Horn Optimization for nuSTORM

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nuSTORM Overview

WHO WE ARE, WHAT WE DO

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Overview – Site Plan

Photo courtesy of nuSTORM collaboration

νSTORM

Overview - Motivation

- 3.8 GeV/c muon decay ring (±10%) + near detector + far detector to study eV-scale neutrino oscillations and neutrino cross sections.
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
    - ↳ Well understood neutrino flux + flavor
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ clean neutrino flux also utilizable
  - Provides a technology test bed for muon facilities;
  - Affordable
    - Old technology; Simple implementation
  - Now has FNAL Stage 1 approval.

Overview - Facility

- 100 KW target station
  - 120 GeV protons from MI;
  - Magnetic horn to collect π+ or π-;
  - Target material: graphite or Inconel;
- A total run exposure of 10^{21} protons over 4-5 years
  - 2.6 x 10^{18} useful muon decays
- Pion beamline to transport and inject the pions, and to accept the muons from pion decay
  - No full-aperture fast kicker or separate pion decay channel needed. "Stochastic injection" used.

Overview - Target

- Gold target produces the most pions– but not recommended (energy deposition in the horn)
  - – Graphite is the baseline target material;
  - – Inconel yields more pions, and energy deposition problem is more tolerable;
  - – Simulation tool: MARS15
- Inconel used in our optimization study

Courtesy of Sergei Striganov, APC, FNAL

Overview – Facility near site

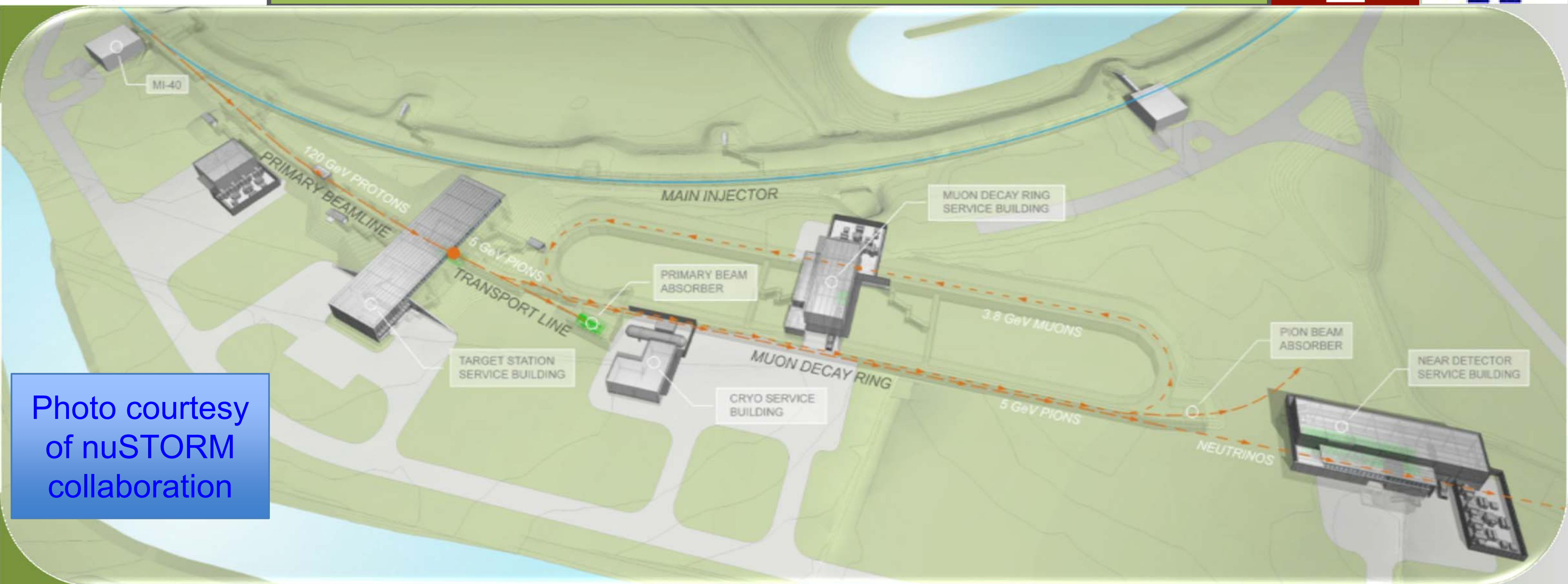
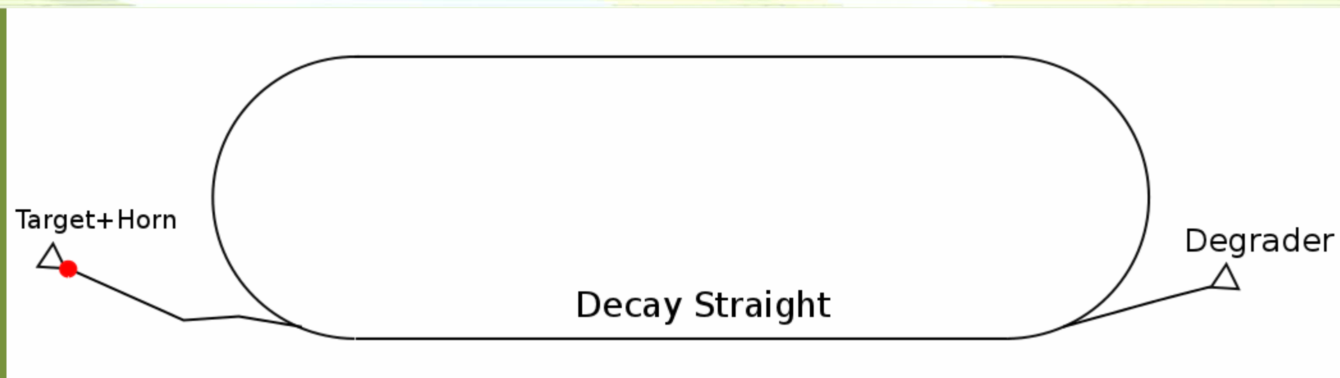


