FFAGs for fundamental research

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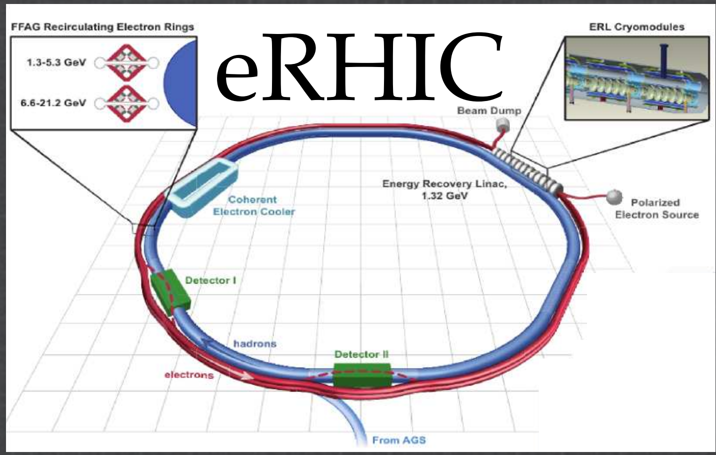


FFAG accelerator

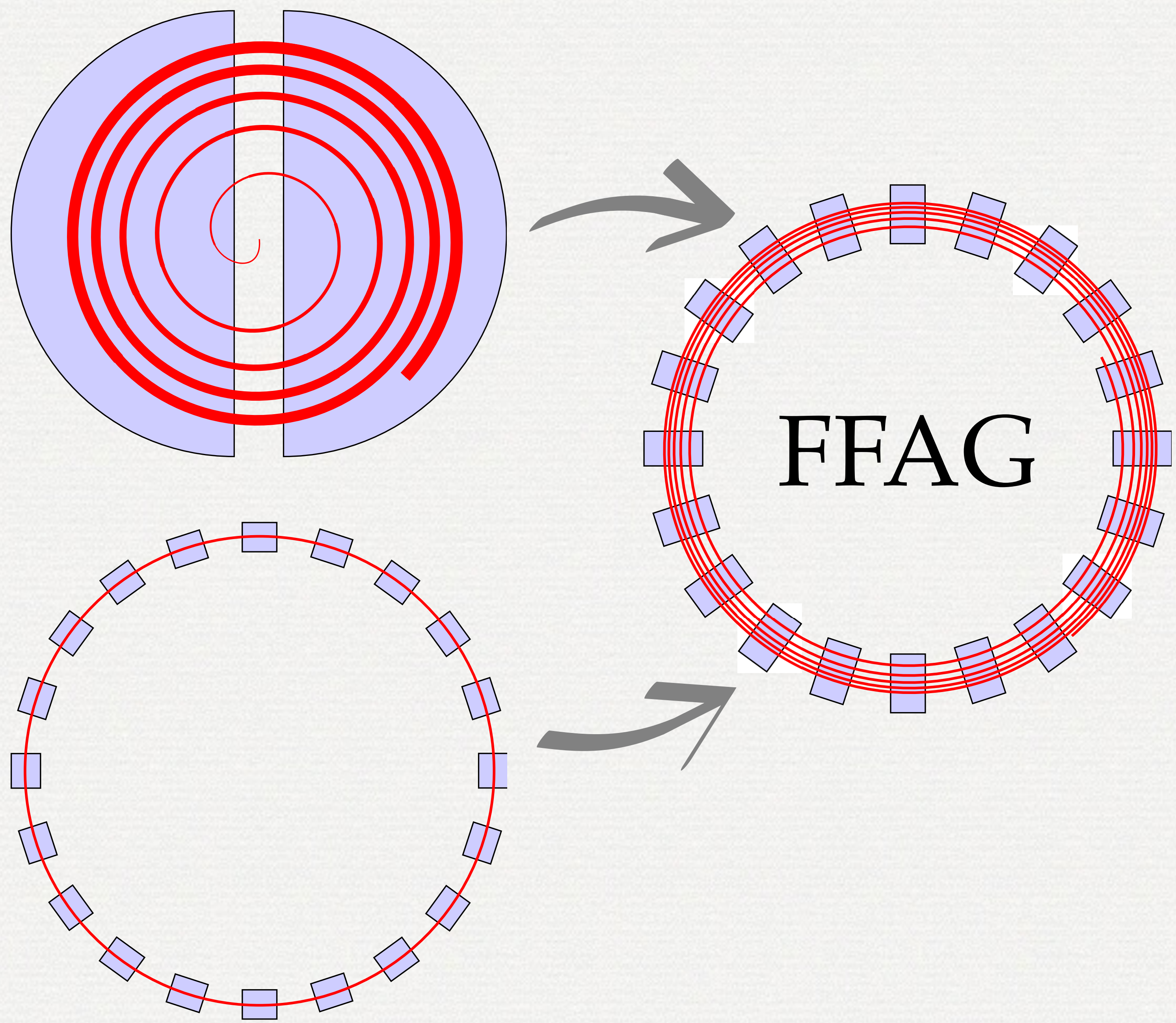
FIXED FIELD ALTERNATING GRADIENT

It combines

- **a static guide field** like cyclotrons:

AND

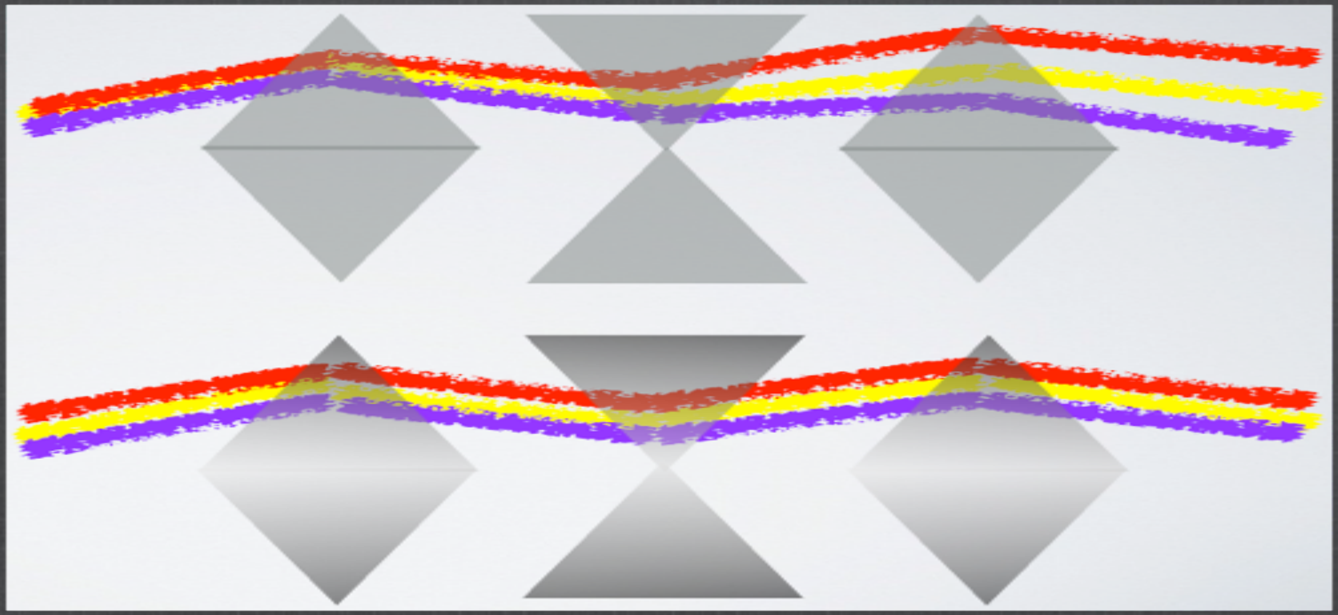
- **a strong focusing.** like synchrotrons:



Zero-chromatic FFAG

Pros:

- stable optics for **very large momentum spread**.
- allows a good working point with a **large acceptance** far from harmful resonances.



→ Quasi-zero beam loss!

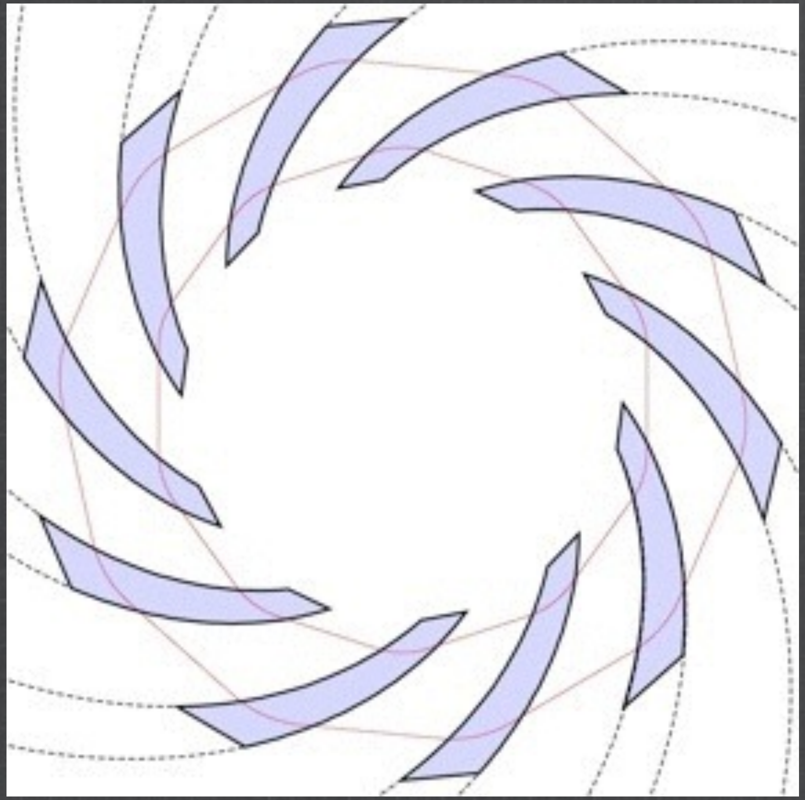
Cons:

- possibly large magnets

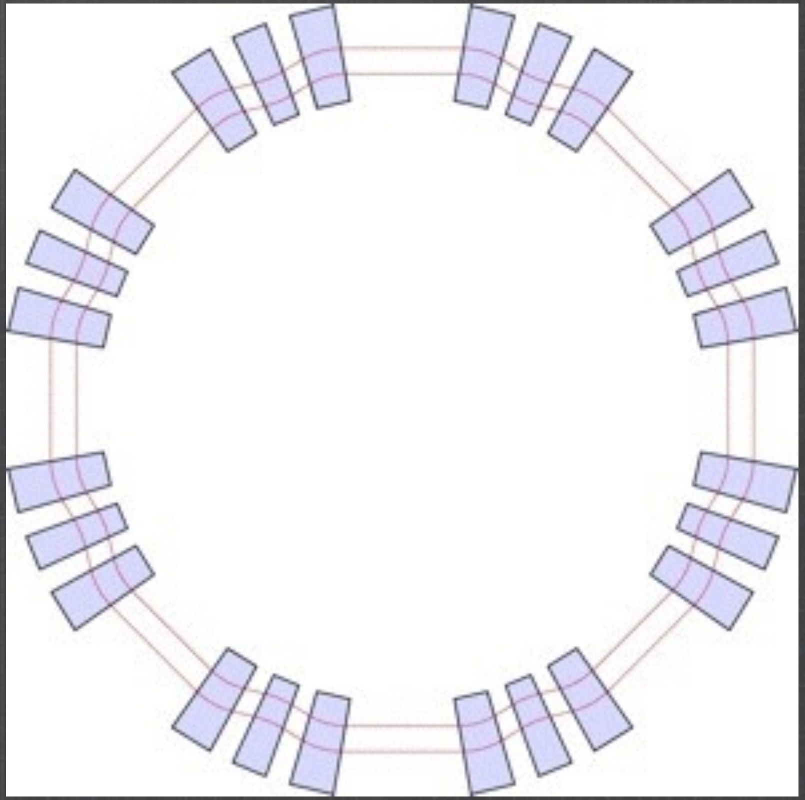
Circular scaling

Constant geometrical field index: $k = \frac{R}{\bar{B}} \frac{d\bar{B}}{dR}$

$$\boxed{B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k \cdot \mathcal{F}(\theta - \tan\zeta \ln \frac{r}{r_0})}$$



Spiral sector: $\zeta = const.$

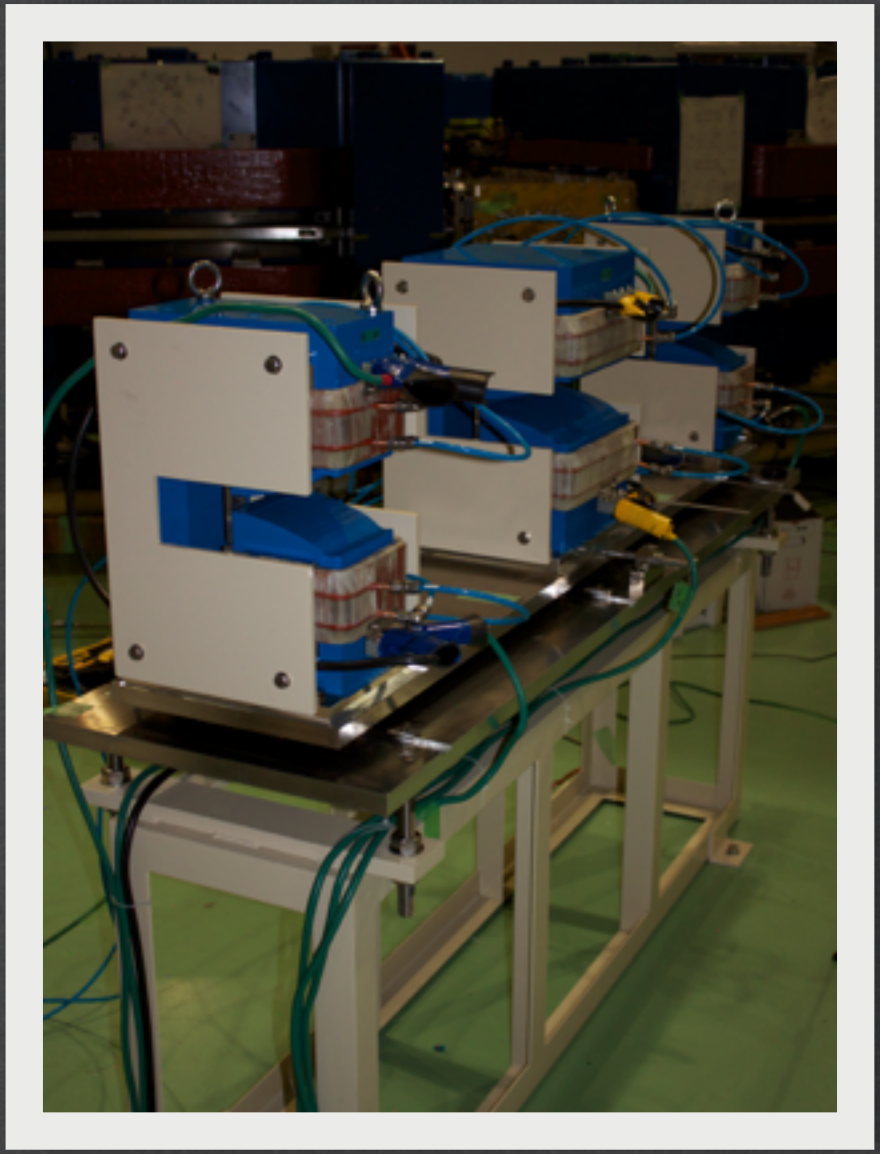


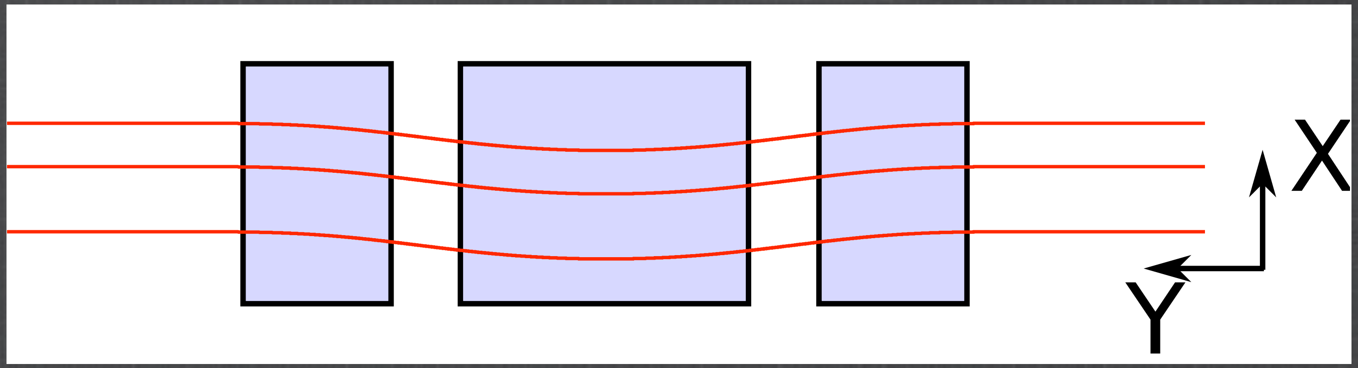
Radial sector: $\zeta = 0$

Straight scaling

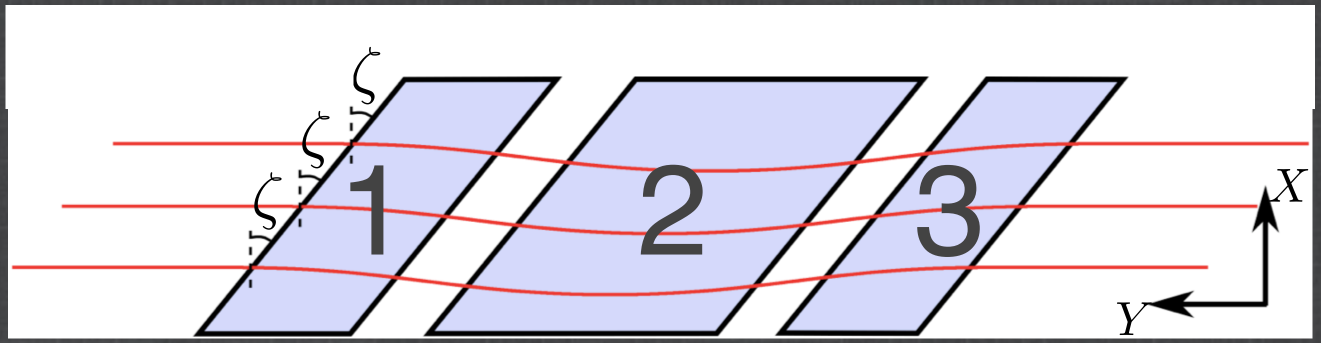
Constant normalised field gradient: $m = \frac{1}{\bar{B}}\frac{d\bar{B}}{X}$

$$\boxed{B(X,Y) = B_0 e^{m(X-X_0)} \mathcal{F}\left(Y - (X - X_0)\tan\zeta\right)}$$





