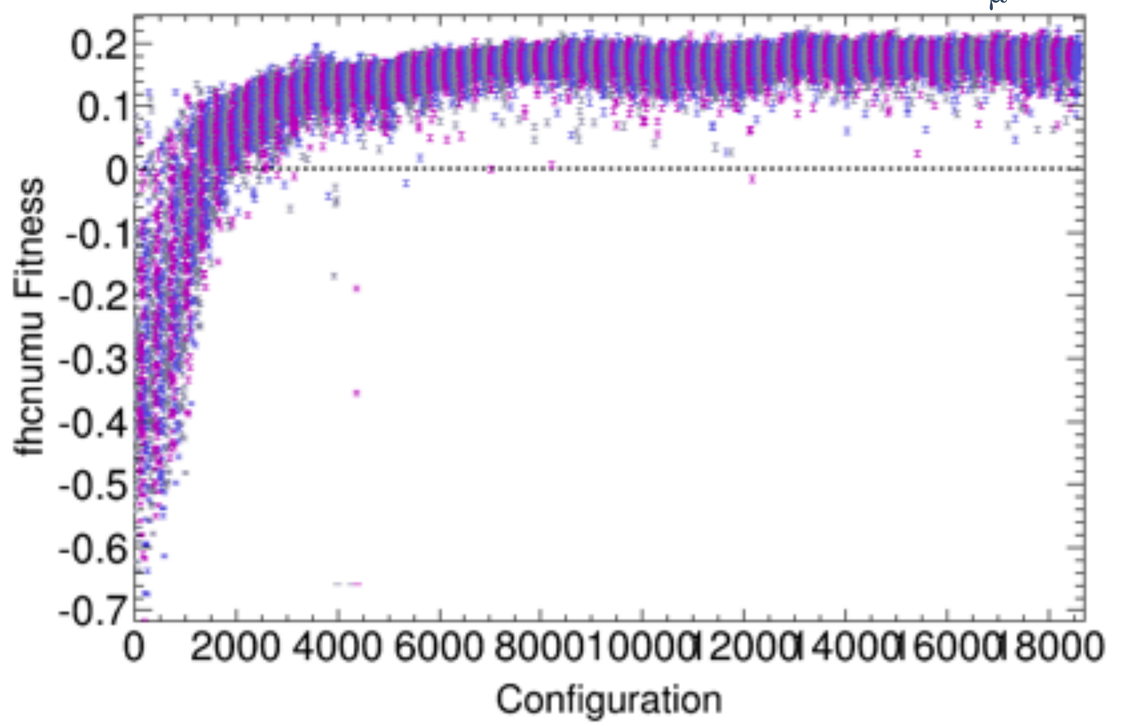
Optimization Procedure

- How the mating works:



Results: Fitness Evolution

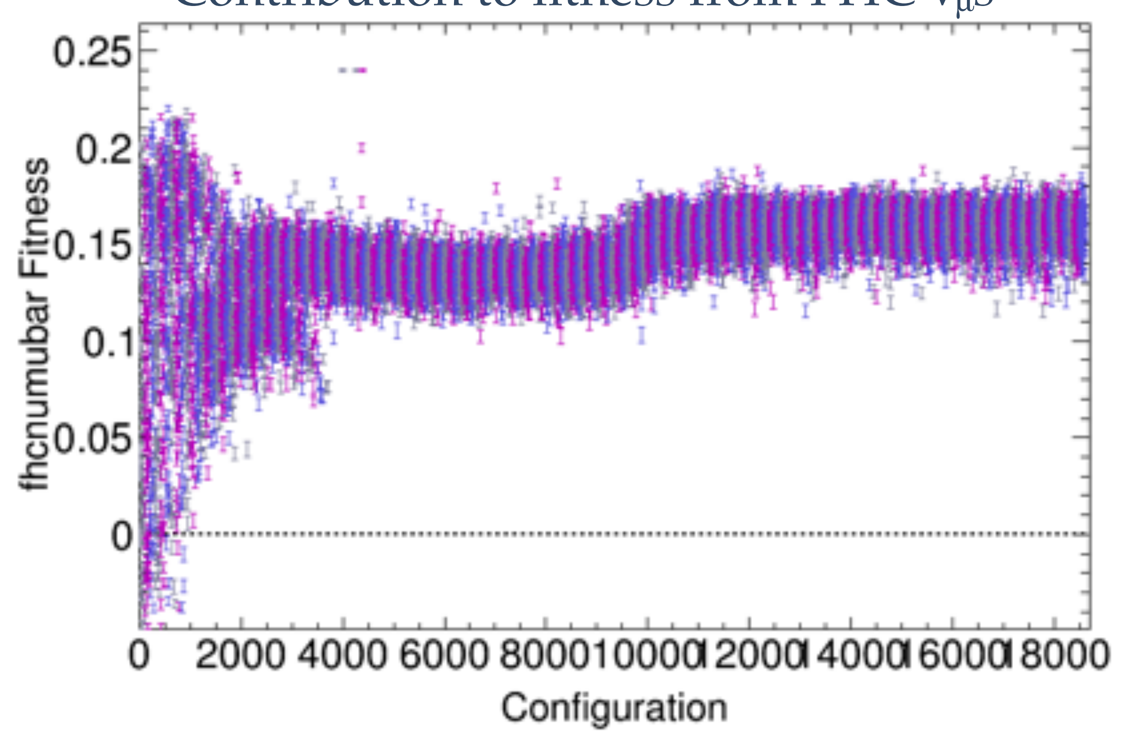
Contribution to fitness from FHC ν_μs



These plots show the change in fitness from the nominal configuration due to changes to the FHC ν_μ and $\bar{\nu}_\mu$ fluxes

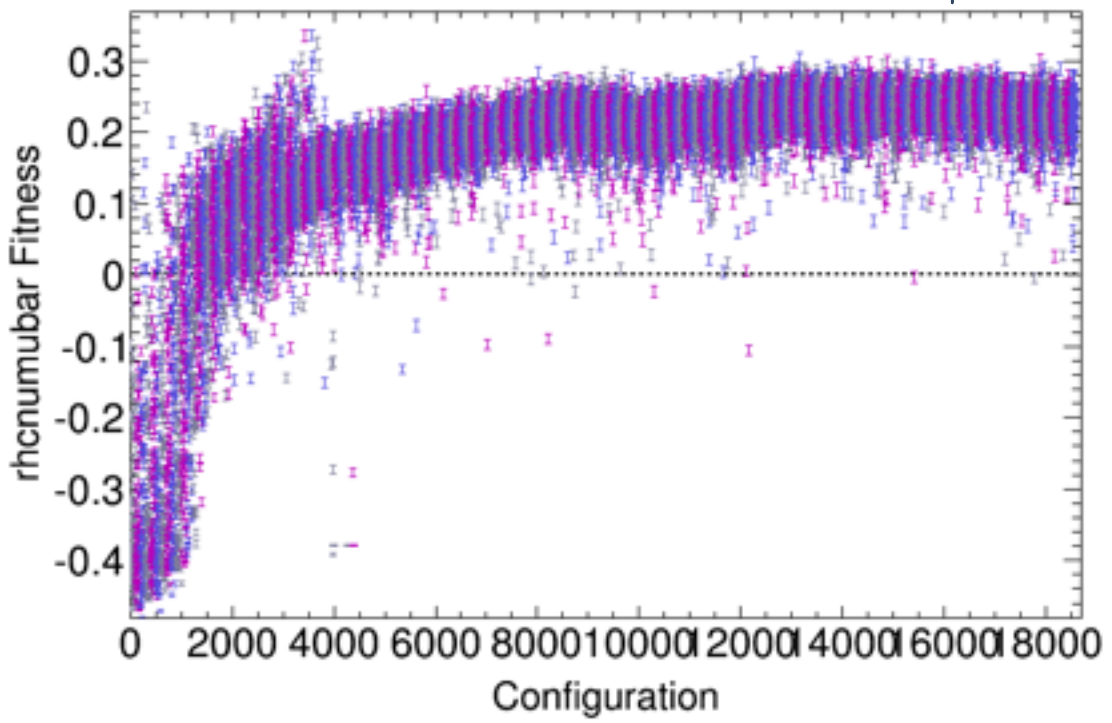
Interestingly, increasing signal (ν_μ) and decreasing background ($\bar{\nu}_\mu$) have roughly equal contributions to the fitness