Photo courtesy of nuSTORM collaboration



← Animation of the pions and muons in the facility

Pion Beamline D&S

WHAT TO OPTIMIZE

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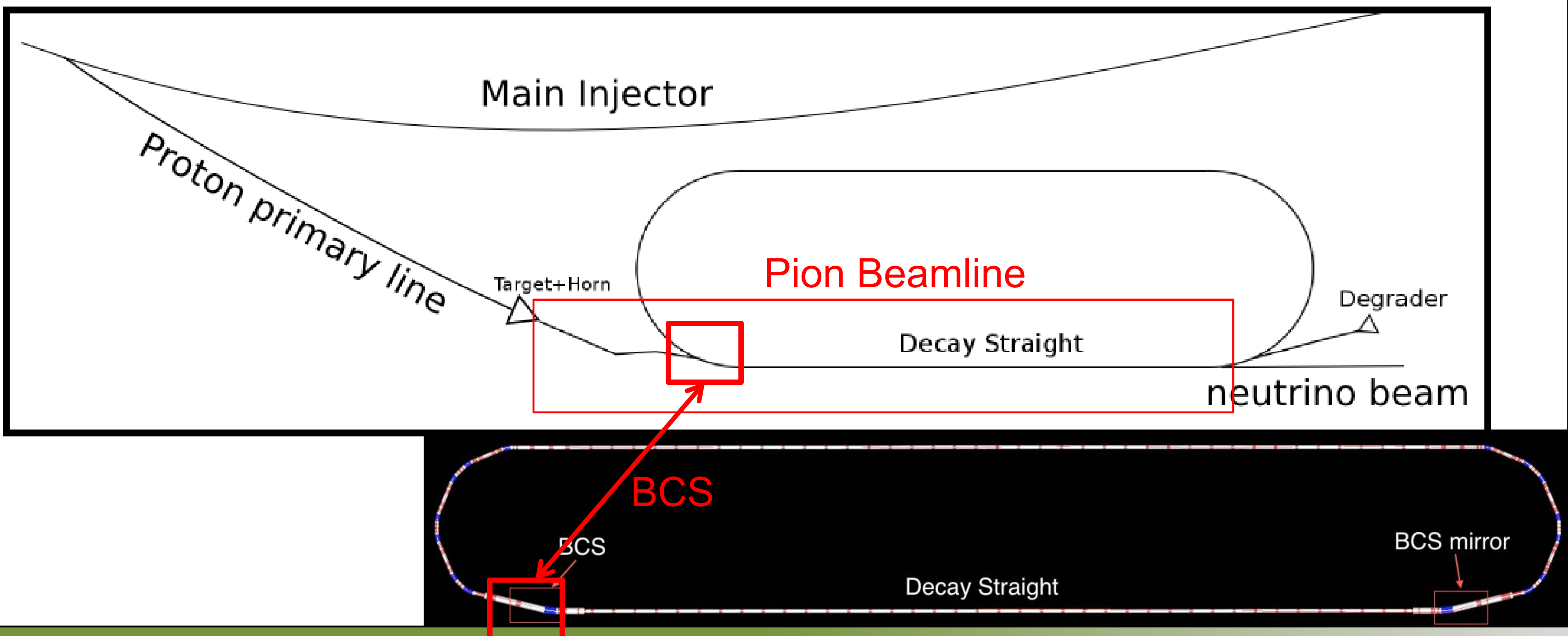
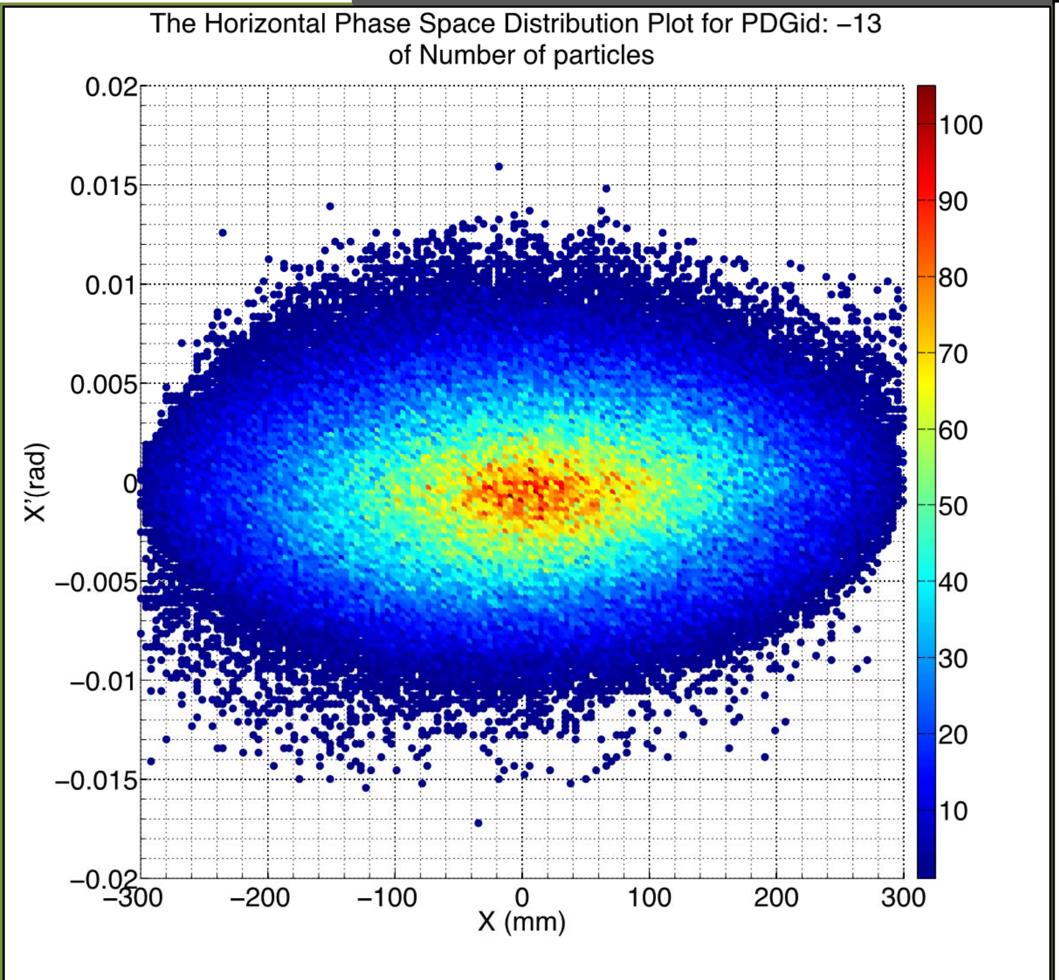
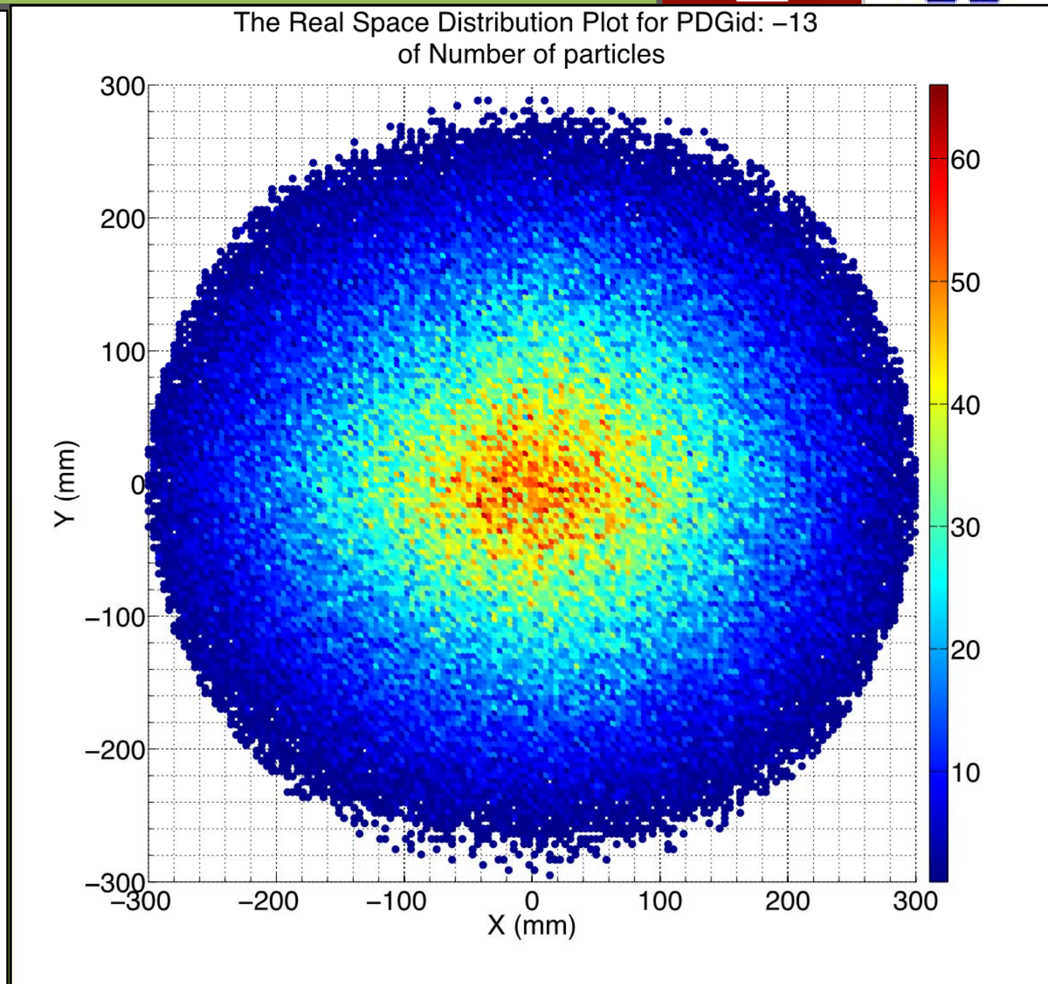
Pion Beamline Definition

- The pion beamline consists of the transport beamline, the beam combination section (BCS), and the storage ring production straight shared by π and μ.
- The pion beamline is designed with reference momentum P_0=5 GeV/c, the simulation was initially done using π+ collected by a NuMI-like horn with slightly different lengths and target position, no full optimization.