Rectangular case: $\zeta = 0$

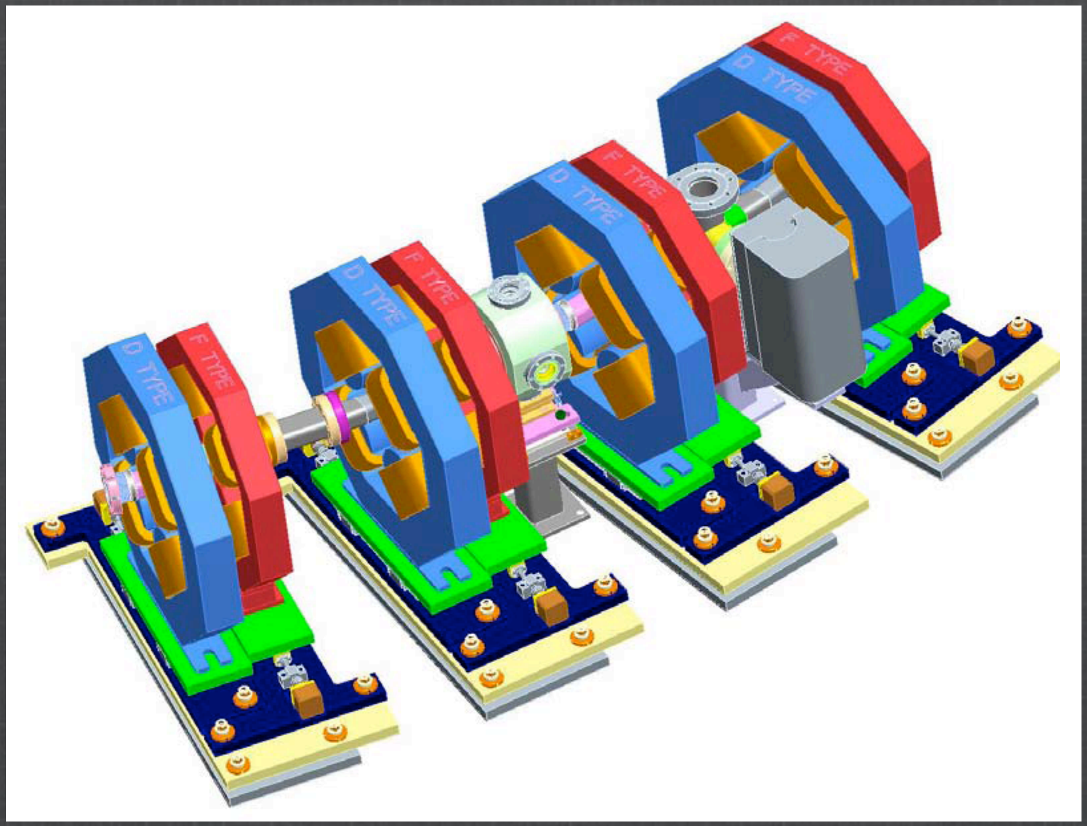


Tilted straight case: $\zeta = const.$

Linear "non-scaling" FFAG

Offset quadrupoles

- very strong focusing (small magnets)
- chromaticity



→ Cyclotron with synchrotron-size magnets

Outline

- Linear NS FFAG: eRHIC
- PRISM
- racetrack FFAG: nuSTORM
- “FFAG beam line”: nuPIL

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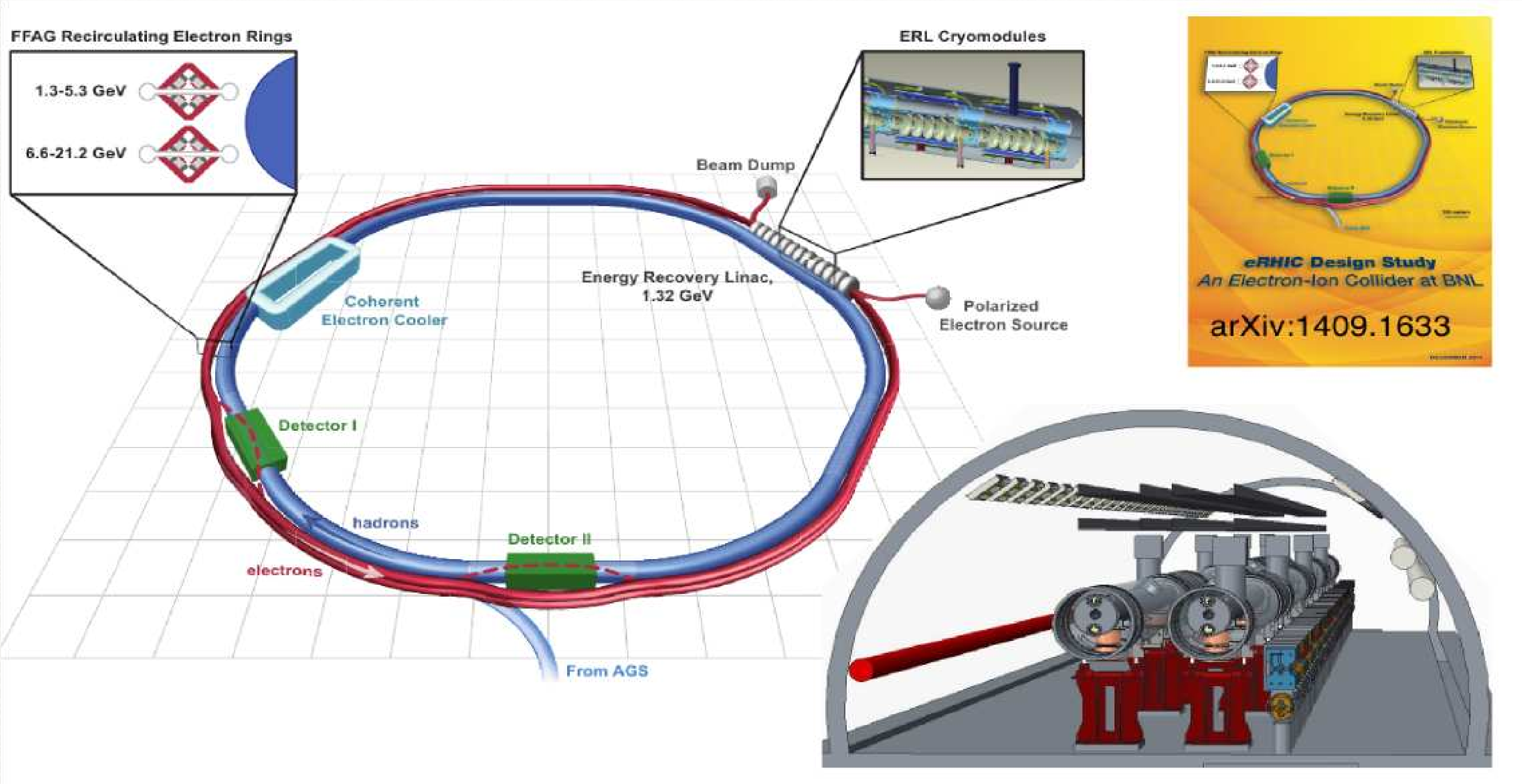
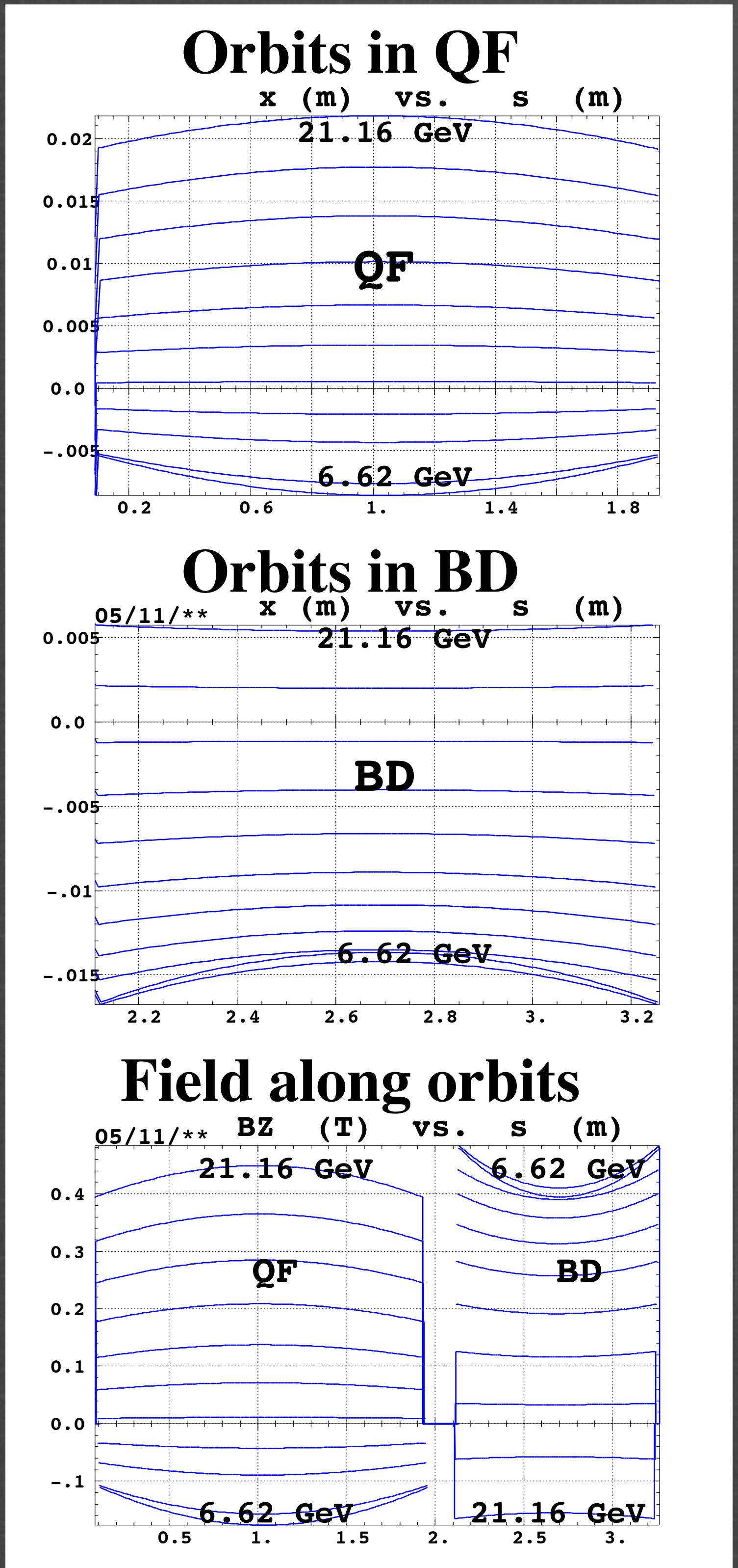
eRHIC



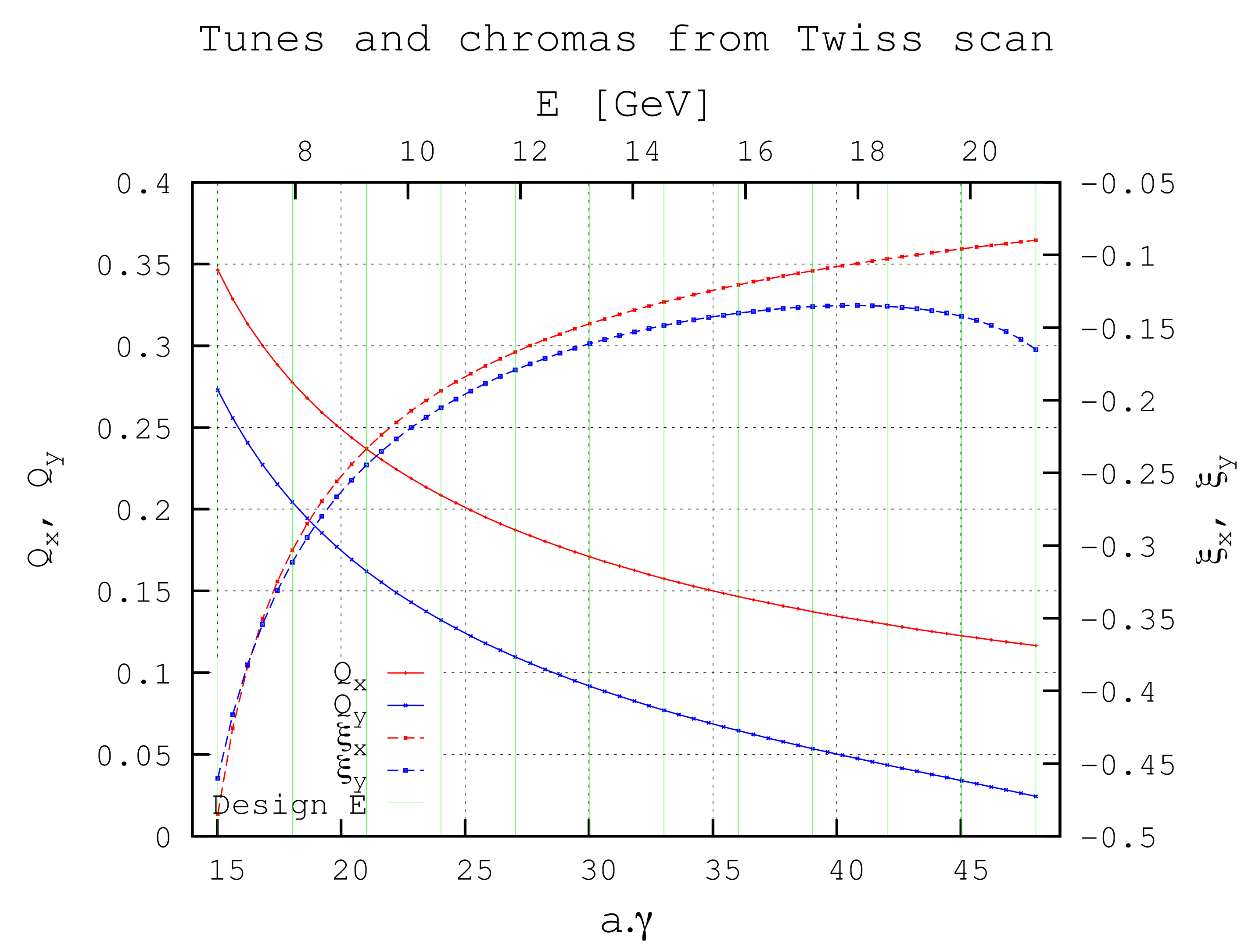
Alongside the existing RHIC, an ERL as polarised electron bunch with linear NS FFAG arcs (permanent magnets).
5 paths in FFAG1, 12 paths in FFAG2

(F. Méot’s courtesy)

eRHIC FFAG2



Arcs optimized to minimize synchrotron radiation



(F. Méot's courtesy)

Outline

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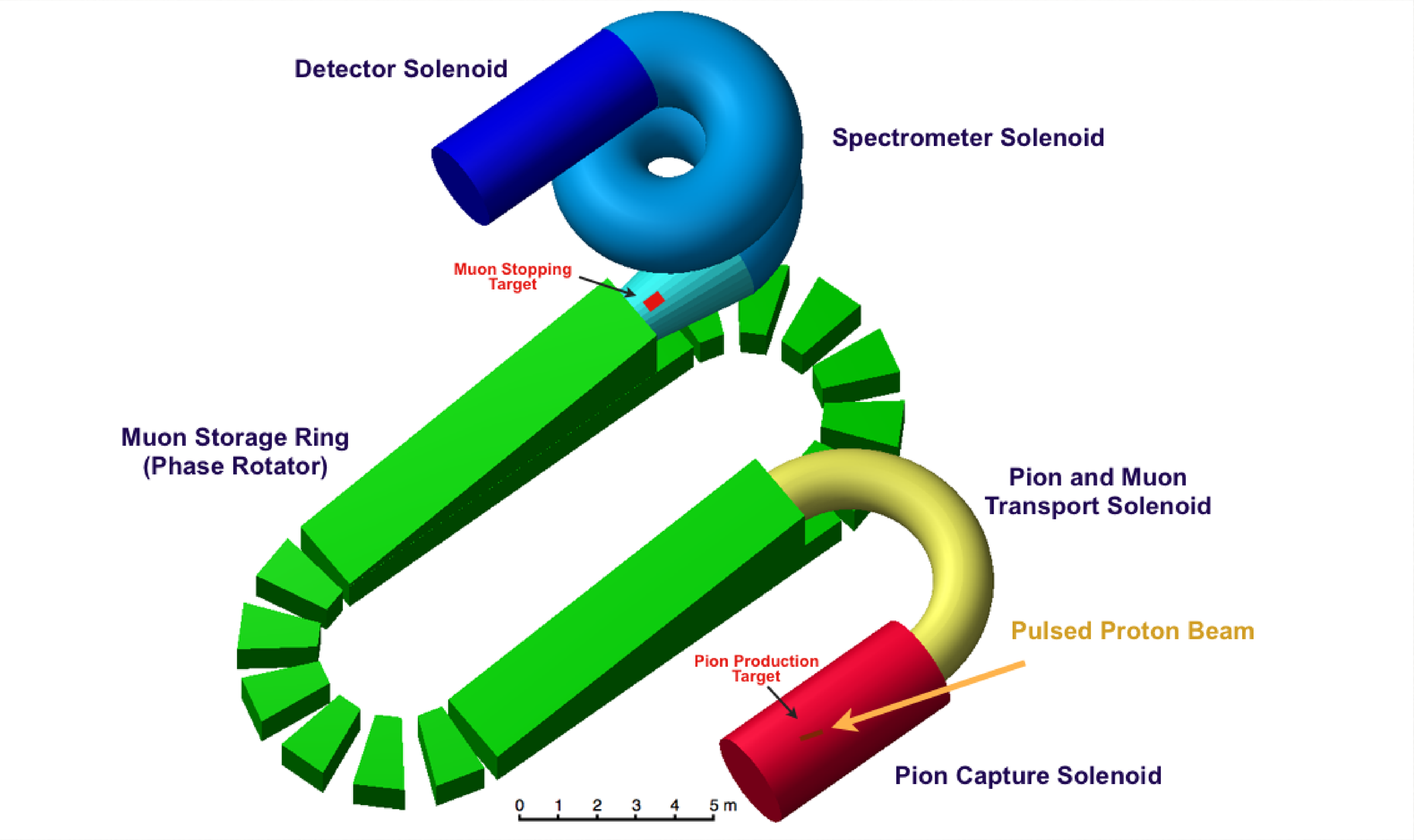
PRISM

Phase Rotated Intense Slow Muon Beam

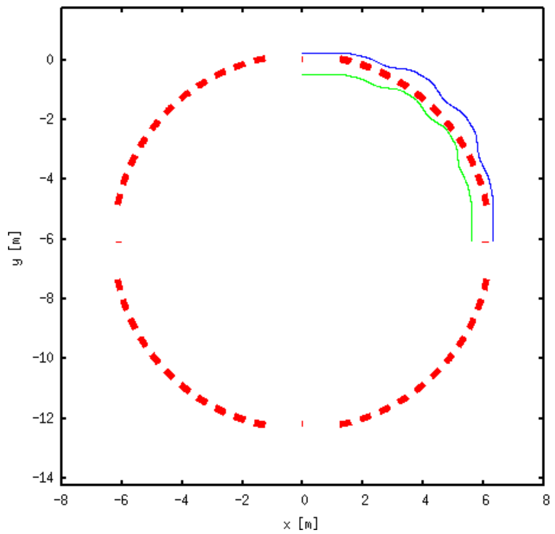


Reduce the muon energy spread by phase rotation and purify the muon beam in the ring.

