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neutrinos from a Pion beam Line (nuPIL) and its potentials

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APC seminar

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Abstract

nuPIL presents a modification of the current LBNF baseline, it is one step beyond the conventional van der Meer horn + decay pipe.

- nuPIL has a cure
  - for many of the concerns that you must already have for the current baseline.

Our team (limited resources and time)

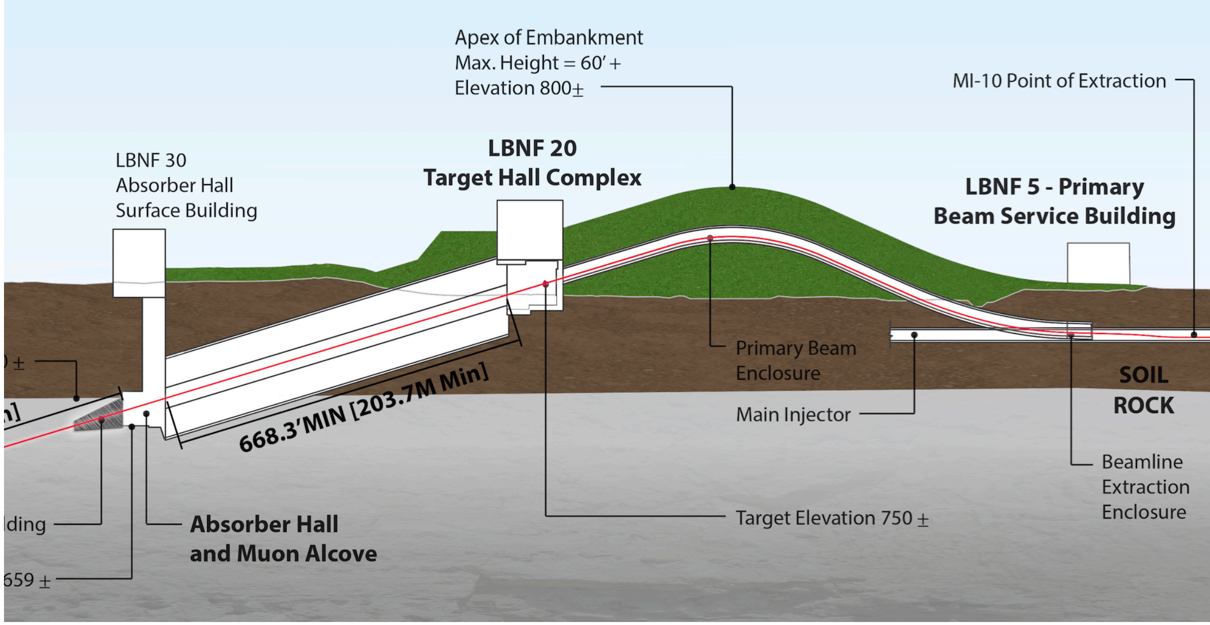
- JB Larange, J. Pasternak @ Imperial College London;
- A. Bross, P. Coloma, H. Mularcyzk (Target summer student) and myself @ Fermilab
- T. Hart @ U Mississippi
- Hope to add your names to this list

Outline

- Introduction
- Beamline design
- Neutrino flux
- Optimization results
- Moving forward

Introduction

- nuPIL is based on a pion beamline that bends pions by 5.8° towards the DUNE detector. With this beamline:
  - We do not need to construct a hill to bend the high energy protons:



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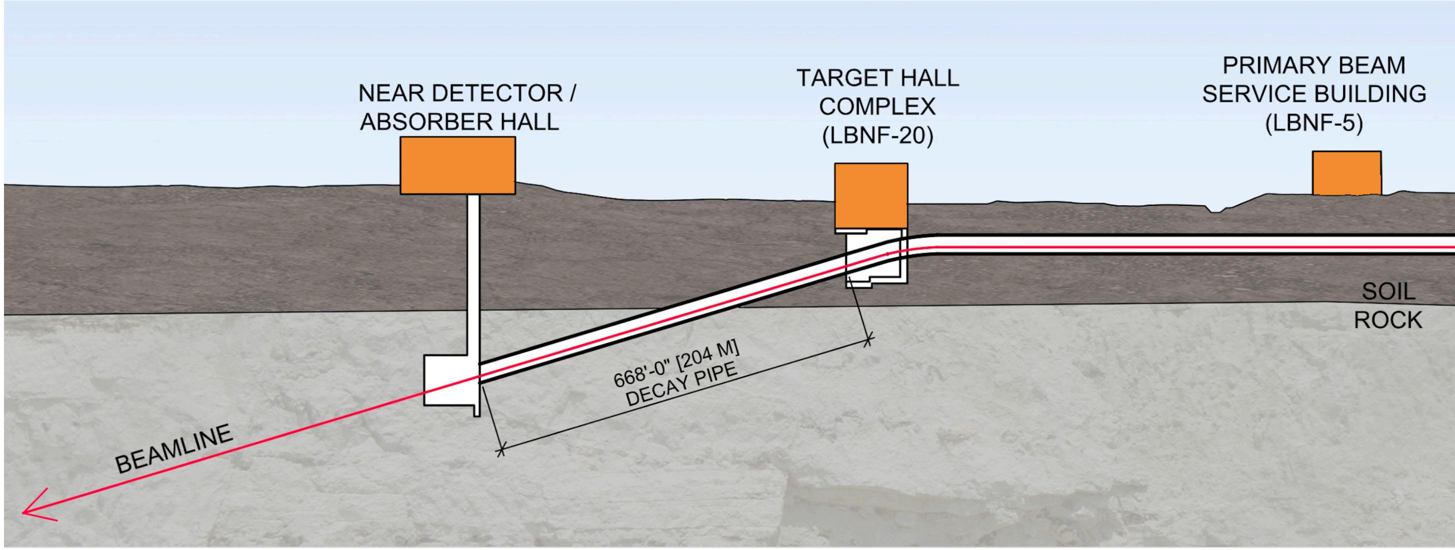

Introduction

- nuPIL is based on a pion beamline that bends pions by 5.8° towards the DUNE detector. With this beamline:
  - We do not need to construct a hill to bend the high energy protons:
  - Bending structure in the beamline provides sign and momentum selection for the pions
    - A flavor-pure nu beam towards the 40 kT LAr det.
    - Much less power sent underground – high E protons absorbed at MI depth

Introduction (cont'd)

- nuPIL greatly suppresses the beam systematics in conventional neutrino facility produced neutrino beams, including
  - Pion/Kaon production, proton & target interaction stability, horn stability, etc.
  - by:
  - pion flux + optics measurable and predictable in the magnetic beamline (decay straight section)
- Inspired by nuSTORM's pion beamline
  - nuSTORM pion beamline was carefully designed to transport and inject pions into a muon decay ring
  - After injection pions are charge-pure, narrow-band

Beamline Design - two scenarios

- 1. Use a decay pipe (204 m in length, 2 m in radius) as the production straight
  - Higher flux, but less likely to measure the beam precisely
- 2. Use a magnetic straight beamline (204 m) instead
  - Full diagnostics in the straight to characterize the pion beam: precisely known neutrino flux at the detector, but less flux due to the finite acceptance of a beamline.
- Both of above have steering bend section (the part that steers the pions towards FD);
- Studied more than 13 lattices, including FODO, FFAG and hybrid.
  - Best designs for these three scenarios are given in this talk

Neutrino Flux Calculation Codes

- In order to calculate the neutrino flux at the FD, doing MC and stochastic decay in G4Beamline is insufficient and unrealistic
  - The flux was calculated based on the modeled decays in G4Beamline, but using the decay angles to calculate the probability of a neutrino at that energy to reach the FD.

$$\mathcal{P} = \mathcal{P}(\alpha, \beta) = \frac{1}{4\pi} \frac{A}{L^2} \frac{1-\beta^2}{(\beta\cos\alpha - 1)^2}$$

	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$

$$\frac{d\mathcal{P}}{dE_\nu^* d\Omega^*} = \frac{1}{4\pi} \frac{2}{m_\mu} [f_0(E_\nu^*) \mp \Pi_\mu f_1(E_\nu^*) \cos\theta^*]$$