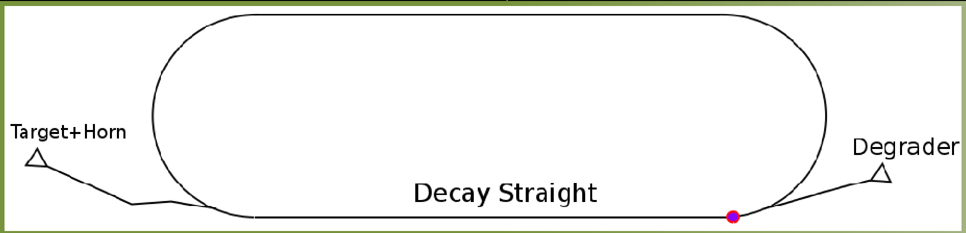


Muons from Pions at the End of the Pion Beamline



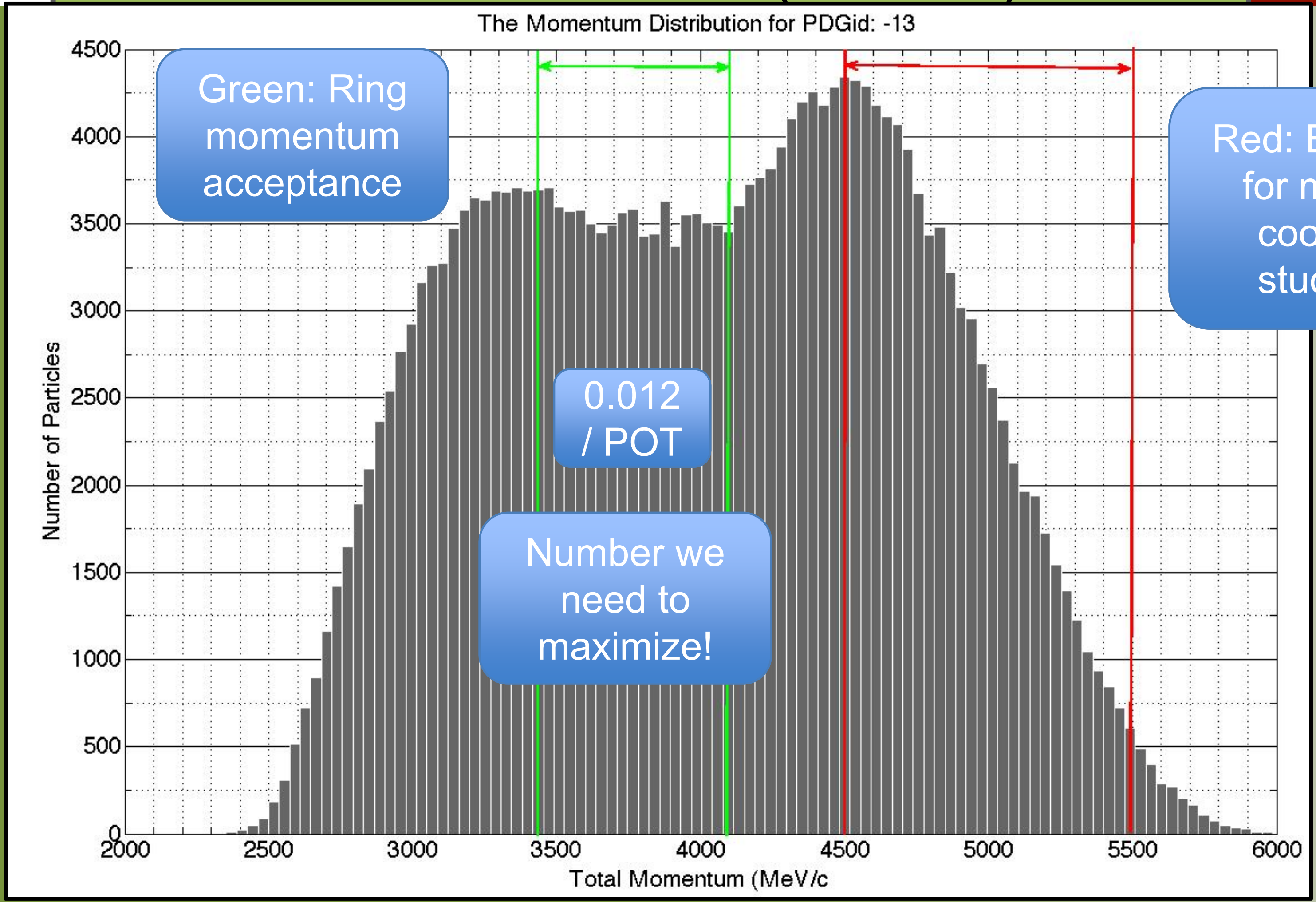


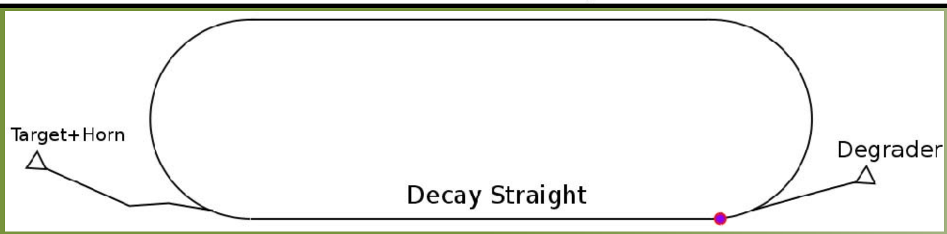
Number of μ+ in 2000 μm needs to be maximized!



G4Beamline used as the tracking tool; Geant4 implemented

Muons from Pions at the End of the Pion Beamline (Cont'd)





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Optimization Goal(s)

- Single Goal: Maximize muons in the transverse and momentum acceptance of the ring --
  - Why not directly use this criterion:
    - Phase space of pions from each horn design is different, need to re-match the optics;
    - Need full Monte Carlo simulation for each design;
    - Too much computing power and time
- Alternative Goals:

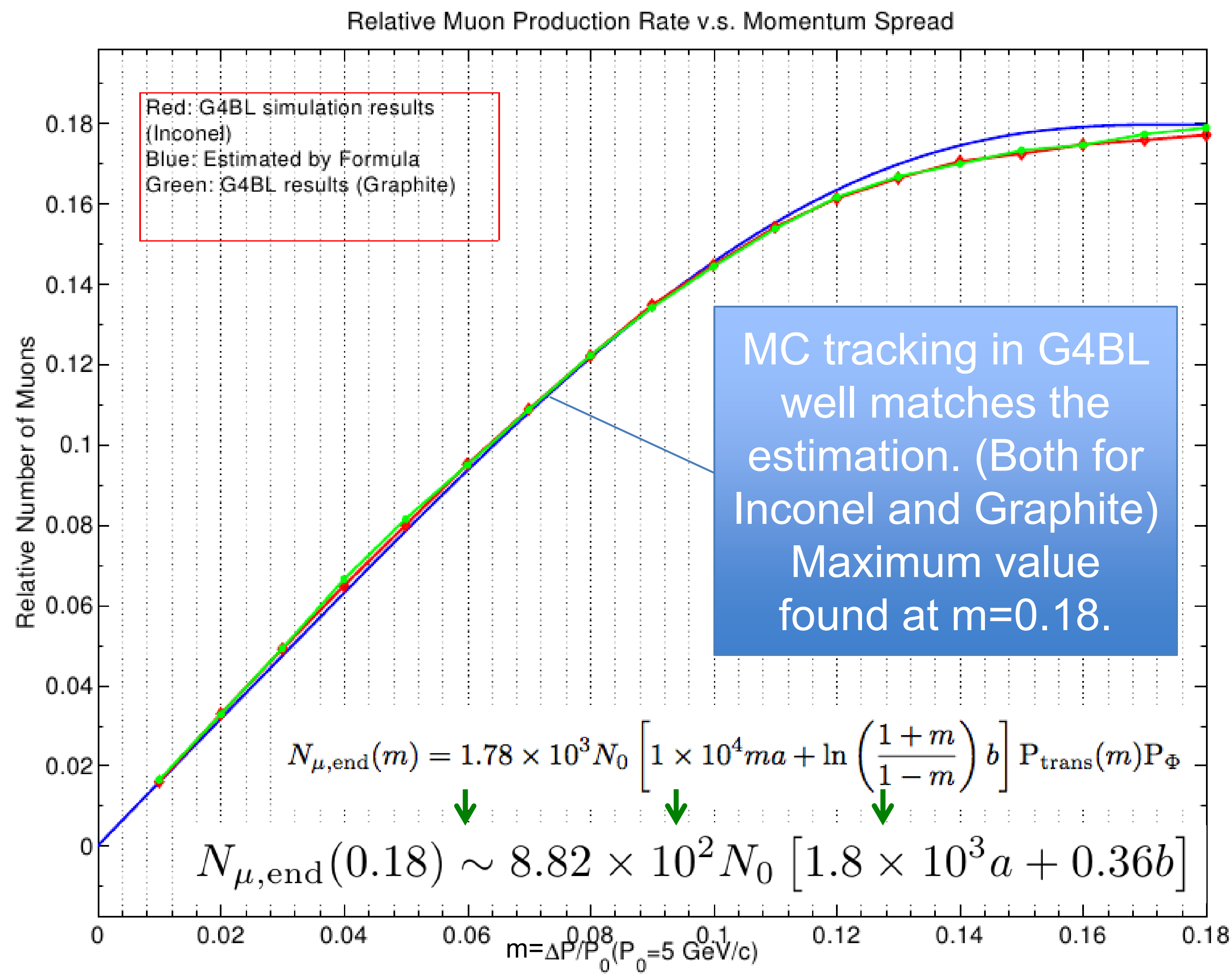
For horns collecting pions, for which the optics can be matched,

- Maximize muons within 3.8+-10% GeV/c, at the end of the production straight ($N_{\mu,end}$)
- Maximize pions within 2000 μm at the end of the horn (N_{π})

They must be optimized simultaneously – No formula for the analytical correlation of the two.

Maximizing $N_{\mu,end}$

- π+ after the horn are linearly distributed in 4-6 GeV/c ( ) $f_{p_\pi}(p_\pi) = ap_\pi + b$ 3.8±10% GeV/c from the *N_0* π+ within *$P_0 x(1 \pm m)$* GeV/c can be estimated. (m=$\Delta P/P_0$ and P_0=5 GeV/c)



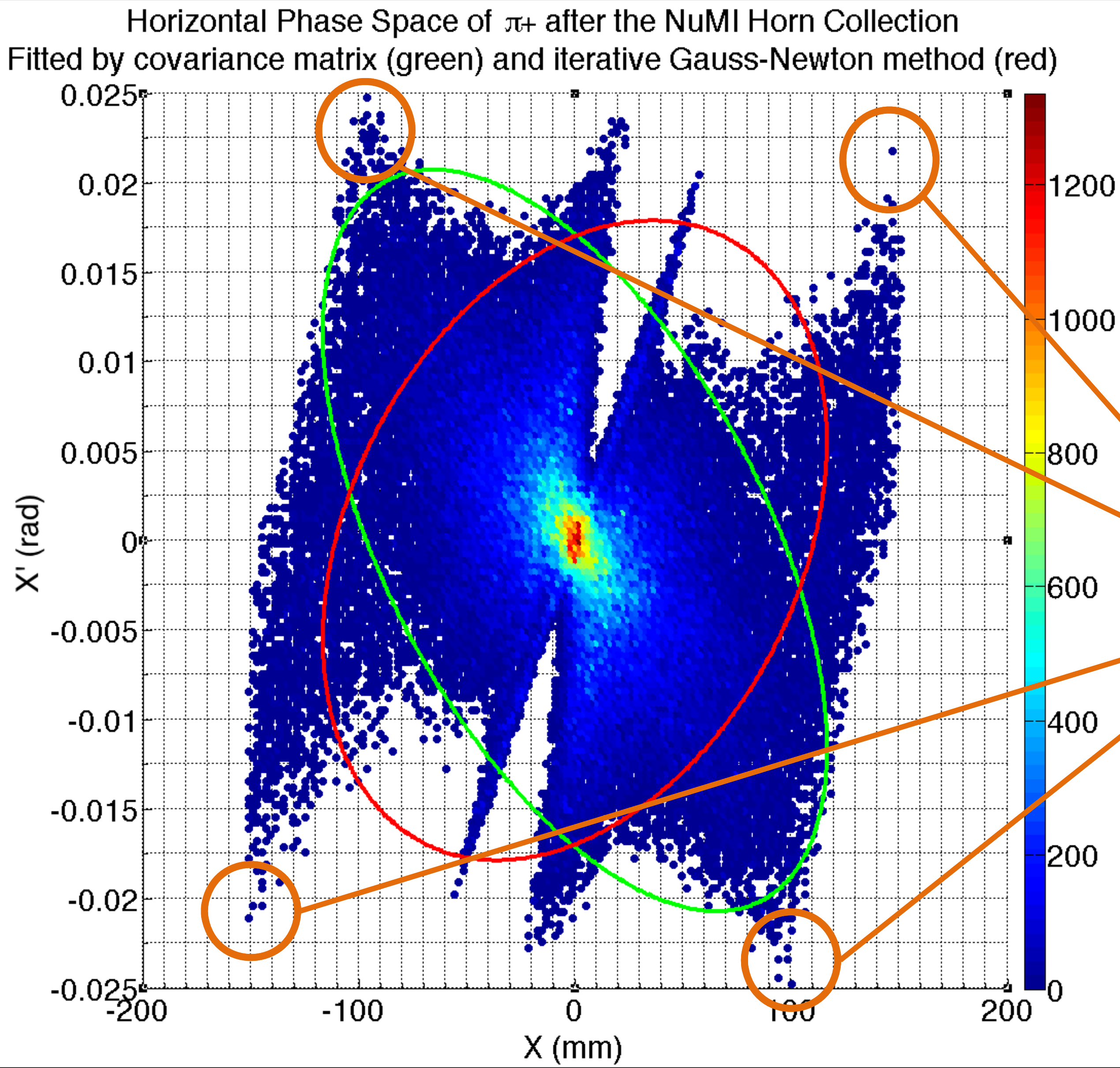
$$N_{\mu,\mathrm{end}}(m) = 1.78 \times 10^3 N_0 \left[1 \times 10^4 ma + \ln\left(\frac{1+m}{1-m}\right) b\right] \mathrm{P_{trans}}(m)\mathrm{P}_\Phi$$

$$N_{\mu,\mathrm{end}}(0.18) \sim 8.82 \times 10^2 N_0 \left[1.8 \times 10^3 a + 0.36b\right]$$

