FNAL Main Injector Tunnel

Photo: Reider Hahn

Neutrino Beam Optimization

NNN15

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31 October 2015

Outline

- Overview of Beam Optimization
- Specific Beam Optimization Efforts
  - LBNF/DUNE
  - BNB
  - J-PARC Neutrino Beamline
  - NuStorm

This is not intended to be an exhaustive description of all current beam optimization work, but an overview of some of the work that is going on in this very interesting field!

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- Specific Beam Optimization Efforts
  - LBNF/DUNE
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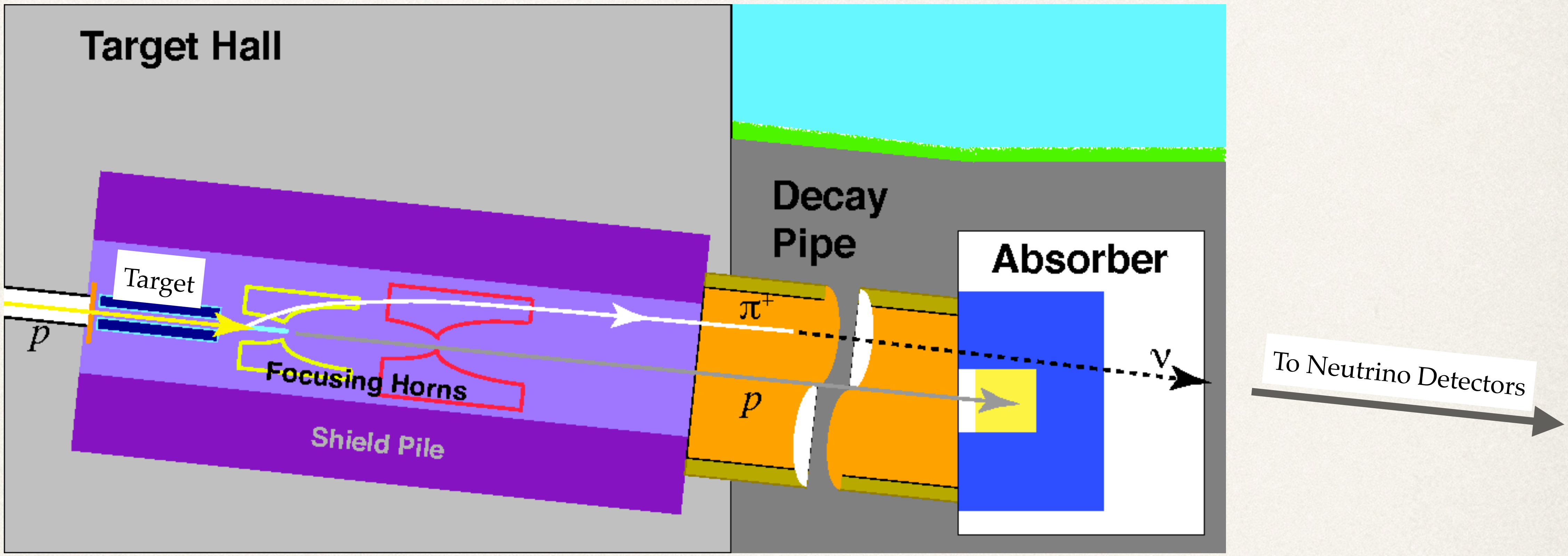
  - NuStorm

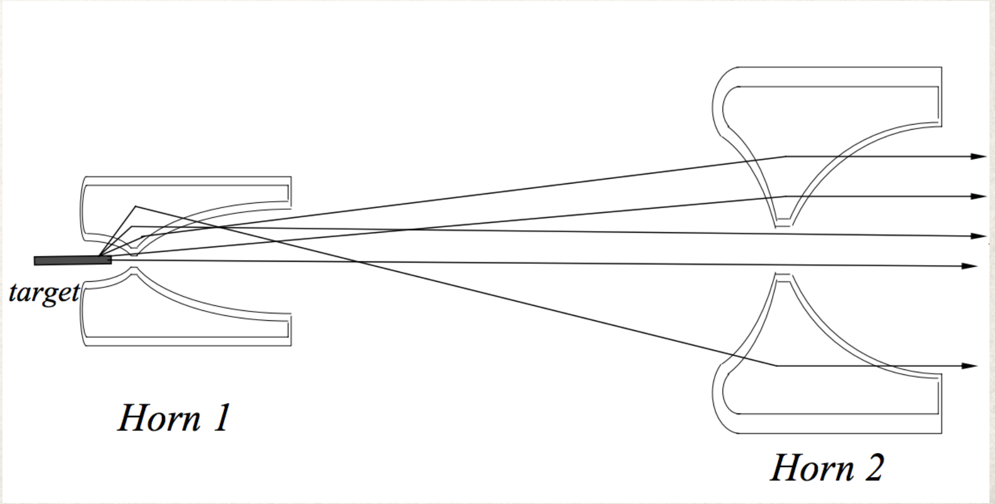
This is not intended to be an exhaustive description of all current beam optimization work, but an overview of some of the work that is going on in this very interesting field!

If you know of other optimization efforts, I'd love to hear about them! laurajfields@gmail.com

Overview of Beam Optimization



- Conventional neutrino beamlines have **a lot** of **configurable parameters**
  - Primary **proton beam** parameters, off -axis angle
  - **Target** shape, size and material
  - Focusing **horn** shape and placement
  - Dimensions of **decay volume**



Overview of Beam Optimization

- First: **what exactly do we mean by beam optimization?**
  - Can be factorized into **two pieces**:
    - Optimizing the **number of protons** on target
    - **Doing the best you can with your protons**

Overview of Beam Optimization

- First: **what exactly do we mean by beam optimization?**
  - Can be factorized into **two pieces**:
    - Maximizing the **number of protons** on target
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This is a **pretty straightforward** (if difficult to solve!) problem — we always want more protons

There are **big efforts** at all neutrino beamlines to **increase beam power**

Overview of Beam Optimization

- First: **what exactly do we mean by beam optimization?**
  - Can be factorized into **two pieces**:
    - Maximizing the **number of protons** on target
    - **Doing the best you can with your protons** →

This is has a **less obvious** solution, but can be very cost effective and is the primary focus of my talk today

Although it is of course **coupled to beam power** — the focusing system has to be able to withstand the many stresses created by the proton beam

Overview of Beam Optimization

- The next question: **what exactly is “the best”** beam?
  - Also **not** a **straightforward** question
  - Ideally, it would mean the beam that gives the **best physics** measurements but:
    - We always want to make a bunch of measurements with one beam, so have to **choose one** (or a very small number) of quantities to maximize
    - Have to take into account **cost and engineering** limitations

“Beam Optimization” is clearly a **complicated concept**

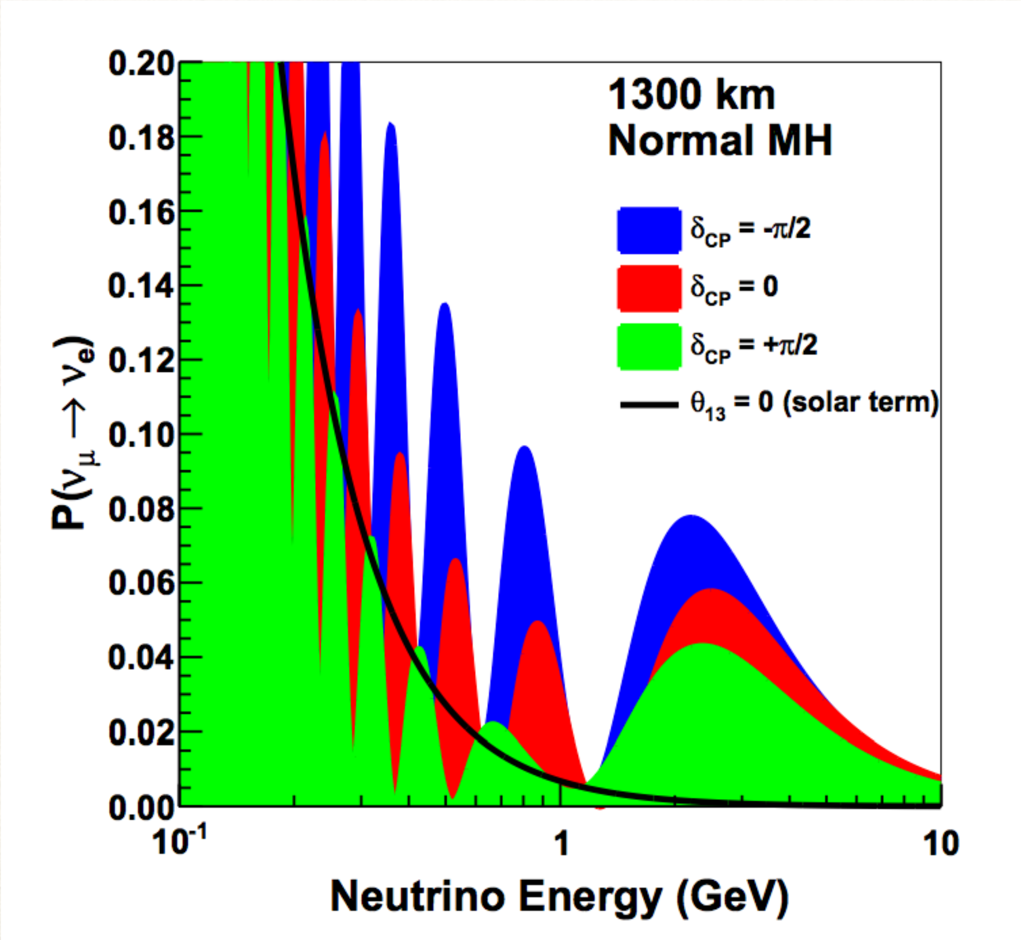
For the purposes of this talk, it primarily means: “How do we **maximize our physics per proton**”

And I’m going to focus on the physics of **neutrino oscillations**

Overview of Beam Optimization

- How **most beams** have been **configured**:
    - **Choose the energy region** where you want to study neutrinos (frequently the region where you want to look for neutrino oscillations)
    - Identify designs that **maximize neutrinos in the region** using basic simulations of the beam and calculations, balancing neutrino yield against:
        - **Technical feasibility**
        - **Cost**

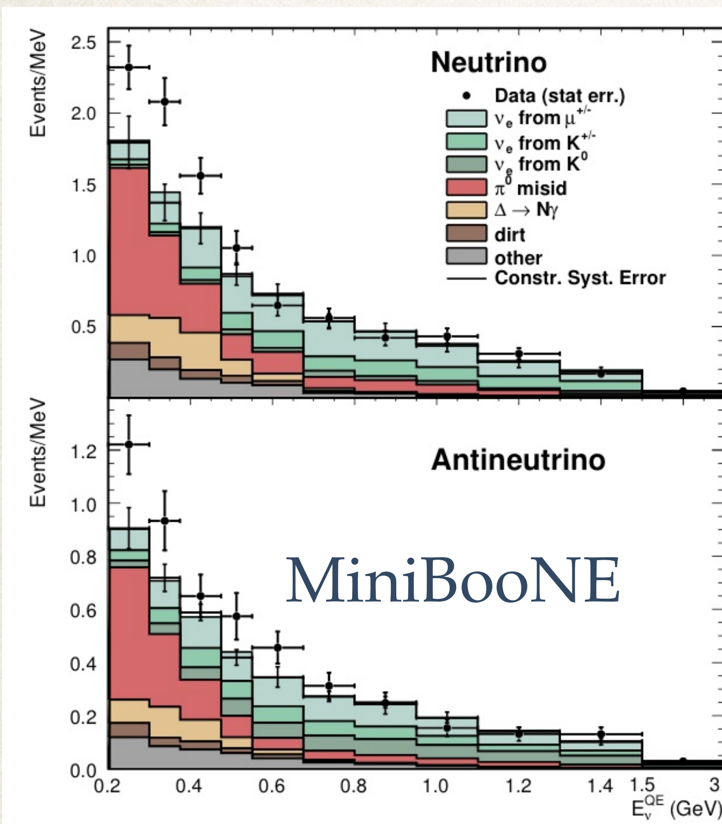
$\nu_\mu \rightarrow \nu_e$ oscillation probabilities for the LBNF/DUNE baseline



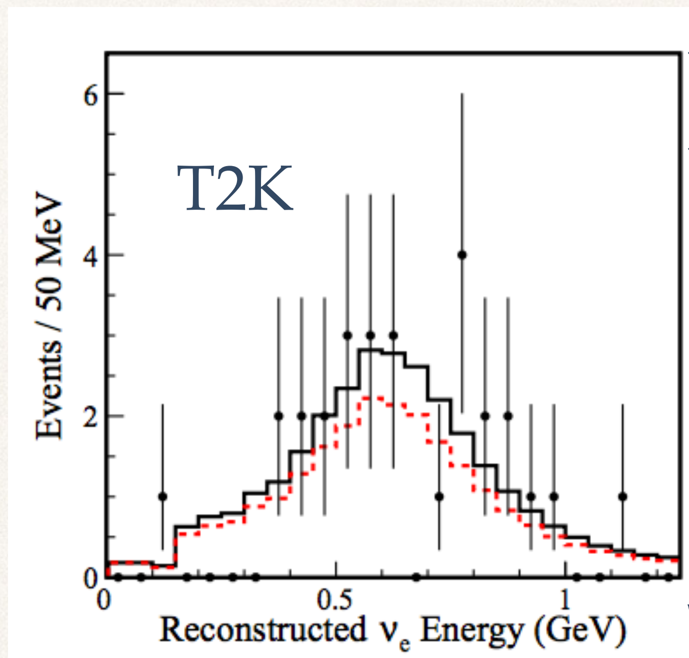
DUNE CDR

Overview of Beam Optimization

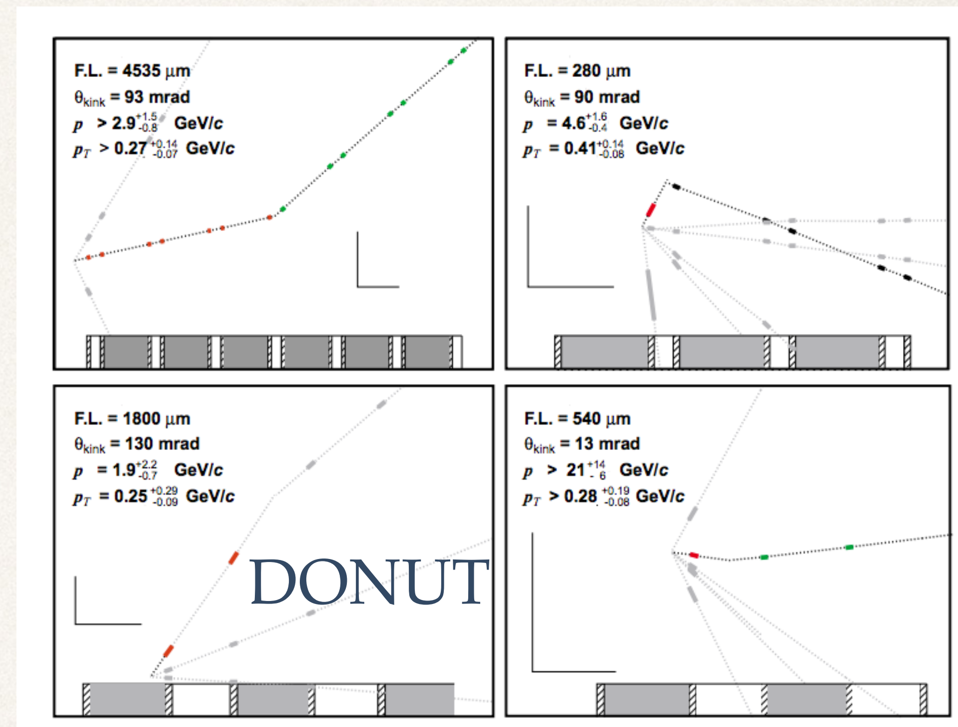
- This strategy has been a **huge success**!