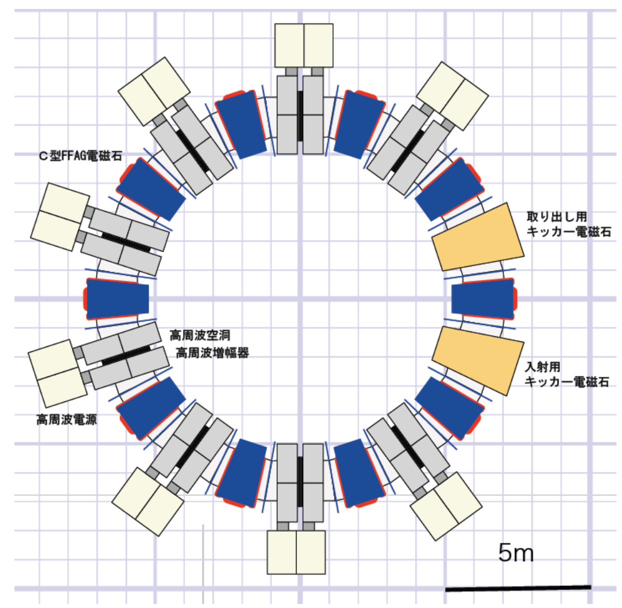
PRISM ring requirements

- Compact ring (circumference ~ 40 m).
- Long drift spaces required for injection/extraction.
- Very large transverse acceptance (30 000 mm.mrad in horizontal, 3000 mm.mrad in vertical)
- Large momentum acceptance (68 MeV/c ±20%)

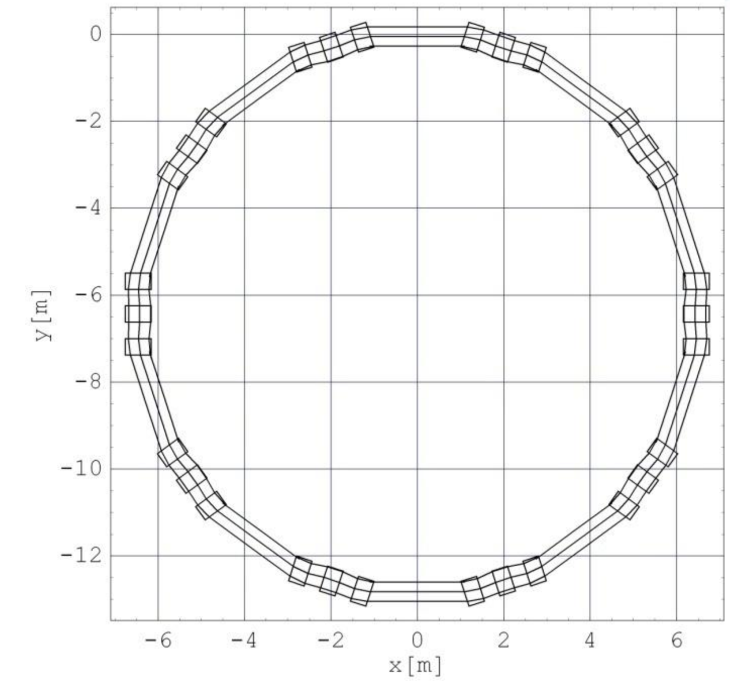
PRISM FFAG ring designs



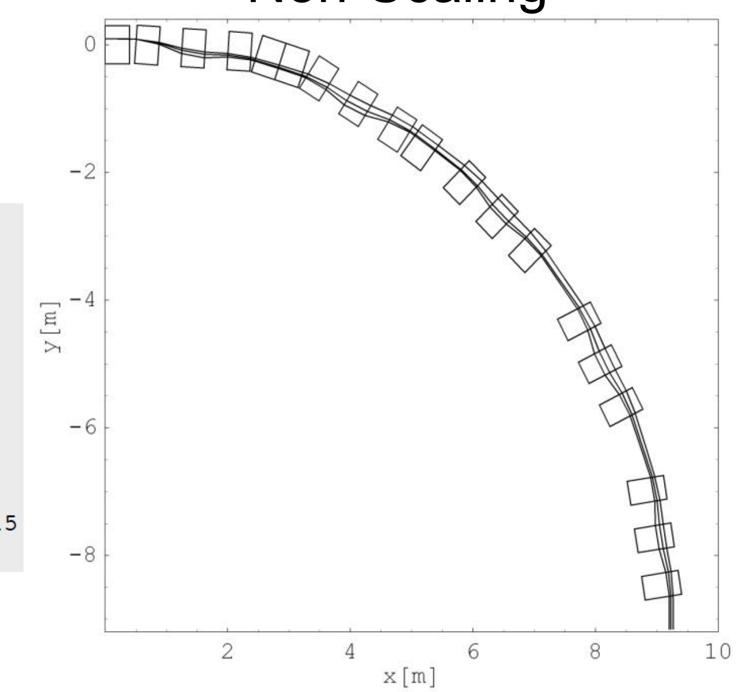
Scaling Superperiodic



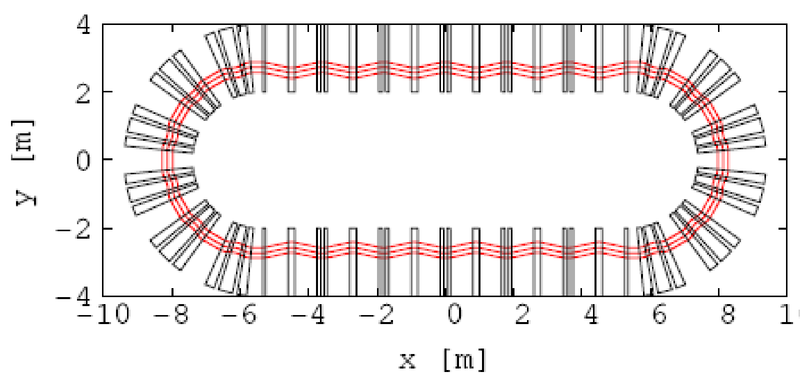
Reference design



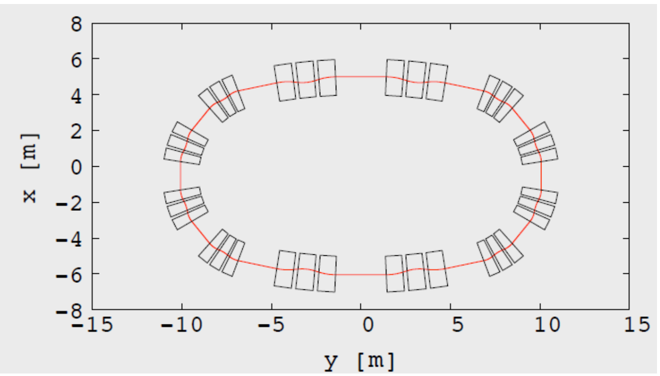
Non-Scaling



Advanced NS-FFAG



Advanced scaling FFAG

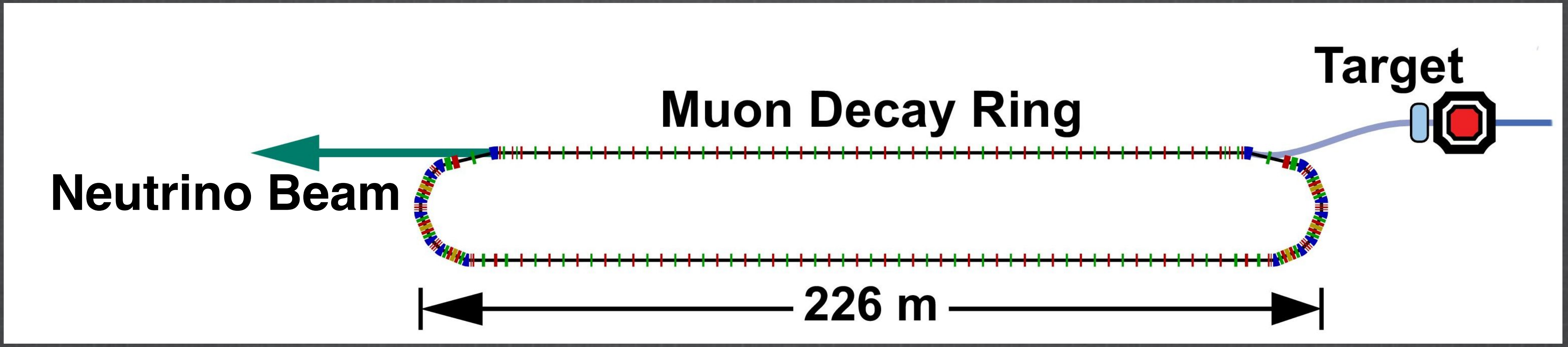


“Egg-shaped”

Outline

- Linear NS FFAG: eRHIC
- PRISM
- racetrack FFAG: nuSTORM
- "FFAG beam line": nuPIL

nuSTORM



1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
3. Accelerator & Detector technology test bed

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

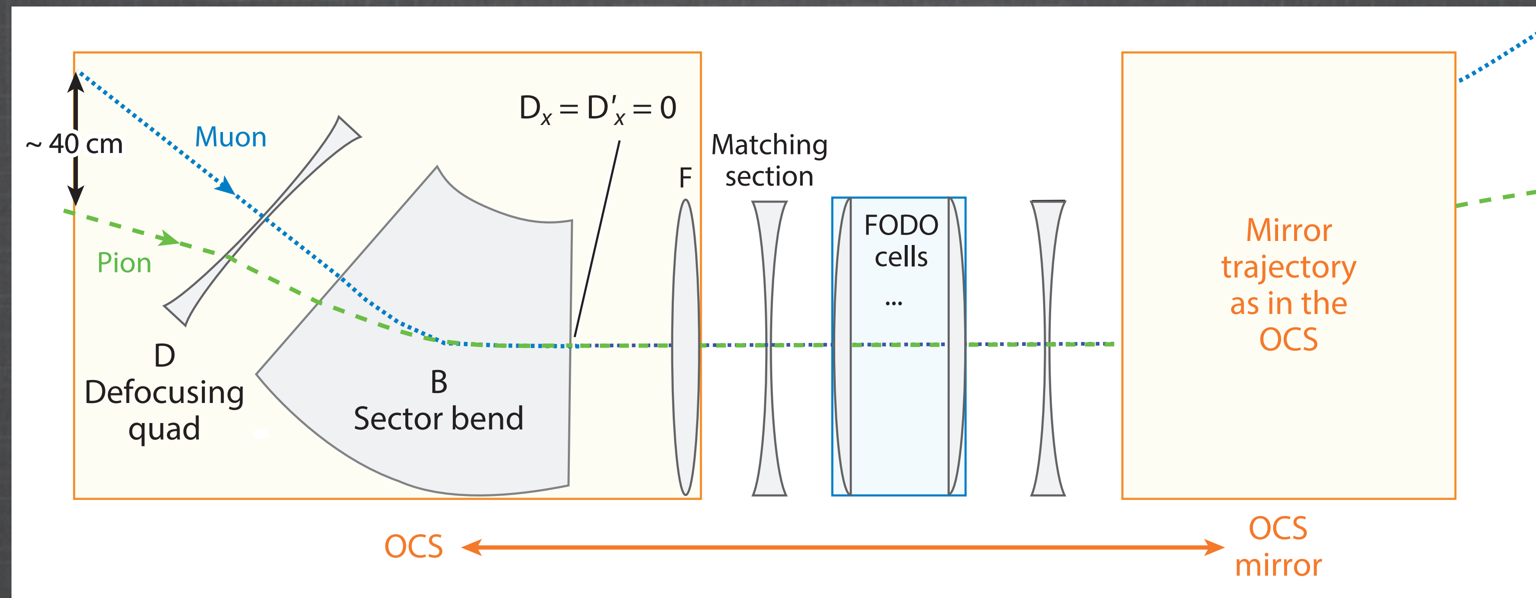
- Potential for intense low energy muon beam
- Enables μ decay ring R&D (instrumentation) & technology demonstration platform
- Provides a neutrino Detector Test Facility
- Test bed for a new type of conventional neutrino beam

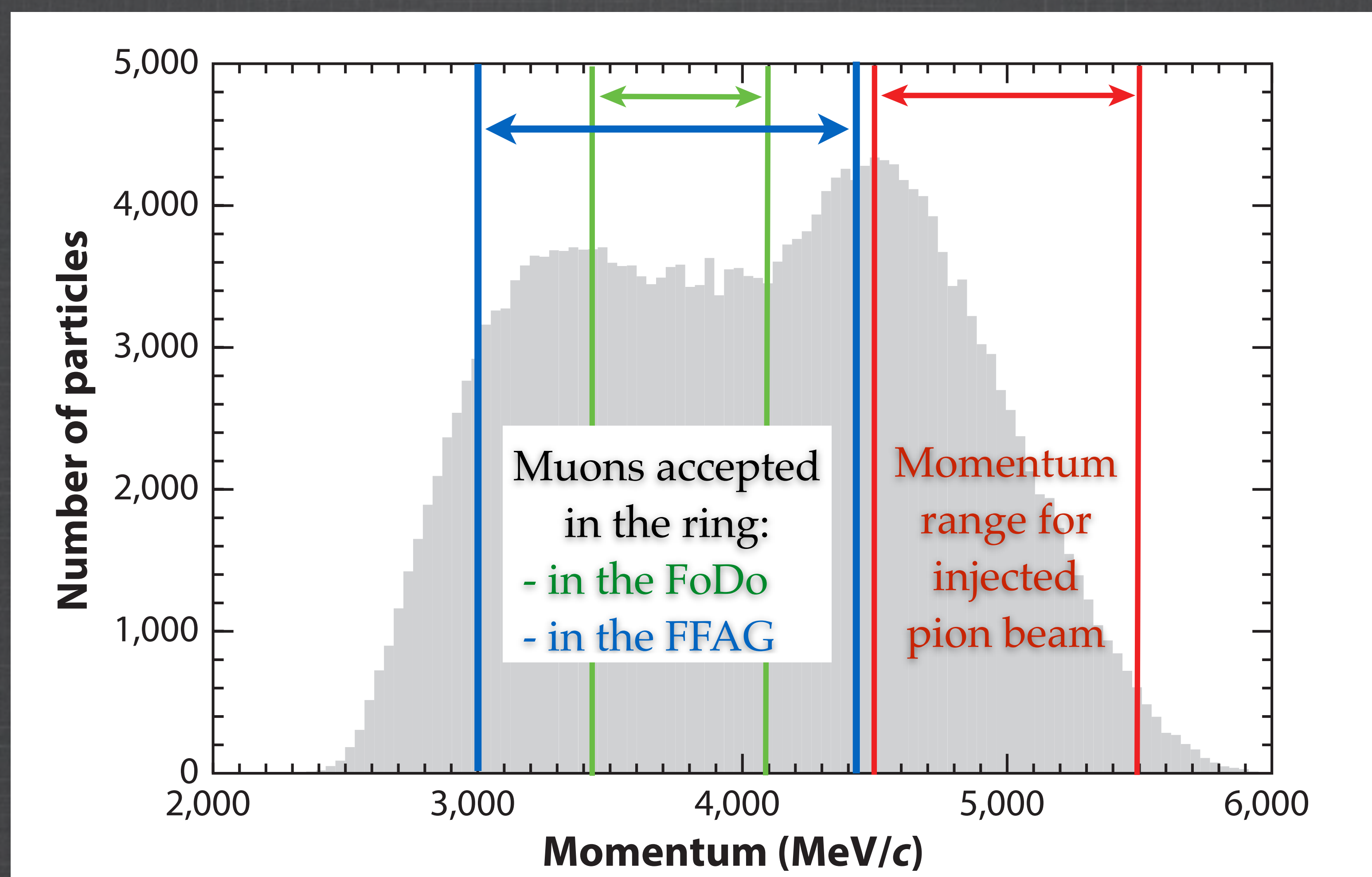
νSTORM

Facility

- 100 kW target station (designed for 400 kW)
  - 120 GeV protons from MI (FNAL), or 100 GeV protons from SPS (CERN)
  - Horn to collect pions (π^+ or π^-)
  - Target material: Inconel
  - 10^{21} protons on target over 4-5 years (3×10^{18} useful muon decays)
- Collection and transport
  - Chicane to select charge of pions
  - Stochastic injection
- Racetrack decay ring
  - large aperture FODO or FFAG.