Maximizing N_{π}

- Different π+ beams from different horn collections have very different phase space distributions
  - Distorted bivariate Gaussian in the phase space – must be fitted in order to obtain Twiss (Optics) parameters for matching;
  - N_{π} obtained from counting π+ in the fitted 2000 μm acceptance ellipse
- Large phase space area (more than 2000 μm) causes fitting bias

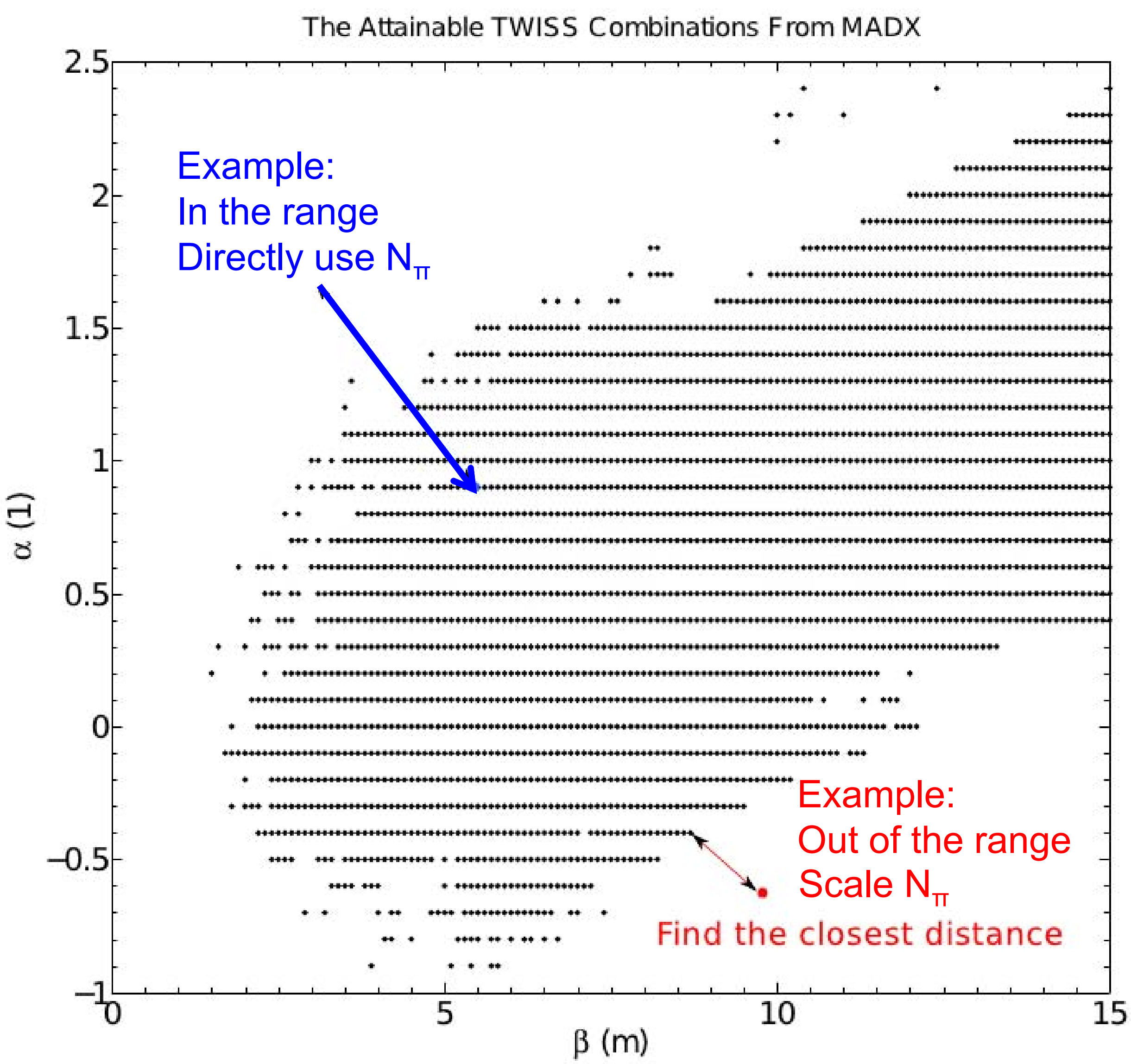
Maximizing N_π (Cont'd)



- Direct statistics gives biased fit – red
- Iterative Gauss-Newton method – green
  - Iteratively discards particles with largest emittance until rms emittance reaches a specific value
- Better match to the core of the beam

Maximizing N_π (Cont'd)

- Is a set of Twiss parameters (α and β) useable?
- A range of feasible Twiss from MADX;
  - Quad. gradient limit
  - Beam size limit in the beamline
  - Able to find a match?
  - Next set of parameters



Big but calm

+

Aggressive but small

Many generations

=

Nature chooses better survives

Big Aggressive

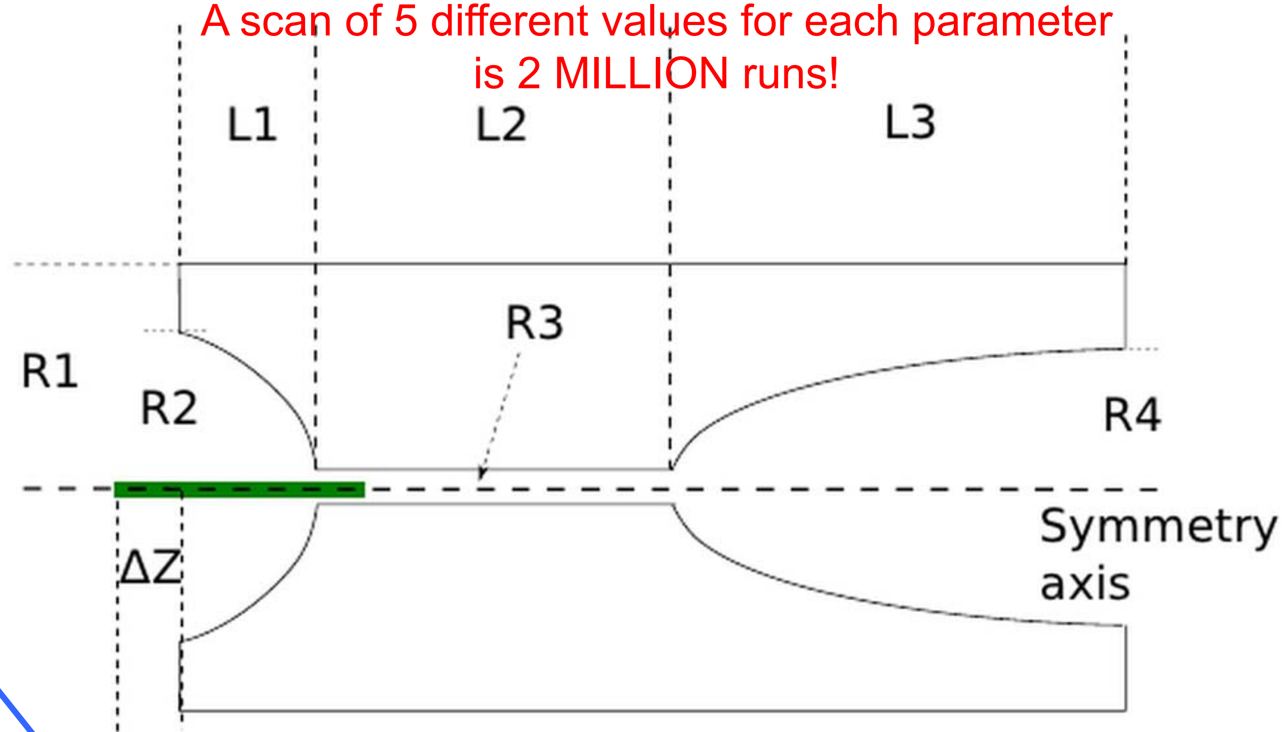
Multiple Objective Genetic Algorithm (MOGA)

HOW TO OPTIMIZE

pyGAmpi

- A python-mpi code to run the Genetic Algorithm (GA), to improve the individuals
  - Different individuals are different combinations of parameters
  - They give different objective values
    - (Different horns yield different N_{π} and $N_{\mu,end}$)
  - Objectives to be maximized / minimized
    - (Max. N_{π} and $N_{\mu,end}$)
  - Parameter constraints;
    - (Current in horn, neck radius, etc.)