Neutrino Flux Calculation Codes

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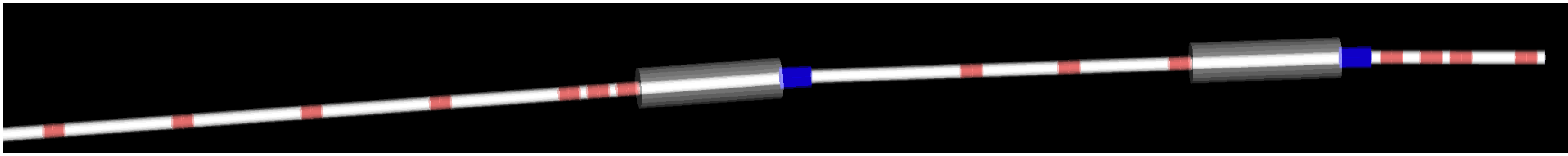
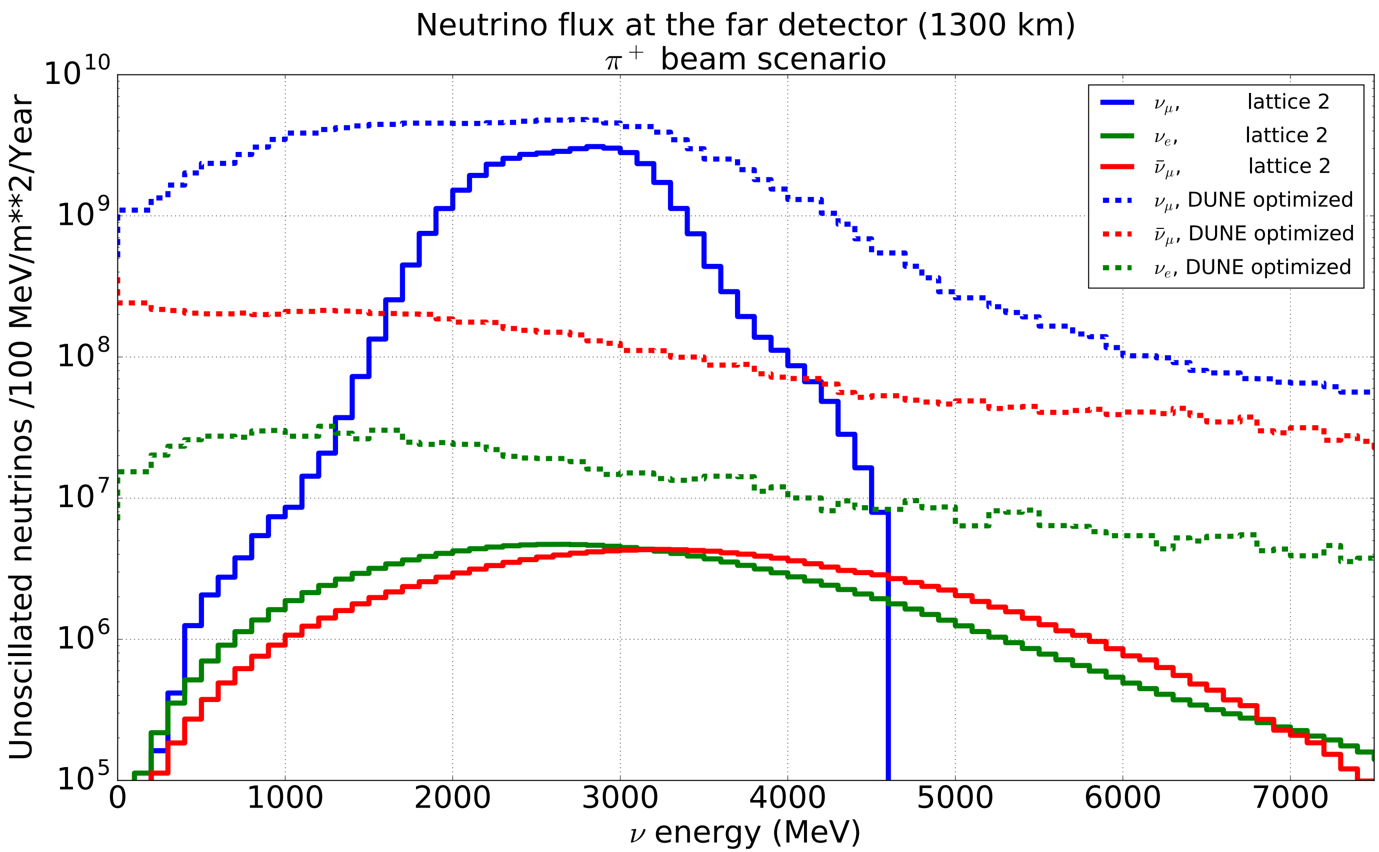
  - The flux was calculated based on the modeled decays in G4Beamline, but using the decay angles to calculate the probability of a neutrino at that energy to reach the FD.
  - Analysis codes developed systematically, will be released on Github in the future, including functionalities of analyzing the losses in G4BL

FODO bend + FODO decay straight



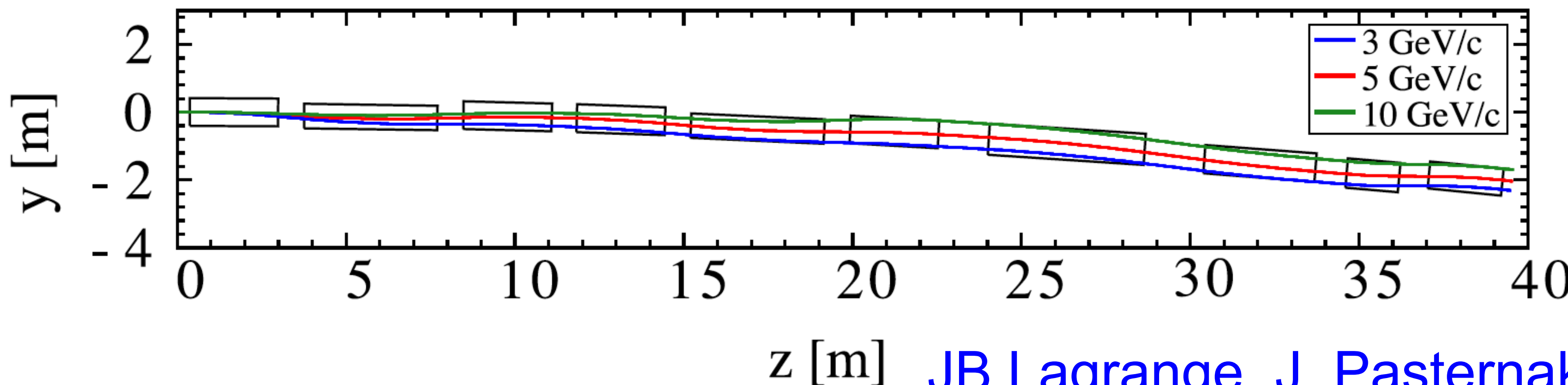


No pi- decay in the straight: (perfect sign selection)