Contribution to fitness from FHC $\bar{\nu}_\mu$s



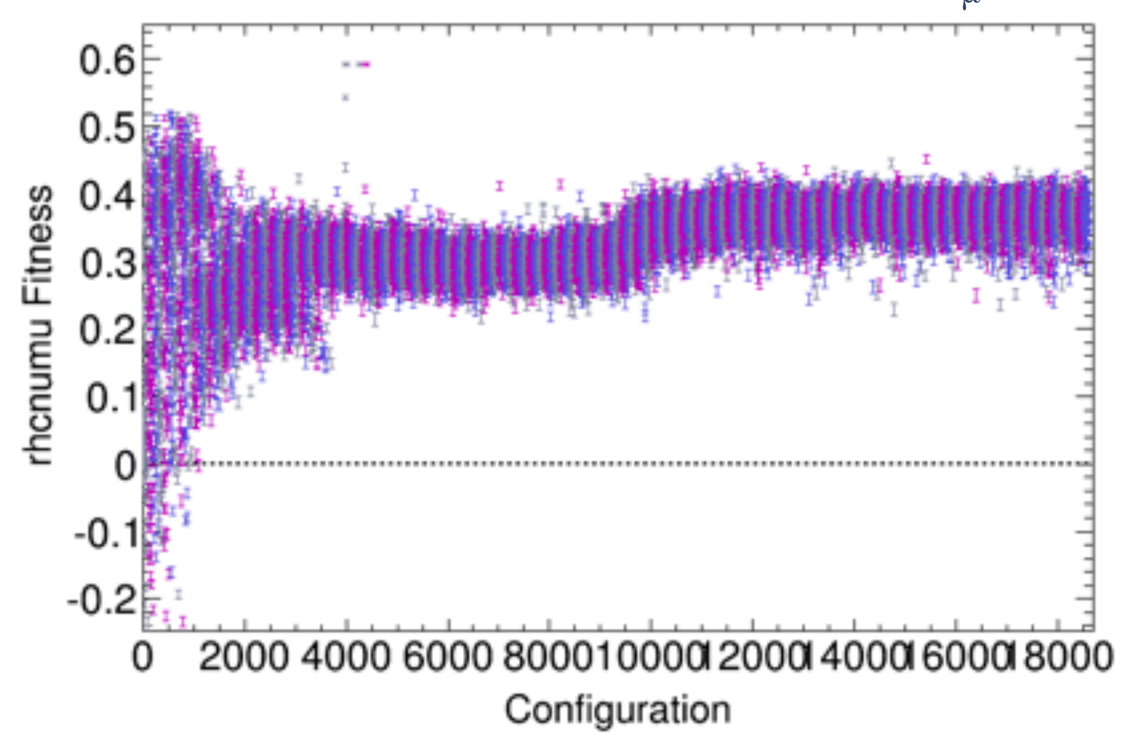
Results: Fitness Evolution

Contribution to fitness from RHC $\bar{\nu}_{\mu}$s



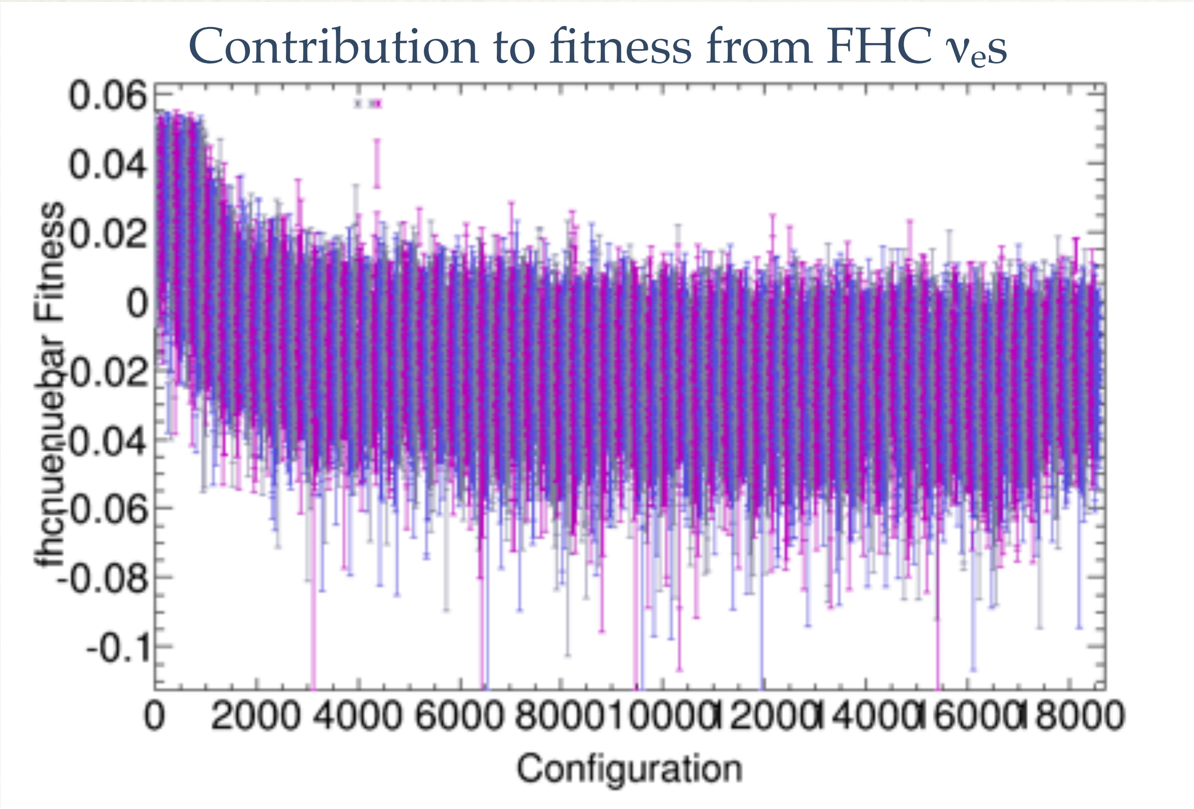
These plots show the change in fitness from the nominal configuration due to changes to the RHC $\bar{\nu}_{\mu}$ and ν_{μ} fluxes

Contribution to fitness from RHC ν_{μ}s



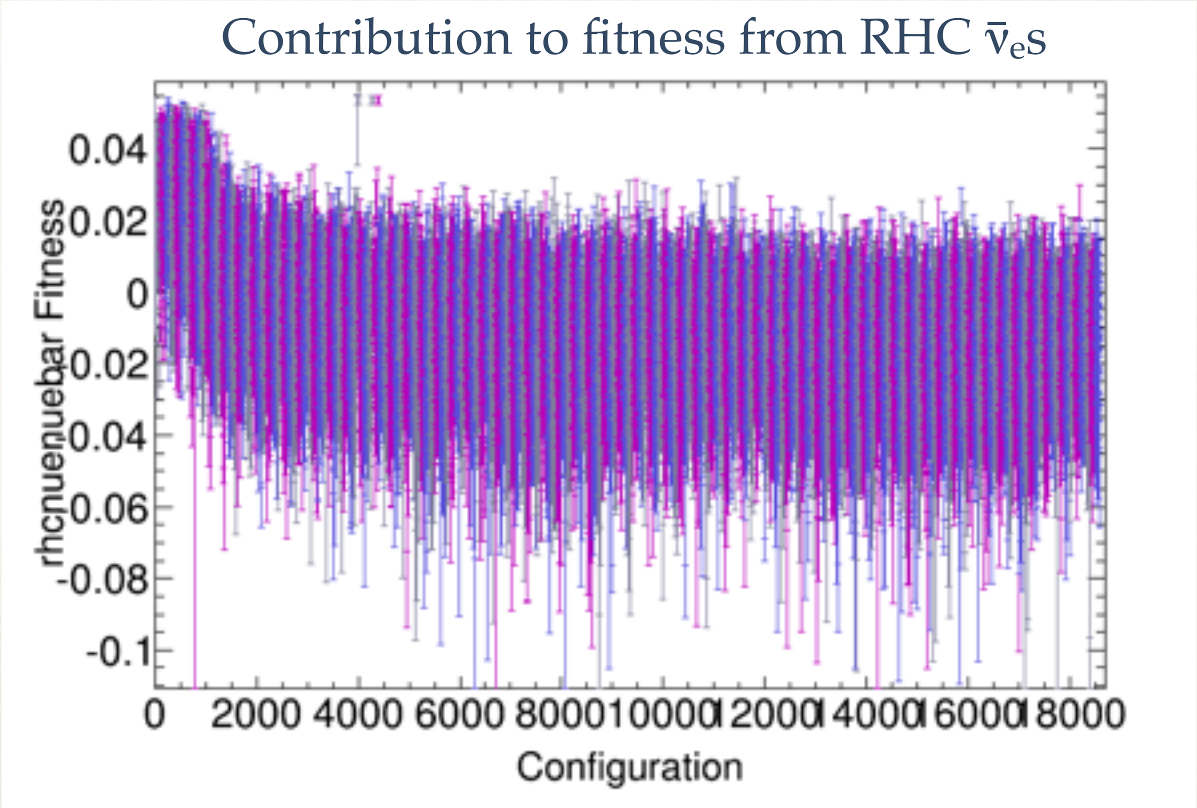
Here the contribution to fitness is larger than in neutrino mode (previous slide), particularly the effect of reducing wrong sign background