Stochastic injection



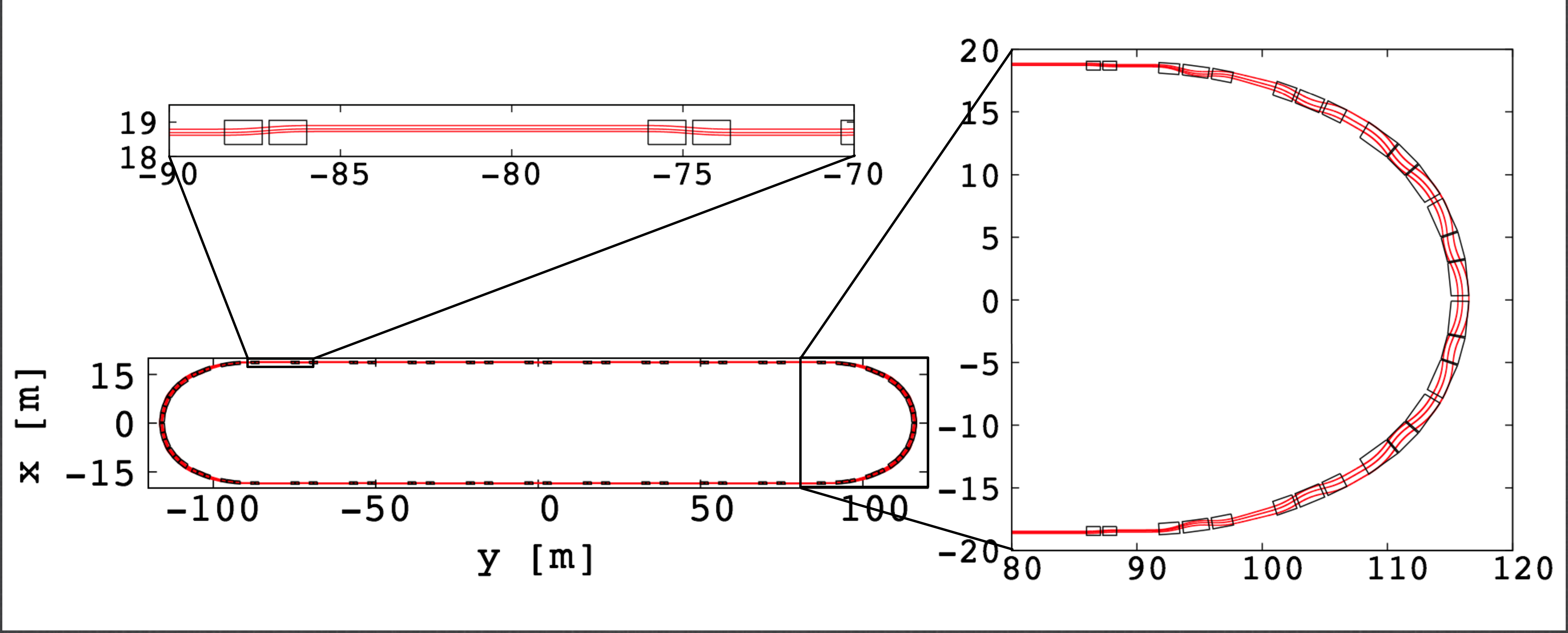


νSTORM Racetrack FFAG

Constraints:

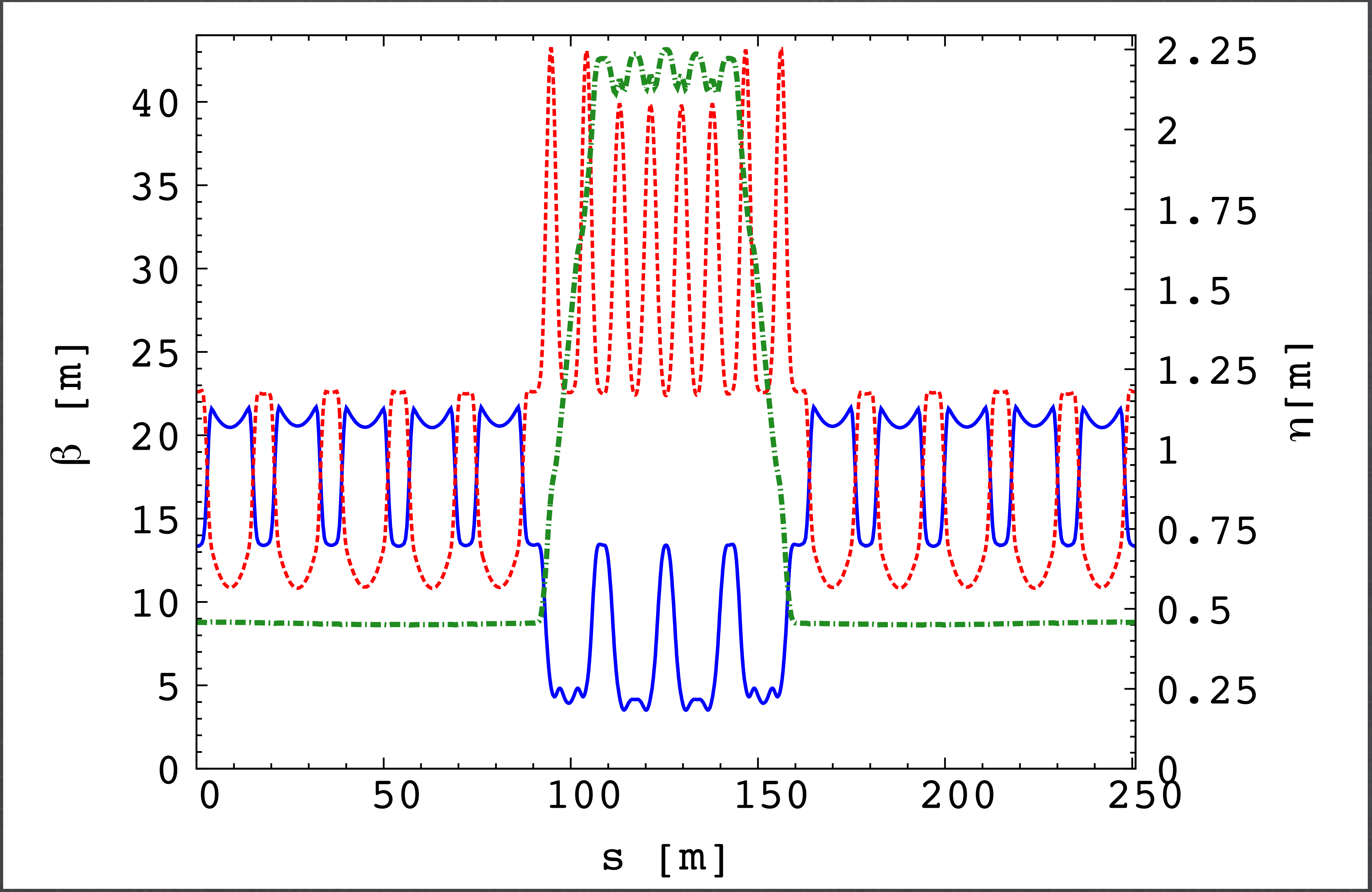
- in the straight part, the **scallop effect** must be as small as possible to collect the maximum number of neutrinos at the far detector.
- **Stochastic injection**: in the dispersion matching section, a drift length of 2.6 m is necessary to install a septum.
- to keep the ring as small as possible, **SC magnets in the arcs** are considered. **Normal conducting magnets in the straight part** are used.
- **large transverse acceptance** is needed in both planes: 1 (2) π mm.rad.

Quadruplet lattice



Quadruplet lattice

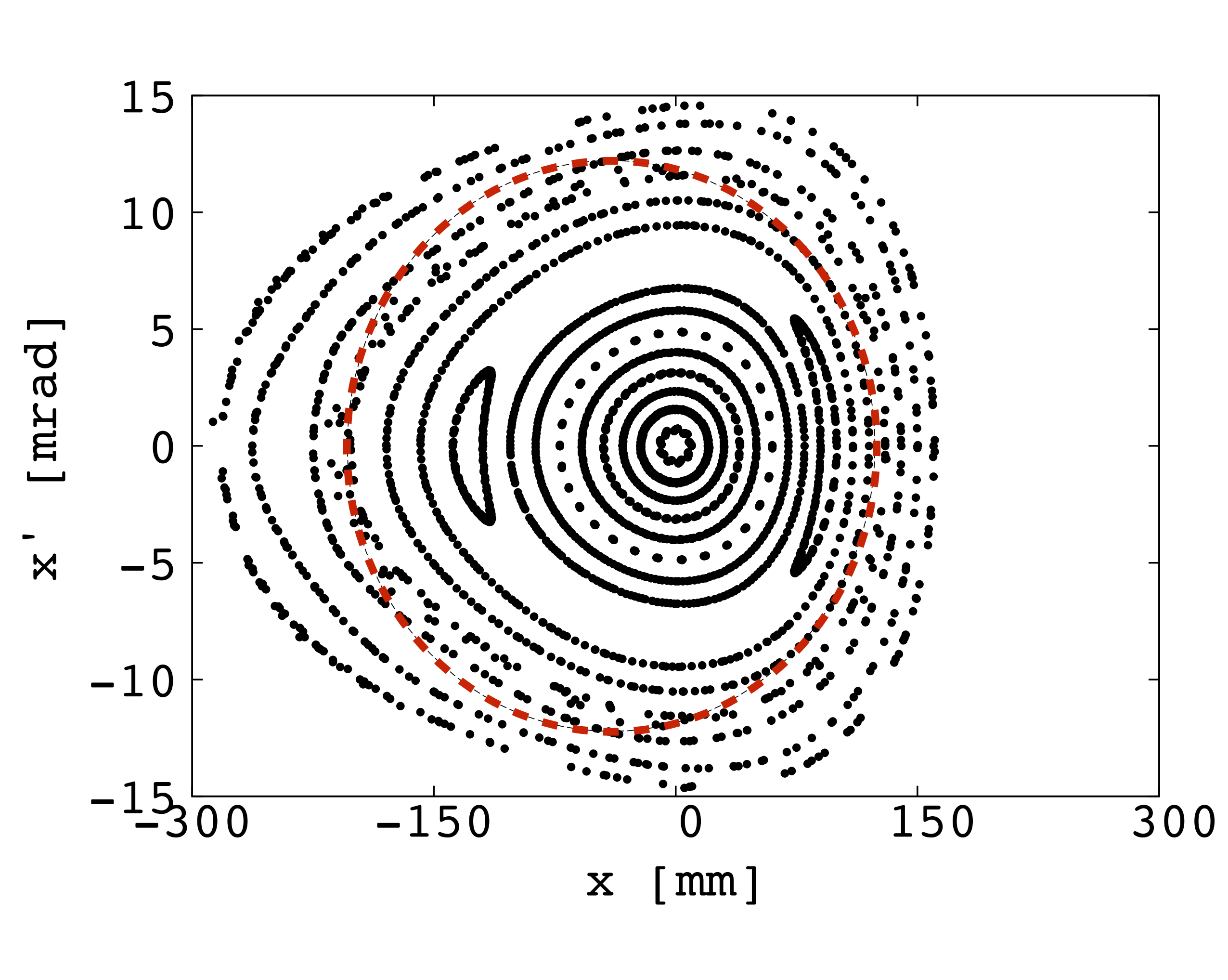
Beta-functions and dispersion at matching momentum



Horizontal (plain blue), vertical (dotted red) beta-functions and dispersion (mixed green) for half of the ring.

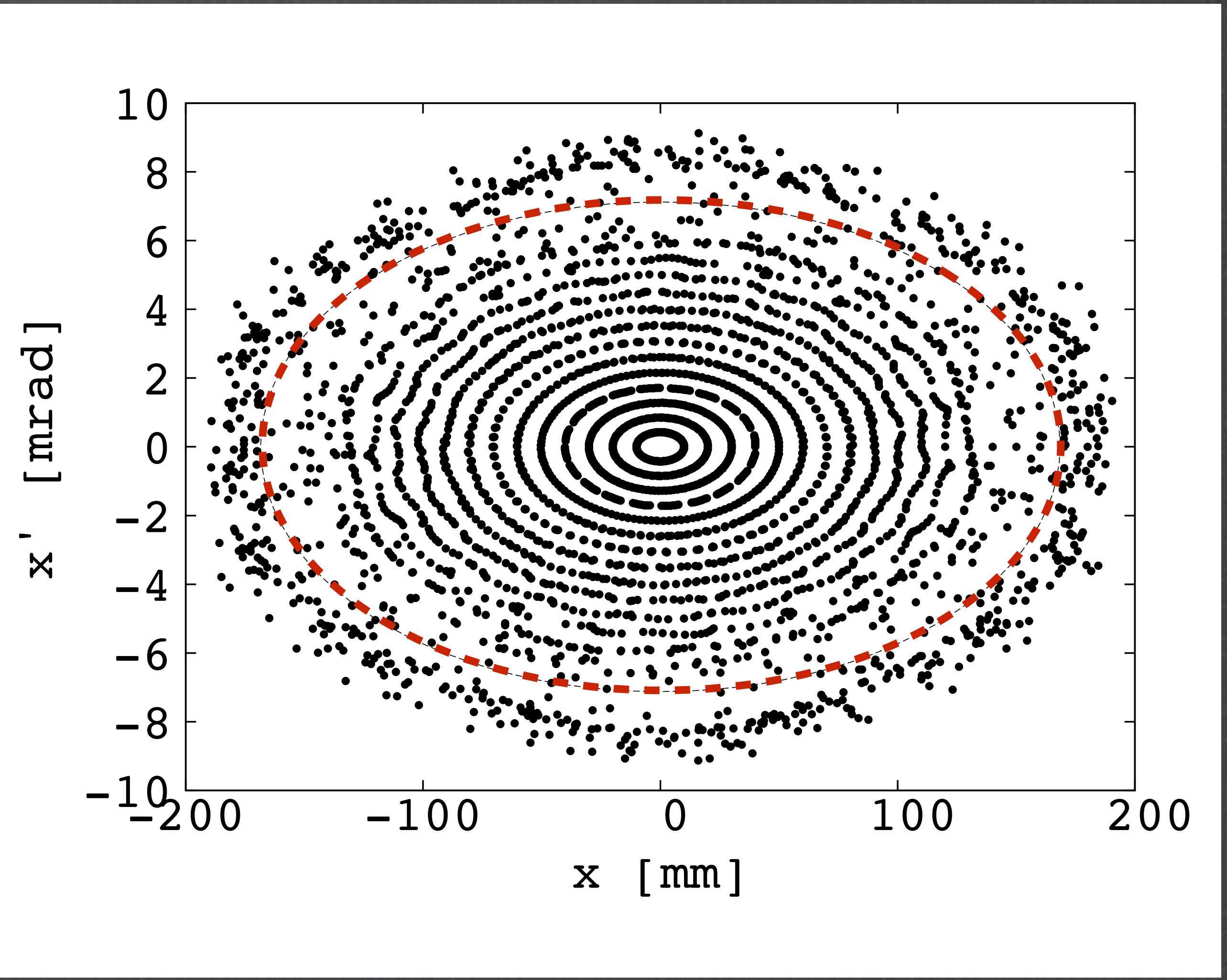
Quadruplet lattice

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns

(Dotted ellipse represents 2 π.mm.rad)

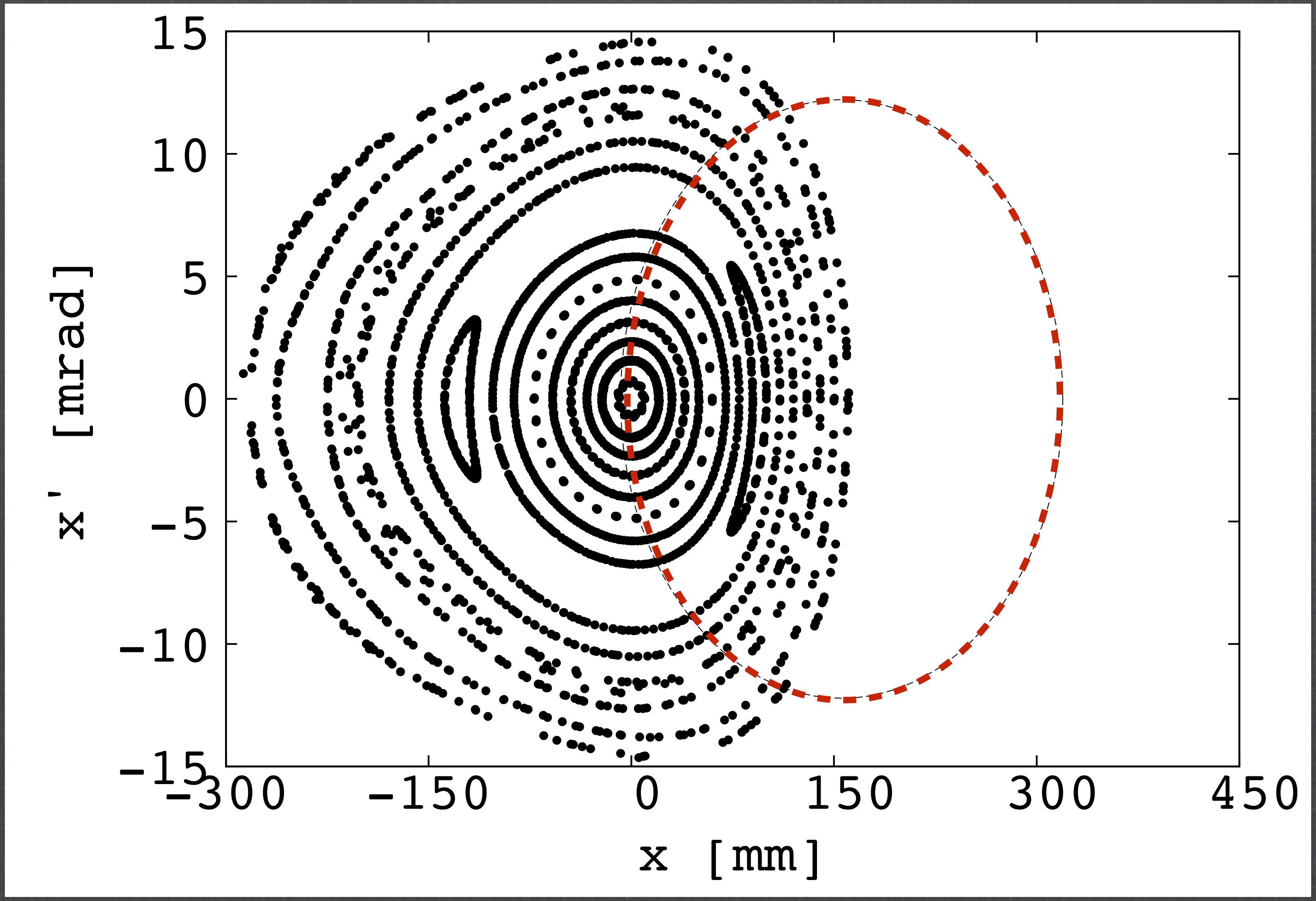


Maximum vertical stable amplitude over 100 turns

(Dotted ellipse represents 1.2 π.mm.rad)

Quadruplet lattice

Muon capture efficiency



Maximum horizontal stable amplitude over 100 turns

(Dotted ellipse represents 2 π.mm.rad 5 GeV/c pion beam position)

Hybrid lattice

zero-dispersion (chromatic!) straight capture section with FFAG arcs and straight zero-chromatic FFAG:

- increase muon capture efficiency of full FFAG lattice
- reduce chromaticity of FoDo lattice.