A scan of 5 different values for each parameter is 2 MILLION runs!



- An individual horn is a combination of the above parameters, and horn the current (9 parameters);
- Select parents based on the objectives, produce offspring;
- Parameters are treated like "genes" – genes of children are the crossover and mutation of the parents' genes;
- Eventually, the whole population will be improved, i.e. gives larger N_{π} and $N_{\mu,end}$

MOGA process

GA starts, a number of random individual horns produced as the first generation

Model the B-field in the horns, based on the parameters of each horn

Track π+ in the individuals, calculate N_{π} and $N_{\mu,end}$ for each case

Select the best individuals, make the offspring. A child generation is generated

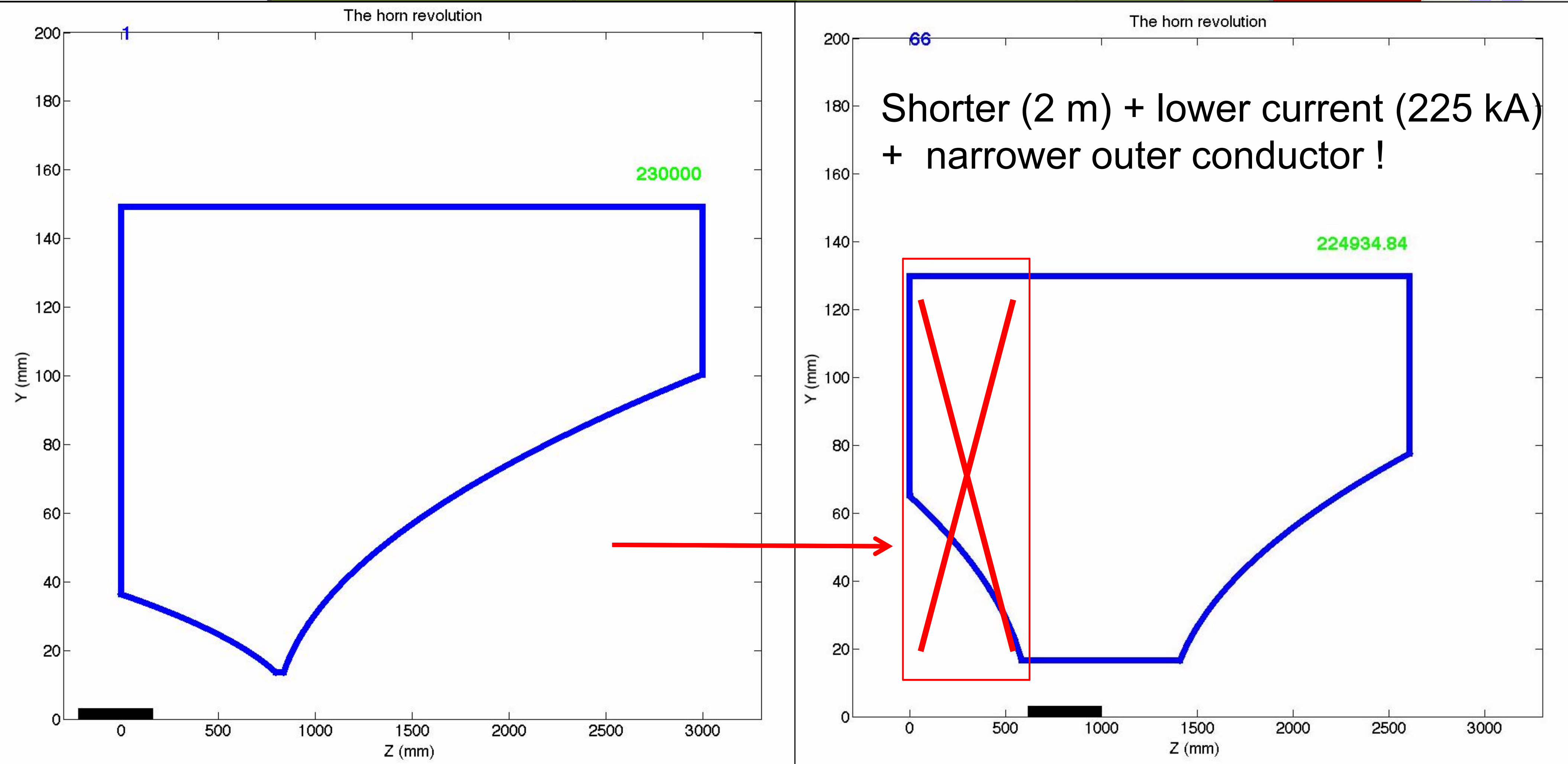
When the maximum generation number is reached, or the population stops improving,stop the algorithm

Population size: 200;
Generation limit: 100;
CPUs used in each generation: ~1200

Optimization Results

IT WORKS

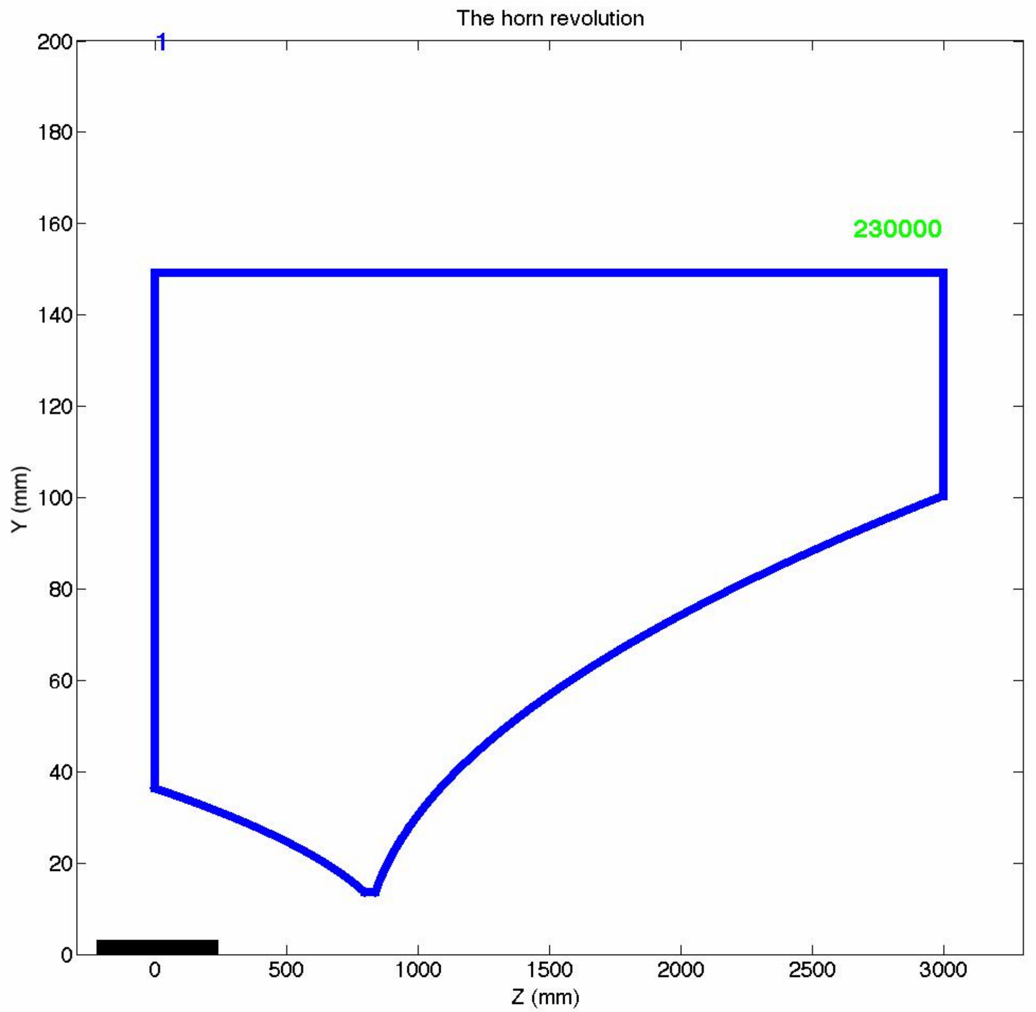
Collection of π+ from a 38 cm Inconel (2.5 interaction lengths)