Results: Fitness Evolution



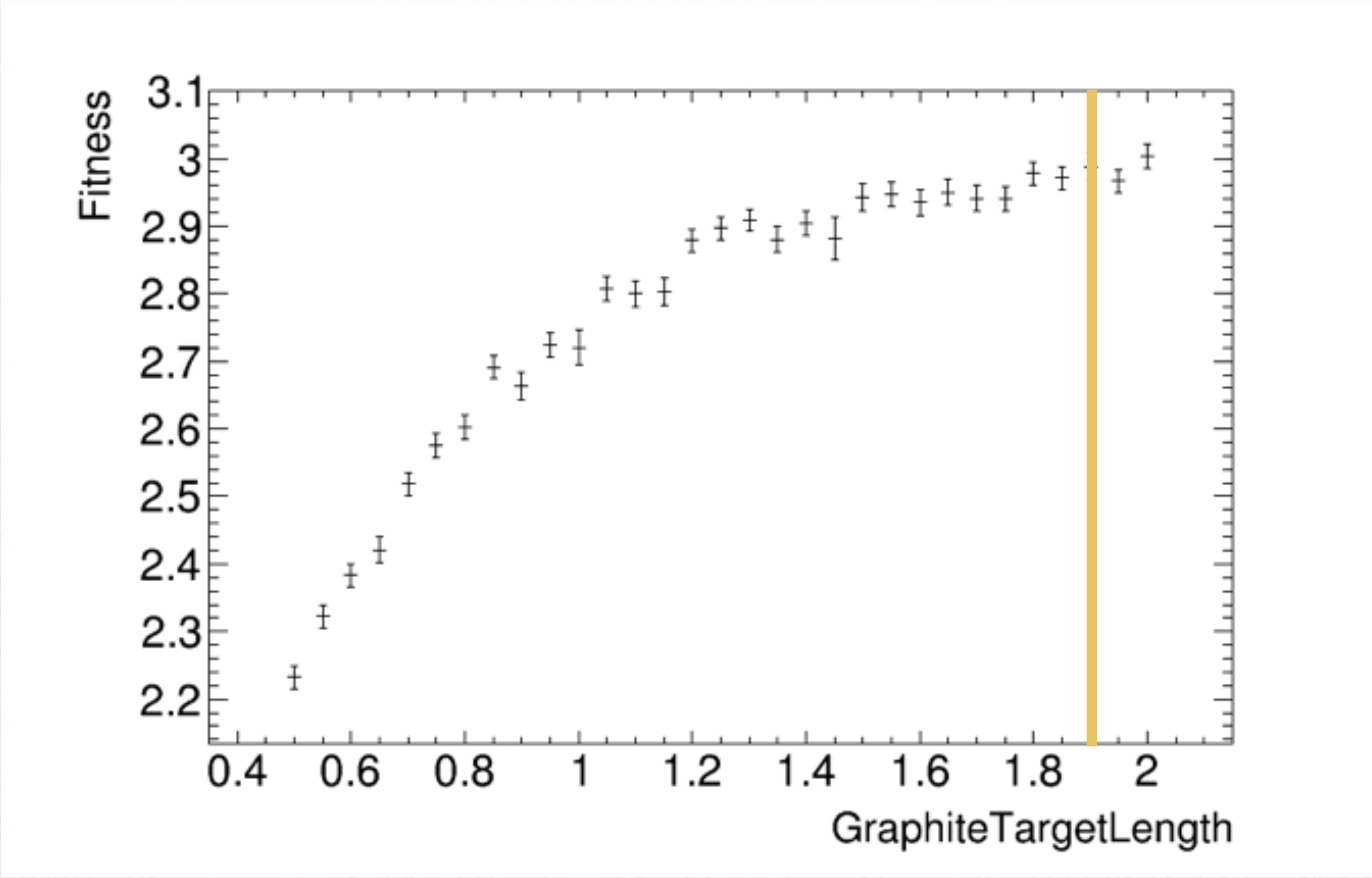
These plots show the change in fitness from the nominal configuration due to changes to FHC ν_e and RHC $\bar{\nu}_e$ fluxes

The intrinsic electron neutrino contamination of the beam changes the fitness very little and is not driving the optimization



Results: Parameter Scan

- To understand the relative importance of the various changes, I also did a parameter scan around the optimized configuration

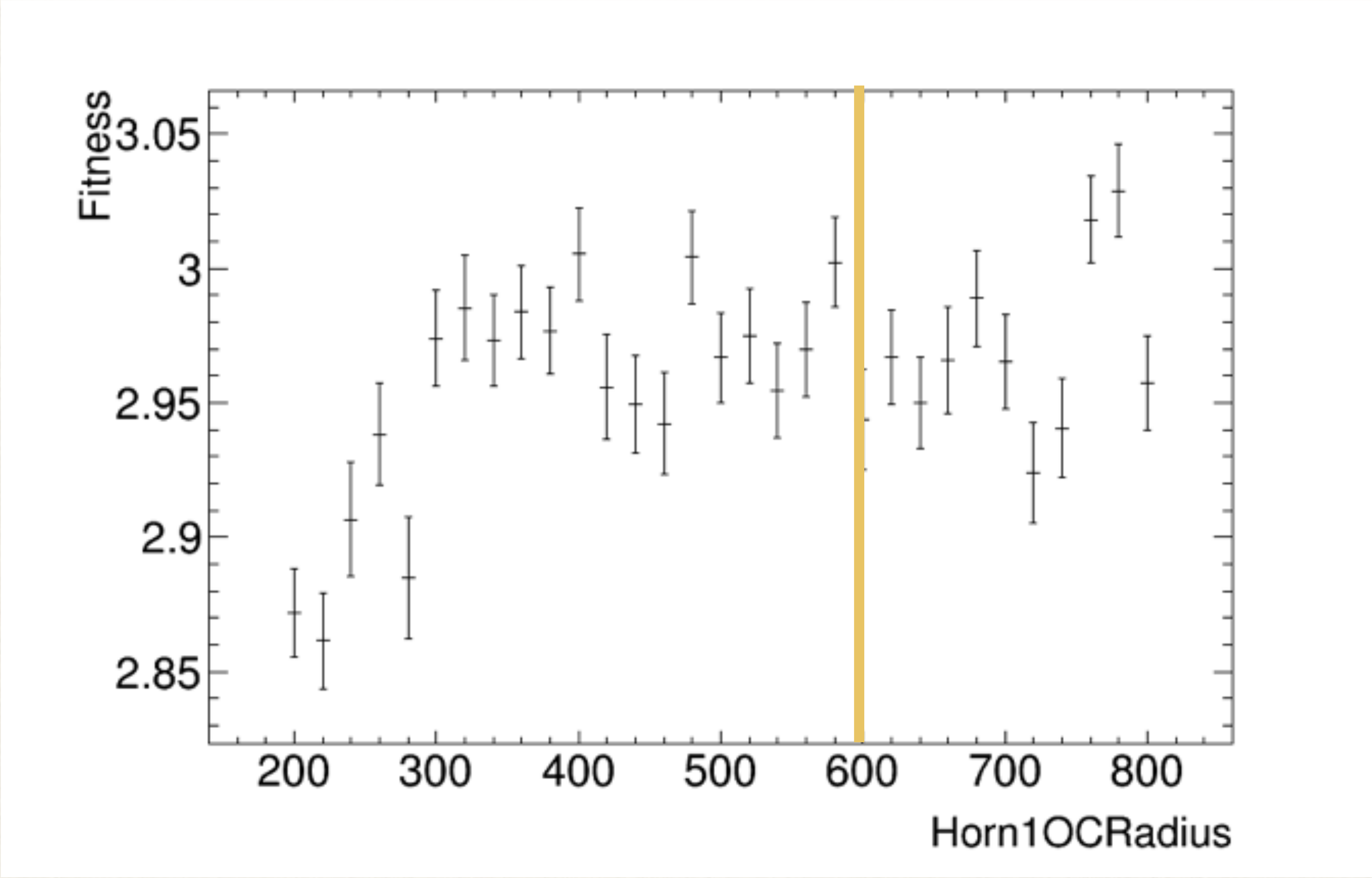


This shows how the fitness varies with target length with all other optimized parameters fixed

Yellow line shows value chosen by optimization

Results: Parameter Scan

- To understand the relative importance of the various changes, I also did a parameter scan around the optimized configuration