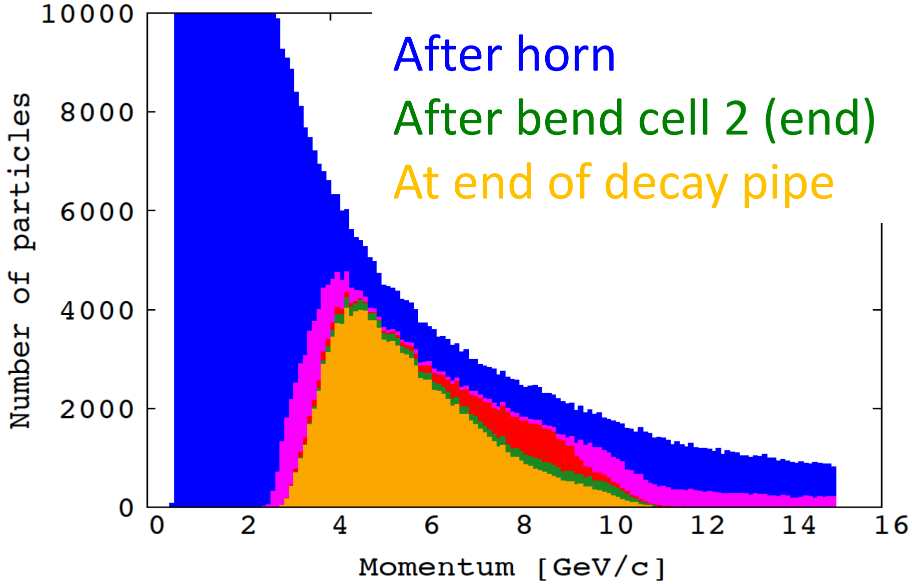
comparing with LBNF + DUNE CDR flux

DBA – narrow band beam – need more flux

Beamline design – lattice 11 – FFAG bend + DP



JB Lagrange, J. Pasternak



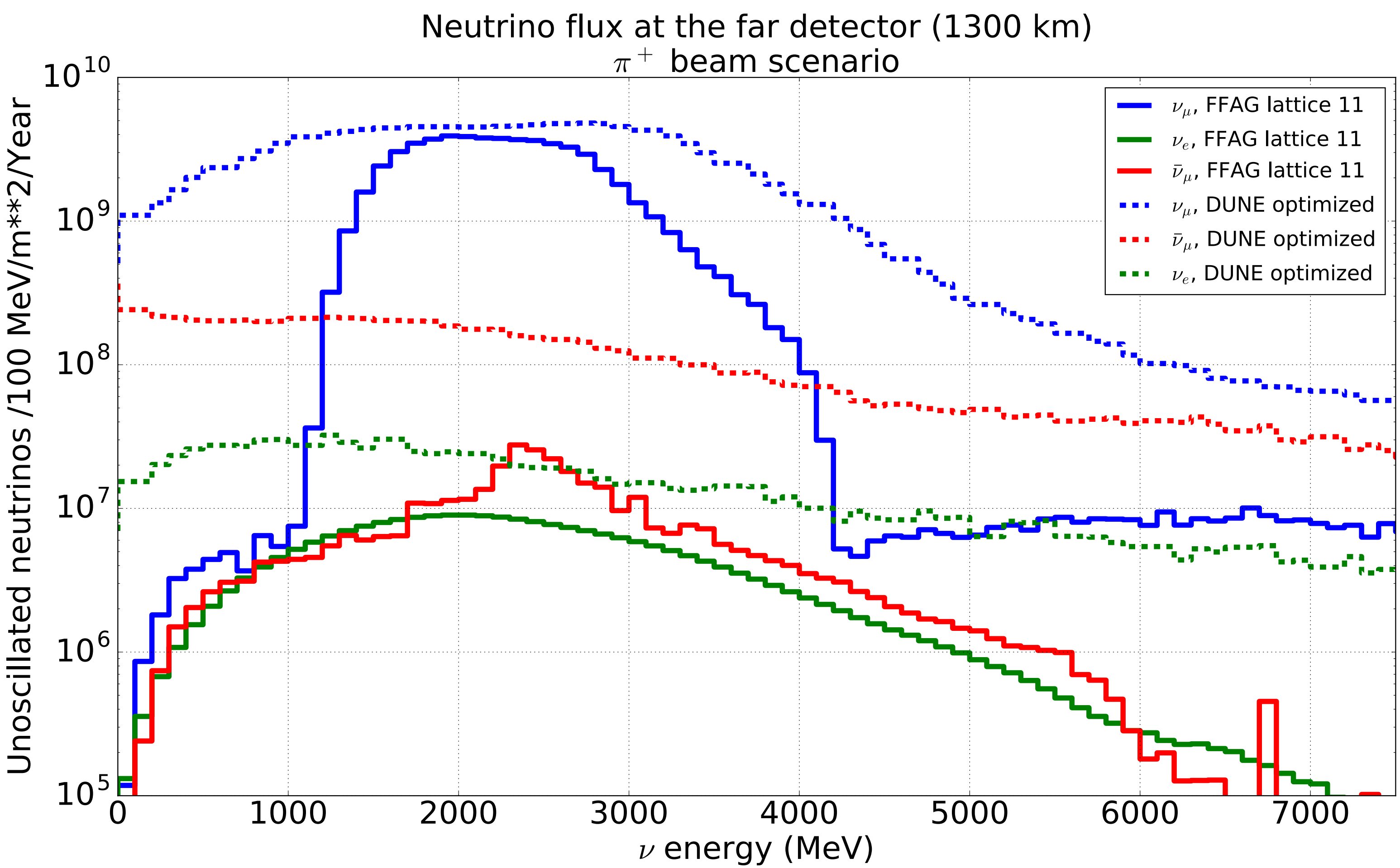
Scaling FFAG

Starts with a single NuMI-like horn (designed for nuSTORM) and a 38 cm Gold target (other robust targets later)

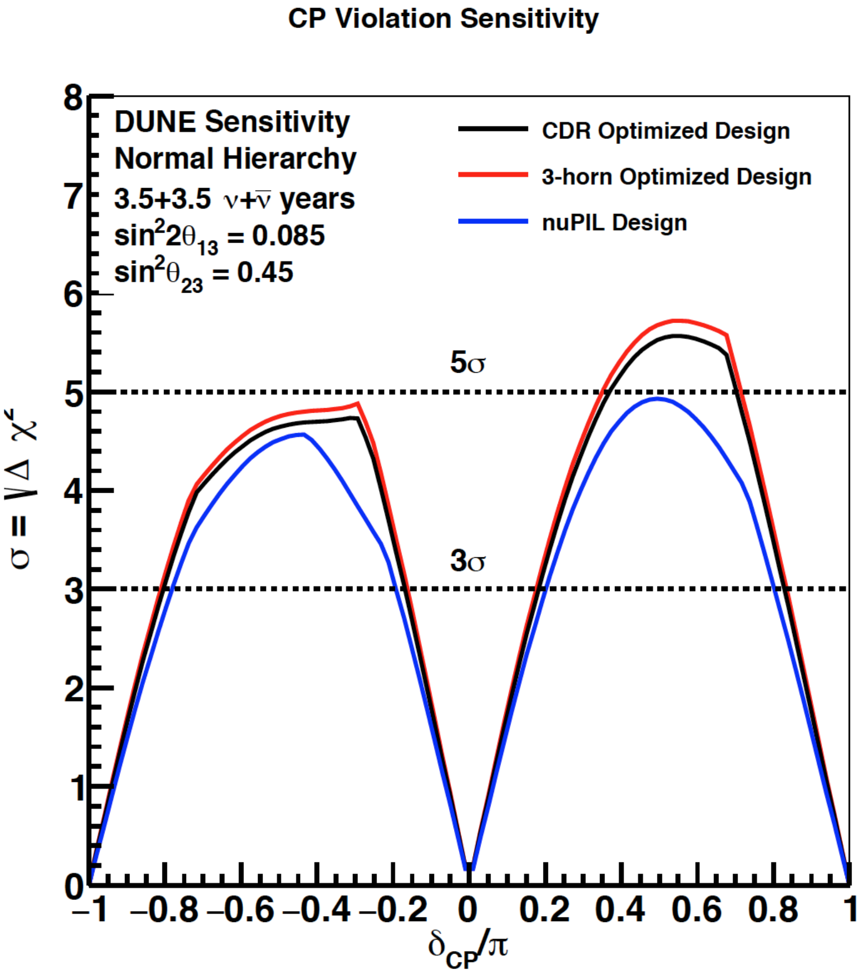
No horn optimization was done at this step.