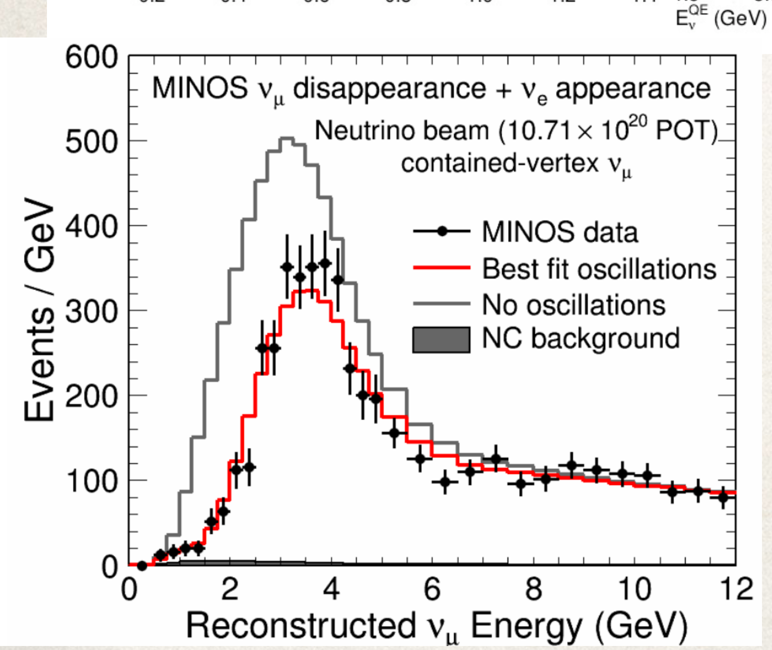
Phys. Rev. D86, 052009 (2012)



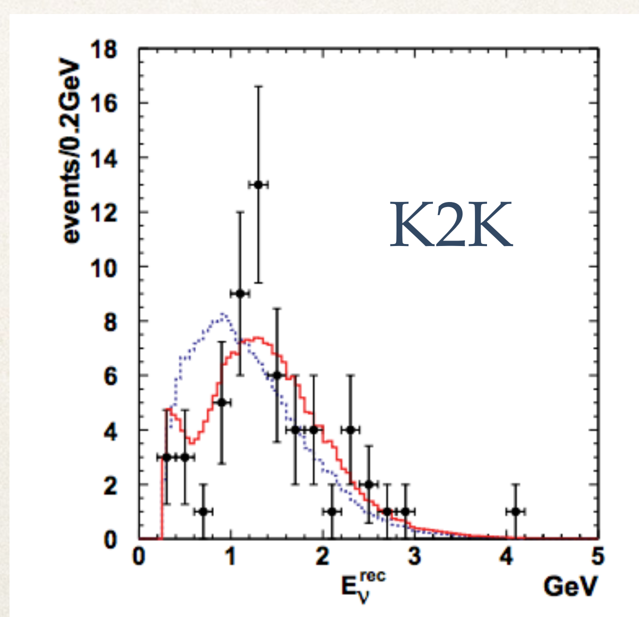
Phys. Rev. D 91, 072010 (2015)



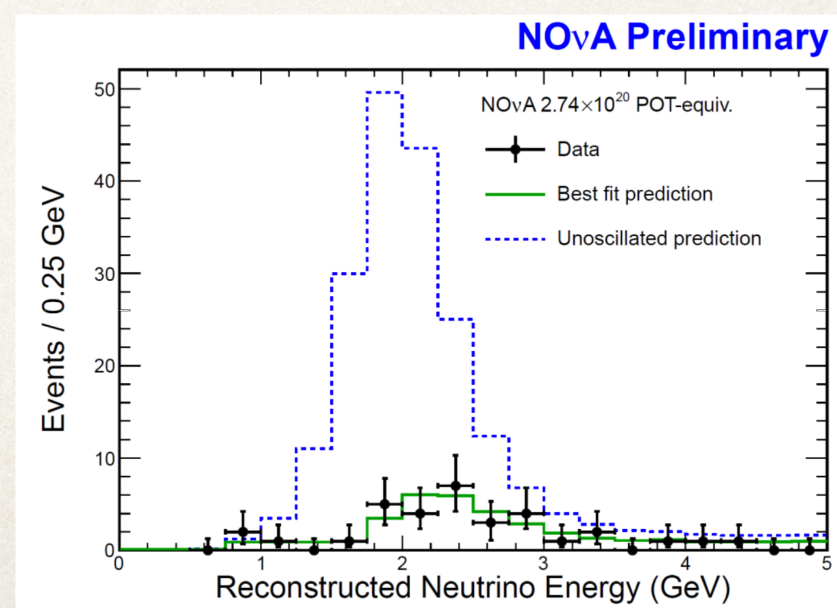
Phys.Lett.B504:218-224,2001



Phys. Rev. Lett. 112, 191801 (2014)



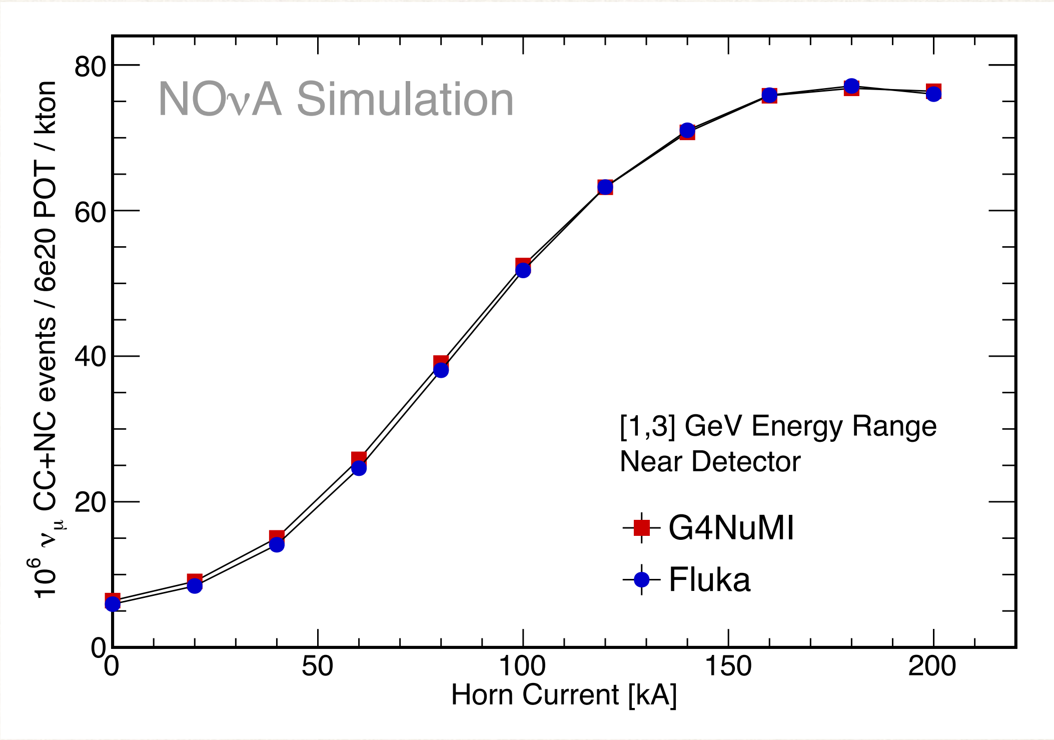
Phys.Rev.D74:072003,2006



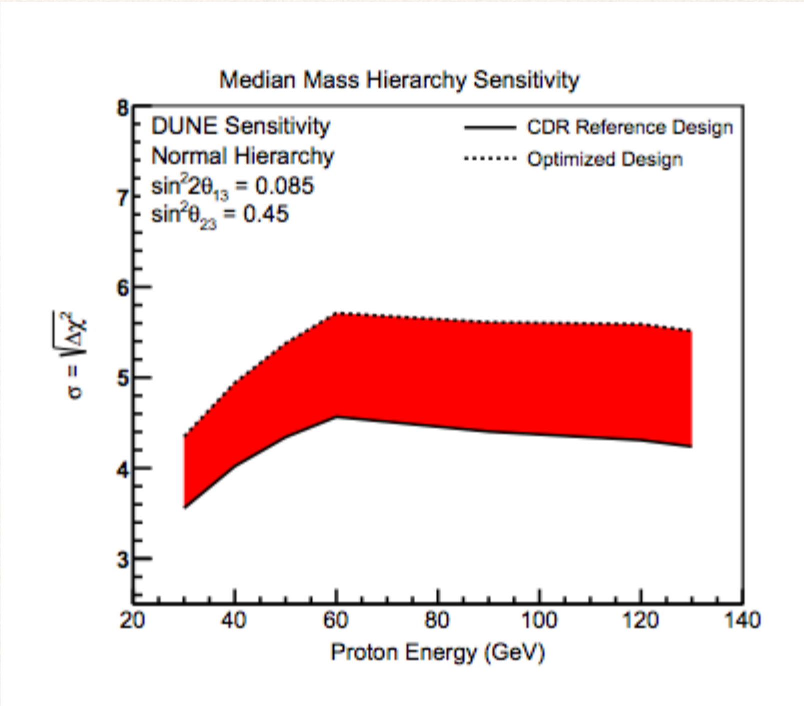
M. Messier DPF 2015

Overview of Beam Optimization

- But we are entering a **new era** for two reasons
  - **Advances in computing** power have made it feasible to do detailed simulations of many, many beam options
    - And to simulate not just the number of expected neutrinos, but **detailed estimates** how how well each beam accomplishes many different **physics goals**



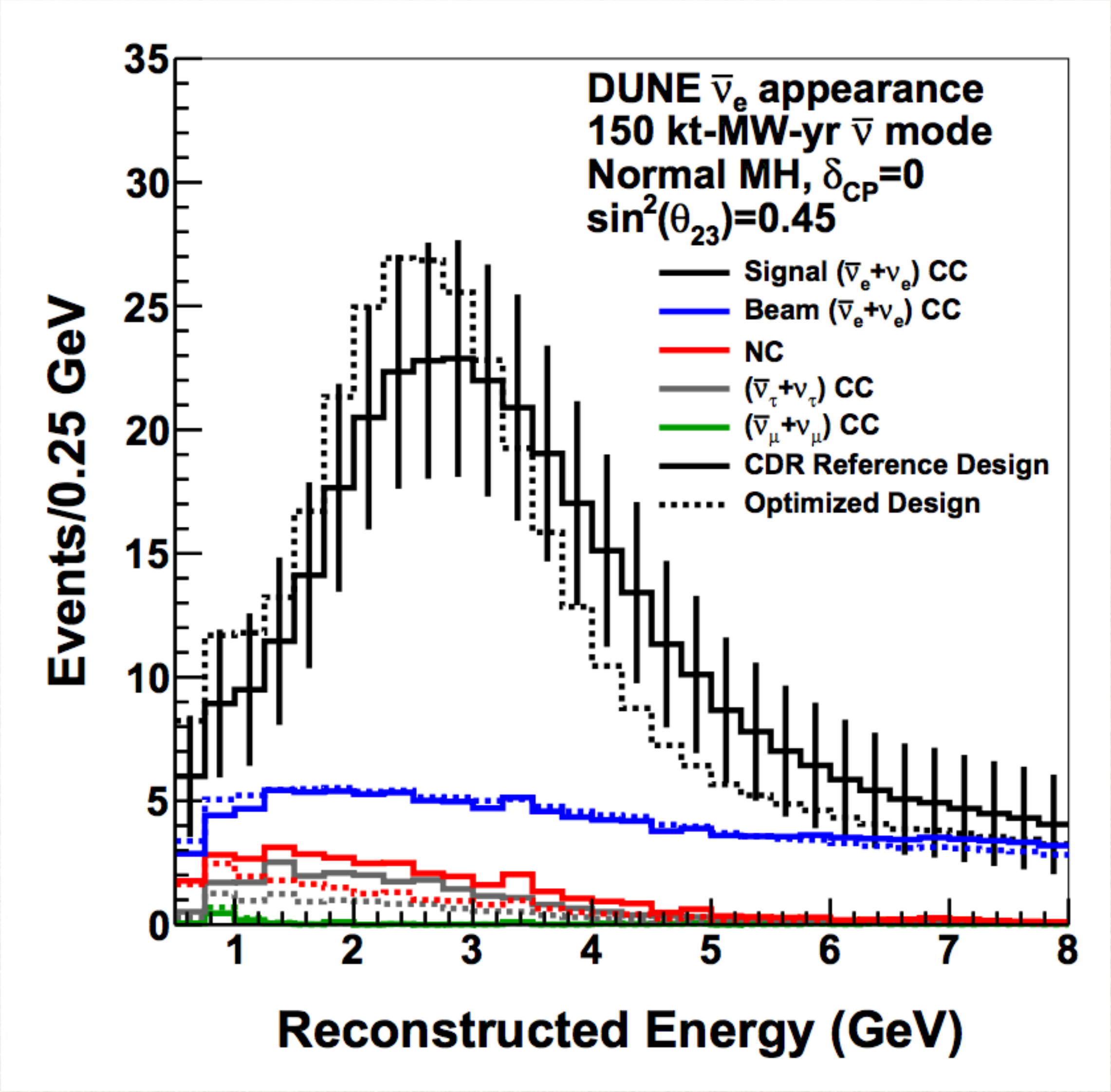
Kuldeep Kaur
FNAL User's Meeting 2015



DUNE CDR

Overview of Beam Optimization

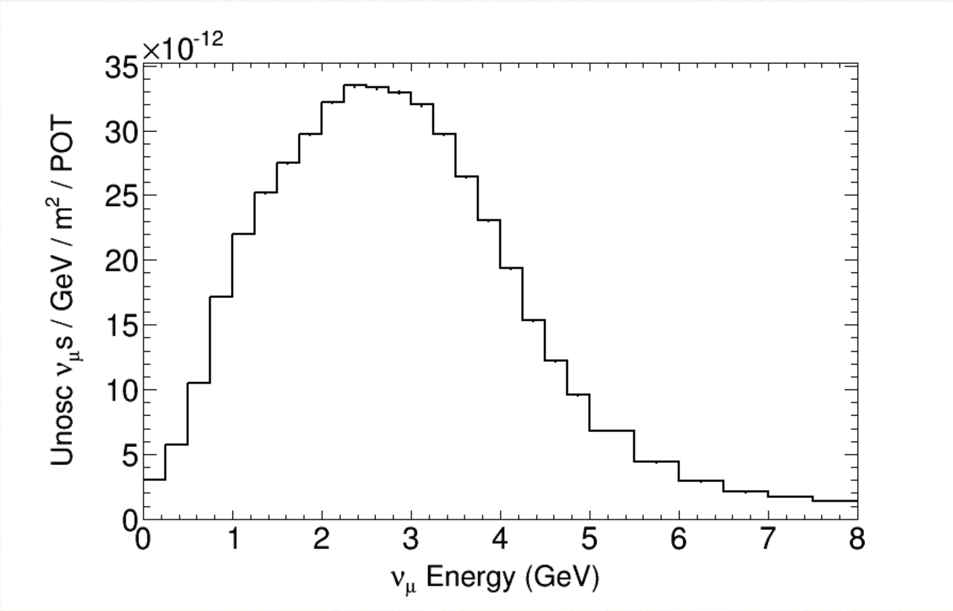
- Also, intense neutrino beams mean we have to **worry about a lot more than signal statistics**
  - High energy and wrong sign backgrounds, systematic uncertainties, energy resolution