To be implemented

Outline

- Linear NS FFAG: eRHIC
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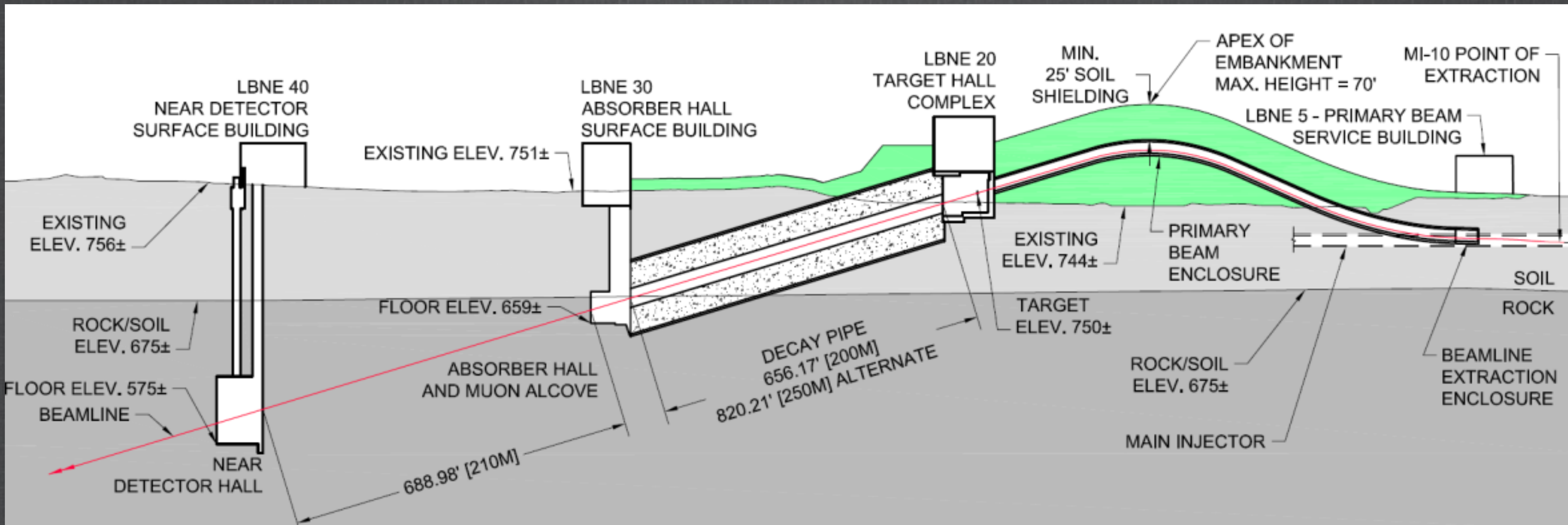
- “FFAG beam line”: nuPIL

LBNF baseline



(LBNF Letter of Intent, Jan 2015)

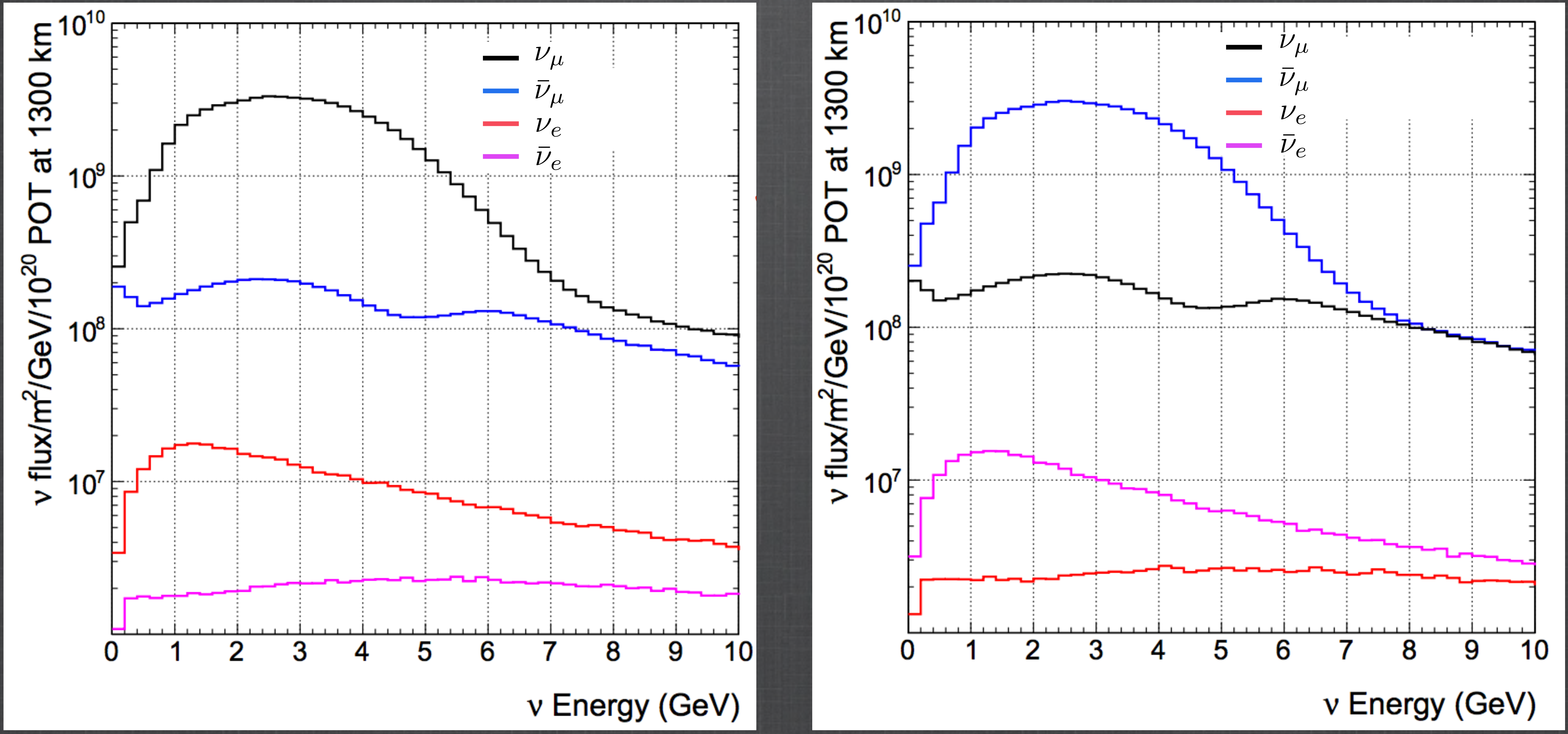
Decay pipe:

- 6 (4?) m diameter,
- filled with Helium,
- 7 m of concrete around the pipe to shield it.

➡ 20 m diameter tunnel!

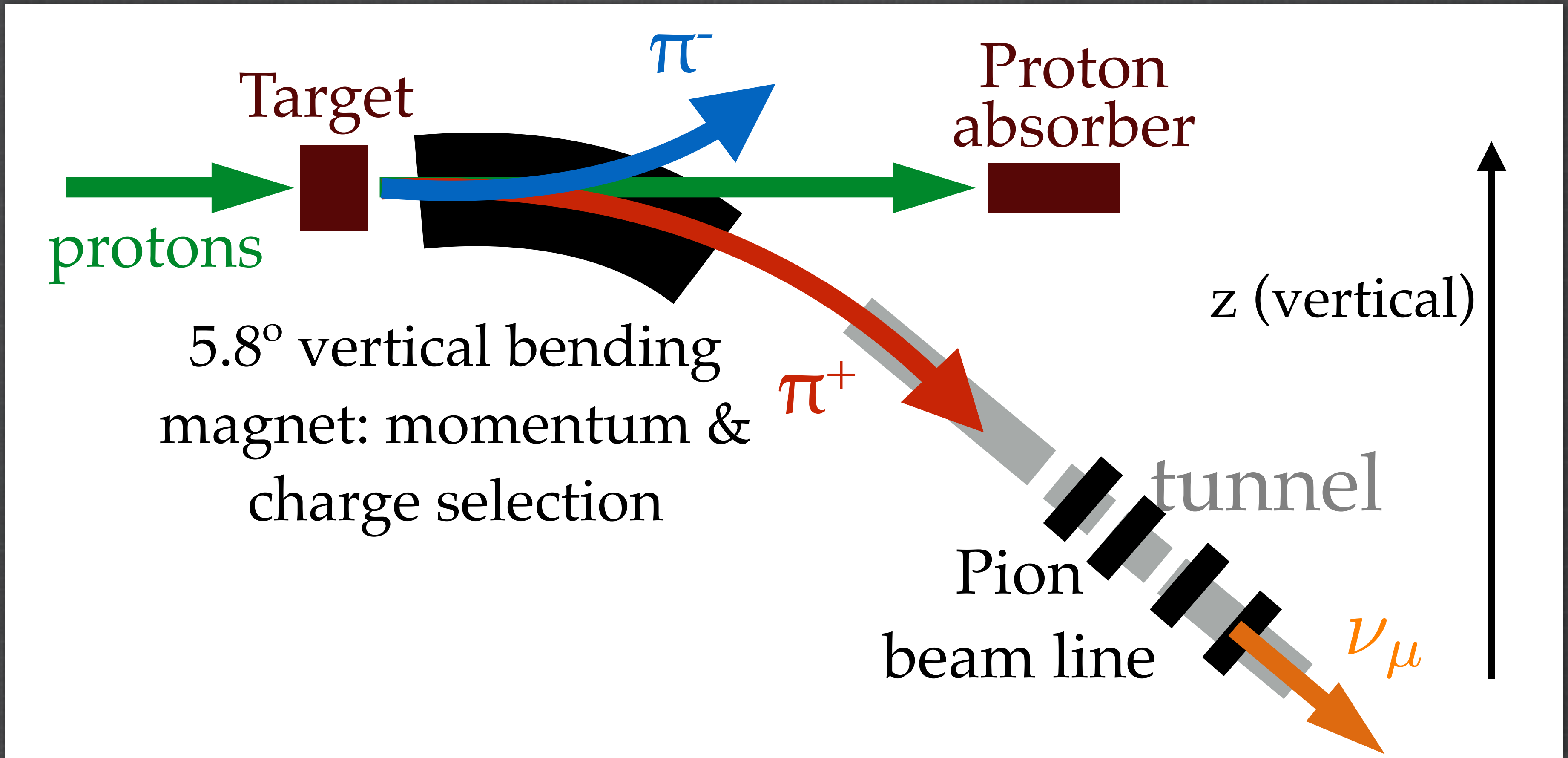
Neutrino Flux at DUNE

(CDR-Physics Volume)



Inevitable background from wrong-sign particles decay (DUNE detector not magnetized: rely on high-resolution imaging to statistically discriminate neutrinos from anti-neutrinos.)

nuPIL



Pion beam line

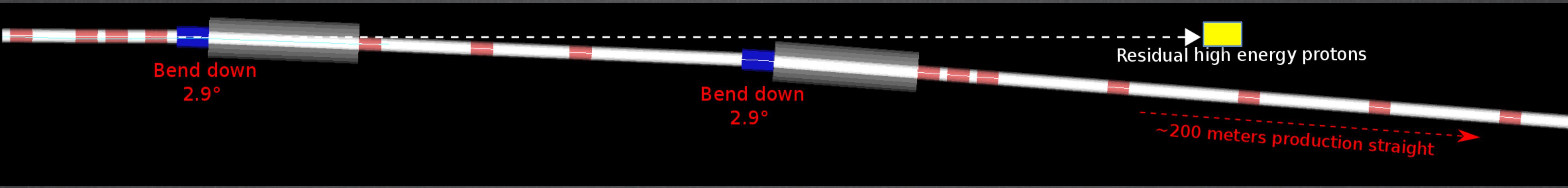
- clean, well known flux
- smaller tunnel (conventional pion beam line)
- Detector does not need to be magnetised

➡ **nuPIL (<u>Neutrinos from Pion Injection Line</u>)**

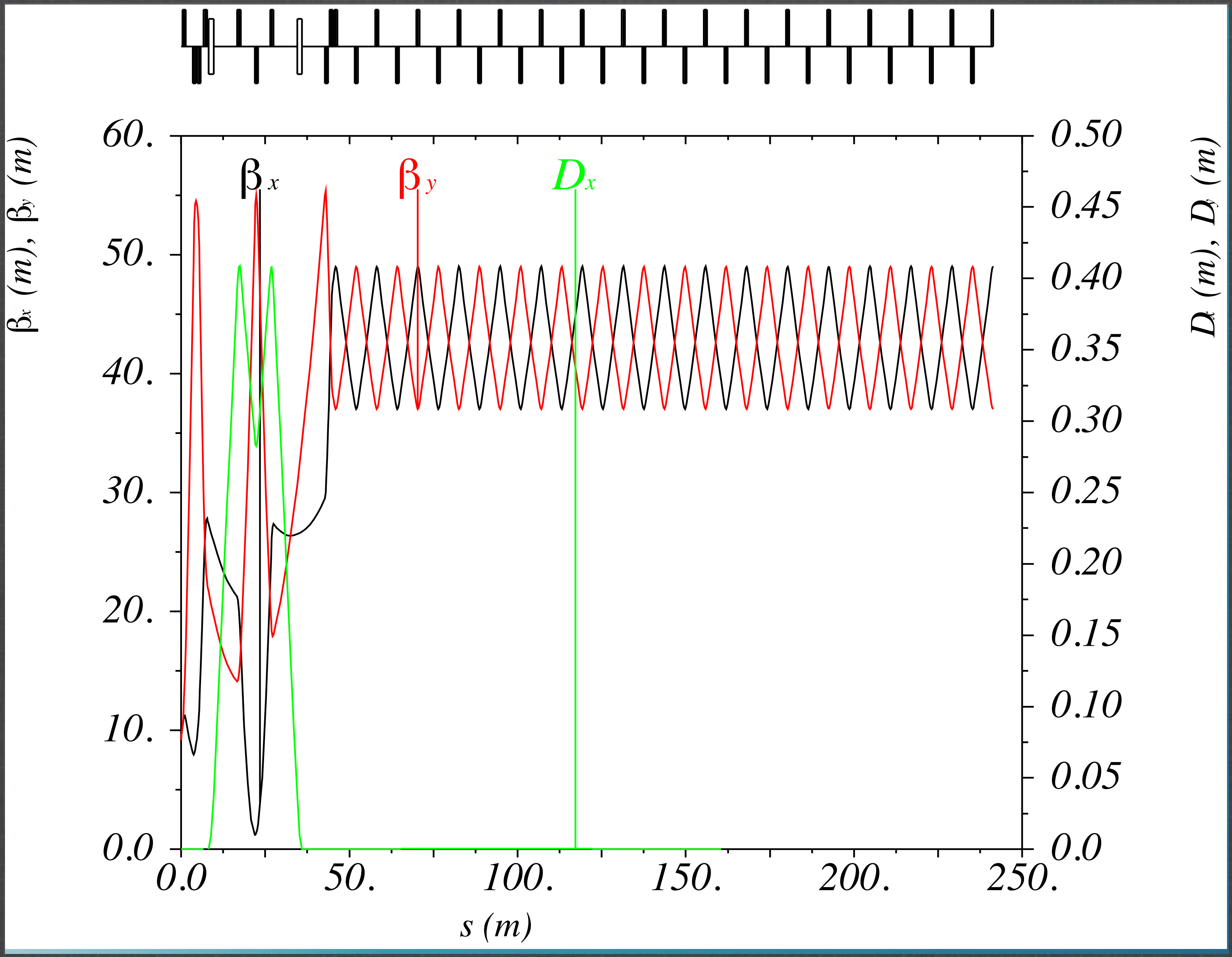
General Parameters

- Very large momentum acceptance (pions 7 GeV/c ± 50%)
- Large transverse acceptance (2000 mm.mrad in both planes)
- Normal conducting range (KEK radiation hard coils)
- C-shape magnet

FODO design

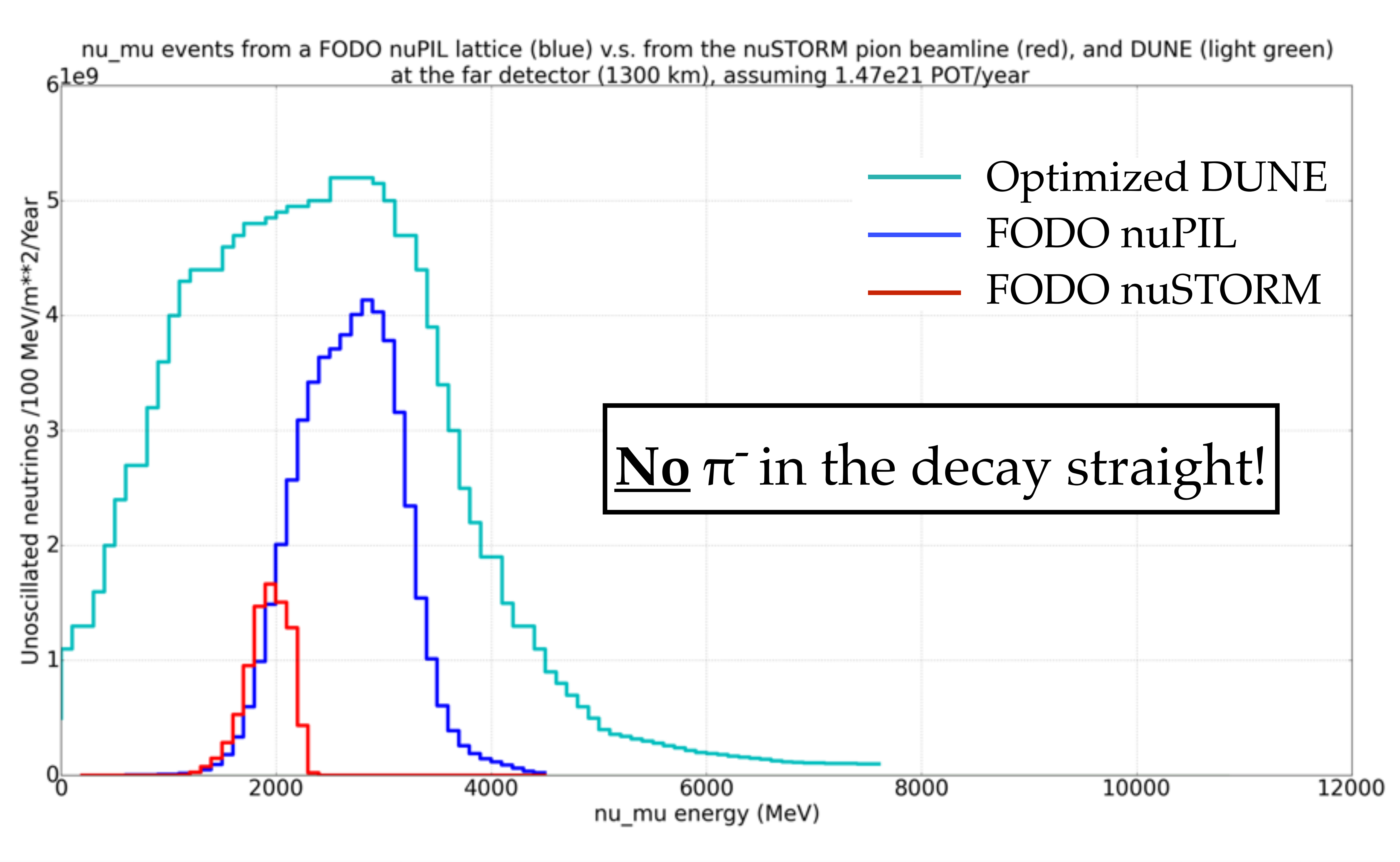


Bend down
2.9°
Bend down
2.9°
Residual high energy protons
~200 meters production straight