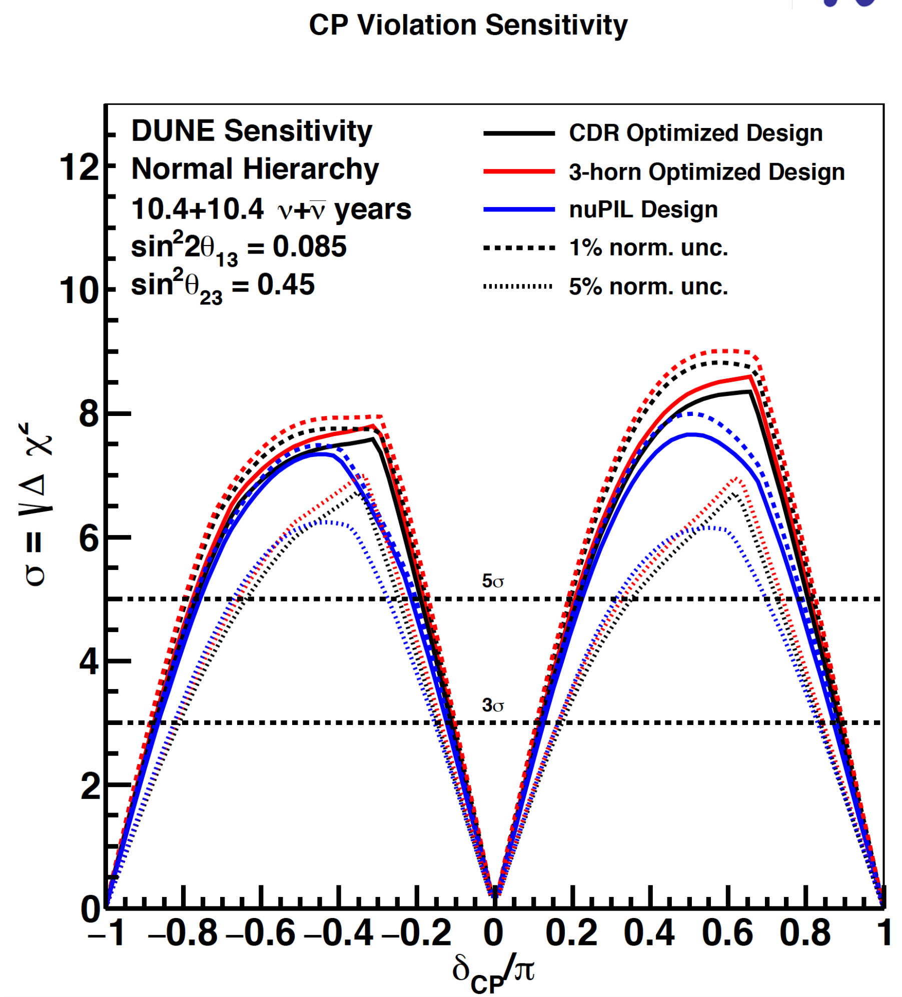
Beamline performance for lattice 11

Significant improve from FODO due to large momentum acceptance of the FFAG bend



Physics reach from lattice 11



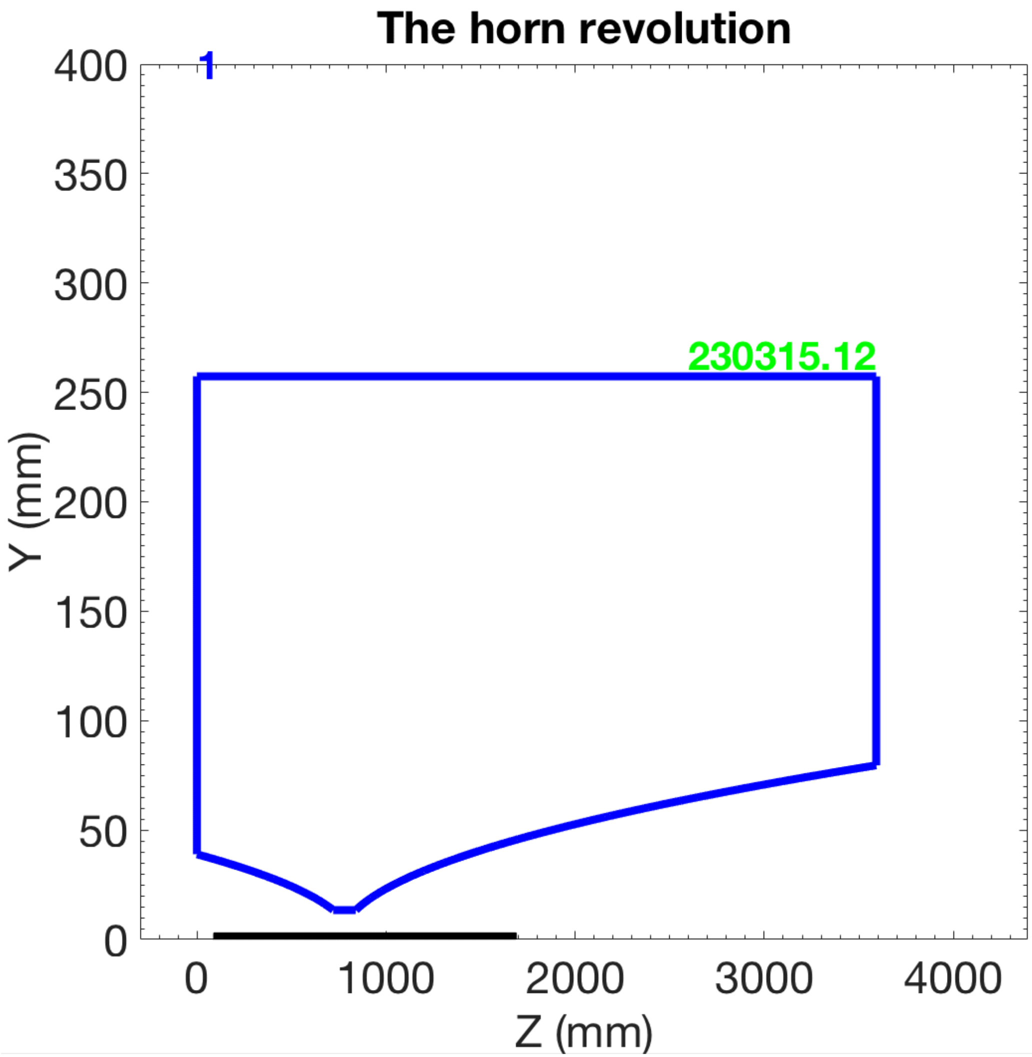


With more uncertainties,
nuPIL with lattice 11 without optimizations can already do better than DUNE+LBNF at some δ values, however LBNF claims a 2% unc.

Genetic Algorithm (GA) Optimization of the horn

- Target and horn used for nuPIL preliminary studies was designed for nuSTORM (with 38 cm Inconel target), and Gold target can not tolerate proton power at 1.1 MW.
- Perform an optimization on the horn with a 4 interaction lengths Carbon target (simulated in MARS)
  - Objective function: pions (selected sign) in the acceptance of lattice 11, which was characterized by the multi-particle tracking in lattice 11
  - Single horn optimization from nuSTORM experience might yield 20% increase

Horn optimization with a 1.6 m Carbon target

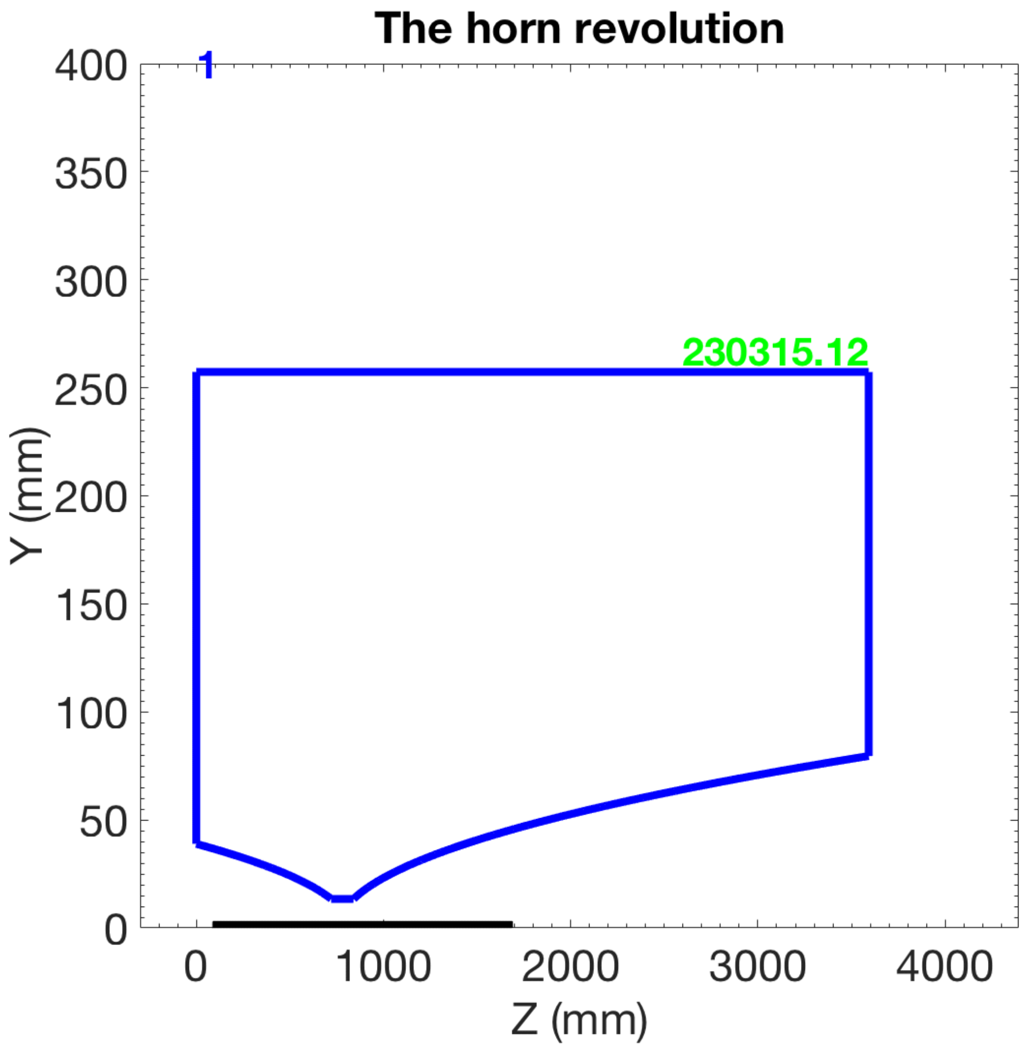


GA:
Throws in a seed among a group of random horns;

Let the seed guide the revolution

Faster – but often optimized solution looks like the seed – mutation added in the algorithm.

Horn optimization with a 1.6 m Carbon target



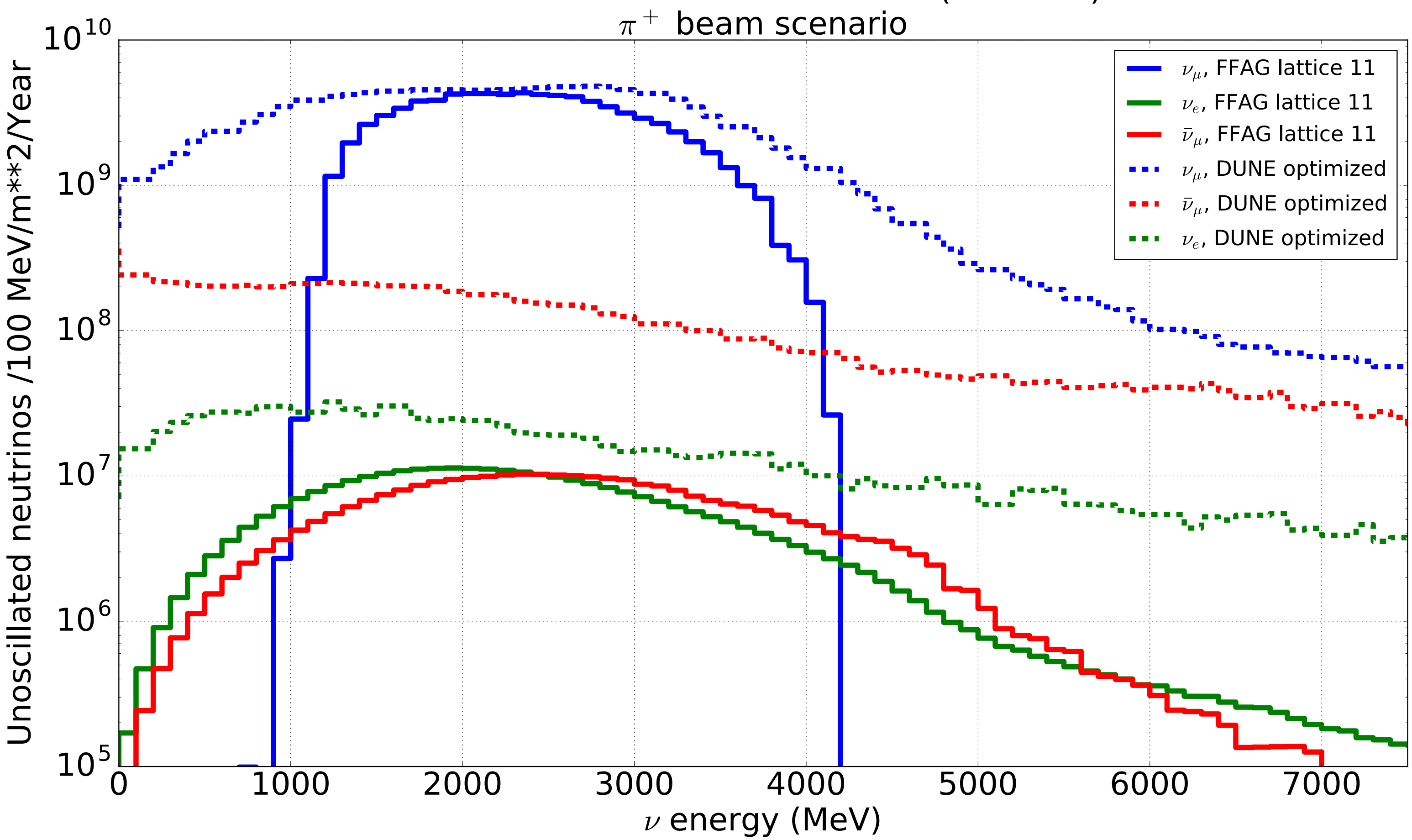
GA movie:

Always needs a narrow neck, two competing choices at the late stage of the optimization – diversity of the solutions

GA result

pi+ only in the tracking

A 38% increase in integrated nu flux!!

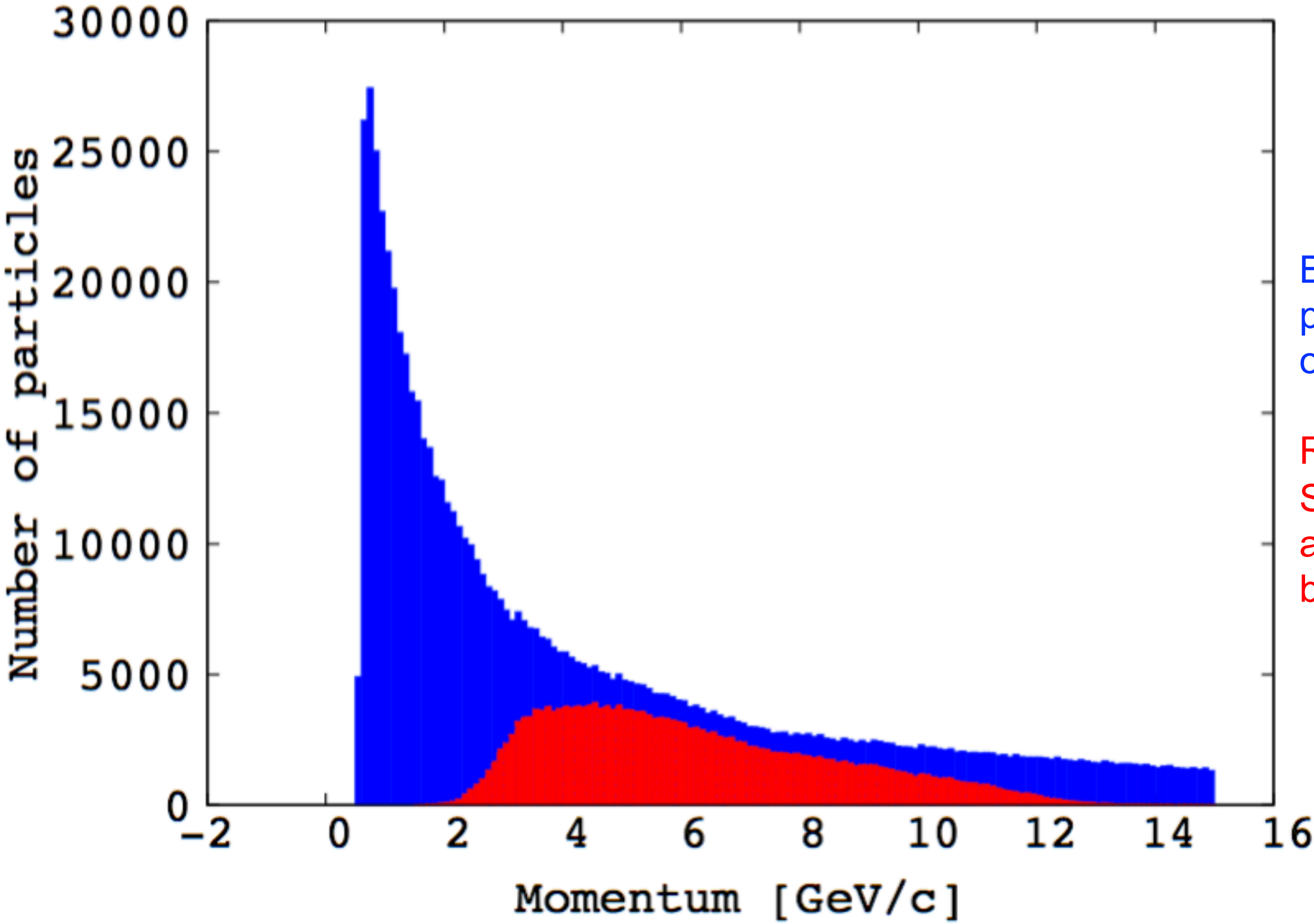


Two-horn opt. shows another 10% inc. in accepted pions

Lattice 13 – FFAG lattice for a hybrid nuPIL

- Based on the optimized horn and target another FFAG design was made to better connect to a FODO decay channel
  - Why FODO?
    - No scallop angle – an FFAG straight will make 20% of the decay become off-axis because of the scallop angle;
  - How?
    - Matching from the end of the bend to the FODO cells using 6 quads
  - Optimization?
    - The hybrid lattice will have a fairly large momentum acceptance, therefore the optimization needs to be done directly based on the neutrino flux we get from the lattice –
      - Not only considering the acceptance of the lattice but also the angular divergence, probability for pions to decay before encountering loss
    - Use GA – large degree of freedom