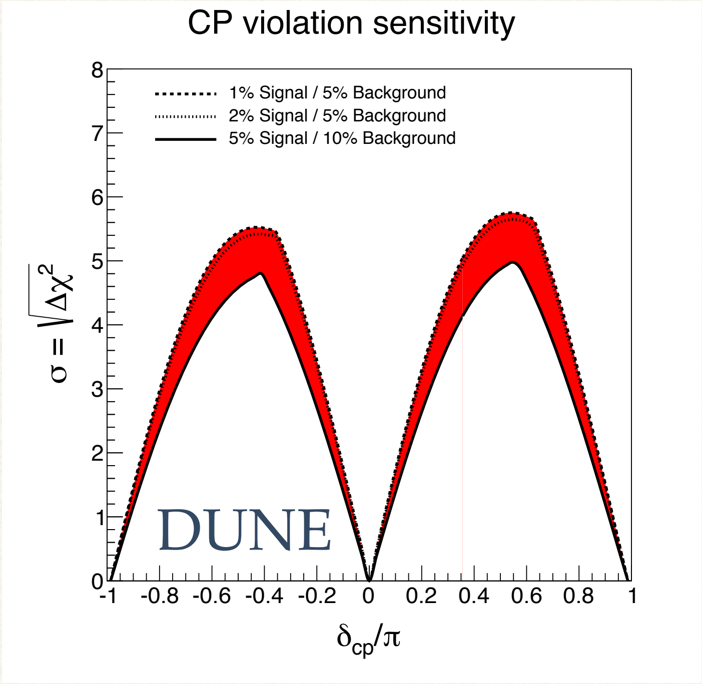


DUNE CDR

Overview of Beam Optimization

- What we'd like to do is to **simulate a bunch of beam configurations**, estimate the physics performance of each configuration, and **pick the best one**

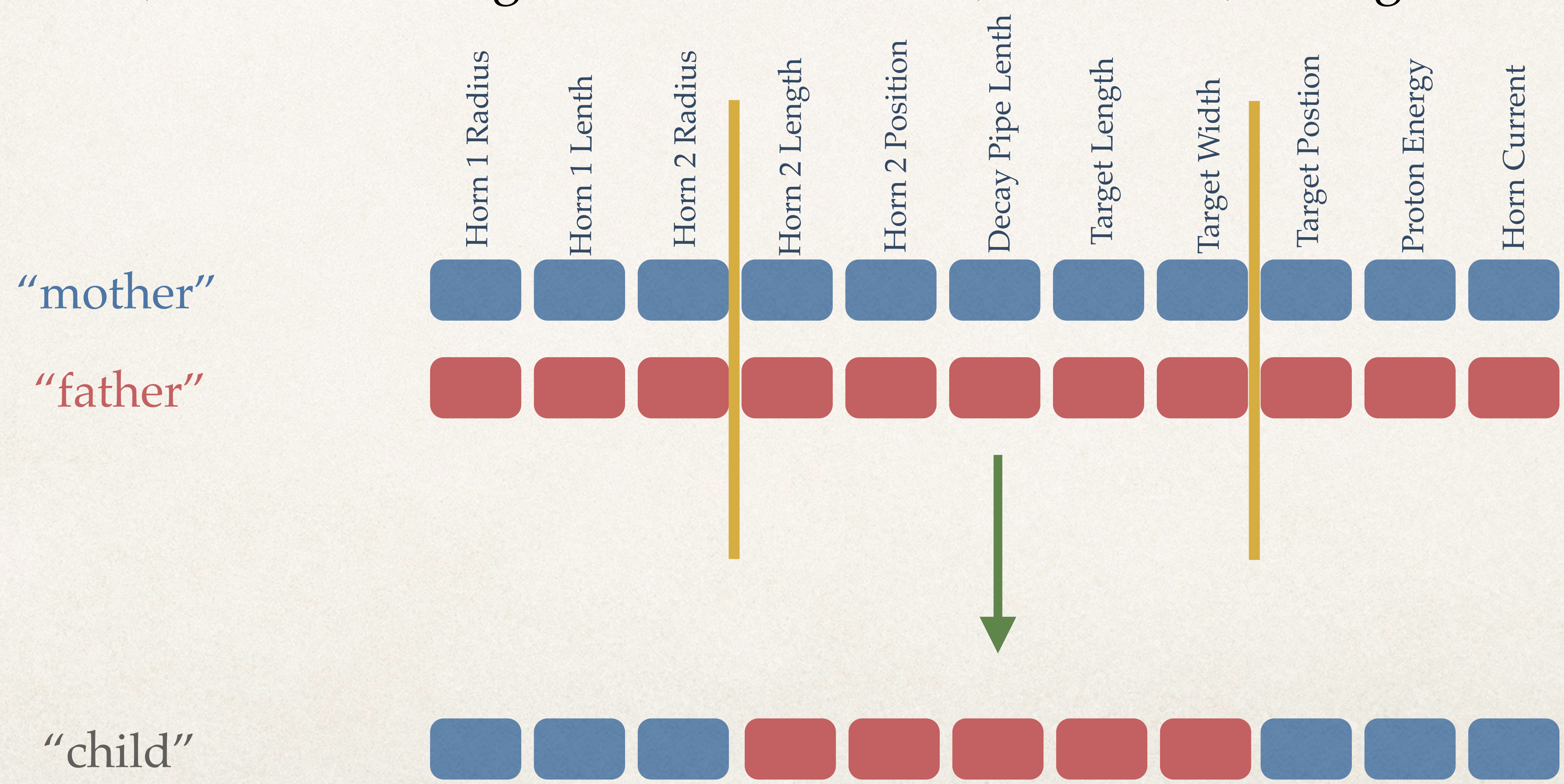




- But considering e.g. just 20 parameters, each with 20 possible values, scanning over the available phase space would take much **longer than the lifetime of the universe**, even with very fast simulations.

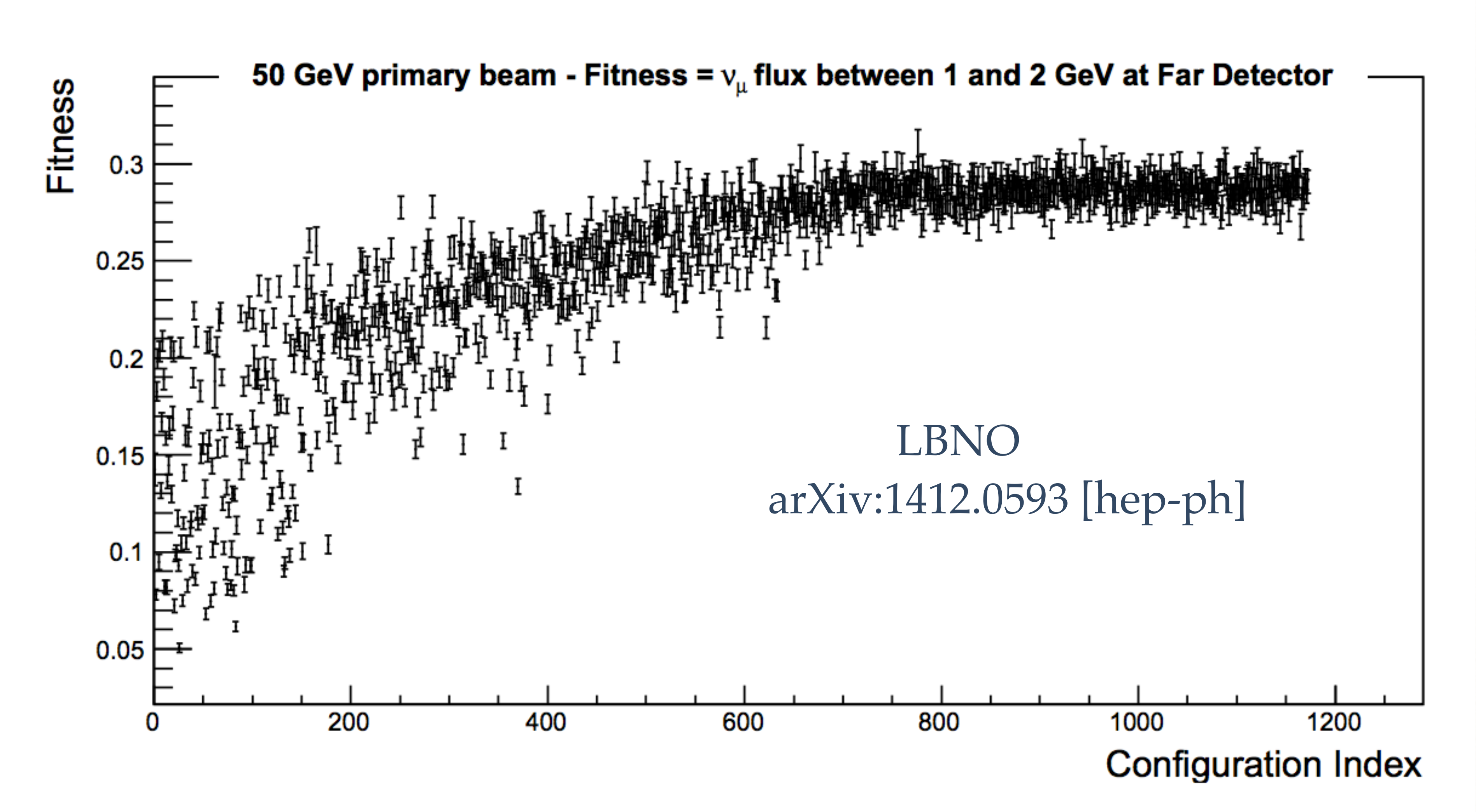
Overview of Beam Optimization

- We can **speed things up** with modern algorithms, e.g. **a genetic algorithm**:
  - This algorithm views each **beam configuration** as an organism; initially, a population with **randomly generated traits** is simulated
  - Configurations are judged based on fitness (number of neutrinos or some physics deliverable) and mated together to form new (and better) configurations



Overview of Beam Optimization

- Repeating this **survival-of-the-fittest** procedure over **many generations** eventually converges on a **optimal beam design**



LBNO
arXiv:1412.0593 [hep-ph]

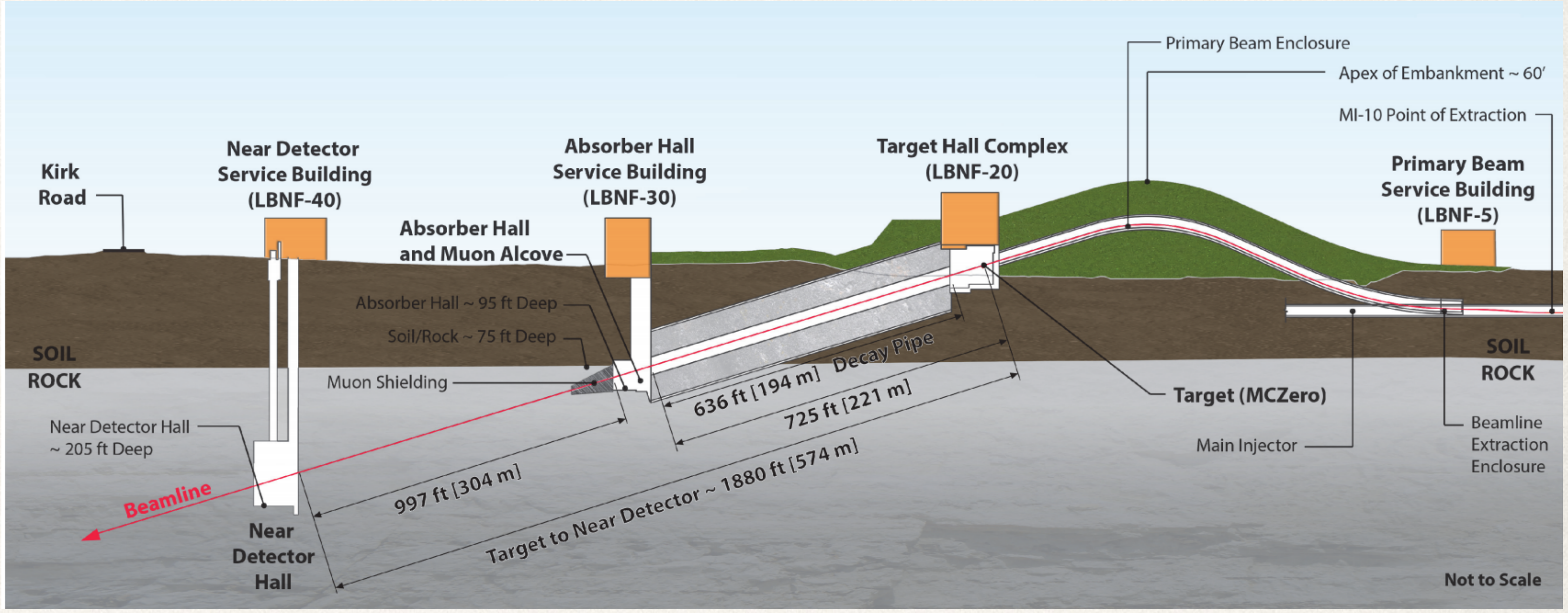
We know these algorithms give us **good beam designs**

We can **never know** whether they have given us **the best** possible beam designs

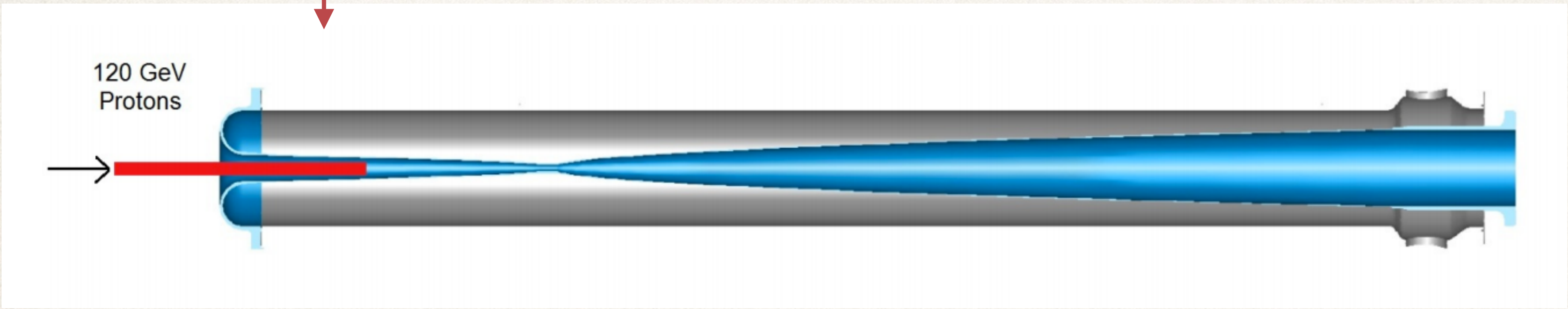
LBNF/DUNE

LBNF Overview

- "First truly international **mega-science project** hosted in the United States"