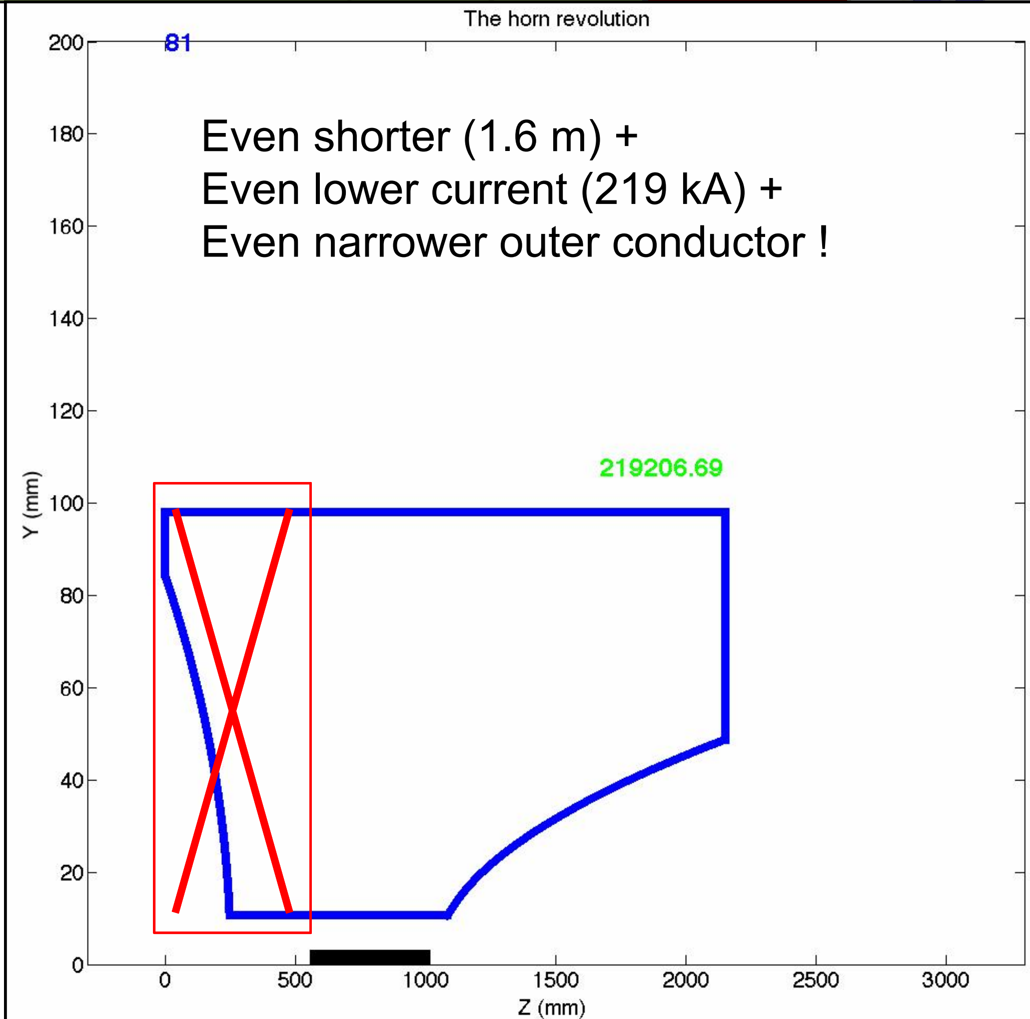


$N_{\mu,end}$ increased by 14%; N_{π} increased by 18%;
Then, Pion beamline re-matched; π+ re-tracked;
μ+ in both 2000 μm and 3.8±10% GeV/c increased by 8.3%

Why not as high?
Higher-order effects not considered:
Beta-beat, phase space difference for off-momentum particles, etc.

Collection of π+ from a 46 cm Inconel (3 interaction lengths)





$N_{\mu,end}$ and N_{π} increased by ~20%; (If just changing the target length: ~5%)

Then, Pion beamline re-matched; π+ re-tracked;

μ+ in both 2000 μm and 3.8±10% GeV/c increased by ~16%

Conclusions

IMPORTANCE OF THE OPTIMIZATION

Conclusions and Future

- nuSTORM benefits from the optimization:
  - Expect 8.3% more neutrino flux, with a 38 cm Inconel target;
  - Expect 16% more flux, with a 46 cm Inconel target.
- Other horn-based projects – e.g. LBNE:
  - Algorithm is expected to work if the objectives are known;
  - Algorithm may be less complicated and faster, if no beamline tracking is needed;
  - MOGA allows adding other constraints to obtain a more realistic design + optimization
- Future:
  - Modify the objectives based on further ring design studies;
  - Collaboration work with other projects if needed and interested.