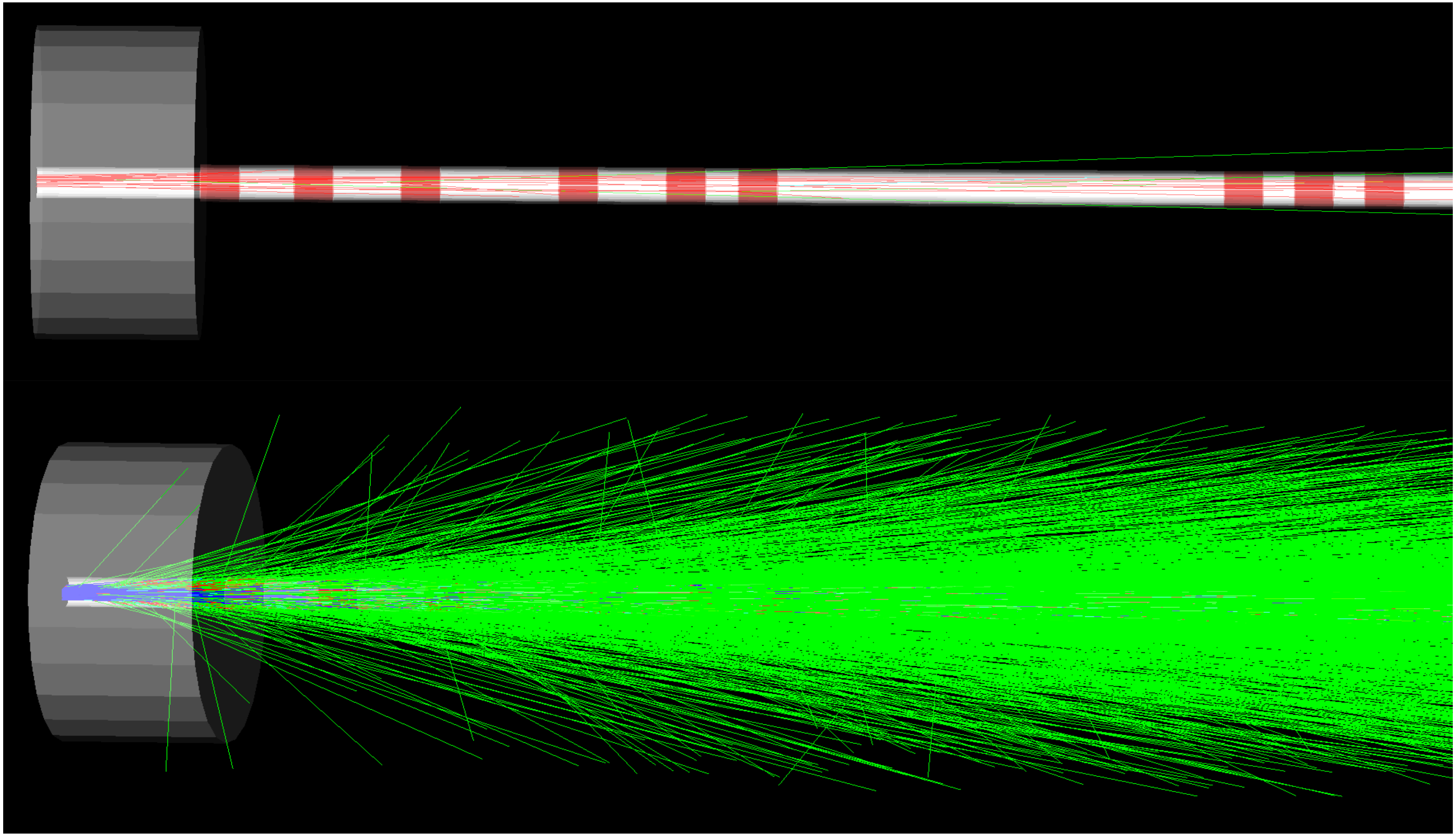
Lattice 13 performance



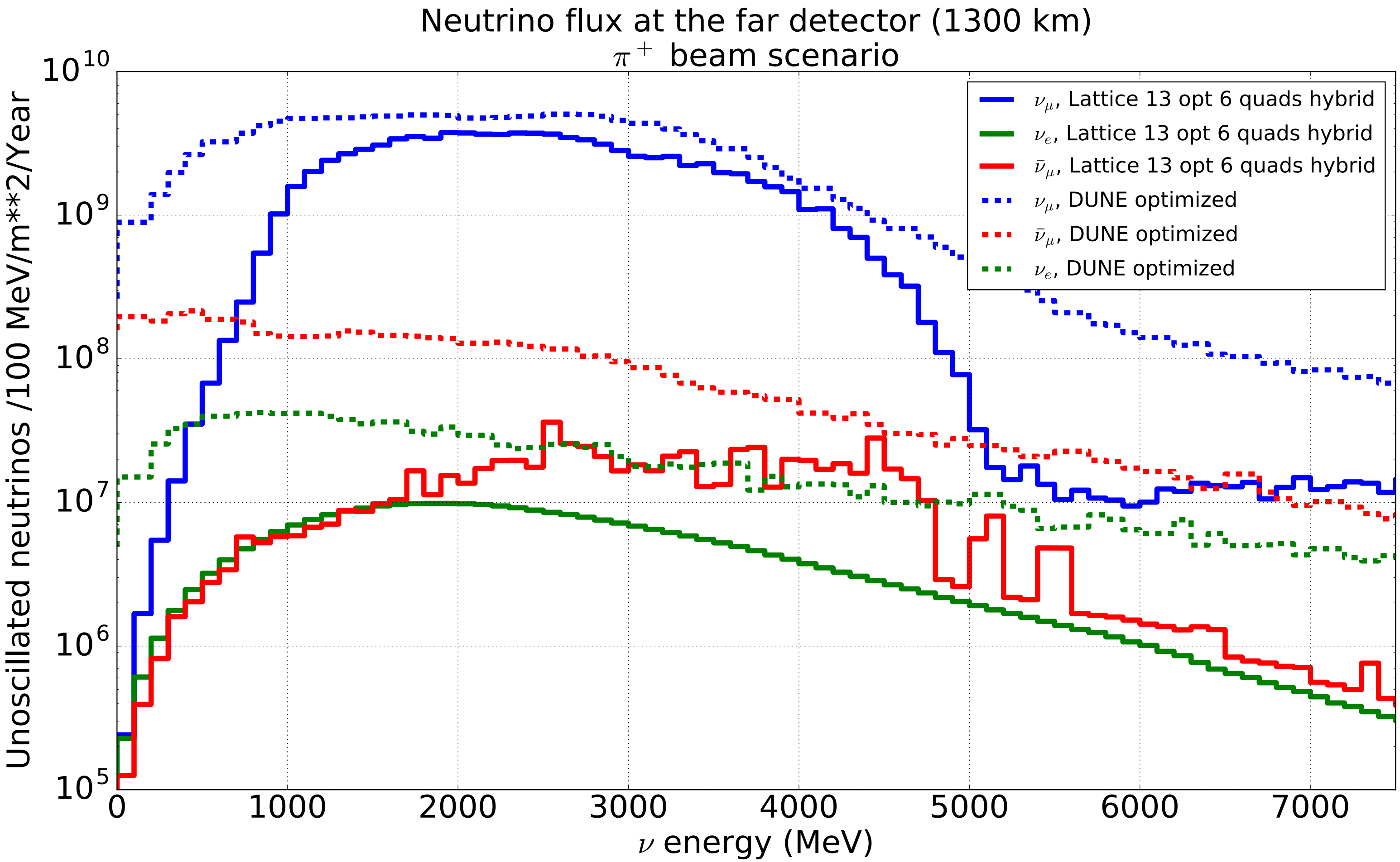
Blue:
pion+ after the optimized horn

Red:
Survived pion+ after the lattice 13 bend.