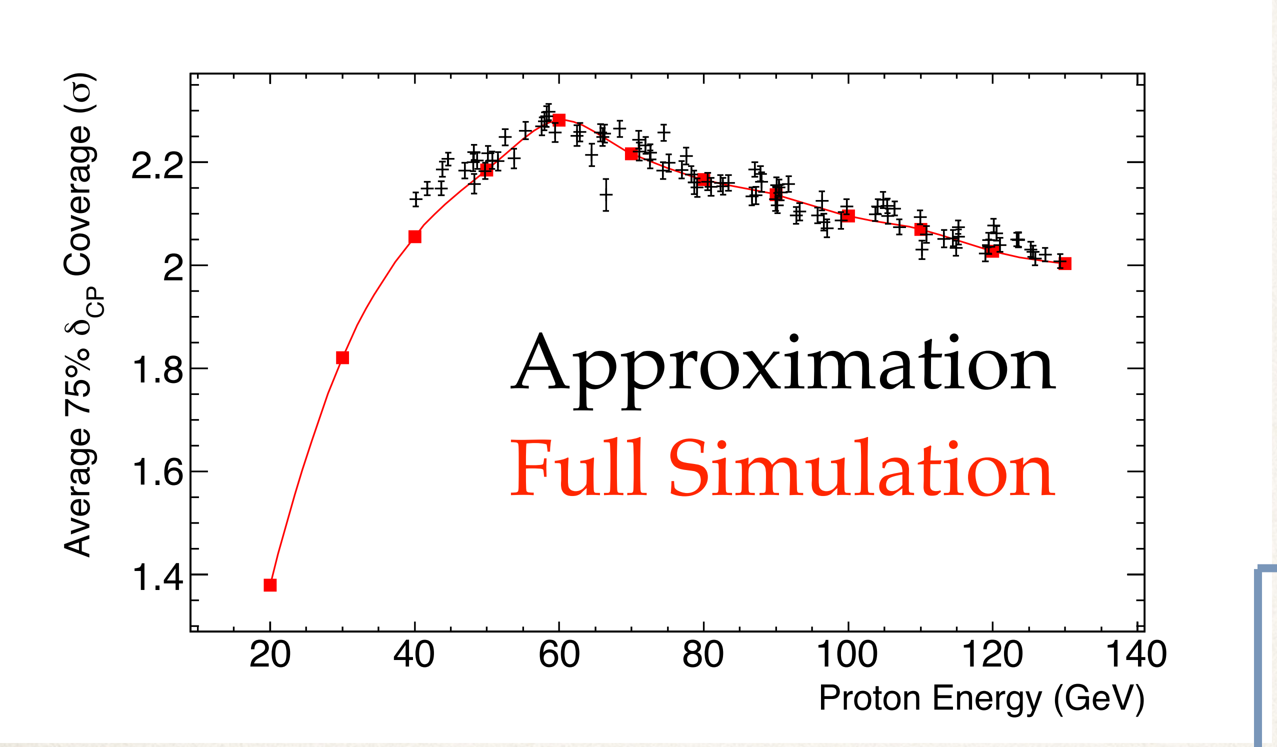
Baseline design uses (2) NuMI horns and NuMI-like target



- 60-120 GeV protons from **Fermilab's Main Injector**, to DUNE detectors in Illinois and South Dakota

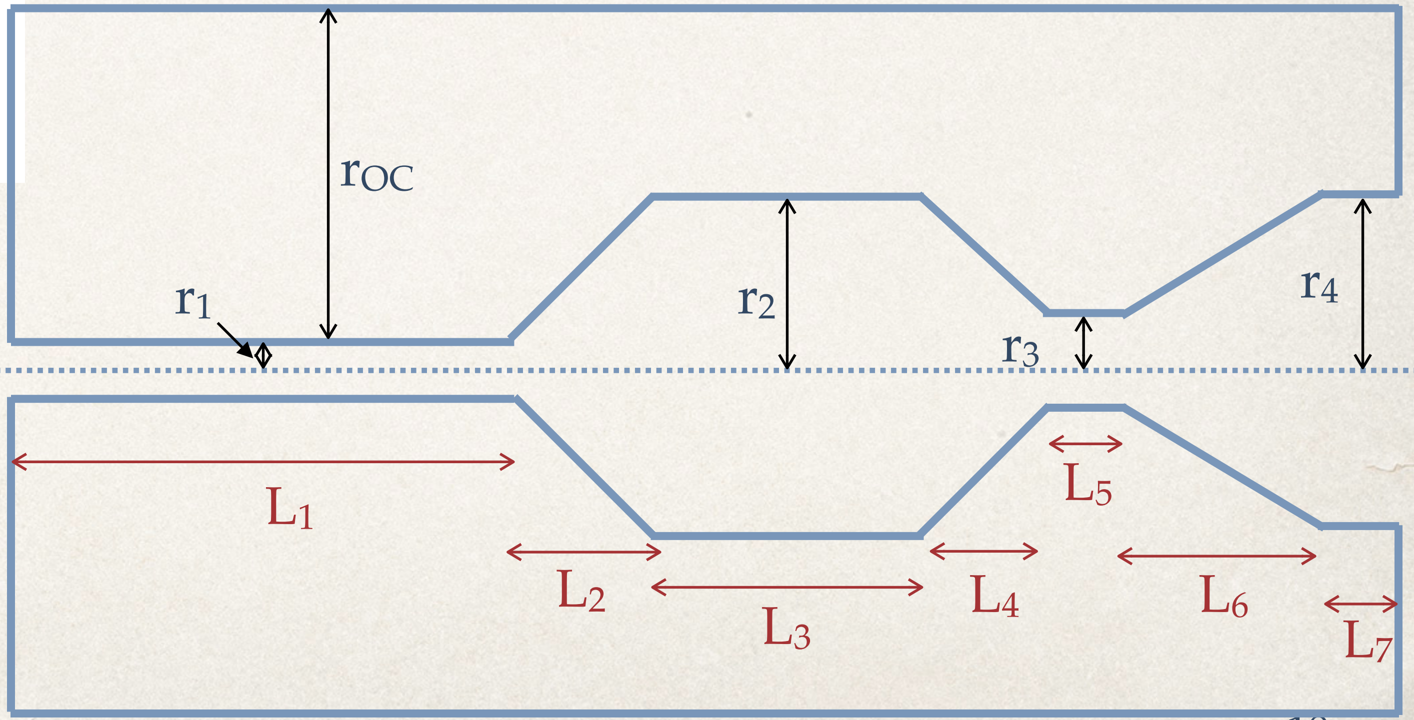
LBNF Beam Optimization

- Has also implemented a **genetic algorithm** that optimizes a fast approximation of CP sensitivity



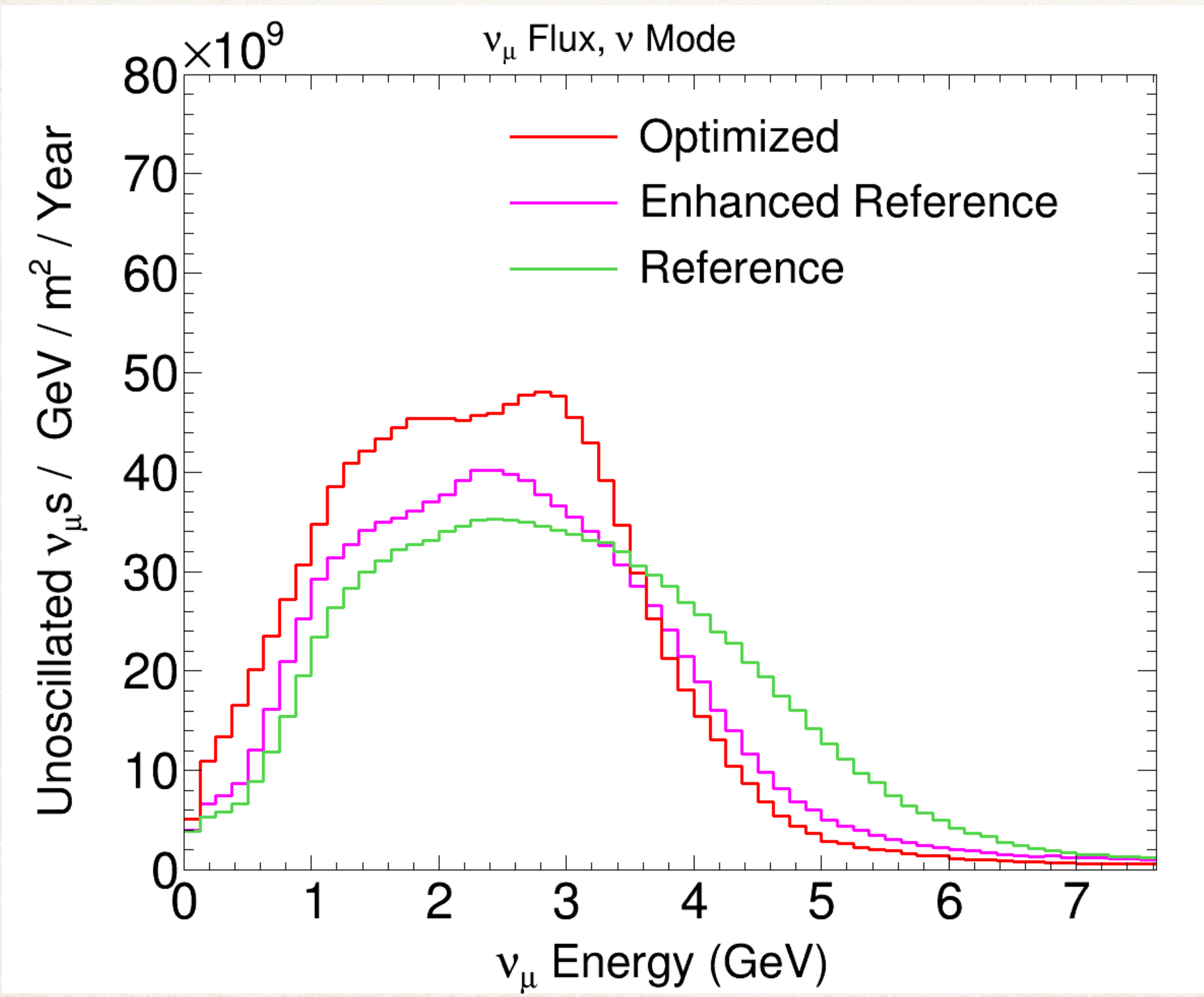
Fast approximation **reduces computation time** from ~ a week to ~ an hour, and tracks full simulation well

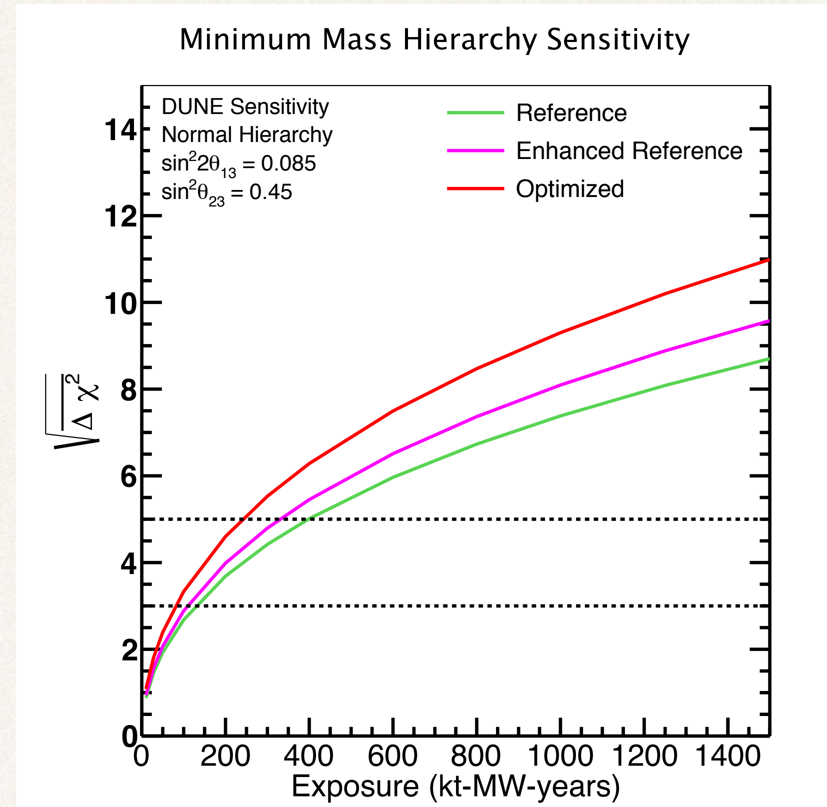
Considered **dramatically different first focusing horn shape** (known to effectively focus low energy particles and based on previous work by T2K and LBNO), also modifications to **target, primary proton beam and second focusing horns**

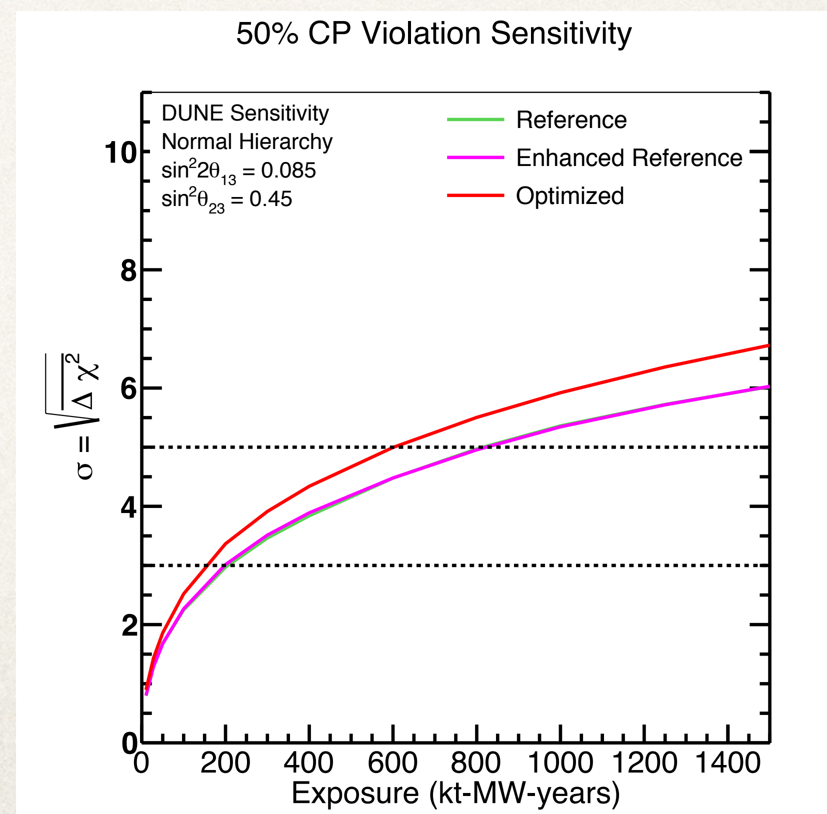


LBNF Beam Optimization

- **Improved performance** of optimized beam:



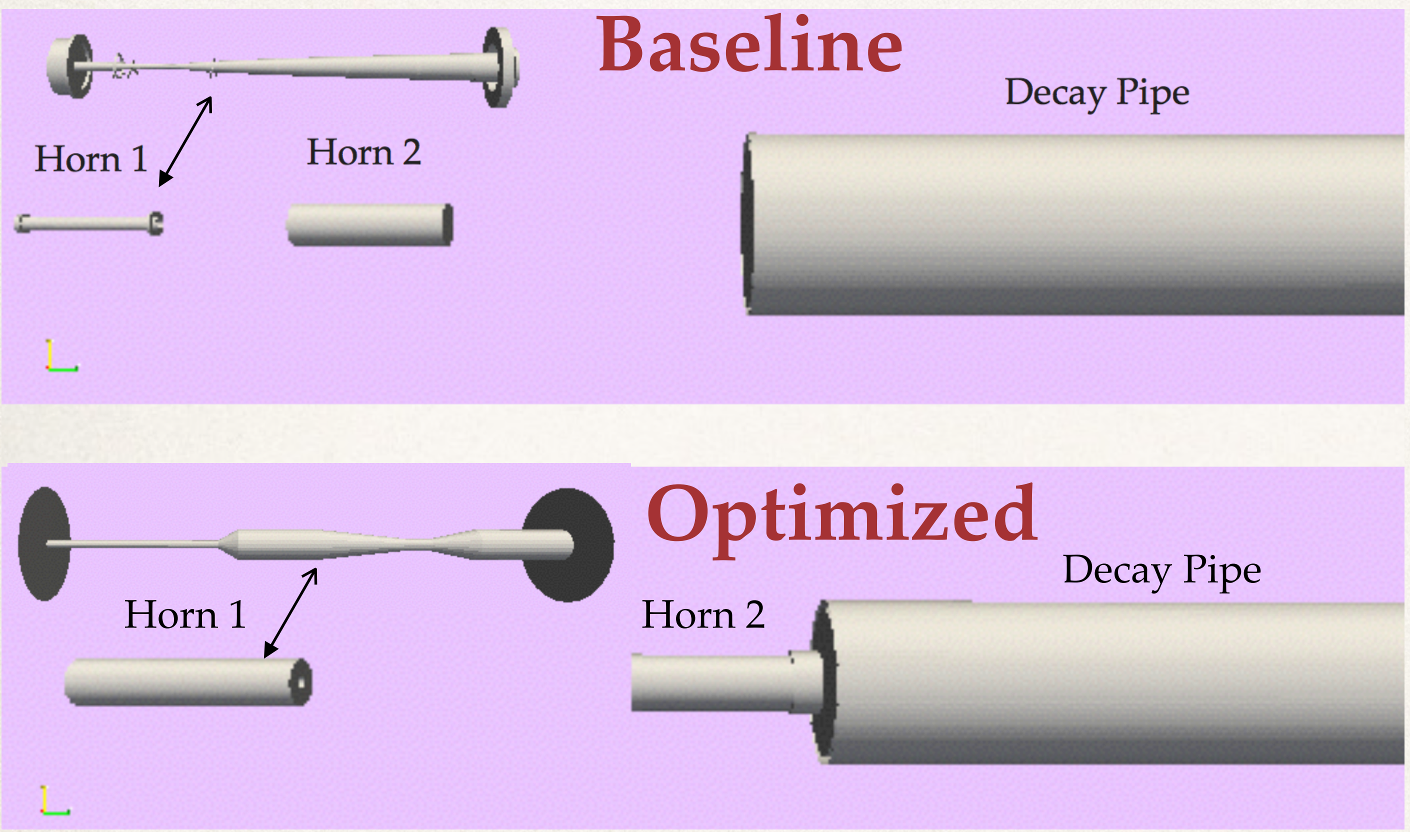




DUNE CDR

DUNE Beam Optimization

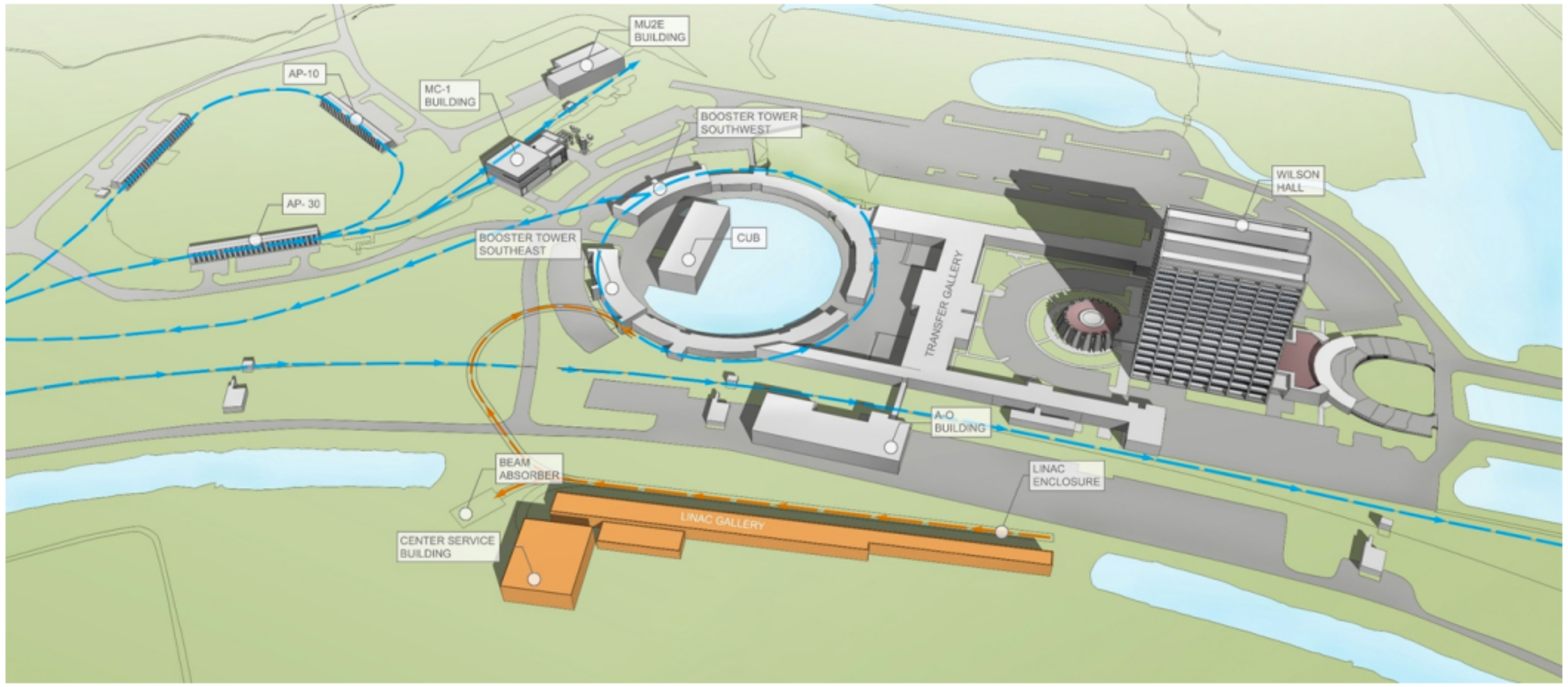
- Preferred beam has **significant changes** from baseline design:



- Substantial changes to the shape, size and position of **horns** — longer and wider horns
- A much **longer target** (> 1.5 m vs 1 m in baseline)
- **Larger target chase** (~20 m) needed to accommodate optimized horns (now included in baseline design)
- Target transverse dimensions and proton beam not substantially altered

DUNE Beam Optimization

- Plans to increase beam power:



PIP-II replaces upstream portion of linac feeding into 8 GeV Booster:
1.03 MW at 60 GeV
1.07 MW at 80 GeV
1.20 MW at 120 GeV

Ready by 2025

Further upgrades (PIP-III) would replace booster with Rapid Cycling Synchrotron (RCS) or SC Linac. Currently in R&D stage.

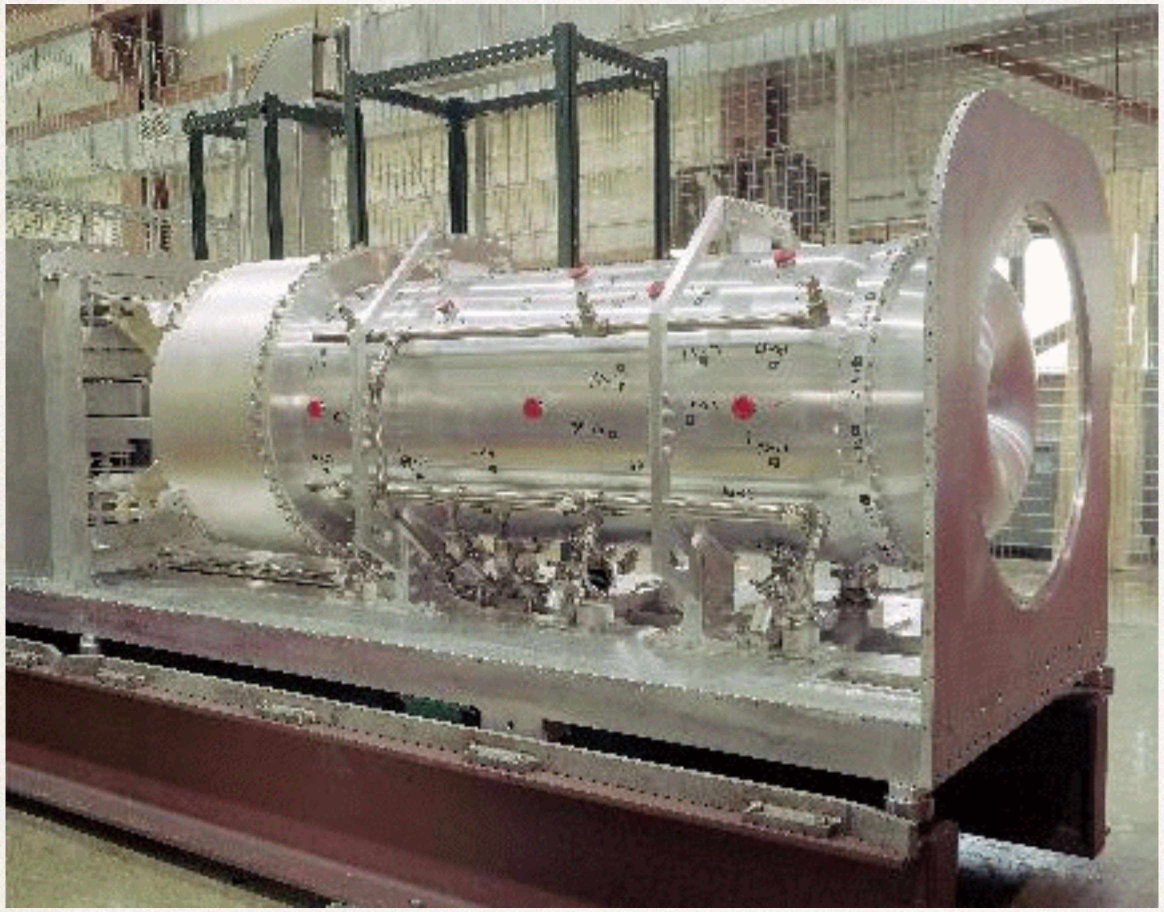
$\geq$ 2.0 MW at 60 GeV
$\geq$ 2.3 MW at 120 GeV