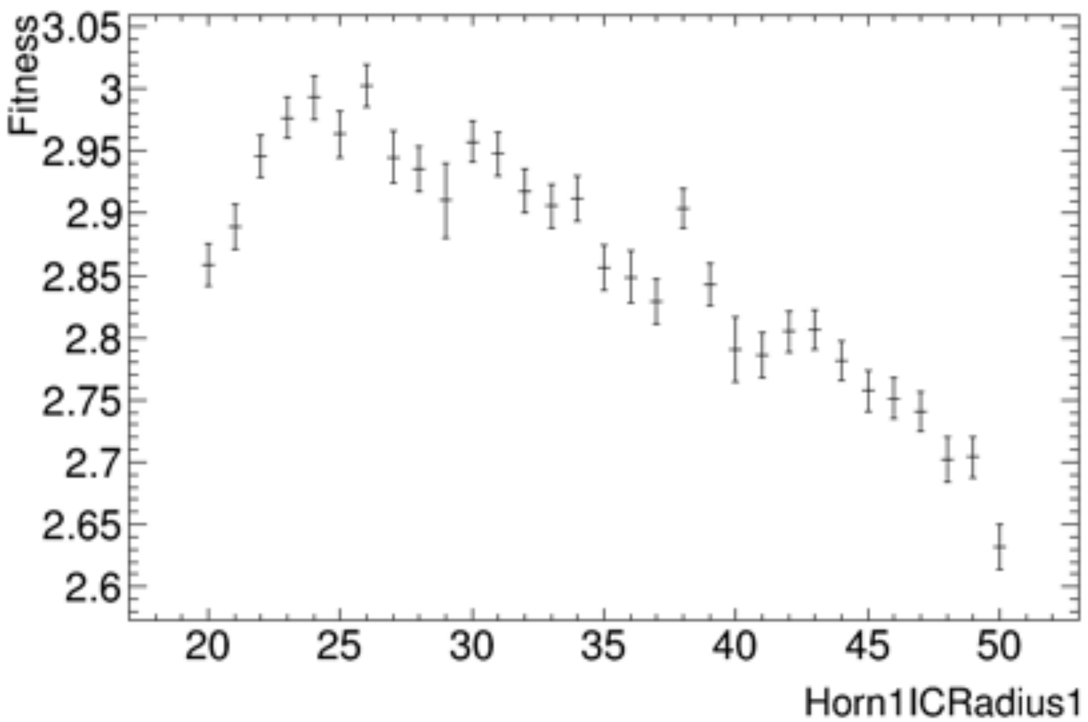


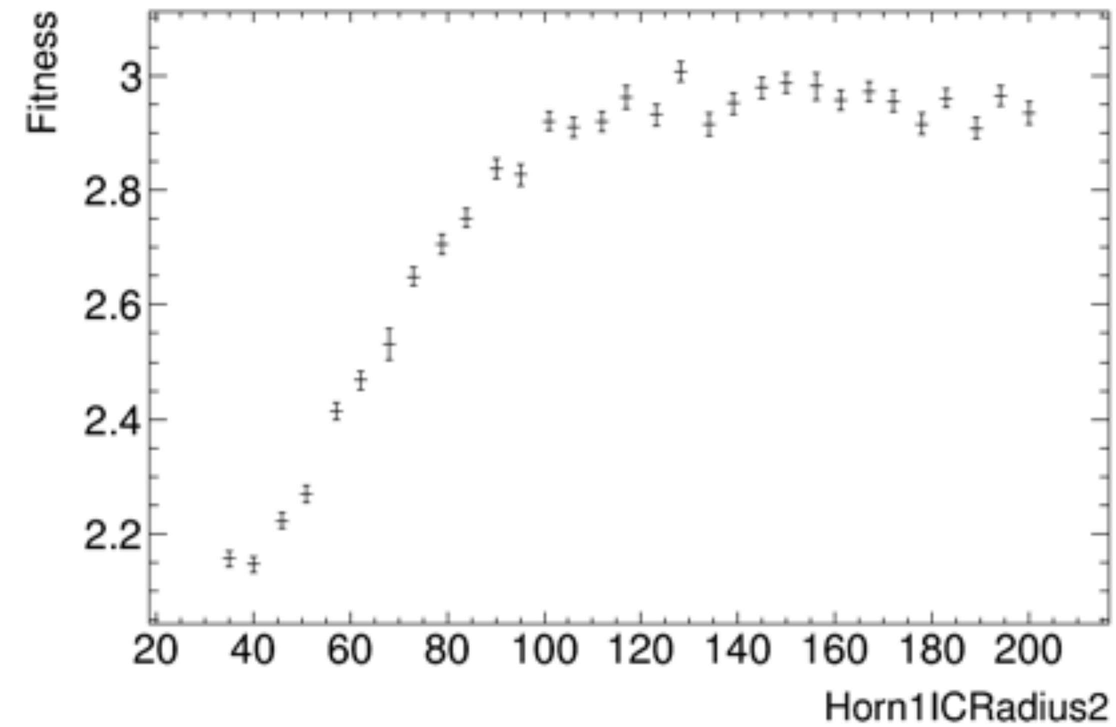
This shows how the fitness varies with horn1 outer conductor radius with all other optimized parameters fixed

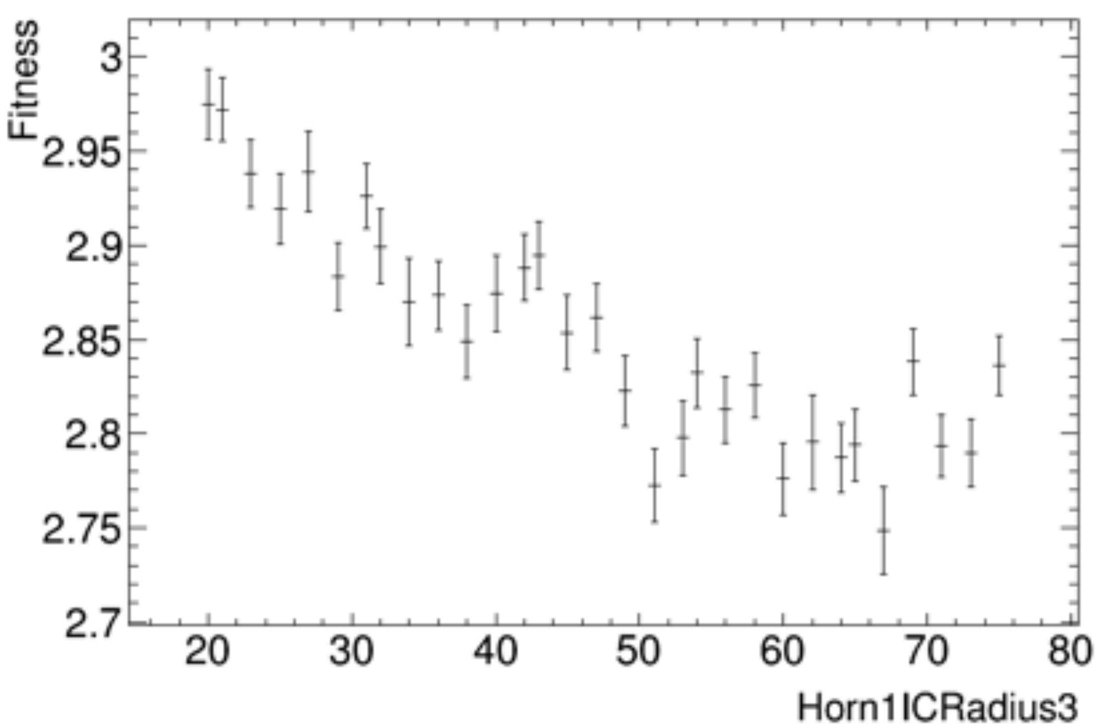
Yellow line shows value chosen by optimization