Hybrid decay straight



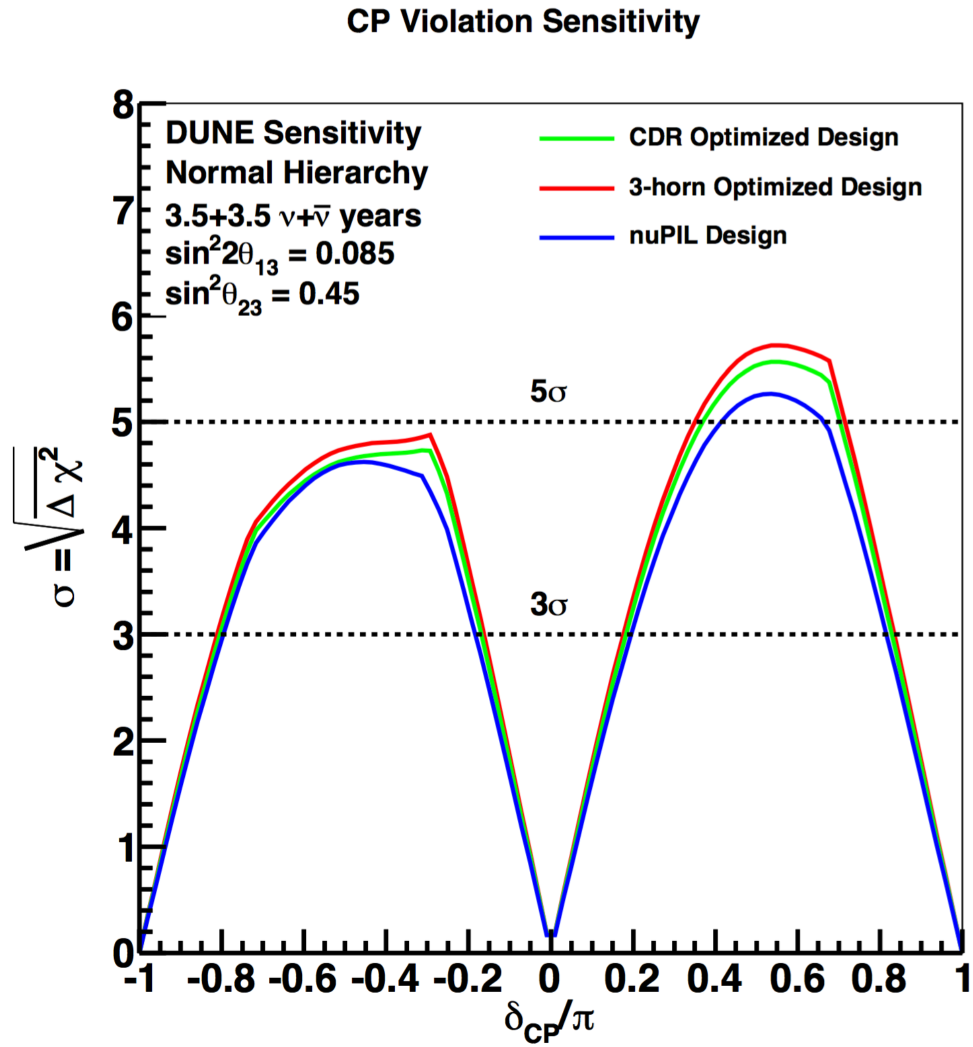
Optimized 6 quad matching result



Wider band but also higher background

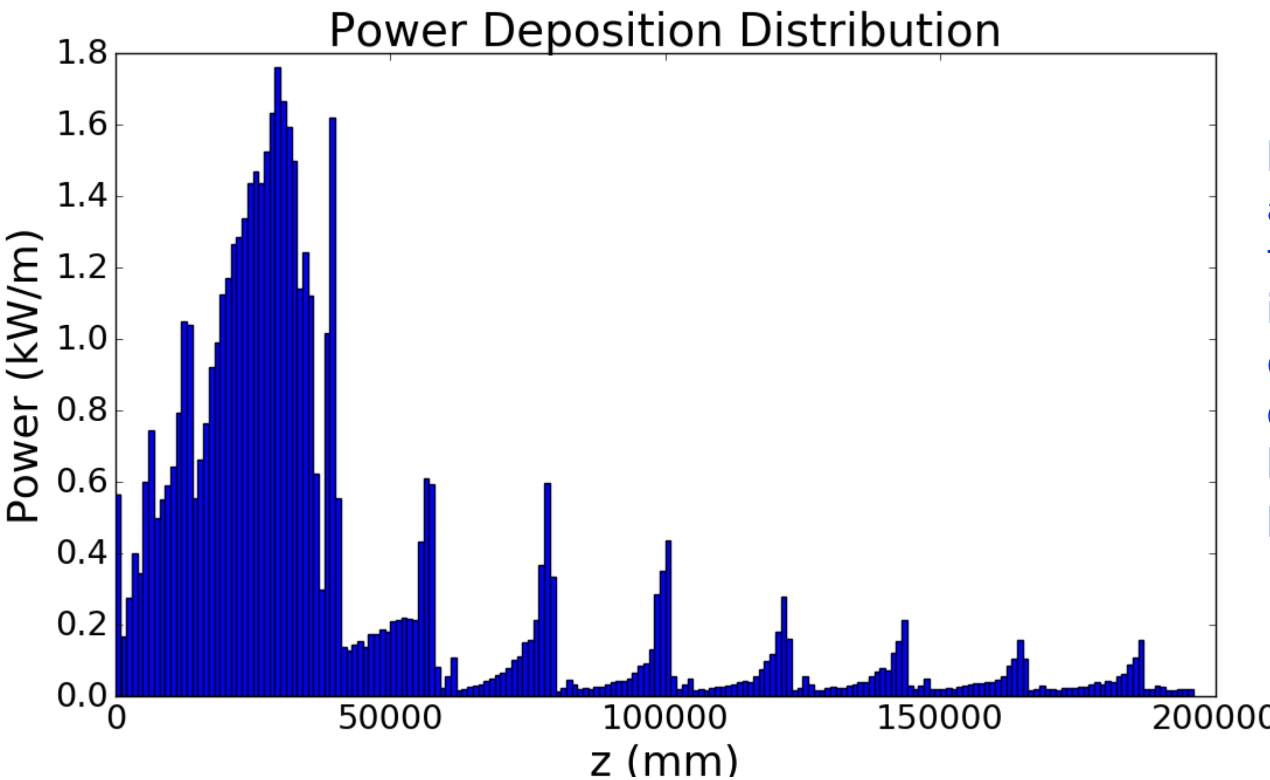
LBNF also improved their design since CDR and moved to 3 horns.

δ_cp coverage from optimized horn, lattice 13 + optimized hybrid



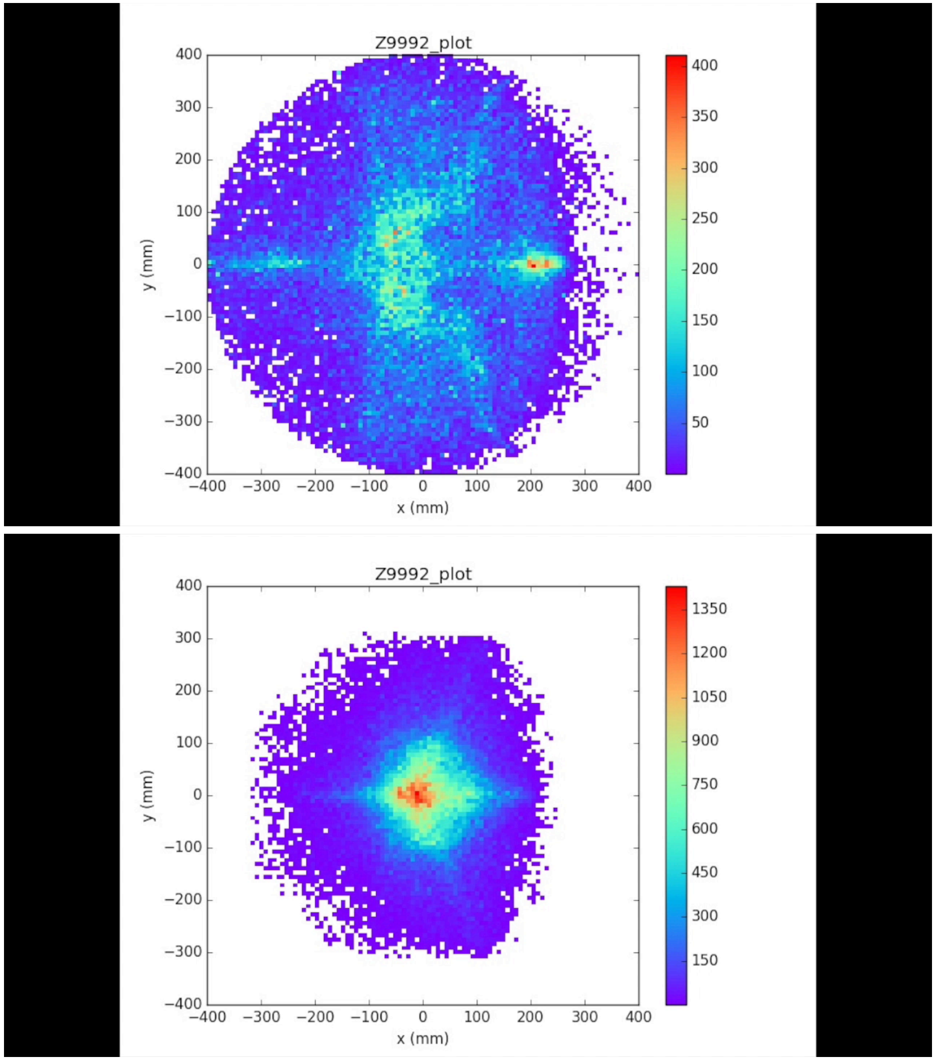
Beam loss

- One big concern is whether we can put beam instrumentations in to determine the neutrino flux precisely



Preliminary studies have been done to analyze the loss due to the aperture. Our goal is to introduce collimators to collimate out unacceptable hadrons as early as possible

Introducing collimators to control loss

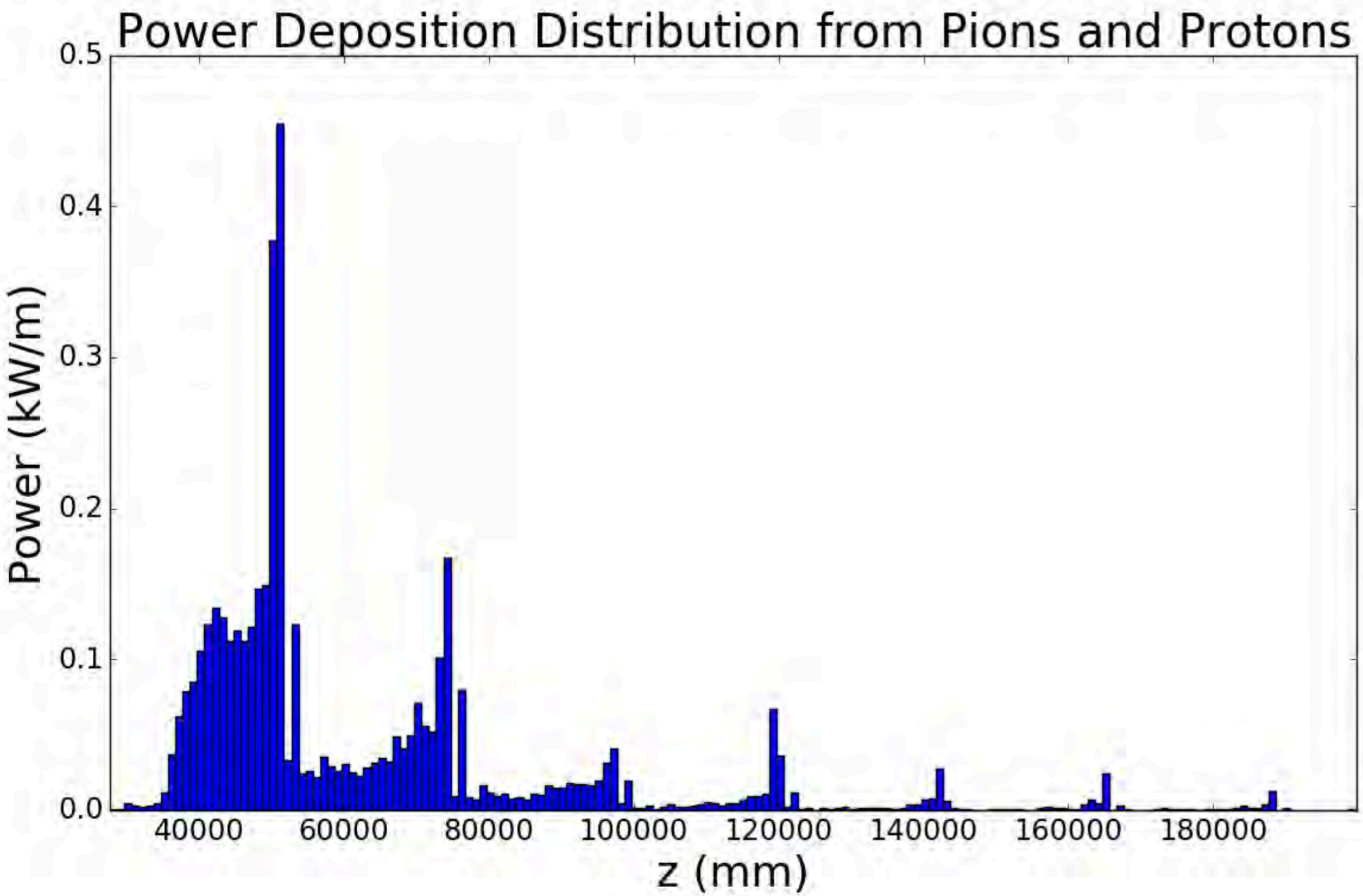


Bad pions (pi- and off-momentum ones) are clearly separated from the good pions at several quad positions, with obviously large radius (see the movie)

(above are bad pions and below are the good ones)

Introducing one collimator reduces the loss after the 1st quad in the triplet cells by 60%, but only affecting the good ones by 8%.