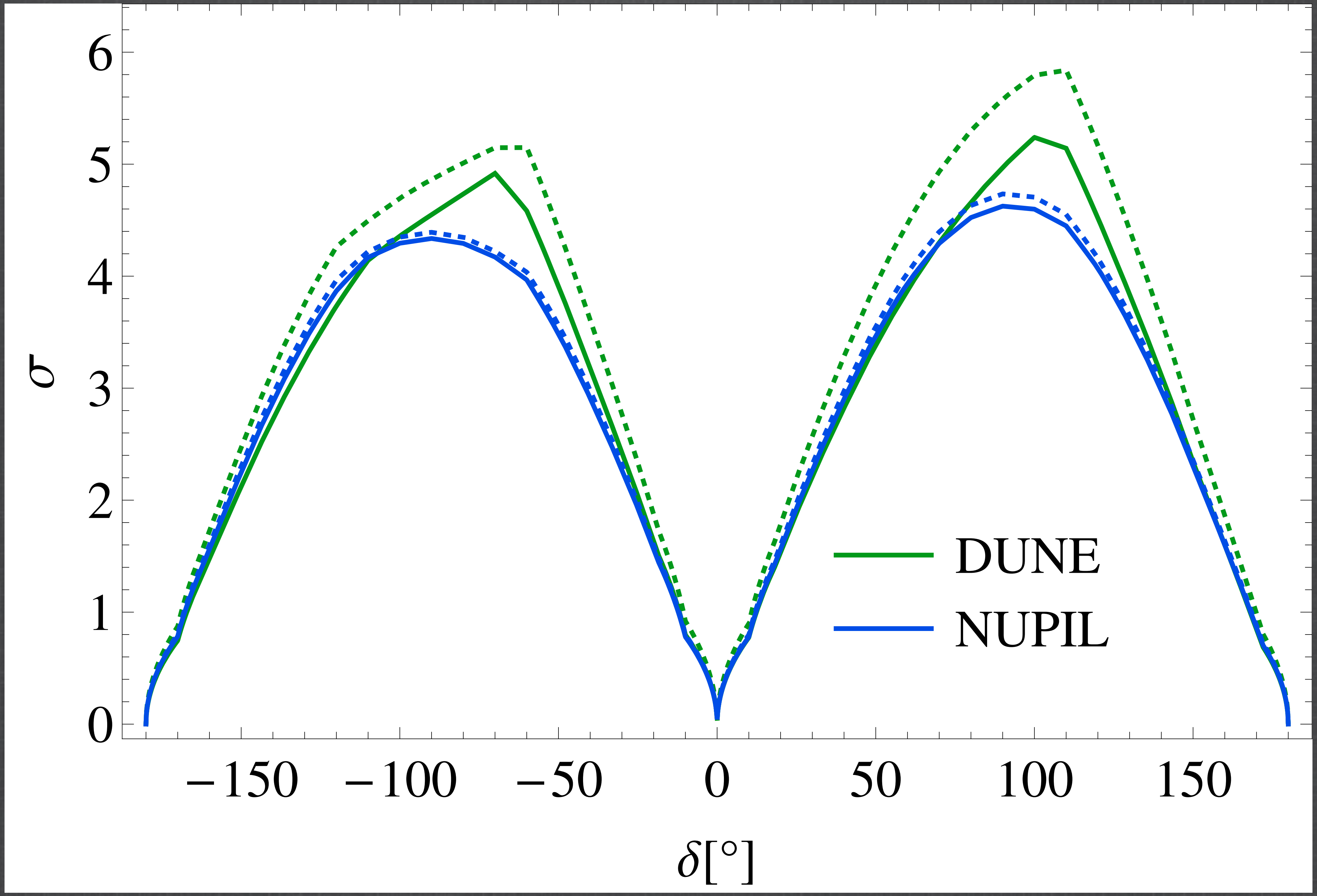
βx
βy
Dx
βx (m), βy (m)
Dx (m), Dy (m)
s (m)
60.
50.
40.
30.
20.
10.
0.0
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0.0
50.
100.
150.
200.
250.

FODO design
Flux

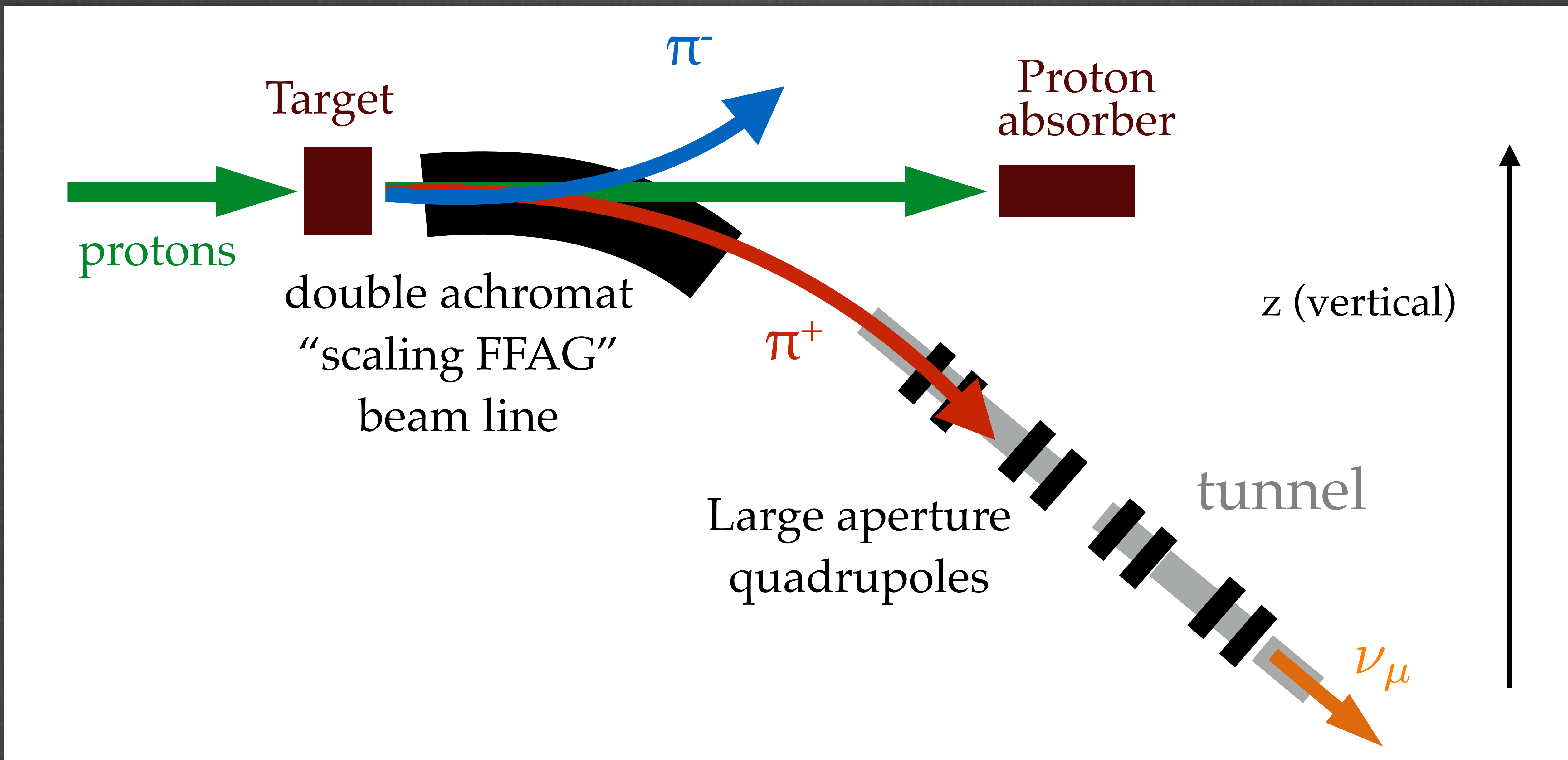


No π^- in the decay straight!

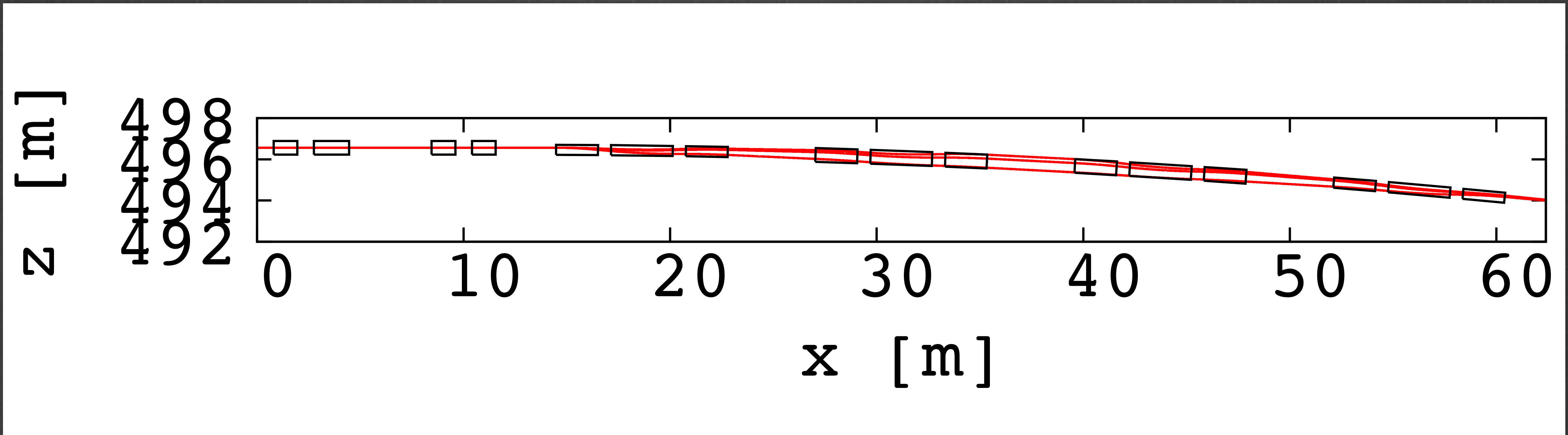
FODO design Sensitivity



Hybrid design concept



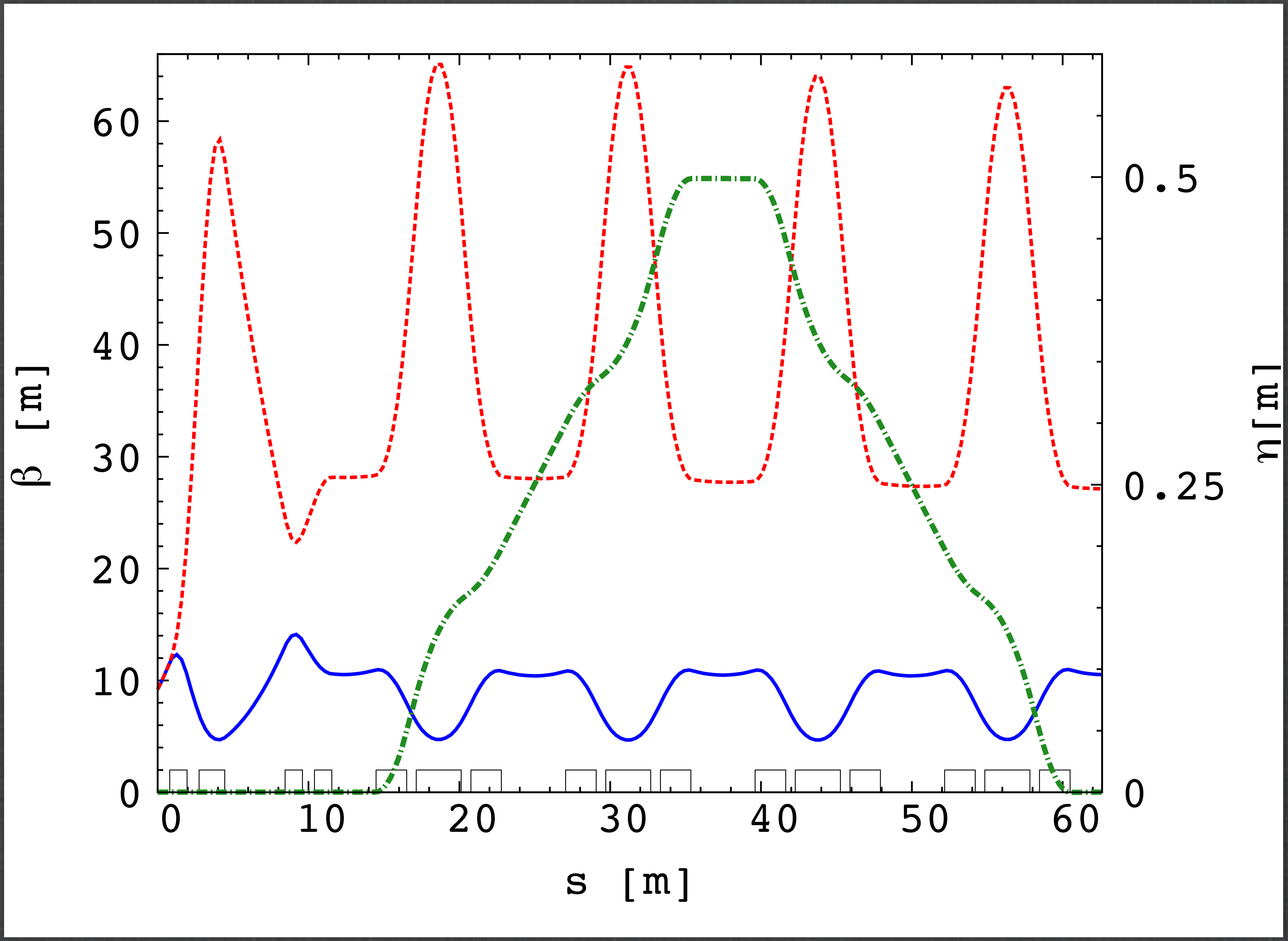
Double achromat FFAG beam line



- Pions trajectories 3.5 GeV/c & 10.5 GeV/c
- Bmax < 1.7 T, excursion < 67 cm.
- k-value = 1988, r_{av} = 496.5 m, $L_{beam\ line}$ = ~60 m.

double achromat FFAG beam line

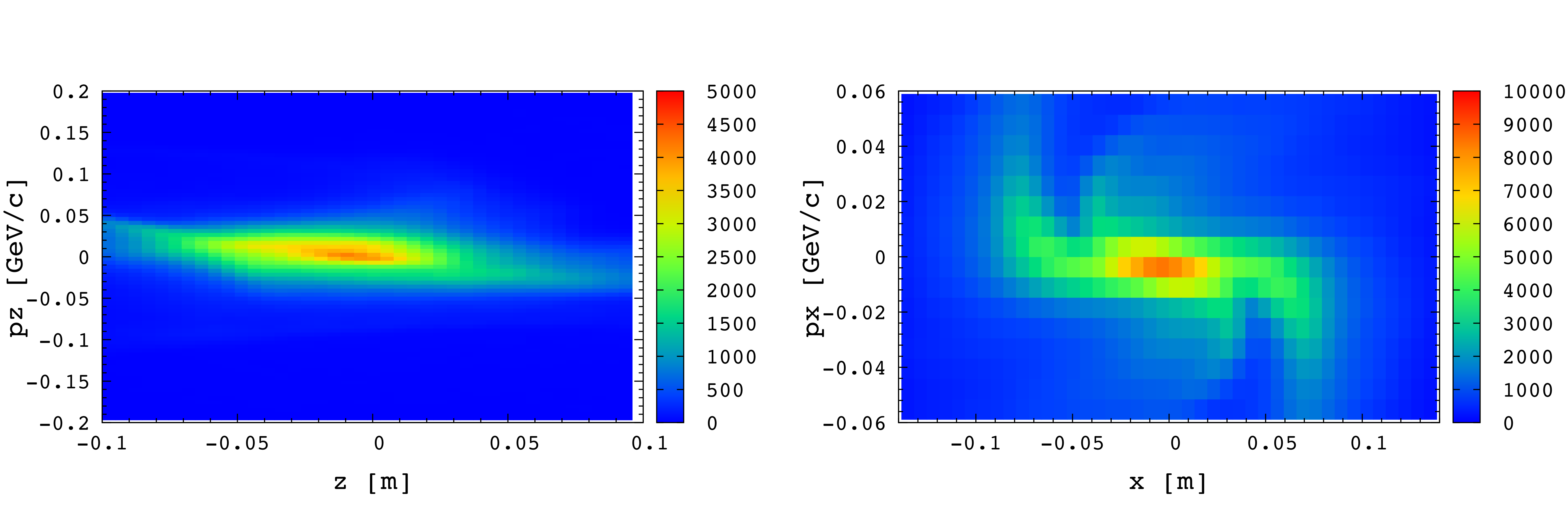
Beta-functions and dispersion at matching momentum