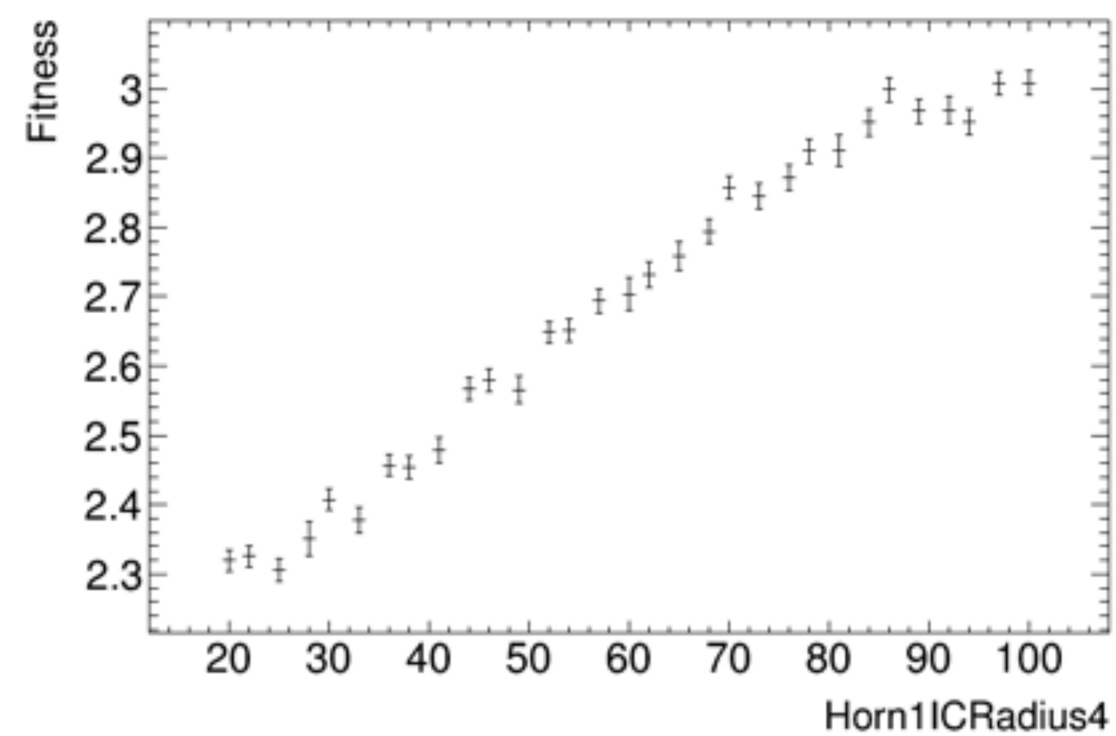
More scan results in backup slides

Results: Parameter Scan

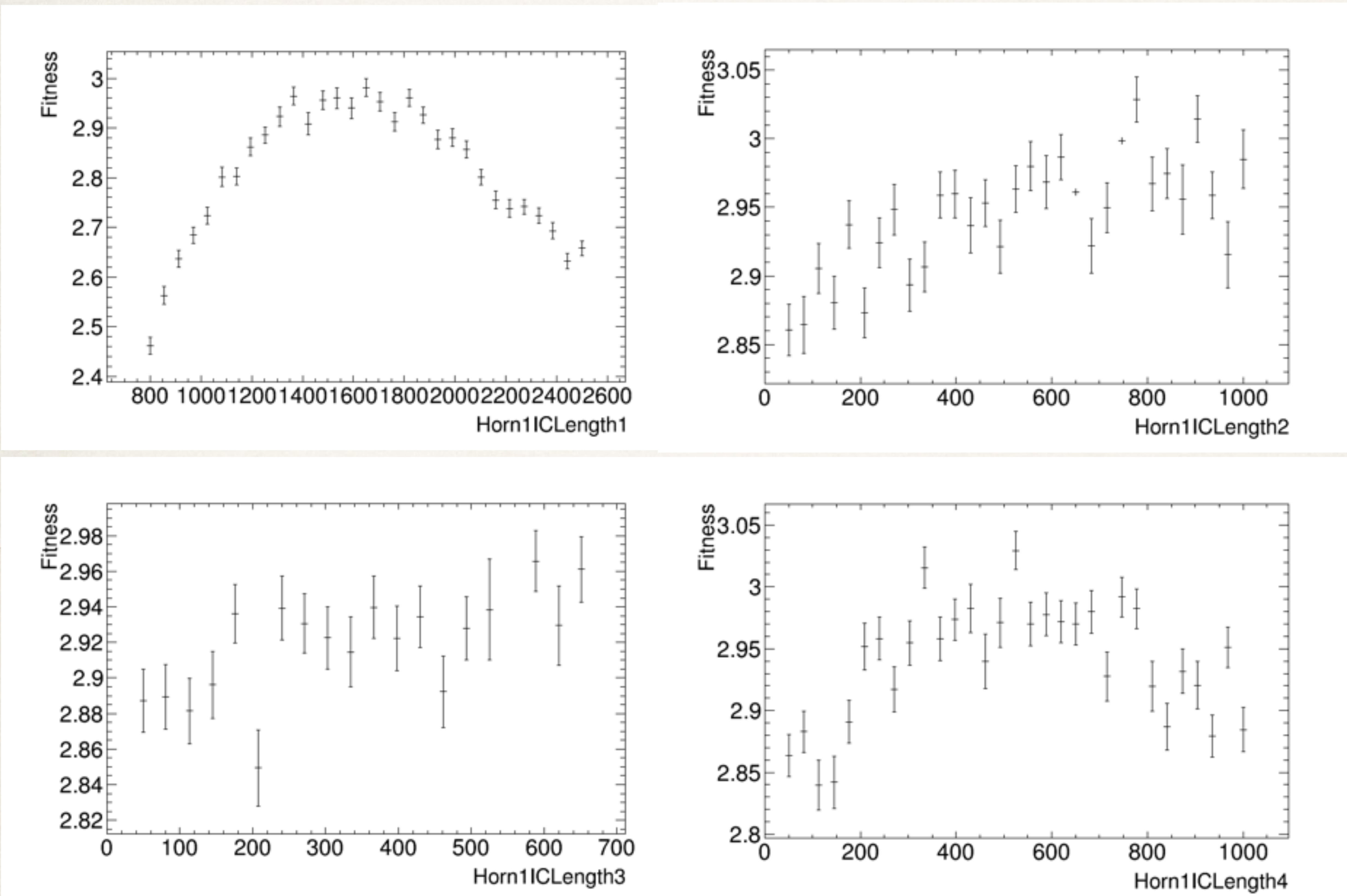




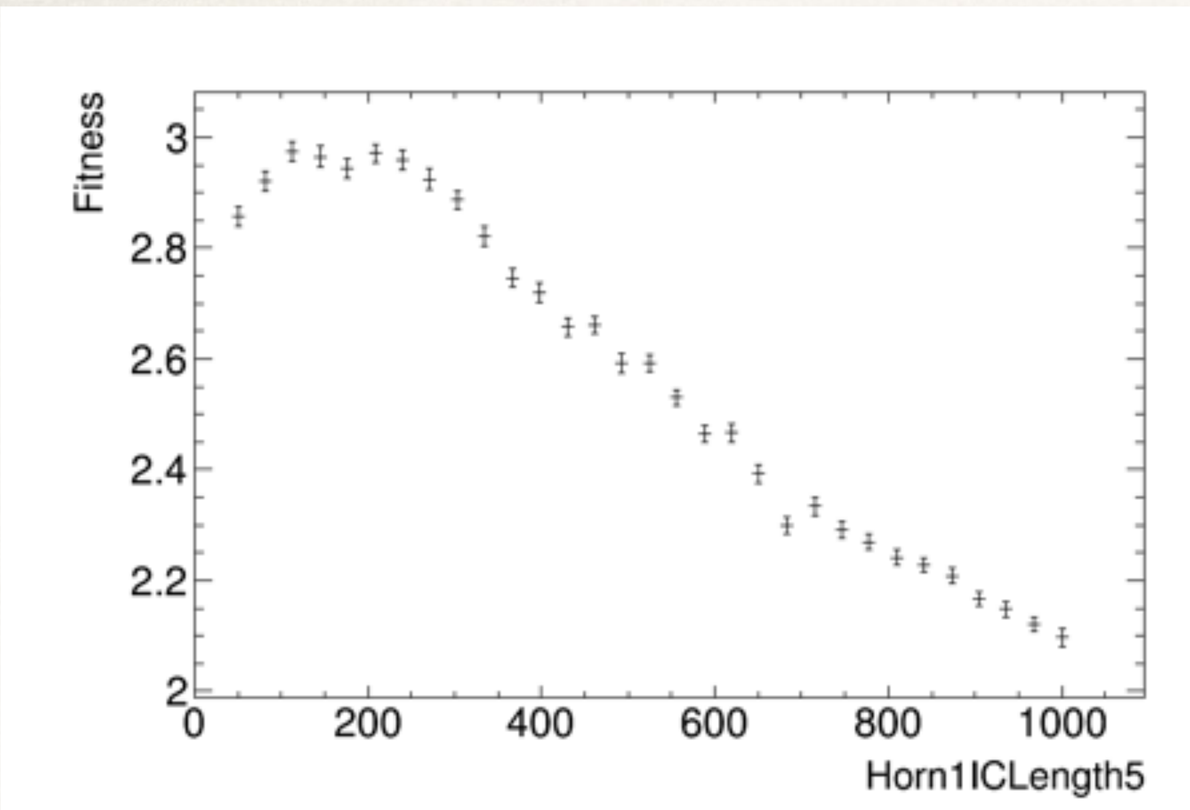


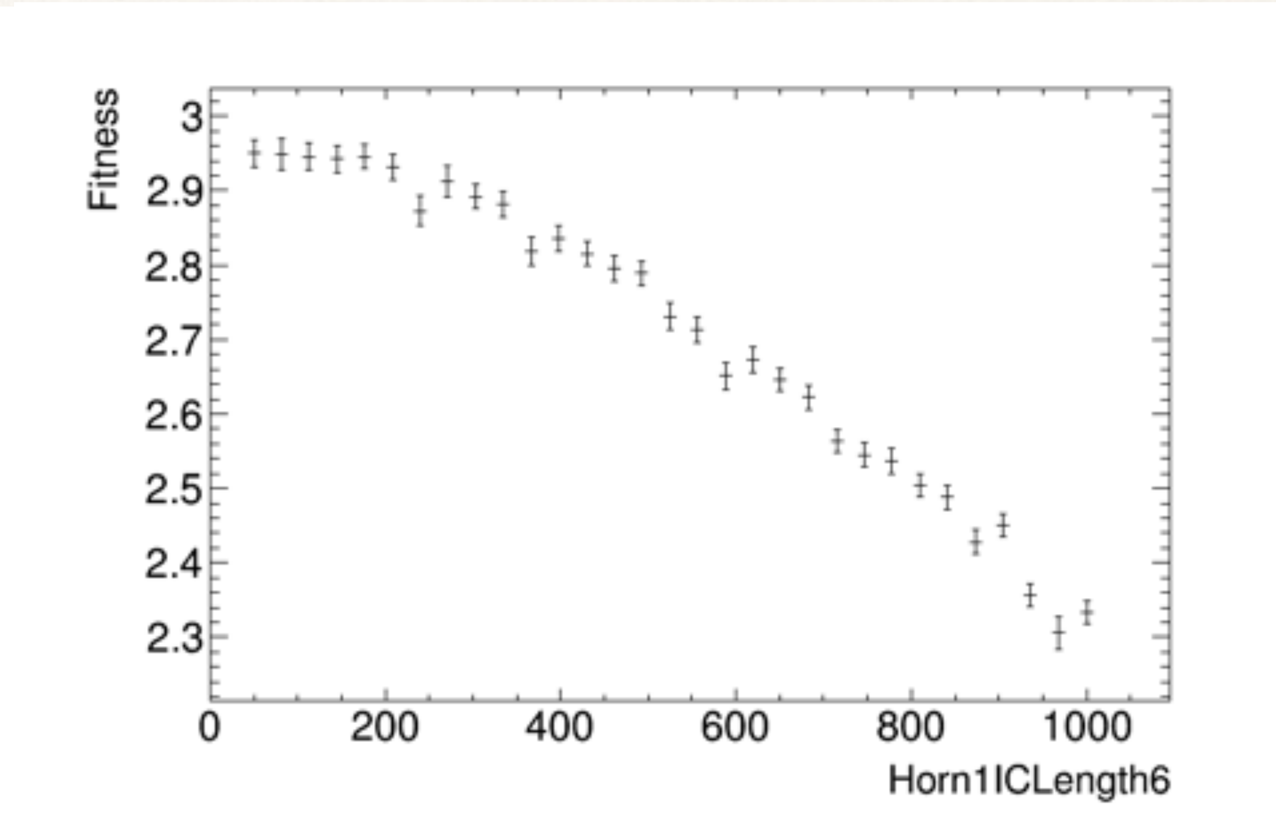