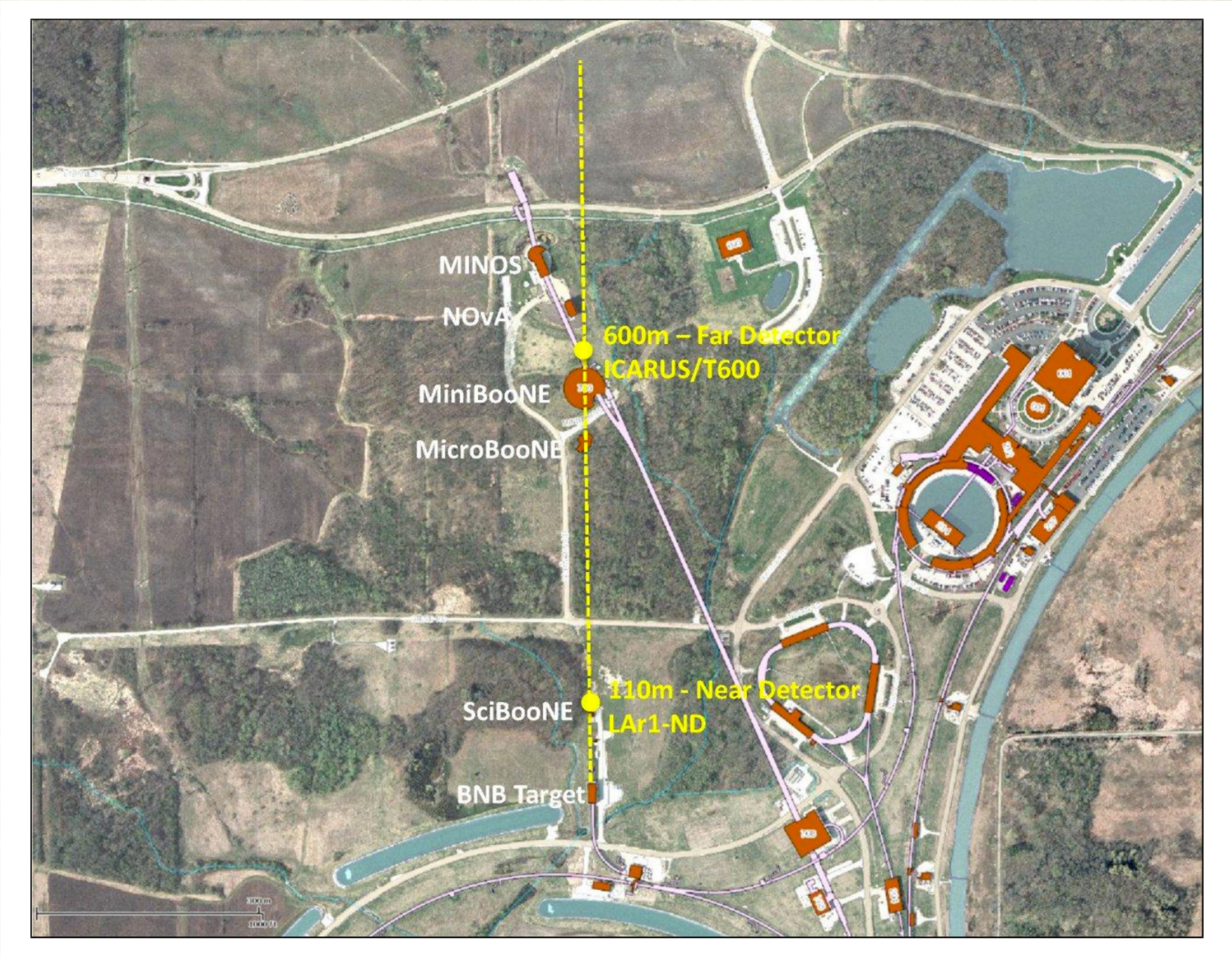
24 / 35

M. Bishai HINT2015

BNB

BNB Overview





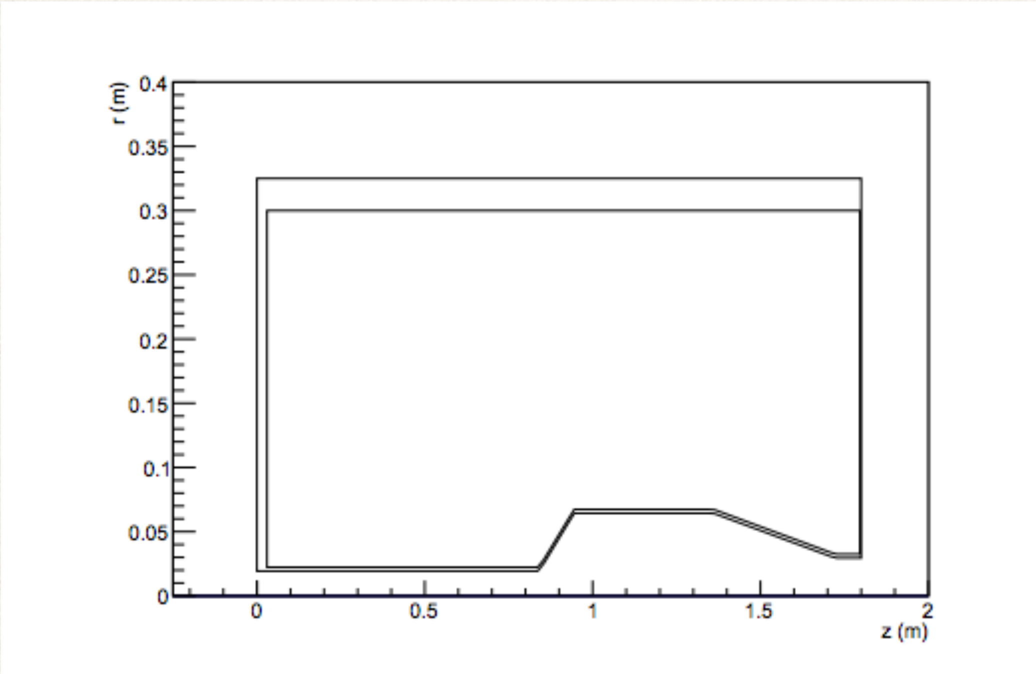
- BNB provides beam for **MicroBooNE**
  - And eventually to **SBND** and **ICARUS**
  - Utilizes an **8 GeV proton beam** and a **single focusing horn**

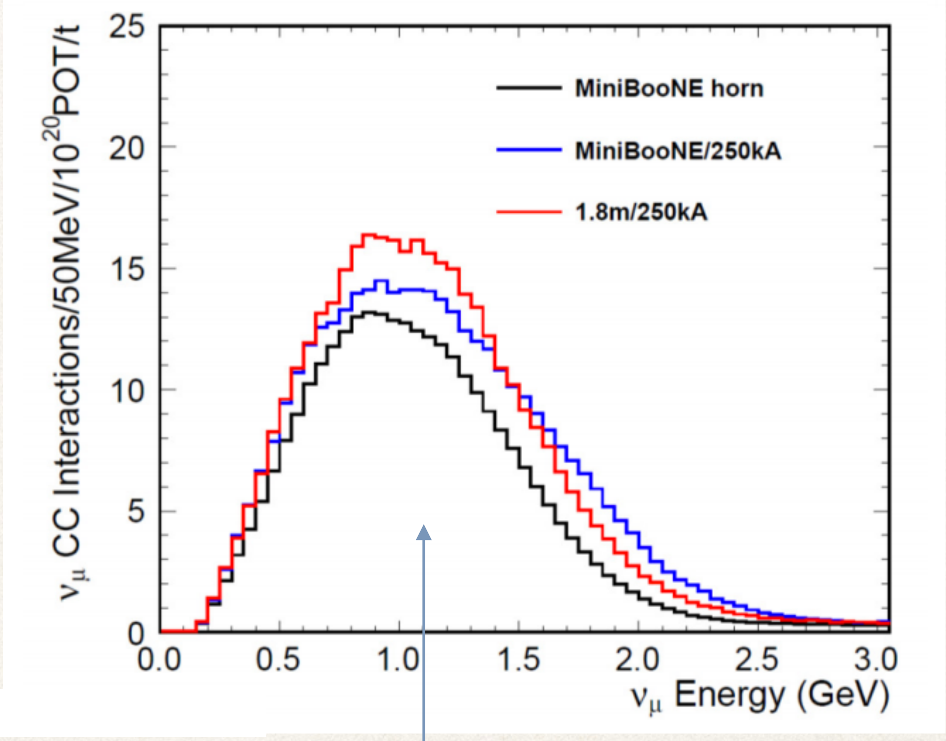
BNB Beam Optimization

- Optimization **strategy**
  - Identify upgrade options that **fit within current enclosure** with minimal changes (**single horn**, less than 3.5 m long) and cost < ~ $6 M
  - Used a genetic algorithm optimizing total number of events:
    - A relatively small **number of parameters** (~10)
    - A **streamlined simulation** of the beam line using simple tracking and reuse of decaying hadrons

BNB Beam Optimization

- Option 1:
  - A new horn with **modified inner conductor shape**, but **length equal** to the current horn





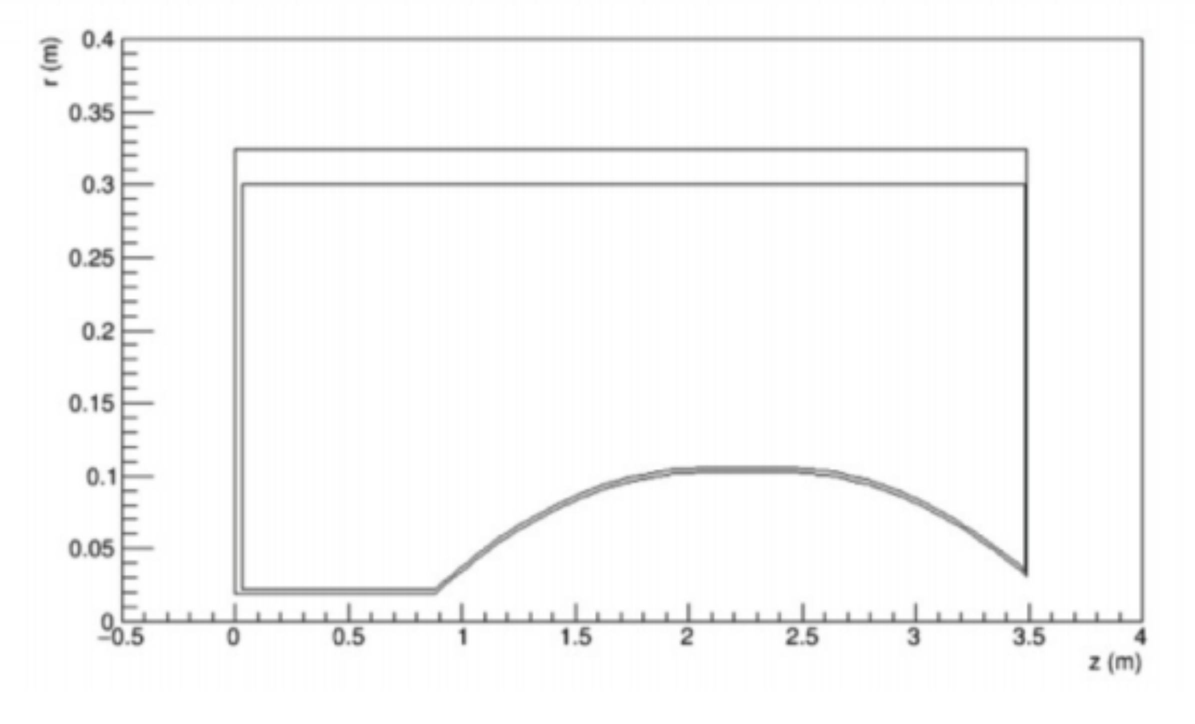
Increases flux in peak by ~25%

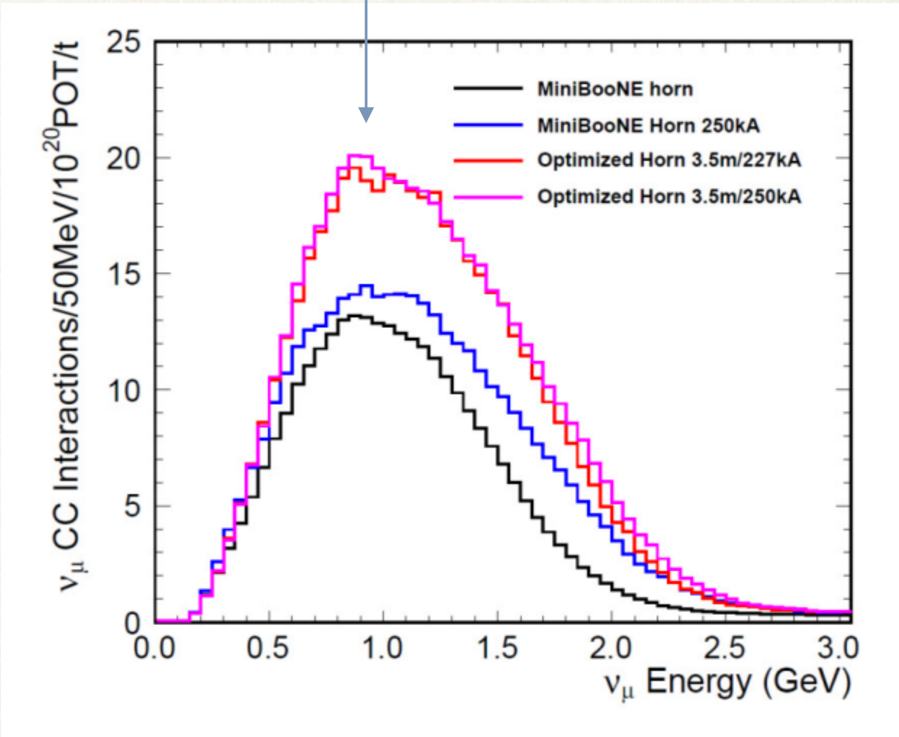
A. Marchioni
FNAL PAC Jun 2015

BNB Beam Optimization

- Option 2:
  - A **longer horn** with modified **inner conductor shape**

Increases flux in peak by up to ~50% depending on current





A. Marchioni
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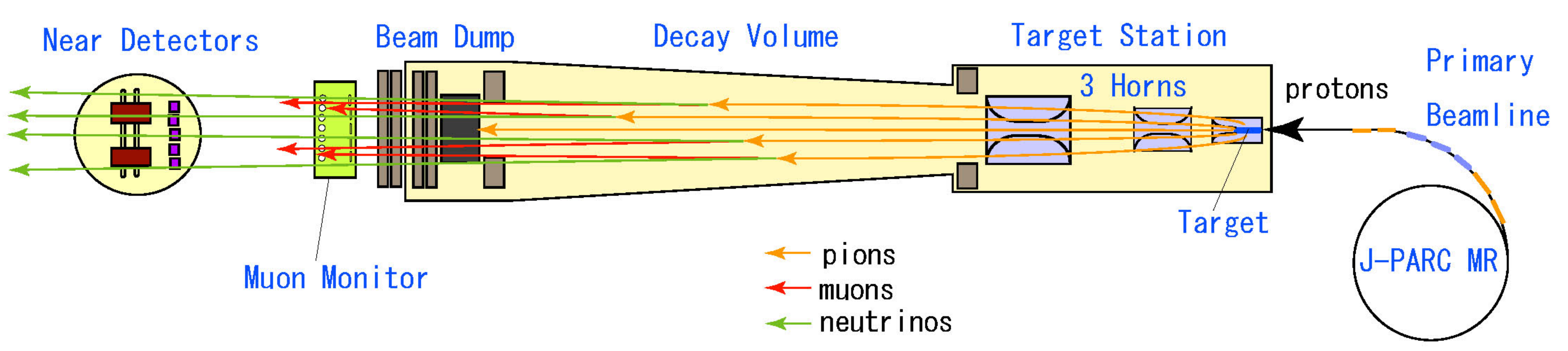
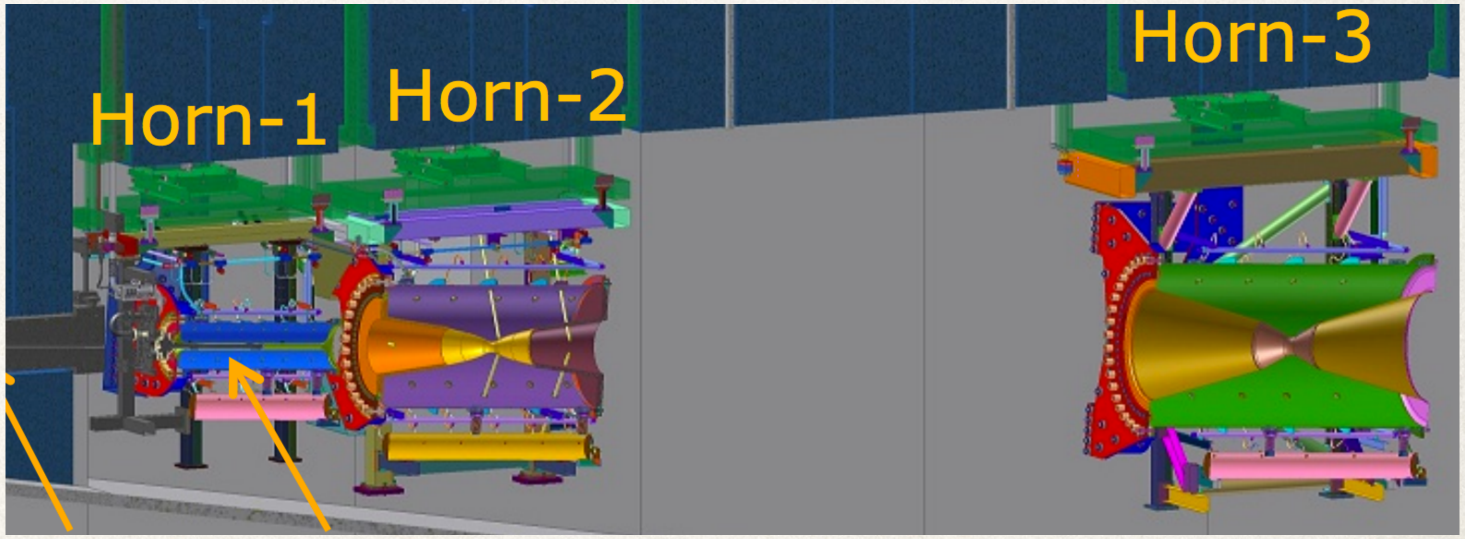
Total increase in peak flux is **up to 200%**, adding in proposed upgrades to power supplies that would enable **opportunistic use of Fermilab protons** (up to 15 Hz from 5 Hz). All options currently under **further study** by BNB team