Horizontal (plain blue), vertical (dotted red) beta-functions and dispersion (mixed green).

double achromat FFAG beam line

~2.9 10^6 particles (distribution from the horn) → 42.6% survival



Surviving particles in vertical (left) and horizontal (right) phase spaces

double achromat FFAG beam line

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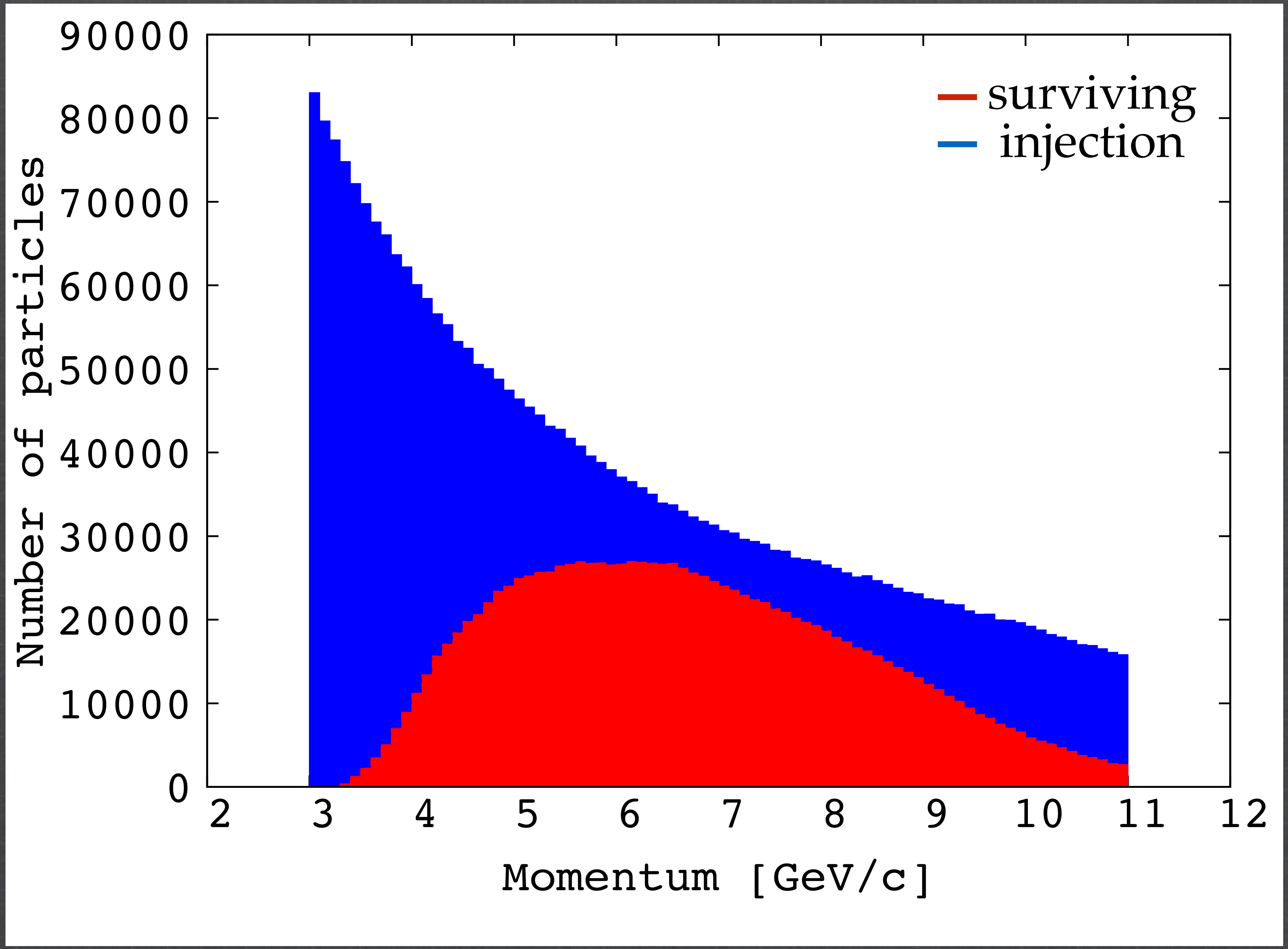
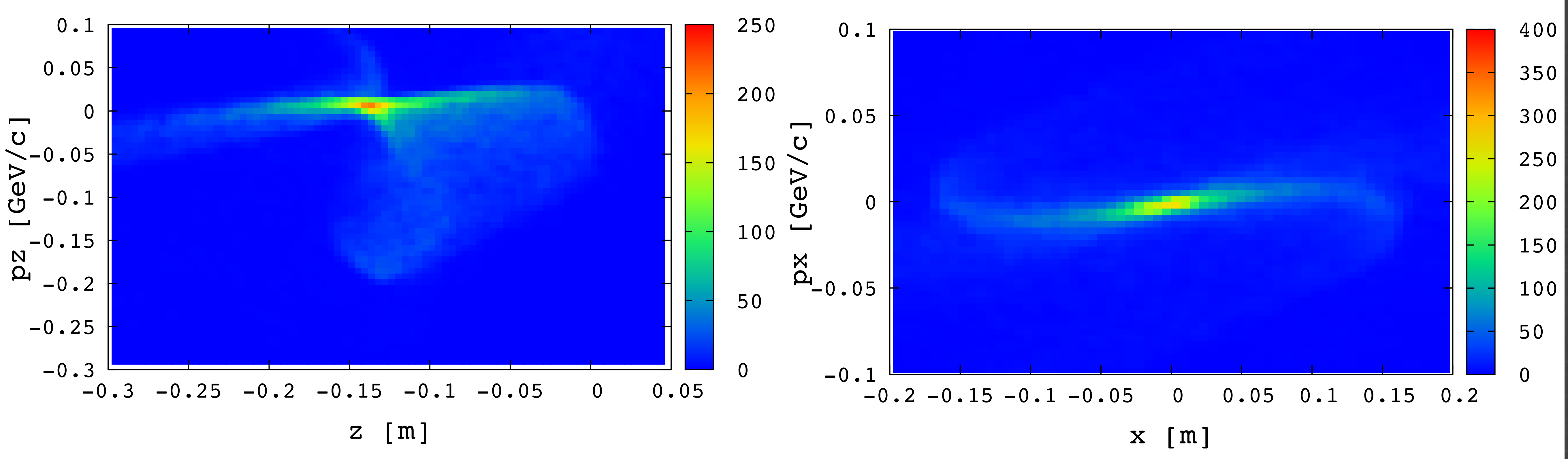


Momentum range at the injection (blue) and for the surviving particles (red) after tracking.

double achromat FFAG beam line

Wrong Sign Survival

~1.1 10^6 particles (distribution from the horn) → 3.2% survival



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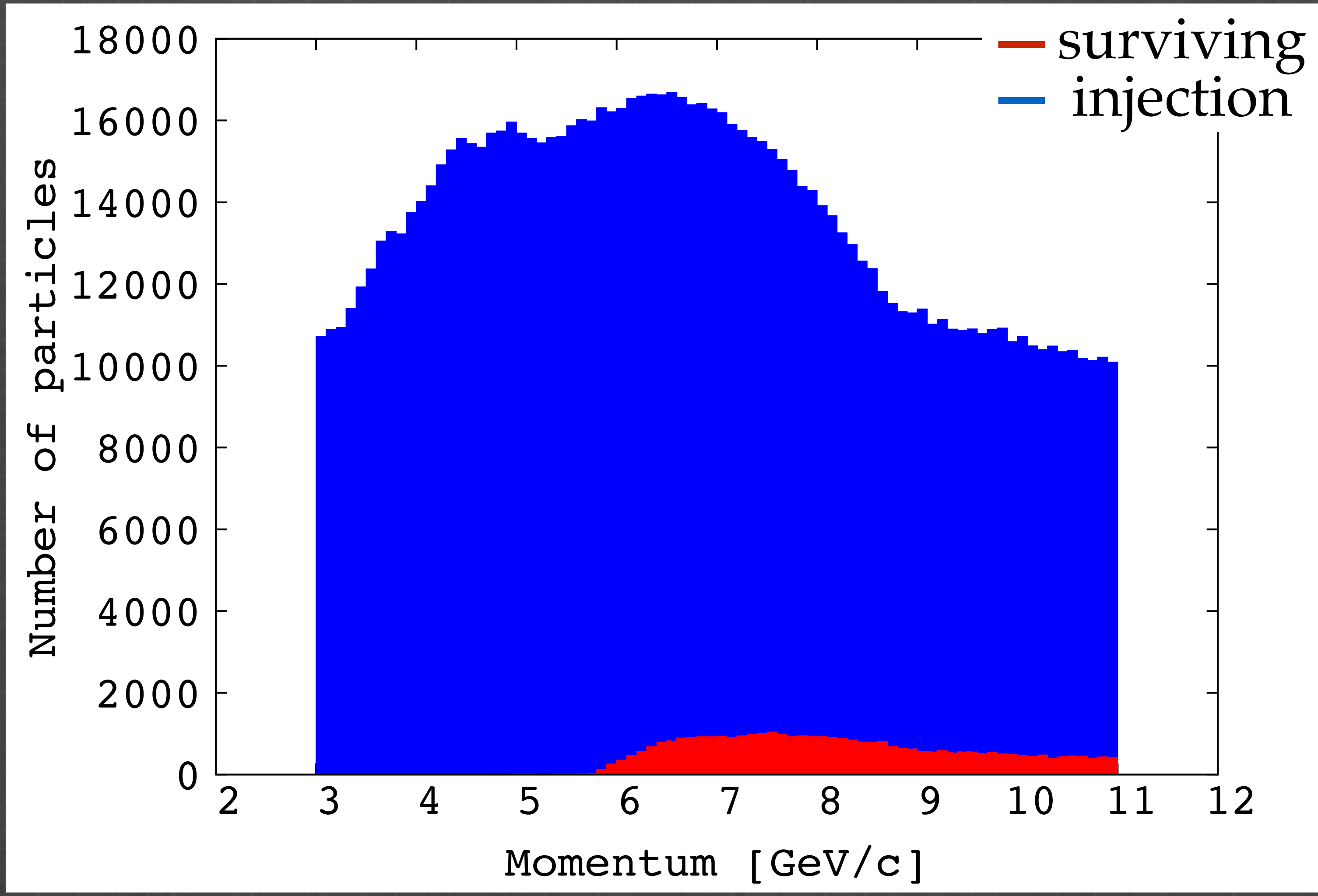

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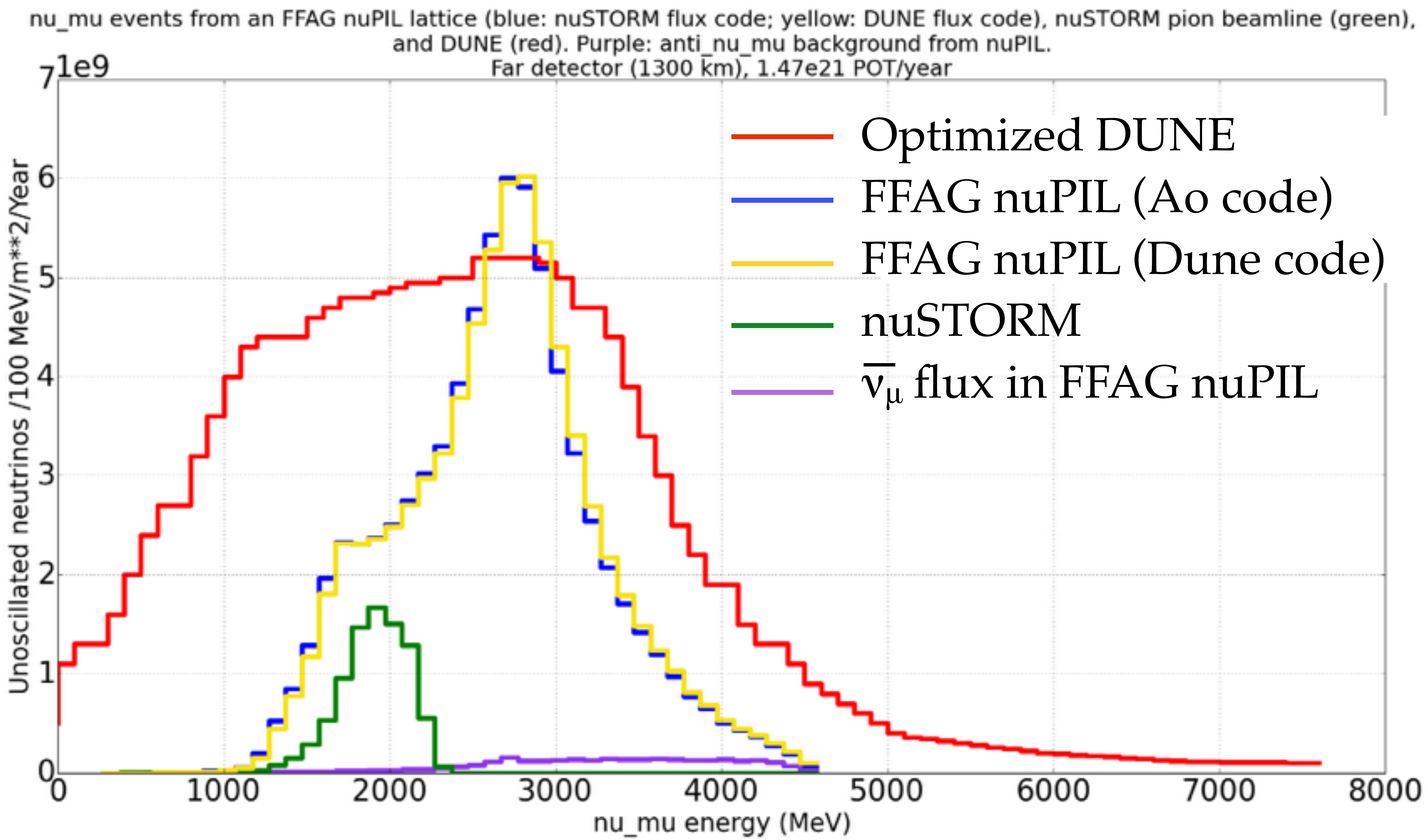
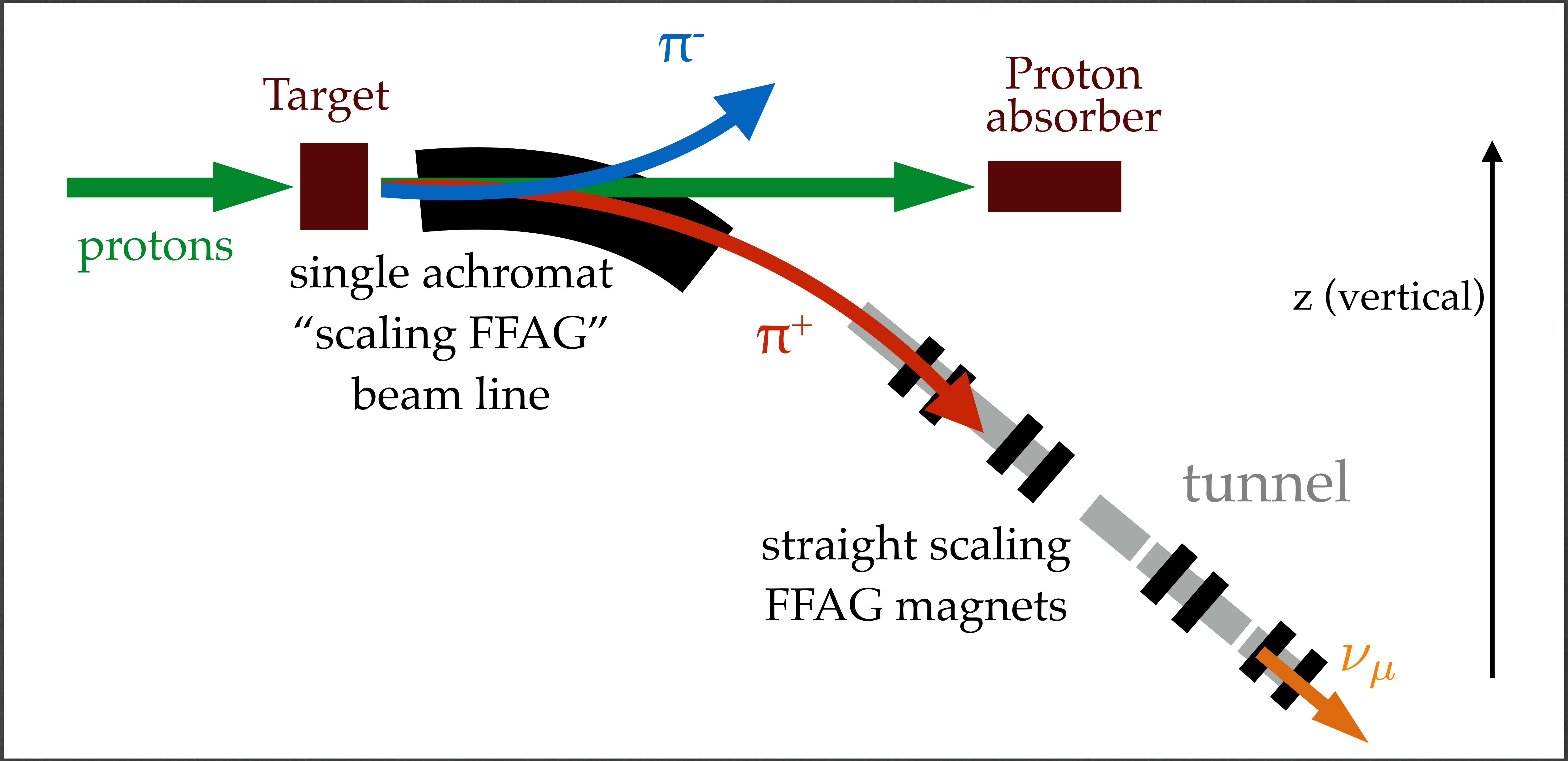
double achromat FFAG beam line