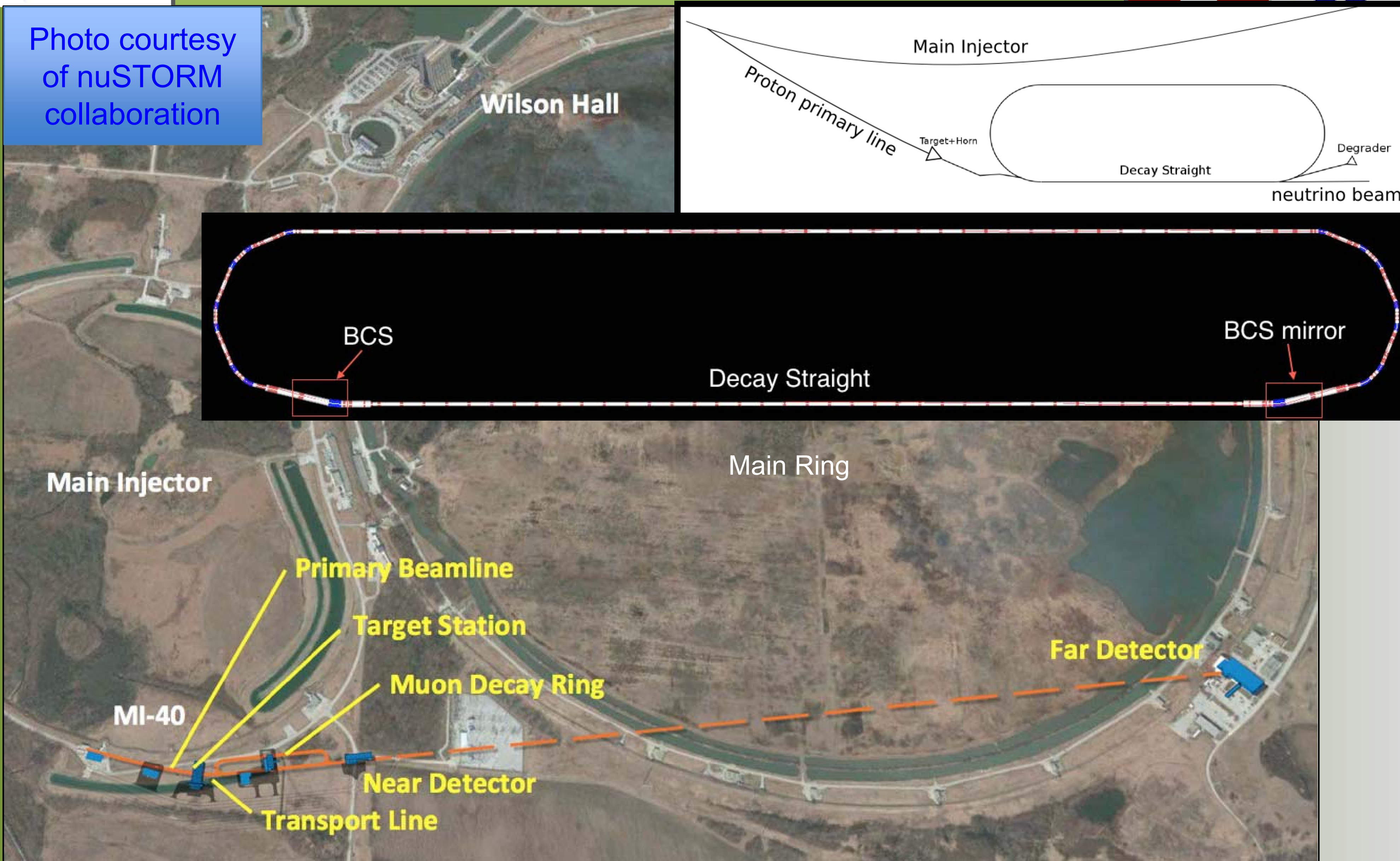
Thanks

YOUR COMMENTS ARE WELCOME

Back Ups

IN CASE I FORGOT

Overview – Site Plan



Introduction-Motivation

- For the past decade, a lot of effort has been spent on neutrino oscillation physics

8 channels accessible by νSTORM

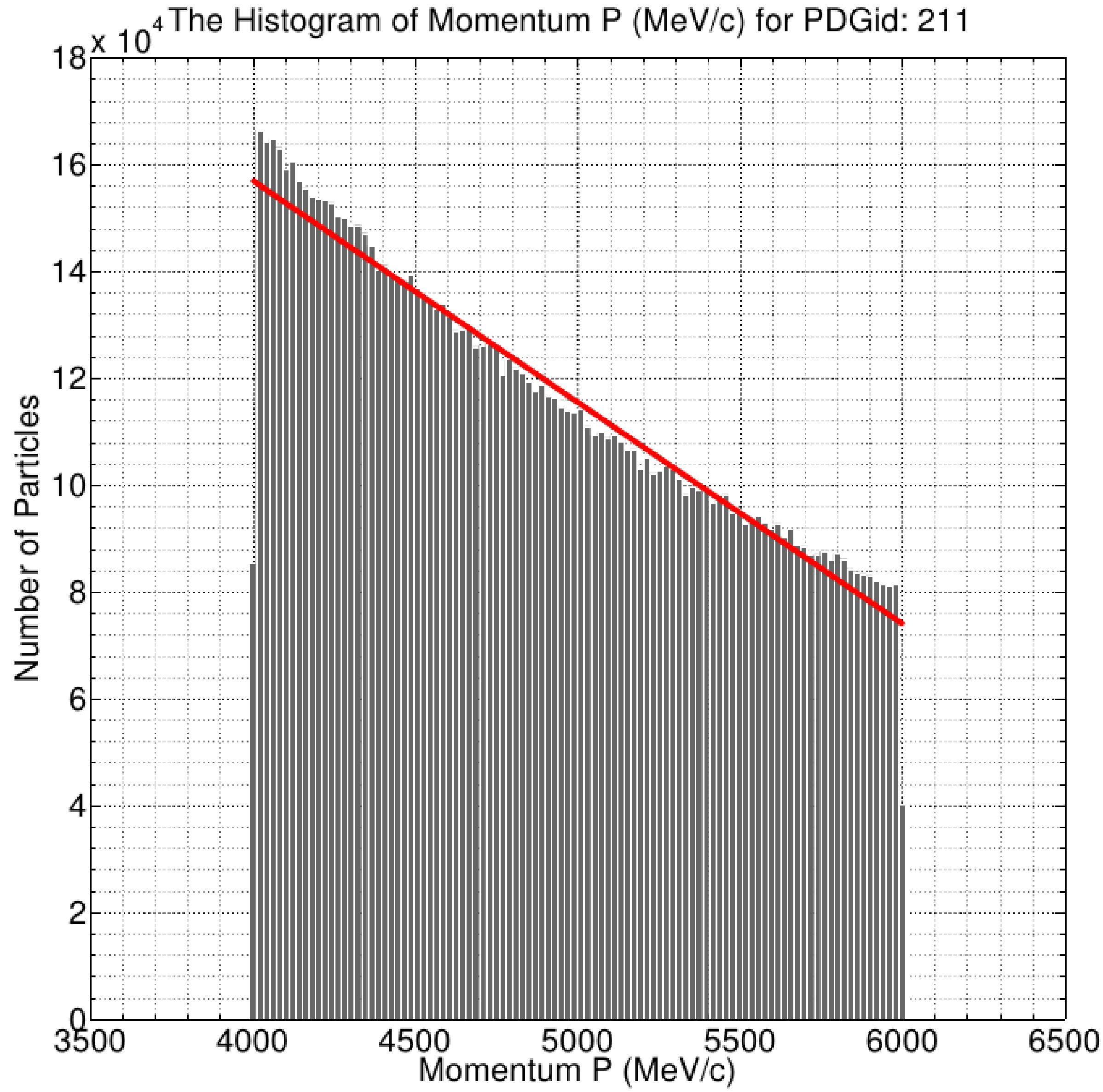
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance ("platinum" channel?)
[illegible]	[illegible]	appearance (atmospheric oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: "golden" channel
[illegible]	[illegible]	appearance: "silver" channel

Introduction-Facility

- 100 KW target station
  - 120 GeV protons from MI;
  - Magnetic horn to collect π+ or π-;
  - Target material: graphite or Inconel;
- A total run exposure of 10^{21} protons over a period of 4-5 years
  - 8 x 10^{12} protons per pulse; cycle time 1.33 sec.
  - A total of 2.6 x 10^{18} useful muon decays, updated from 1.9 x 10^{18} useful muon decays in the proposal
- Pion beamline to transport and inject the pions, and to accept the muons from pion decay
  - No full-aperture fast kicker or separate pion decay channel needed
- Gold target gives the most pion productivity but is not recommended (intensive energy deposition in a horn)
  - Graphite is the baseline target material in the proposal;
  - Inconel yields more pions, but engineering challenges may rise, though better than gold;
- Inconel used in the optimization study

Maximizing $N_{\mu,end}$

- $f_{p_\pi}(p_\pi) = ap_\pi + b$
- e.g. *a*= -1.46935529e-07, *b*=1.23467765e-03
- *a* and *b* changes only slightly w.r.t different horns (Usually a few percent)



Maximizing $N_{\mu,end}$

- The above implies that the maximum number of μ+ within 3.8±10% GeV/c generated is

$$N_{\mu,\mathrm{end}}(m = 0.18) = 8.82 \times 10^2 N_0 \left[1.8 \times 10^3 a + 0.36 b\right]$$

  - Assuming the phase space acceptance of the pion beamline P_Φ for different initial conditions is the same;
  - This has taken the momentum acceptance and decay kinematics into account.
- Horn variation gives slightly different coefficients *a*, *b*, and very different N_0

MOGA process

GA starts, a number of random individual horns produced as the first generation

Model the B-field in the horns, based on the parameters of each horn

Track π+ in the individuals, calculate N_{π} and $N_{\mu,end}$ for each case

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When the maximum generation number is reached, or the population stops improving,stop the algorithm

~40,000 core-hours used in each search