J-PARC Neutrino Beamline

J-PARC Neutrino Beamline Overview

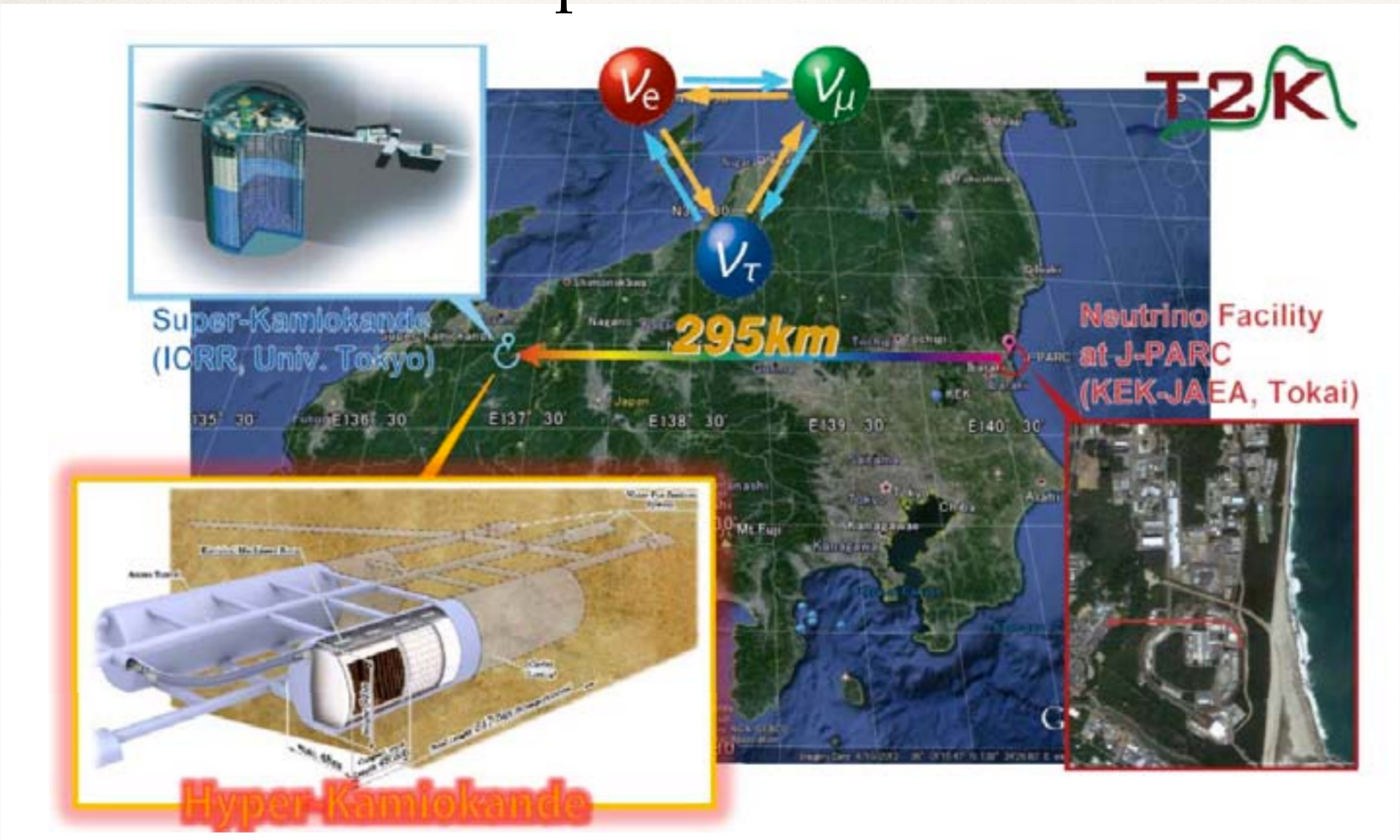


- **30 GeV Proton** beam
    - **Three horn** focusing system
    - Provides beam **T2K detectors** (INGRID, ND280, Super Kamiokande)



J-PARC Neutrino Beamline Overview

- The same beam will host the proposed **Hyper-Kamiokande** experiment:



Slightly different location than SuperK, Same off-axis angle **25 times larger** fiducial volume

J-PARC Neutrino Beamline Overview

- Beam **Upgrade Plans**
  - Much effort focused on **improving beam power**

Beam Power	# of protons/pulse	Rep. rate
350 kW (achieved)	1.8×10^{14}	2.48 sec.
750 kW (proposed) [original plan]	2.0×10^{14} [3.3×10^{14}]	1.30 sec. [2.10 sec.]
1.3 MW (proposed)	3.2×10^{14}	1.16 sec.

T. Sekiguchi HINT2015

- Running at **1.3 MW will require many beam upgrades**, such as:
  - New cooling water pumps
  - Improved stripline cooling
  - Removal of hydrogen produced in horns
  - Radiation studies, Reinforcement of air-tightness

J-PARC Neutrino Beamline Overview

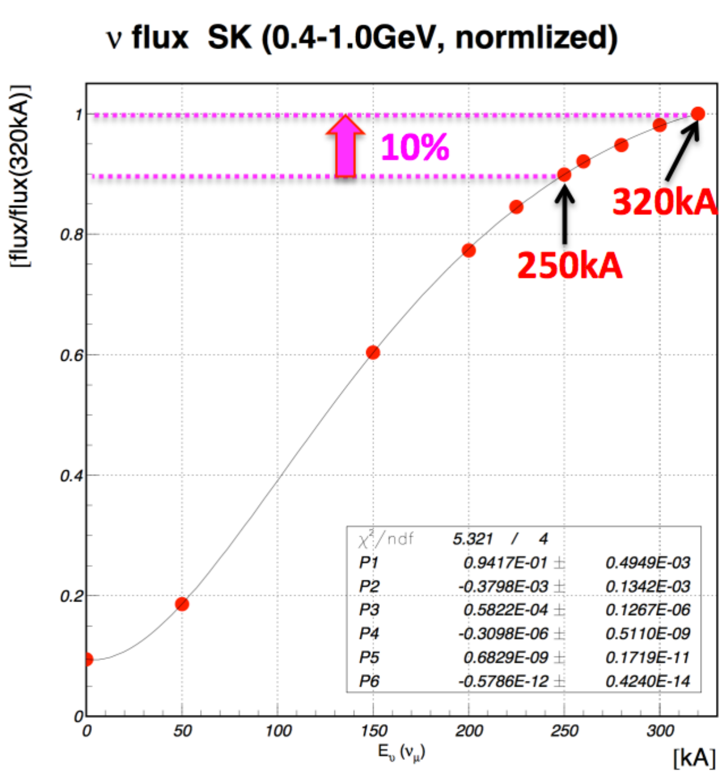
- Also planning to **increase horn currents**:

Horn current

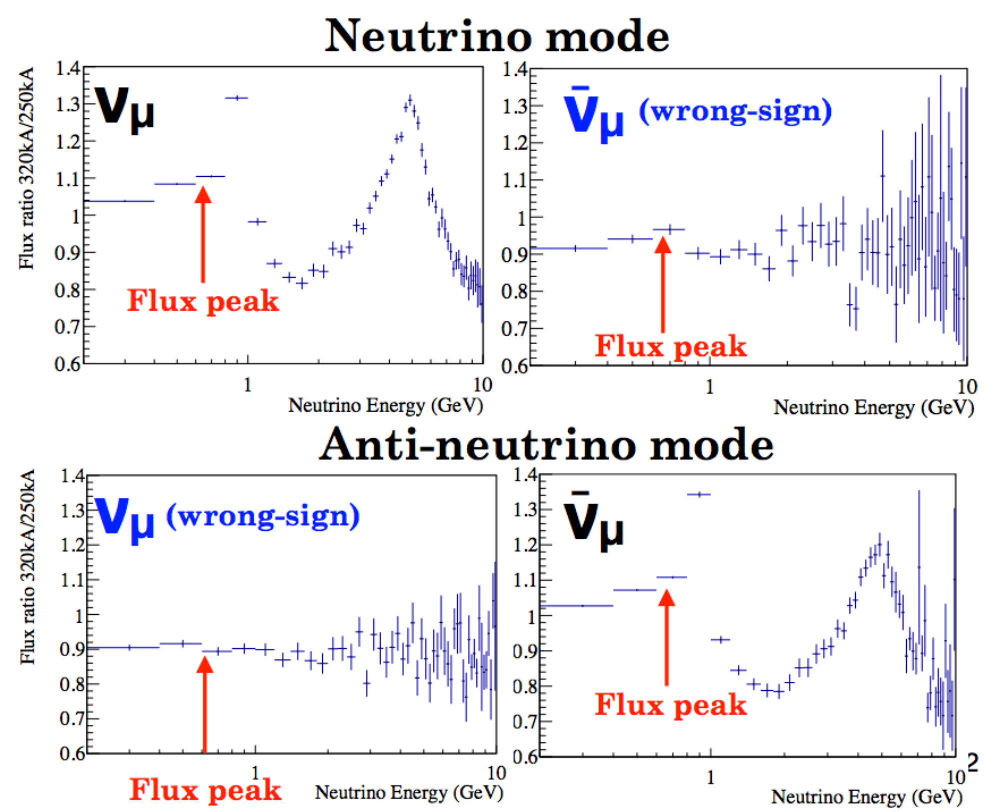
- 250 kA operation for physics data taking since 2010.
  - Mainly due to refurbishment of old K2K PS (rated 250 kA).

Current increase: 250 kA ⟹ 320 kA (rated)

- 10 % improvement of neutrino flux at far detector
- 5~10% reduction of wrong-sign neutrinos around E_ν peak



Courtesy of T.Nakadaira



T. Sekiguchi HINT2015

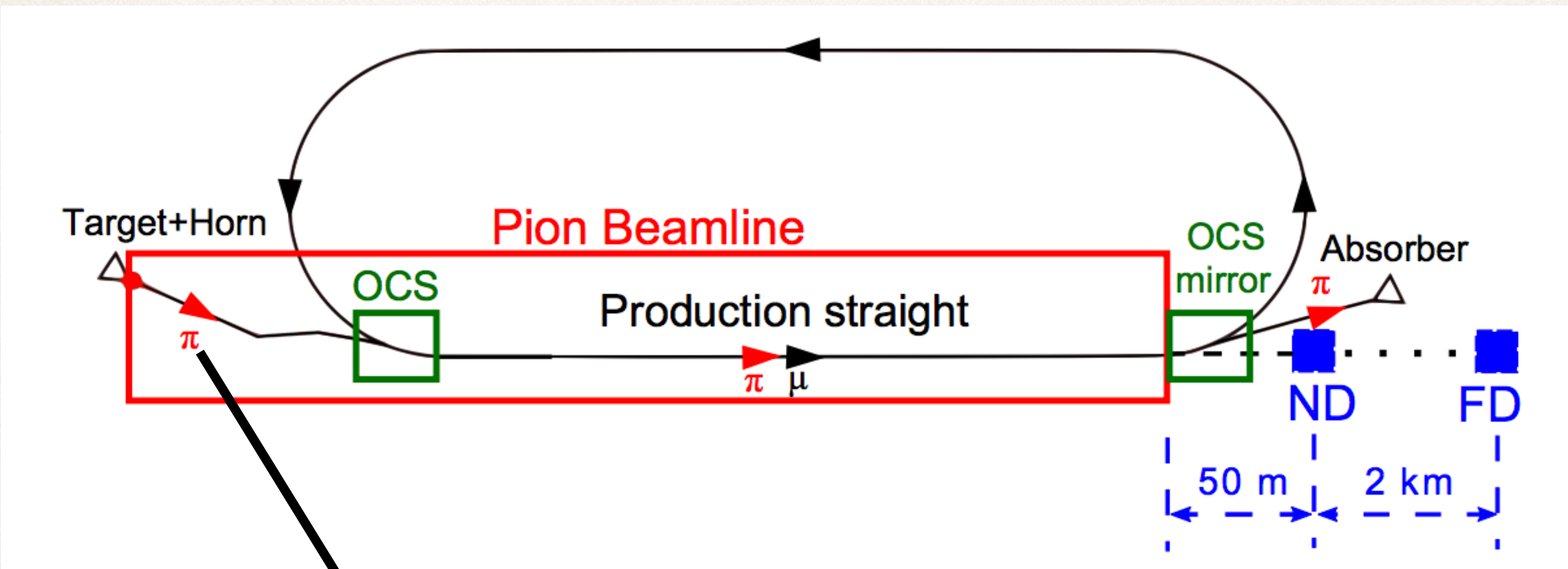
Other **horn and target configuration studies ongoing**, but not yet public

Have also considered alternate off-axis angles

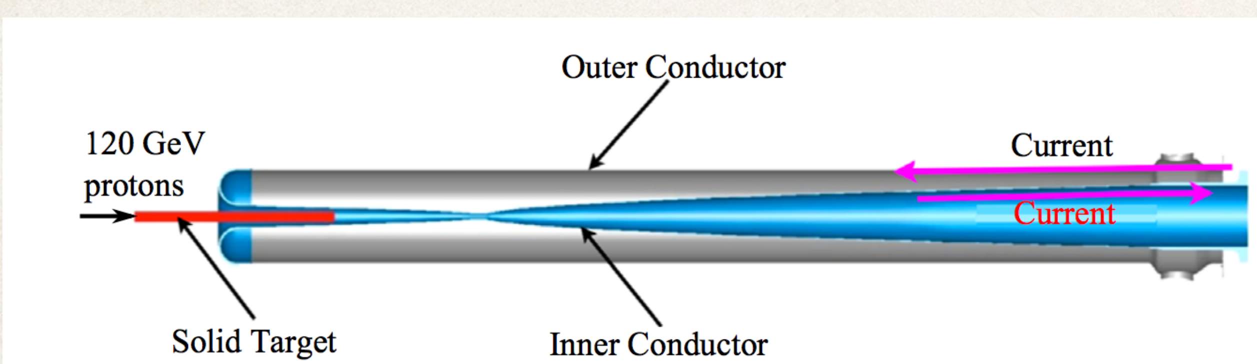
NuStorm

NuStorm Overview

- Not a conventional neutrino beam, but still a **cool example** of neutrino beam optimization:



Design in NuStorm proposal included a single NuMI horn to collect pions

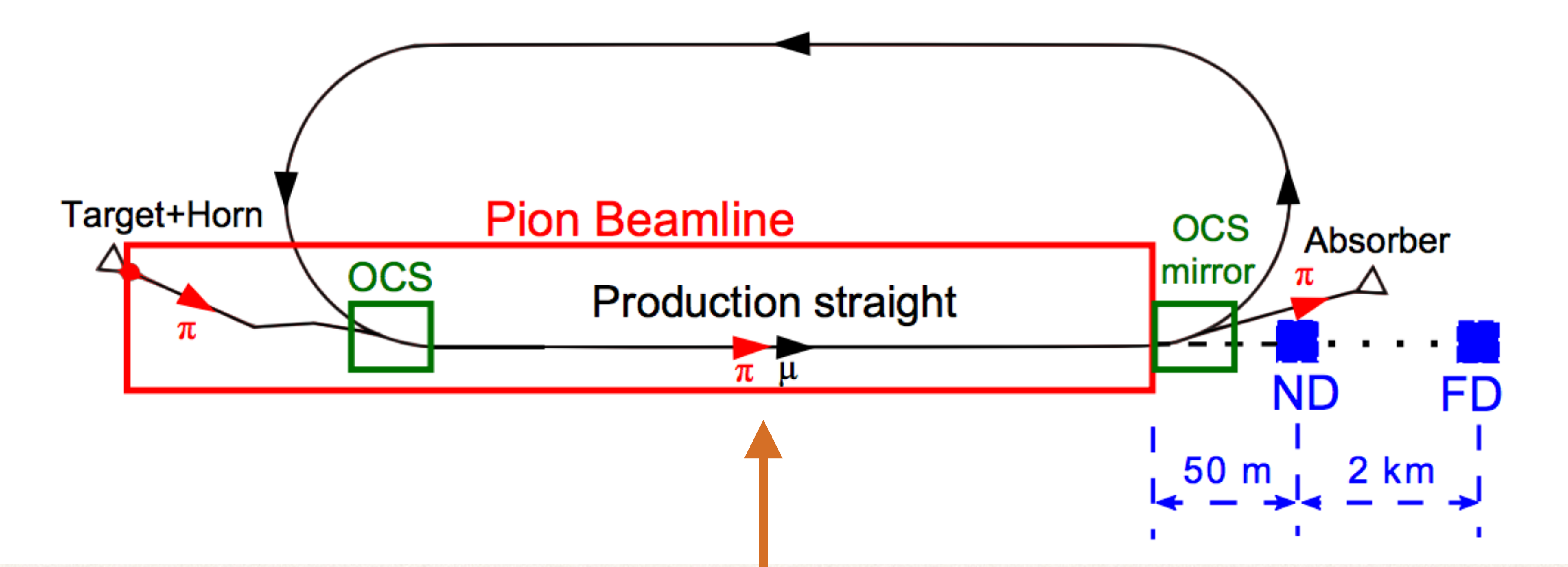


Very **well understood fluxes,** lower backgrounds, for neutrino cross sections and sterile searches

Neutrinos from both
$\boldsymbol{\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e}$ and
$\boldsymbol{\pi^+ \rightarrow \mu^+ \nu_\mu}$

NuStorm Overview

- Not a conventional neutrino beam, but still a **cool example** of neutrino beam optimization:

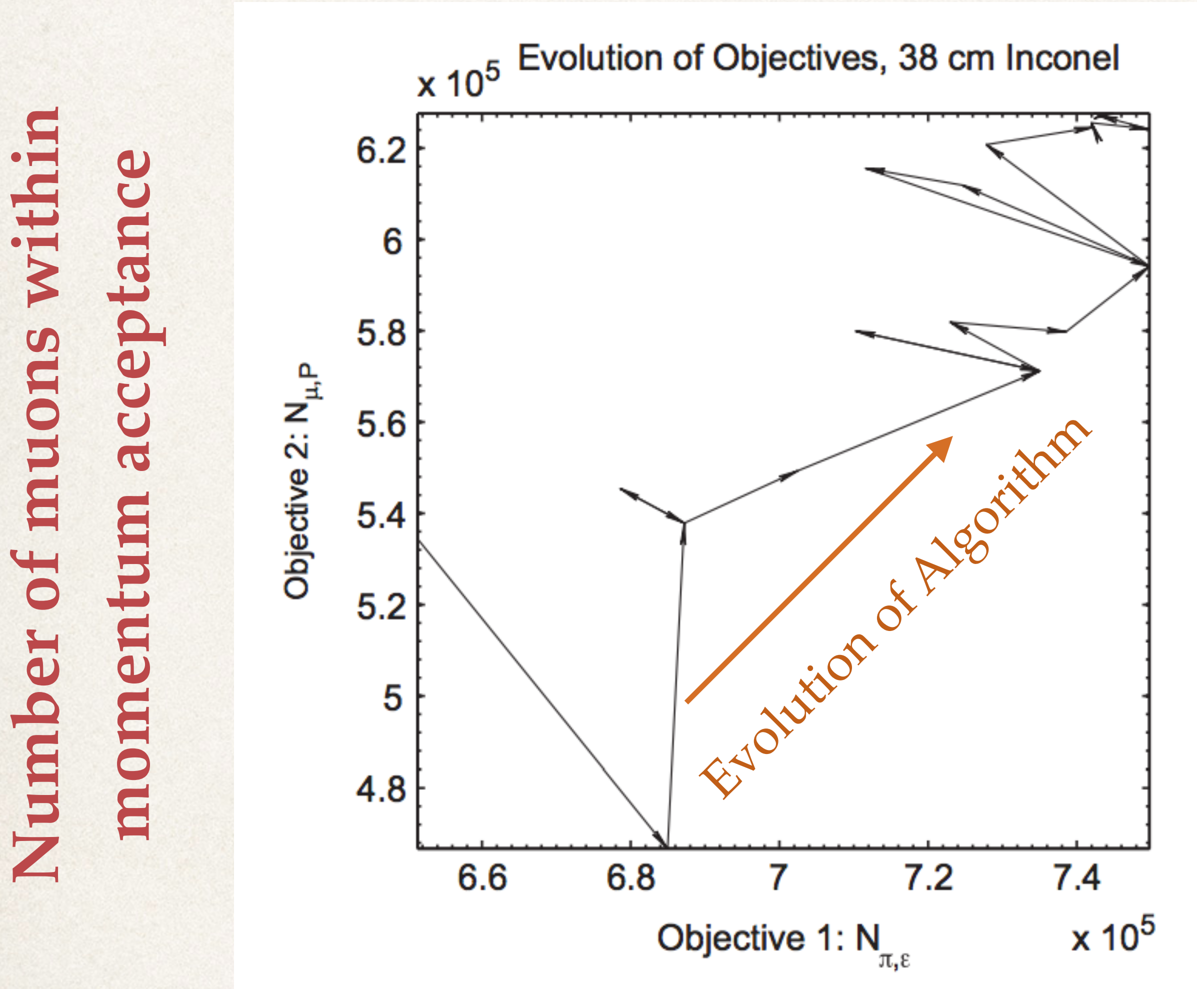


Key requirement of focusing horn: collect pions that will decay to **muons that are within the angular and momentum acceptance** of the muon beamline

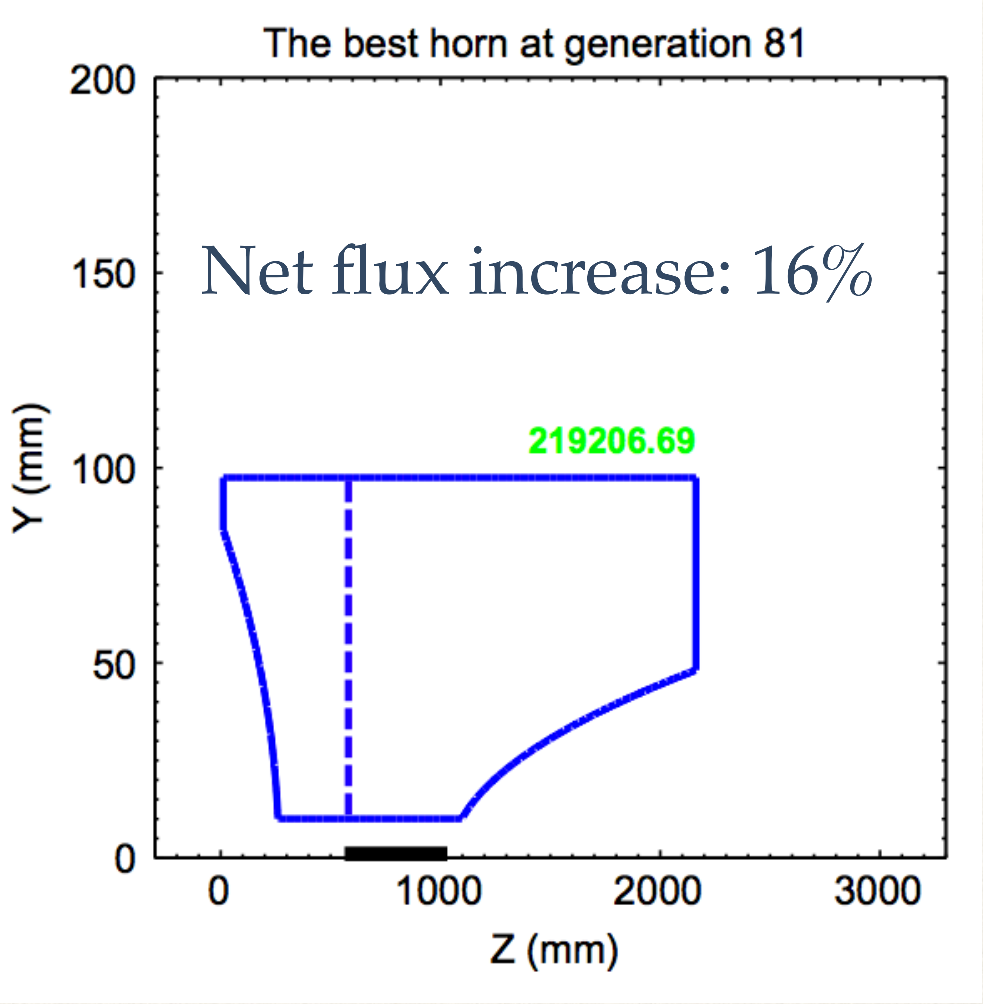
Quite a **different situation than NuMI** (for which the horn was designed)

NuStorm Optimization

- Developed **fast horn-shape optimization** metric that only requires tracking pions to end of horn, and implemented a "**multi-objective**" genetic algorithm:



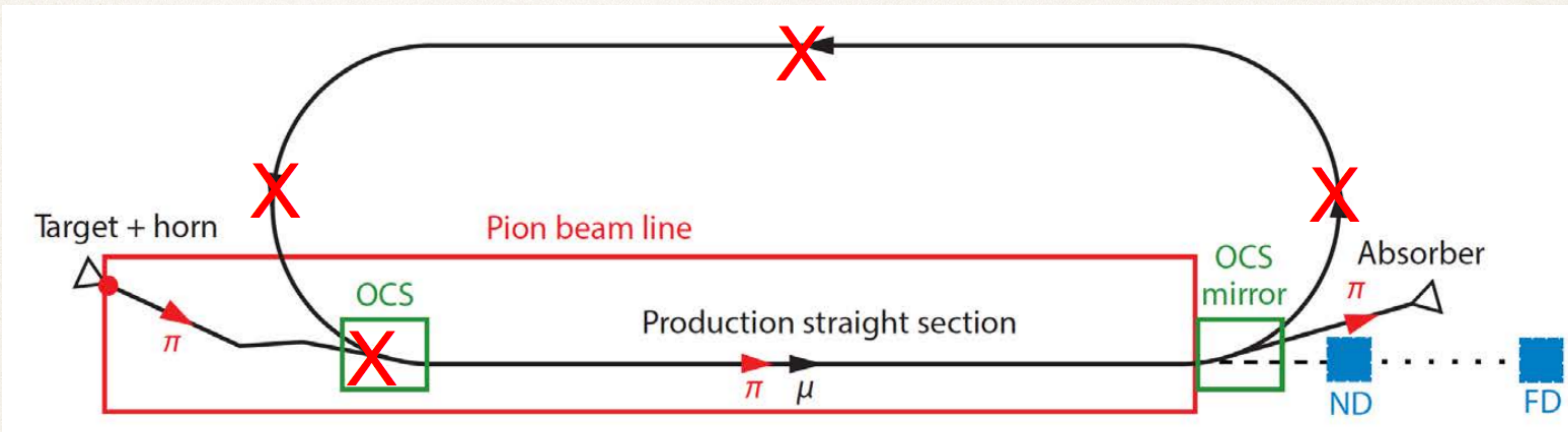
Number of muons within angular acceptance



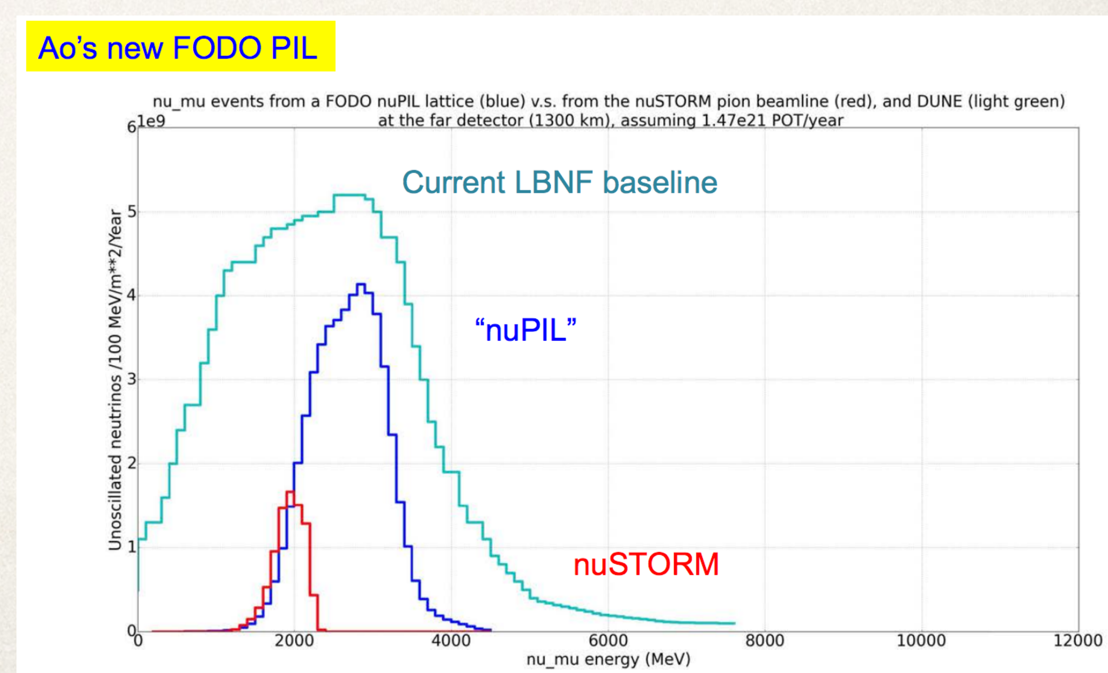
Nucl.Instrum.Meth. A794 (2015) 200-205

NuStorm Optimization

- Another idea: "**Pion Injection Line**": **eliminate muon storage** ring and optimize just pion straight



- Becomes feasible to consider for **long-baseline experiments**
  - **Well understood flux** (measured by beamline)
  - **Optimization ongoing** now



A. Bross NuFact '15

Conclusion

- Neutrino Beamline Optimization is a **fascinating** subject
  - And one with **big payoffs**
- Modern **computing power** and **algorithms**, plus clever simulation **shortcuts** are showing us how to dramatically improve **existing and future beamlines**
  - Requires that extensive **engineering studies** proceed in parallel with simulations
- Beamline optimization offers **benefits beyond just increases in flux**
  - Background reduction, more desirable energy spectra, etc
  - And can be an **economical alternative** to increasing detector size or protons on target

Thank You!

NuStorm Acceptance

- Transverse acceptance:
  - 2000 µm rad (or expressed as 2 mm)And one with **big payoffs**
- Momentum Acceptance:
  - +/- 10% of 5 GeV/c for pions and 3.8 GeV/c for muons
- The number of pions within +/-10% of 5 GeV/c after the horn is 0.29 / POT
- The number of muons within the acceptance of the ring is 0.013 per POT.
  - Optimization increases this to 0.015