Flux

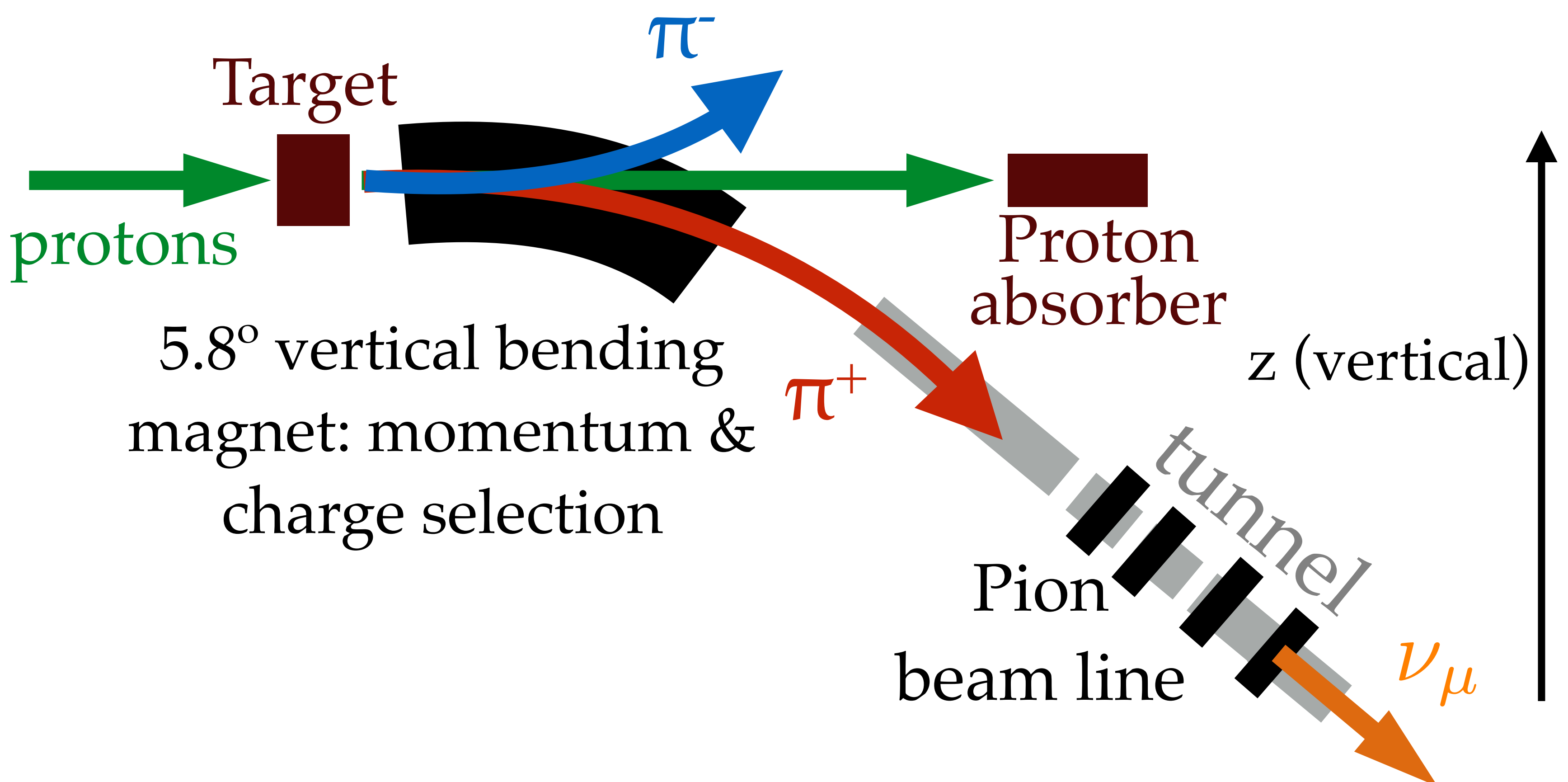


Full FFAG design concept

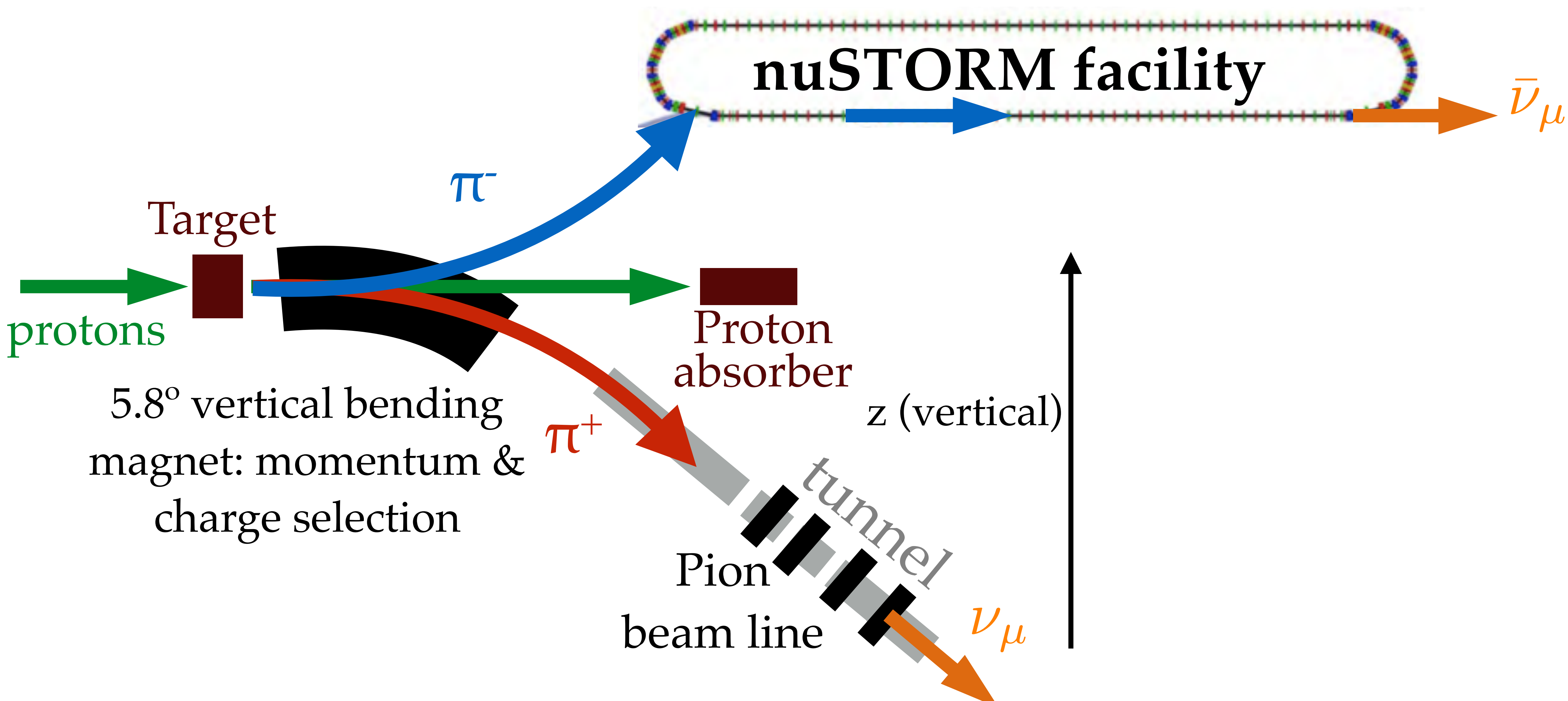


To be implemented

Going even further...

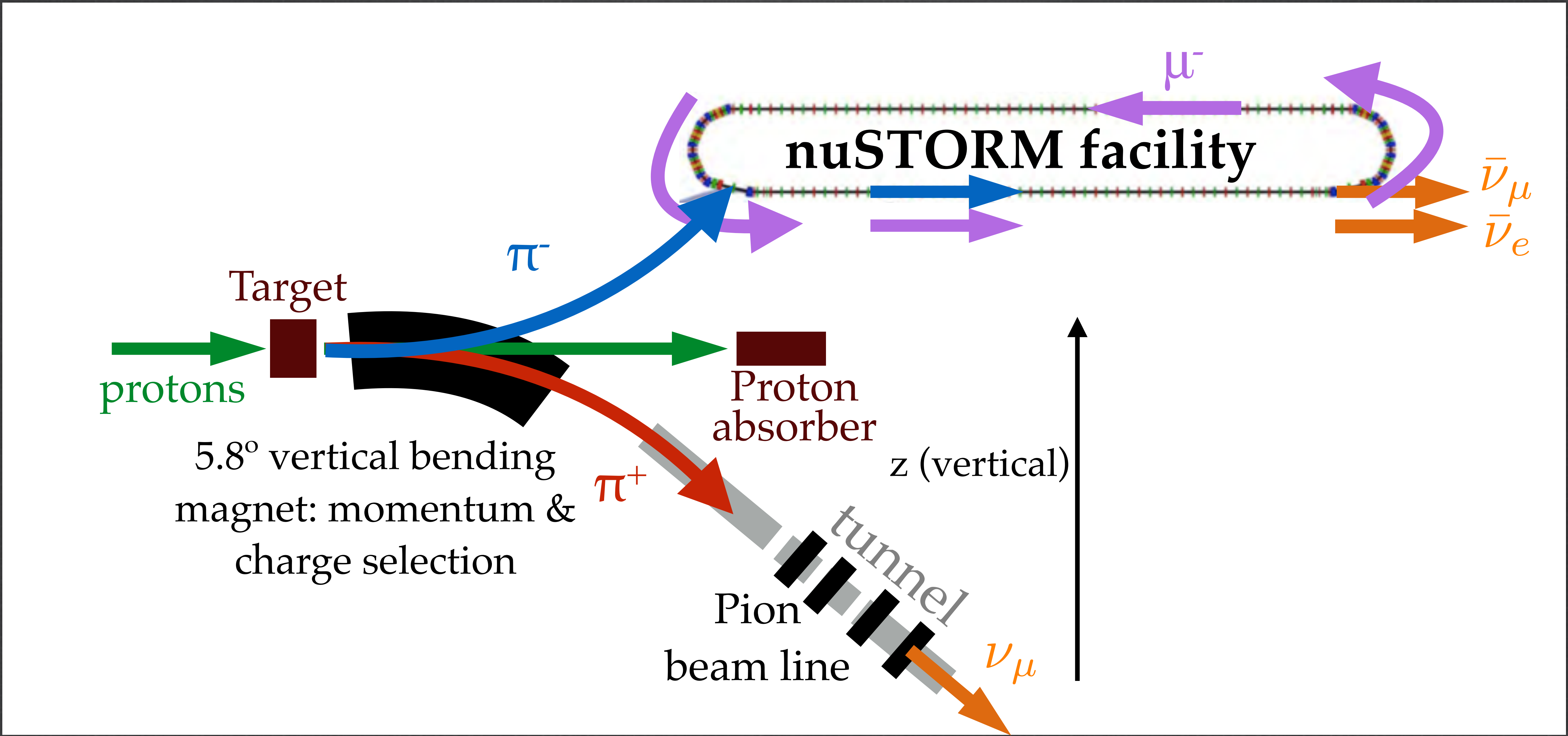


nuPIL <u>AND</u> nuSTORM?



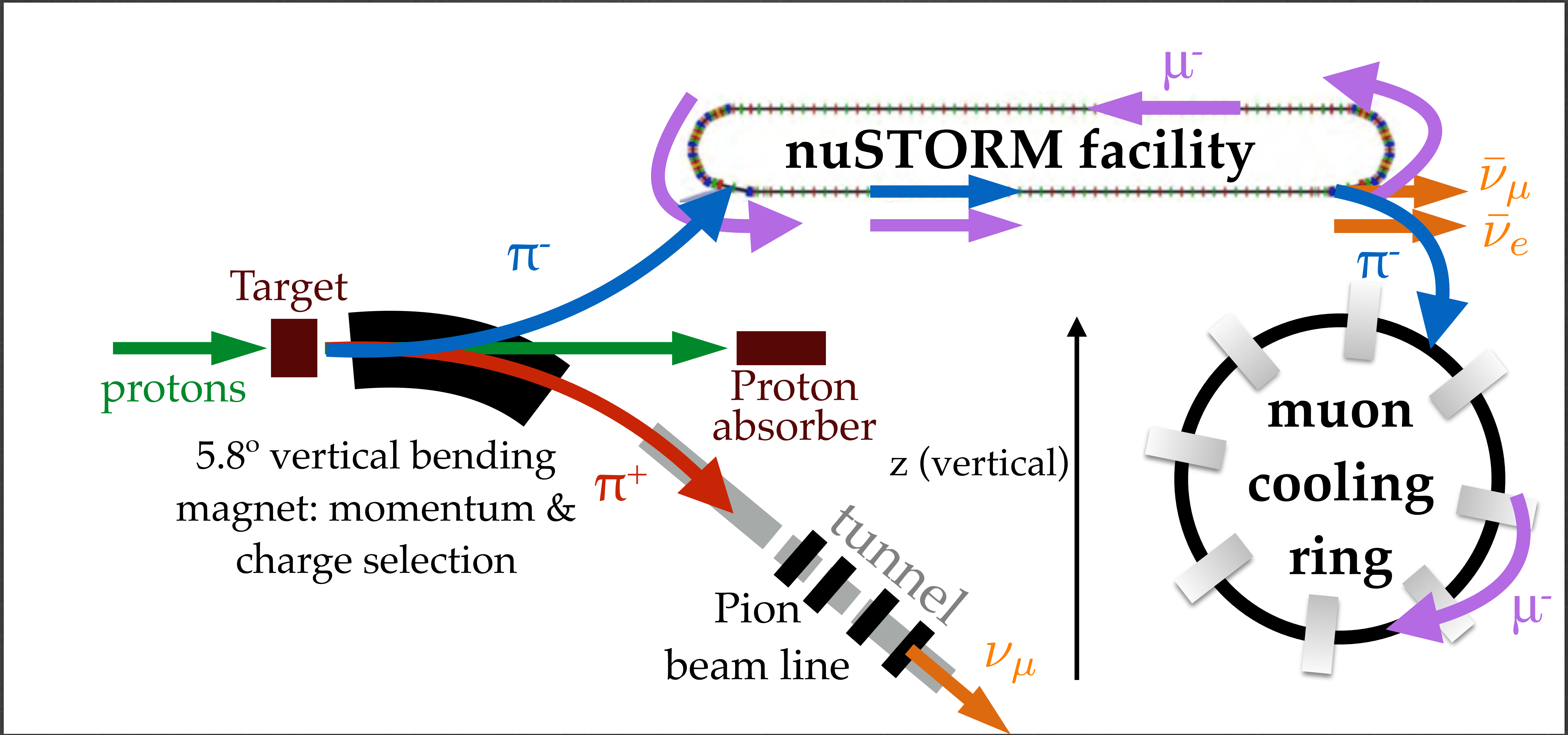
The wrong-sign pions could be used for Short Baseline experiments (i.e. nuSTORM).

nuPIL AND nuSTORM?



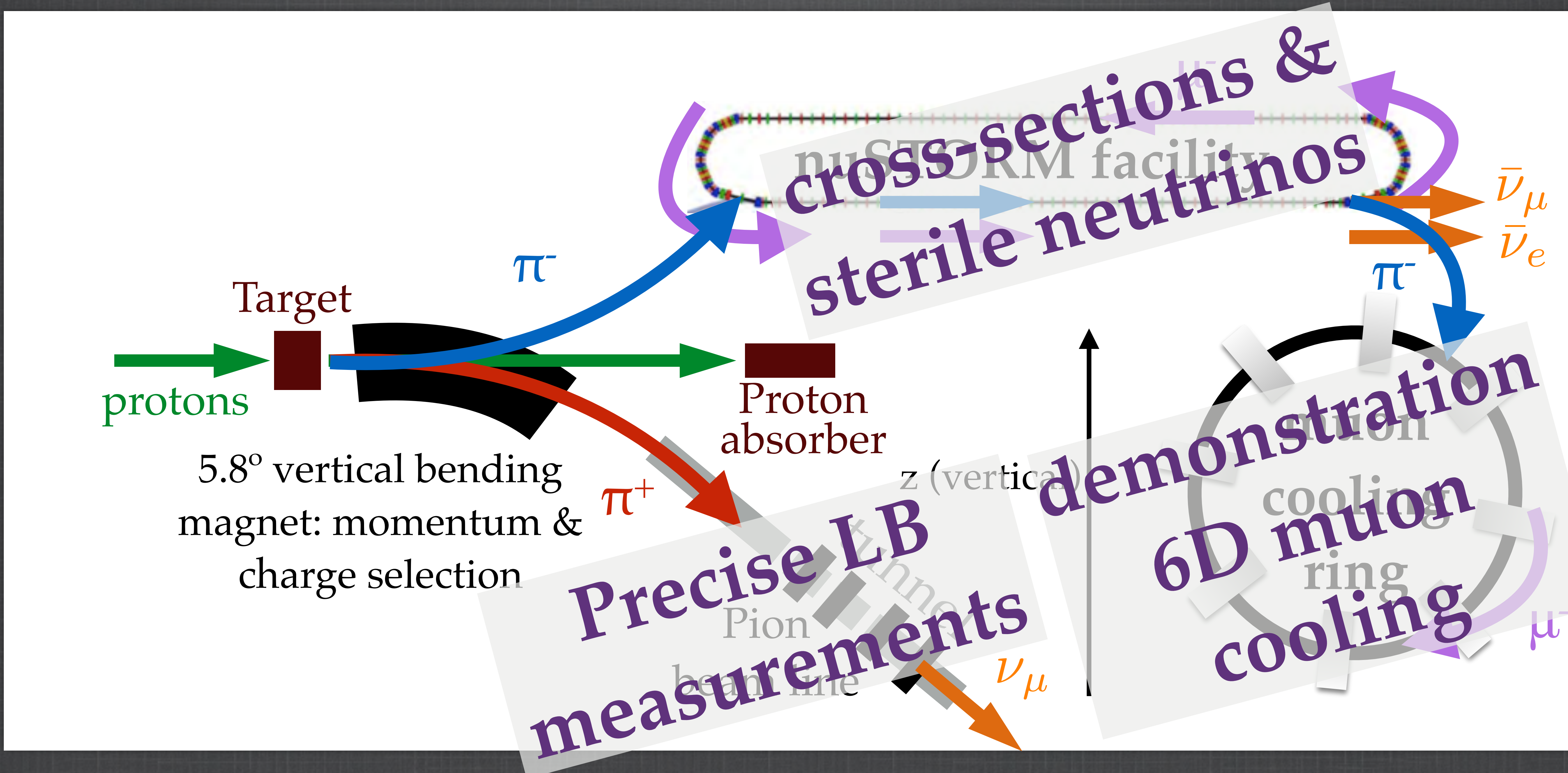
The wrong-sign pions could be used for Short Baseline experiments (i.e. nuSTORM).

nuPIL AND nuSTORM, AND Rubbiatron?



Muon cooling experiment (C. Rubbia's ring) could also be implemented!

nuPIL AND nuSTORM, AND Rubbiatron?



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Thank you for your attention