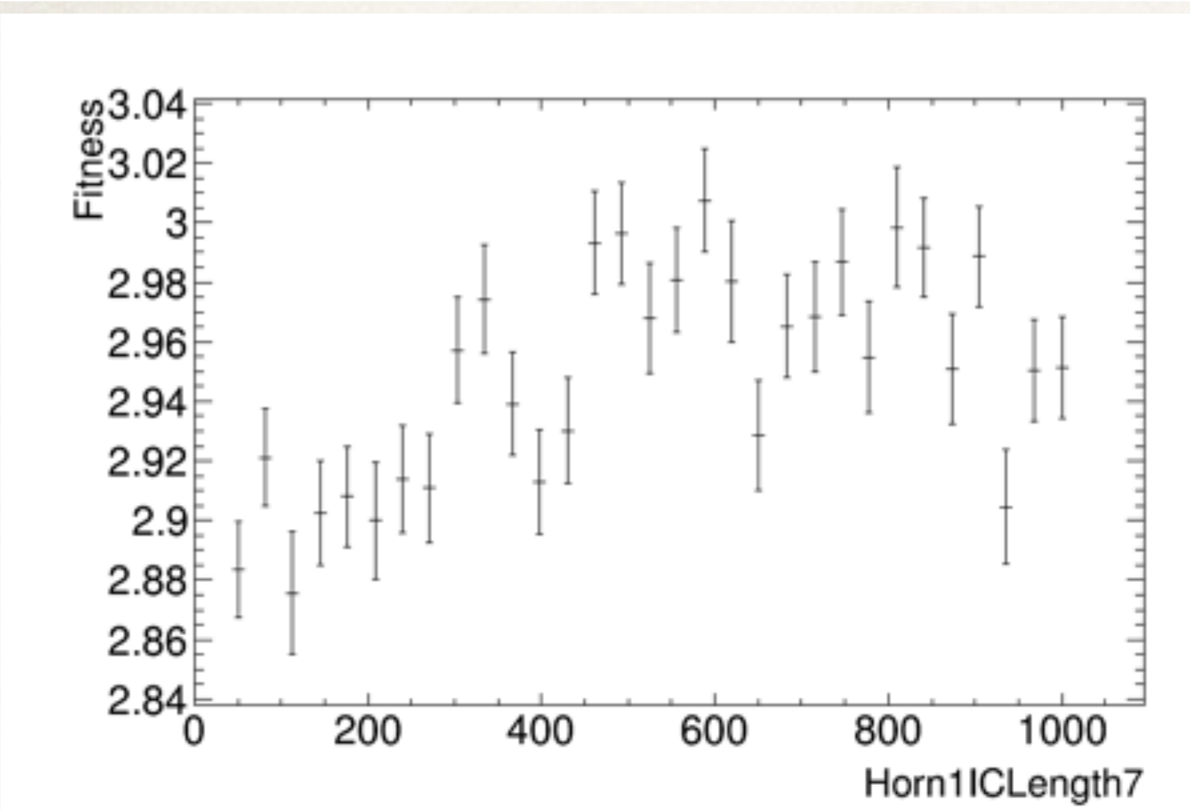
Results: Parameter Scan

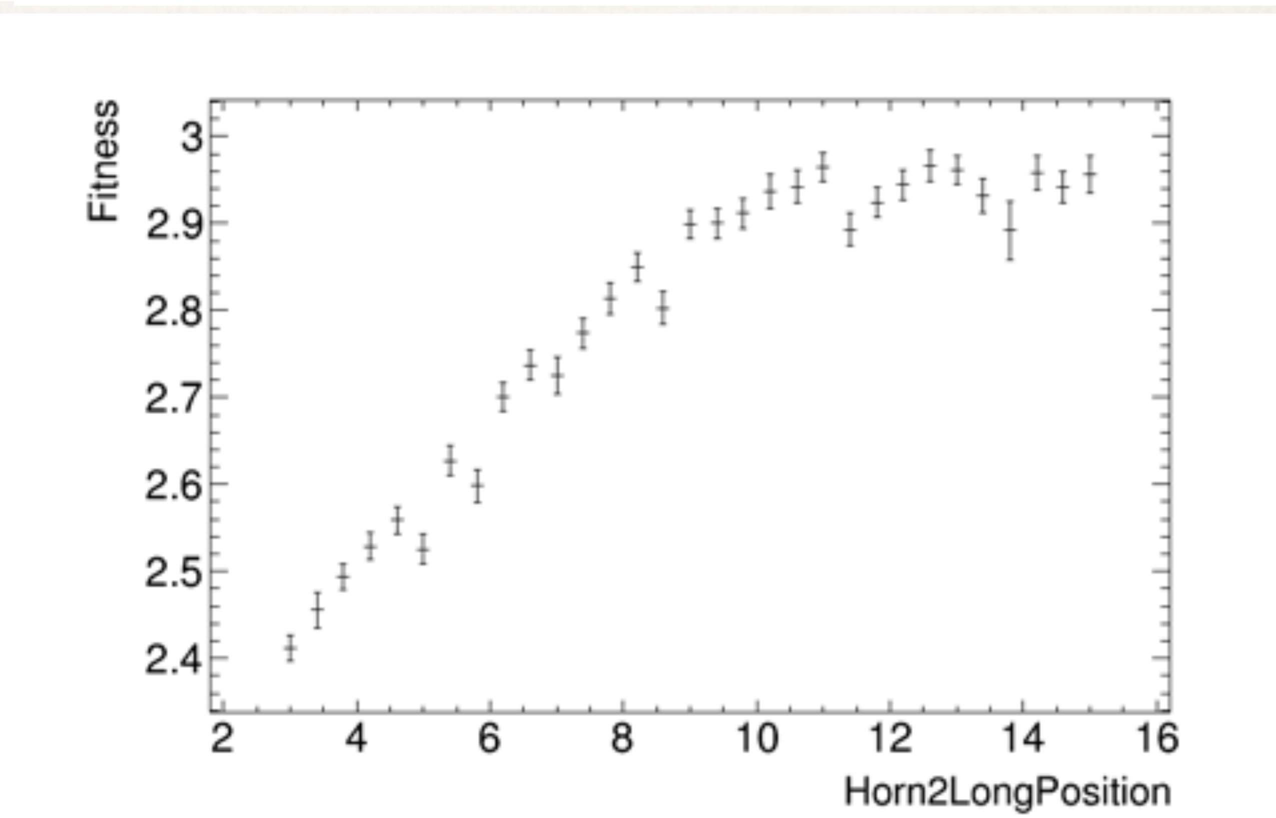


Results: Parameter Scan

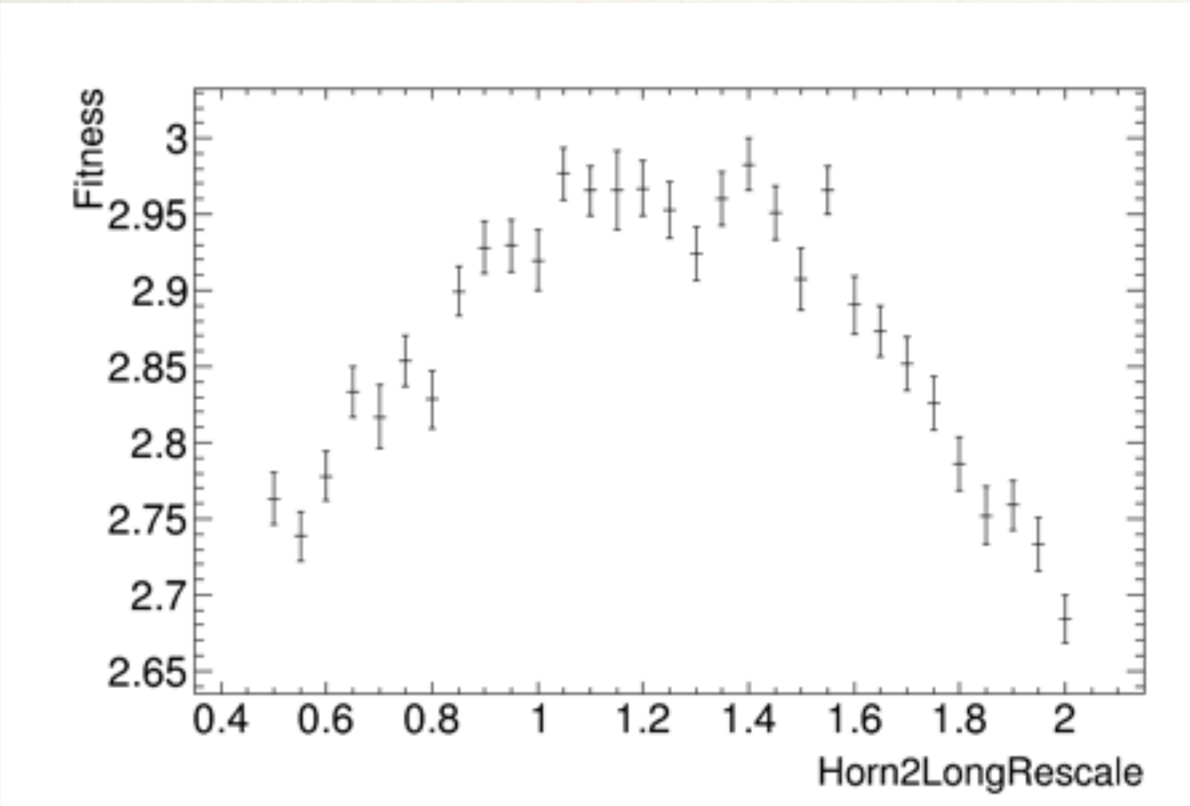


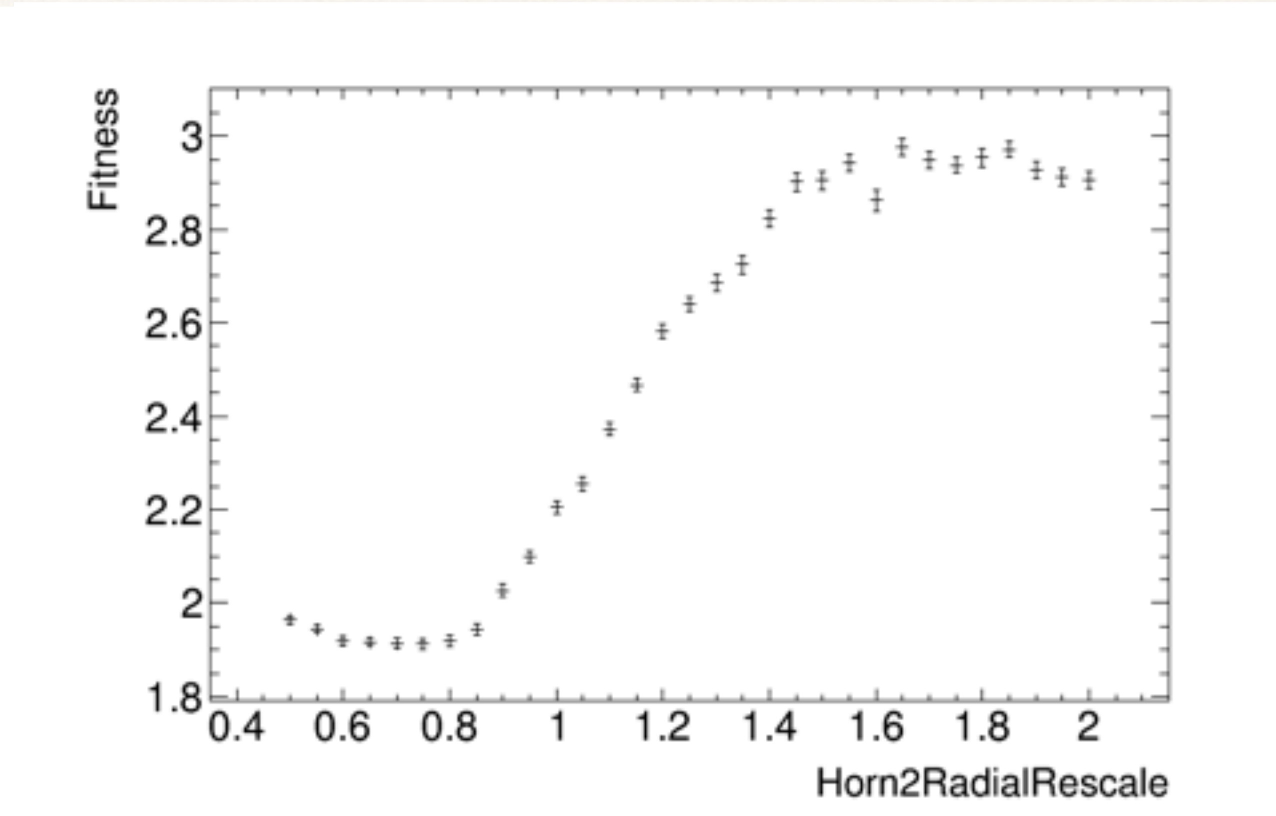