Loss from hadrons after the collimator

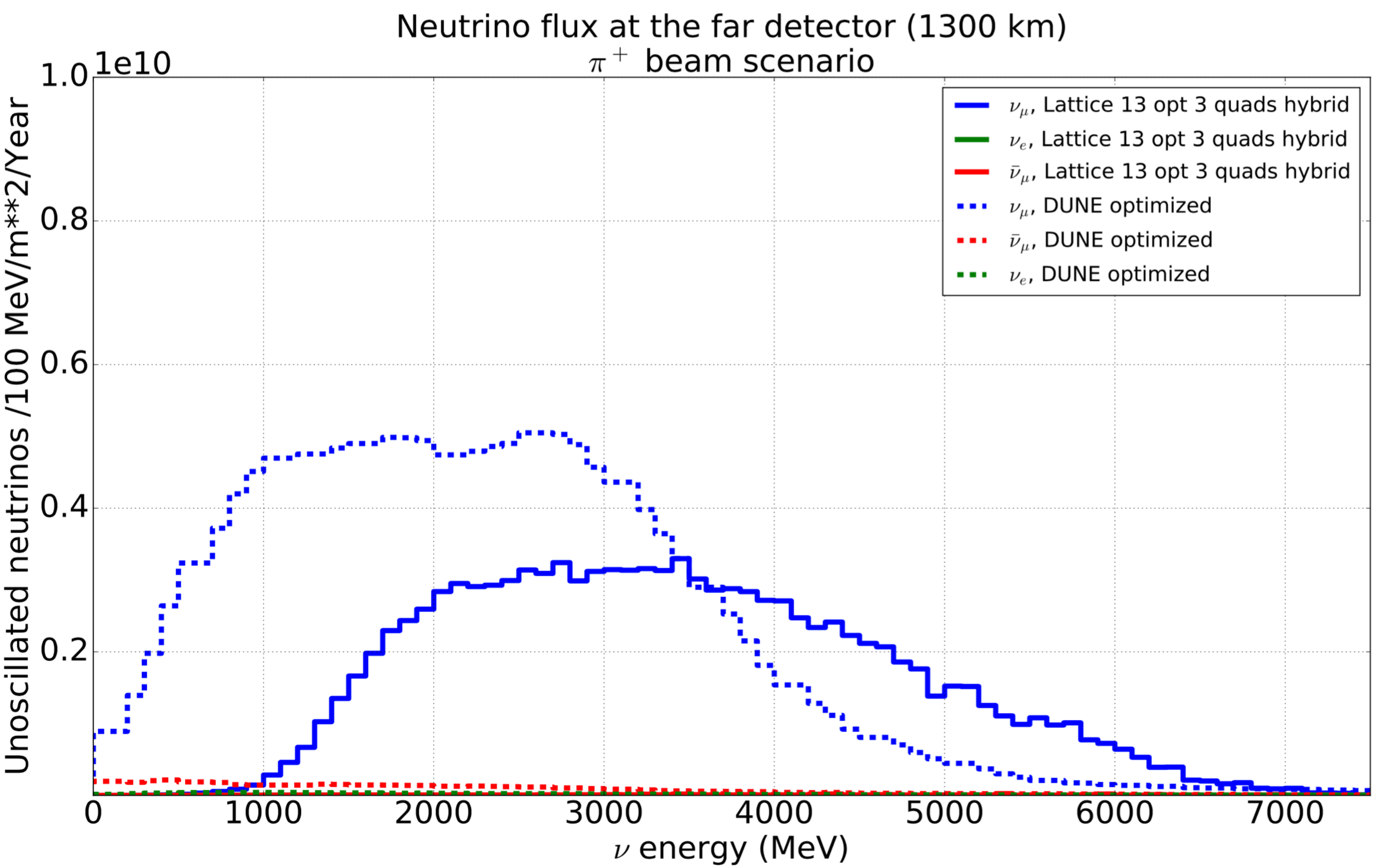


The last 75 meters has ~ 5 W/m loss – place to put instrumentations in.

However the first 125 m will need radiation shield (concrete) and add cost to the design.

Full simulation needed to demonstrate

τ physics



We evaluated the high E potential of this design by shifting P0 to 7.5 GeV/c to 5 GeV/c, and tracking the new beam in the SAME lattice:

Nice reach at high E!

Low E is harder because of γcτ

New FFAG bend at 7.5 GeV/c needed for this beam, pion production drops at high E so full MARS simulation needed.

Others

- Cost?
  - Neutral w.r.t. LBNF;
- Real target + horn?
  - On going with MARS simulations
- Low E but more POT?
  - Needs full optimization on the horn
- Needs?
  - Manpower.
  - "Effective" number of people on nuPIL is only 1.5
- Yields?
  - A new neutrino experiment, for the first time, really accelerator based
  - A path to the future pion/muon facilities, a better world than a decay pipe

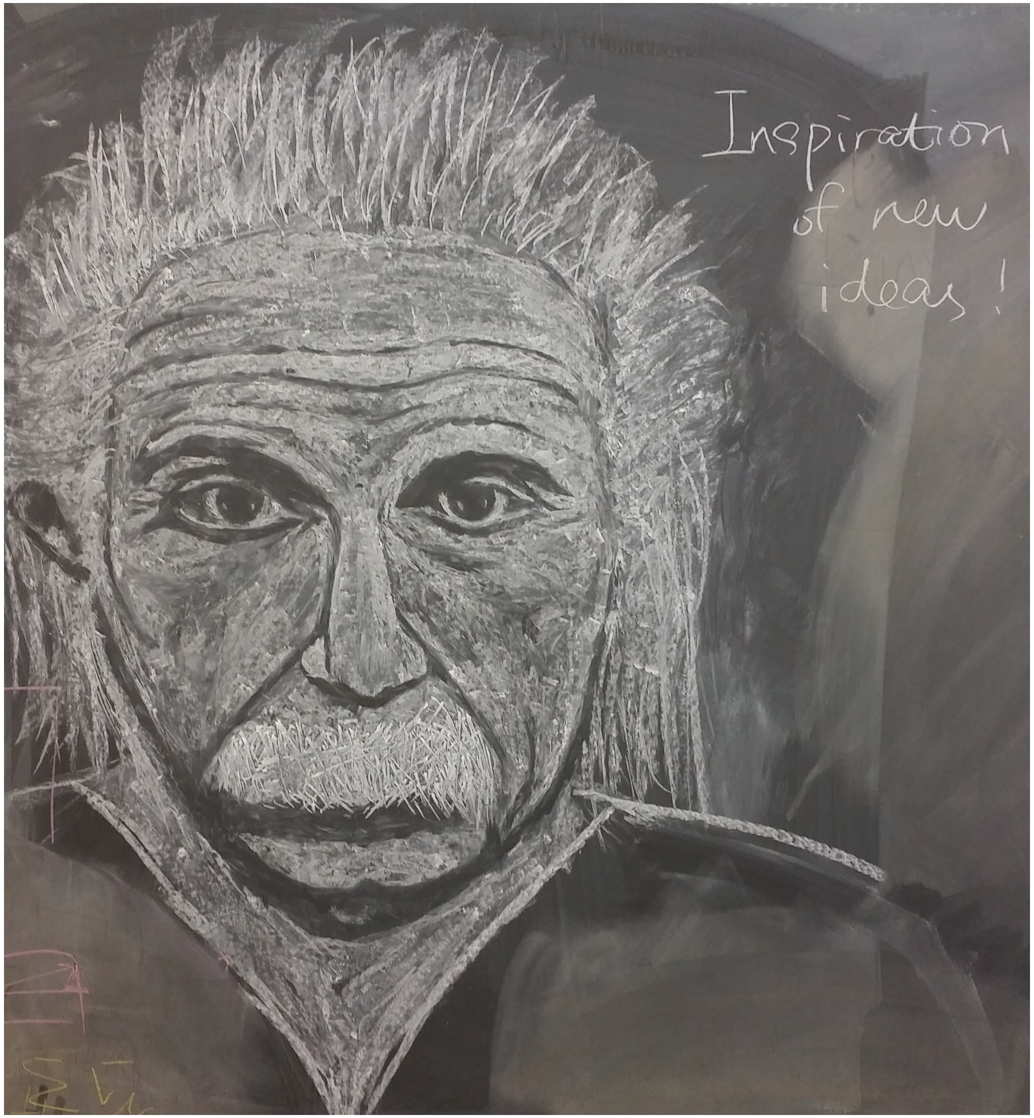
Conclusions

- nuPIL provides a (almost) flavor-pure neutrino beam through a measurable and controlable pion beam
  - It has less systematics uncertainties, less radiation hazard, more reliability, a magnetic beamline rather than a hill, needs a much easier hadron absorber (ND can be a Super ND!)
  - **Again, nuPIL has a cure.**

- DUNE management has not steered their fast moving train for nuPIL, but with a more thorough study, it can.

- Are you willing to witness something ν?

- Thank you for your attention!


Inspiration of new ideas!