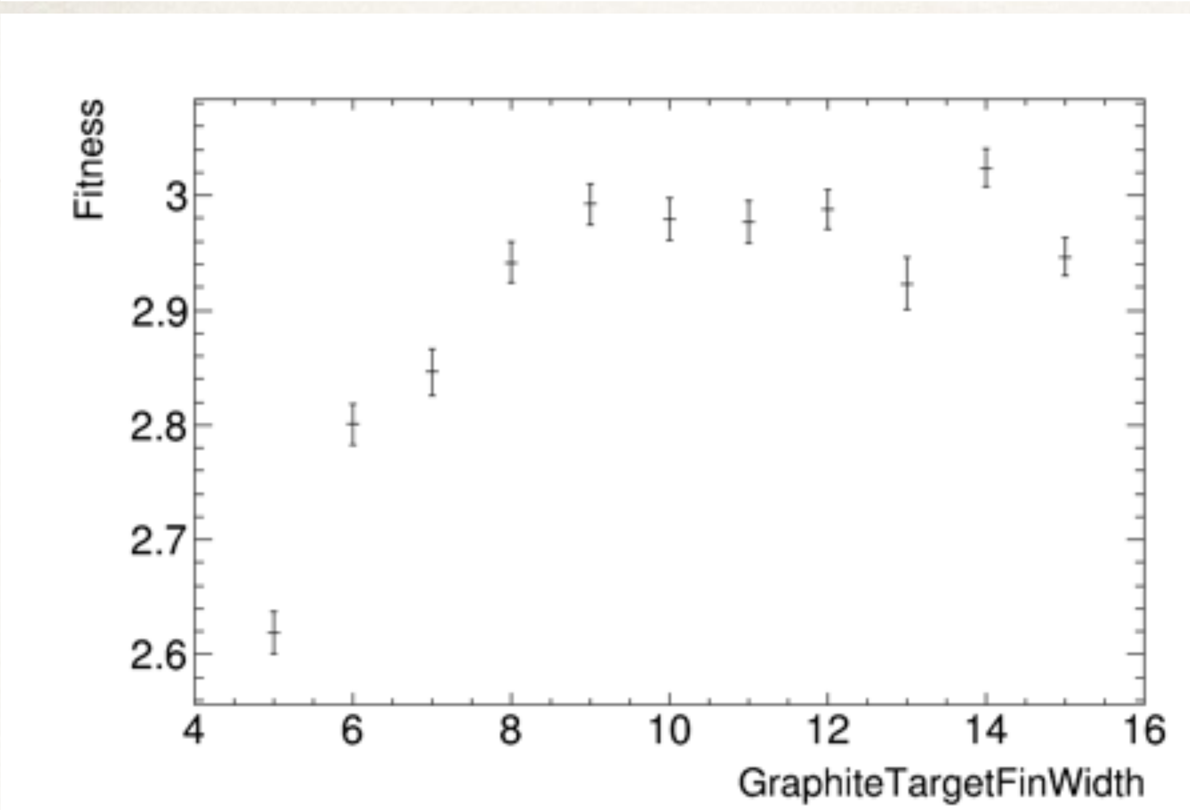


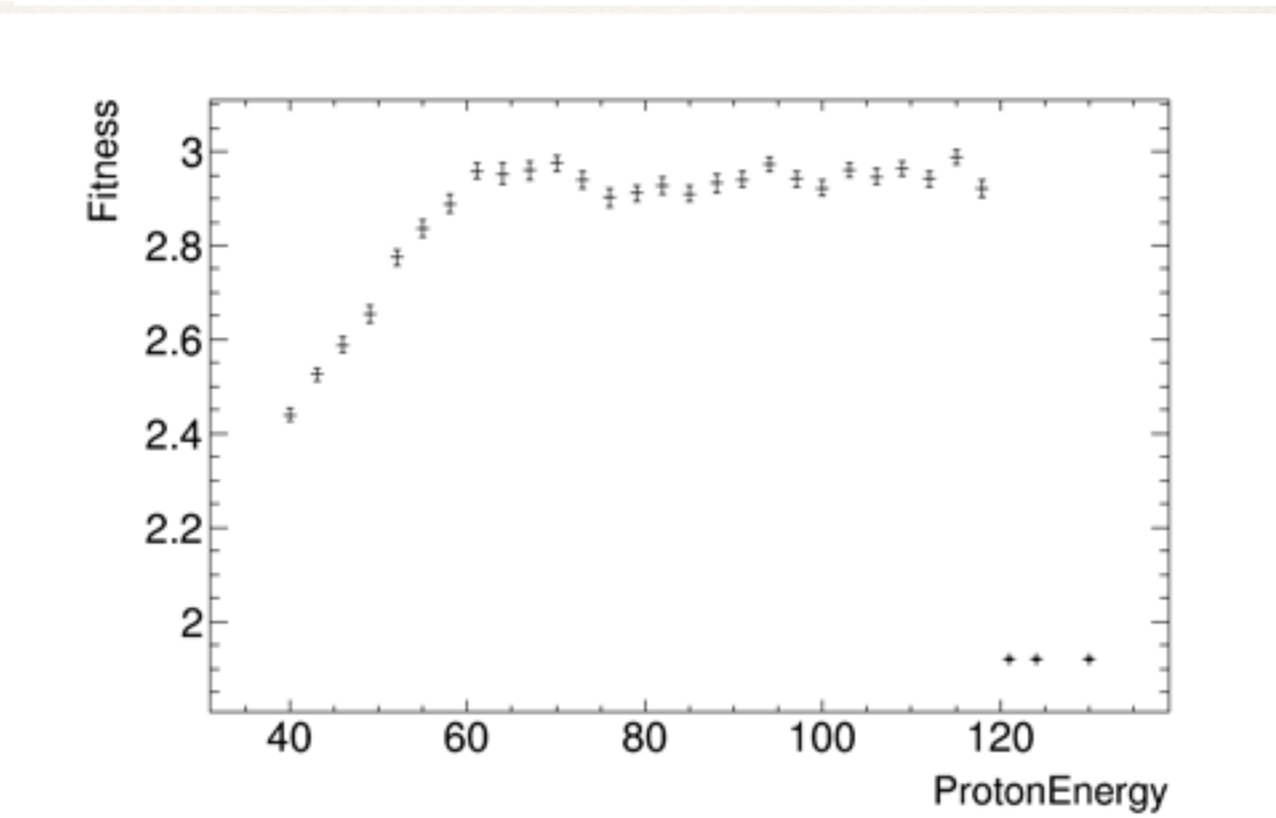


Results: Parameter Scan

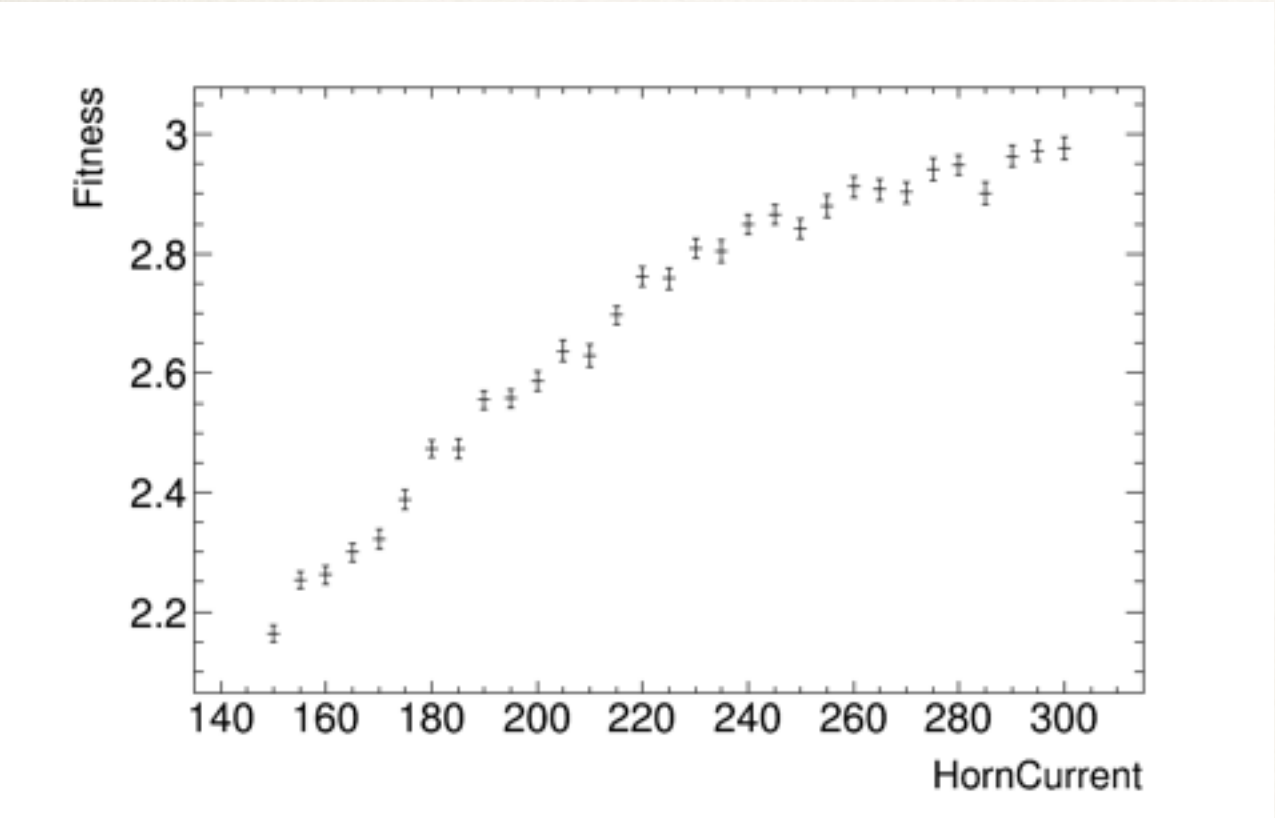








Results: Parameter Scan



Results: Oscillation Parameters Used In FMC

[th12,th13,th23,delta,dm21,dm31] =

[0.593,0.154,0.705,0,7.58E-5,(2.35/-2.27)E-3]

All sensitivity plots assume 3 years x 1.2 MW (or slightly less depending on proton energy) and 34 kTon