nuSTORM and nuPIL

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Outline

- nuSTORM overview
- FFAG decay ring
  - Triplet solution
  - Quadruplet tune point optimization
- nuPIL overview
- Preliminary results

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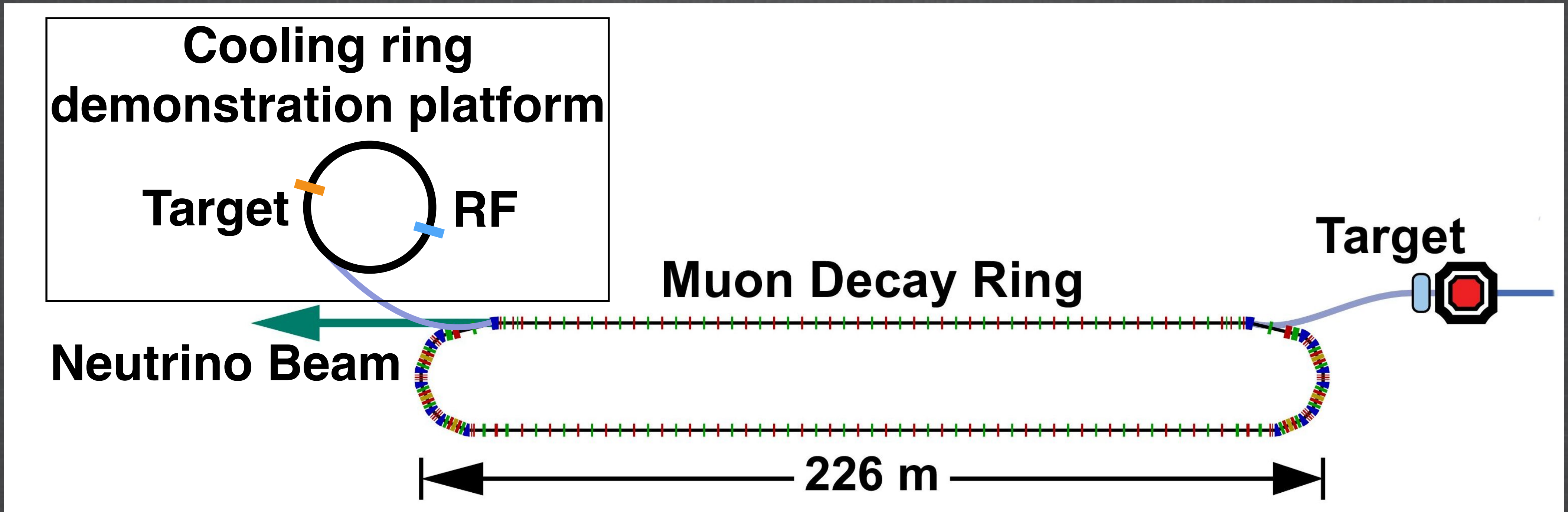
nuSTORM Overview



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

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

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

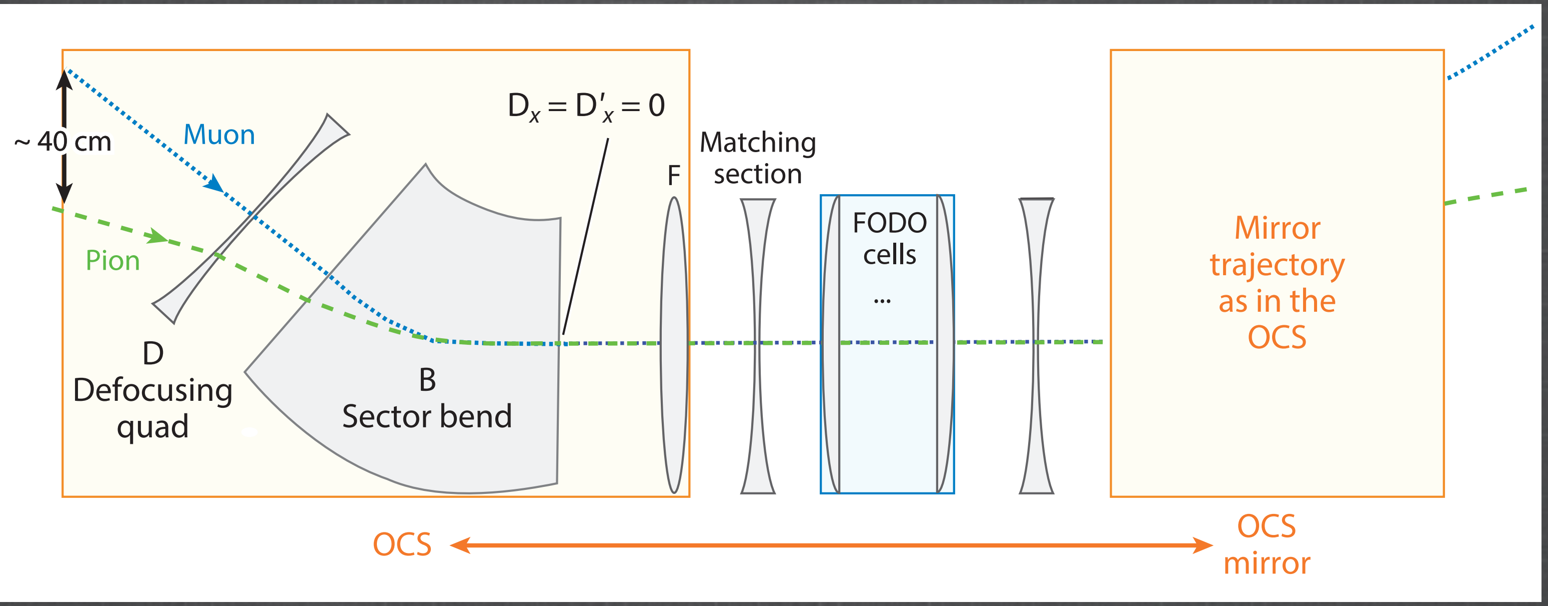
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

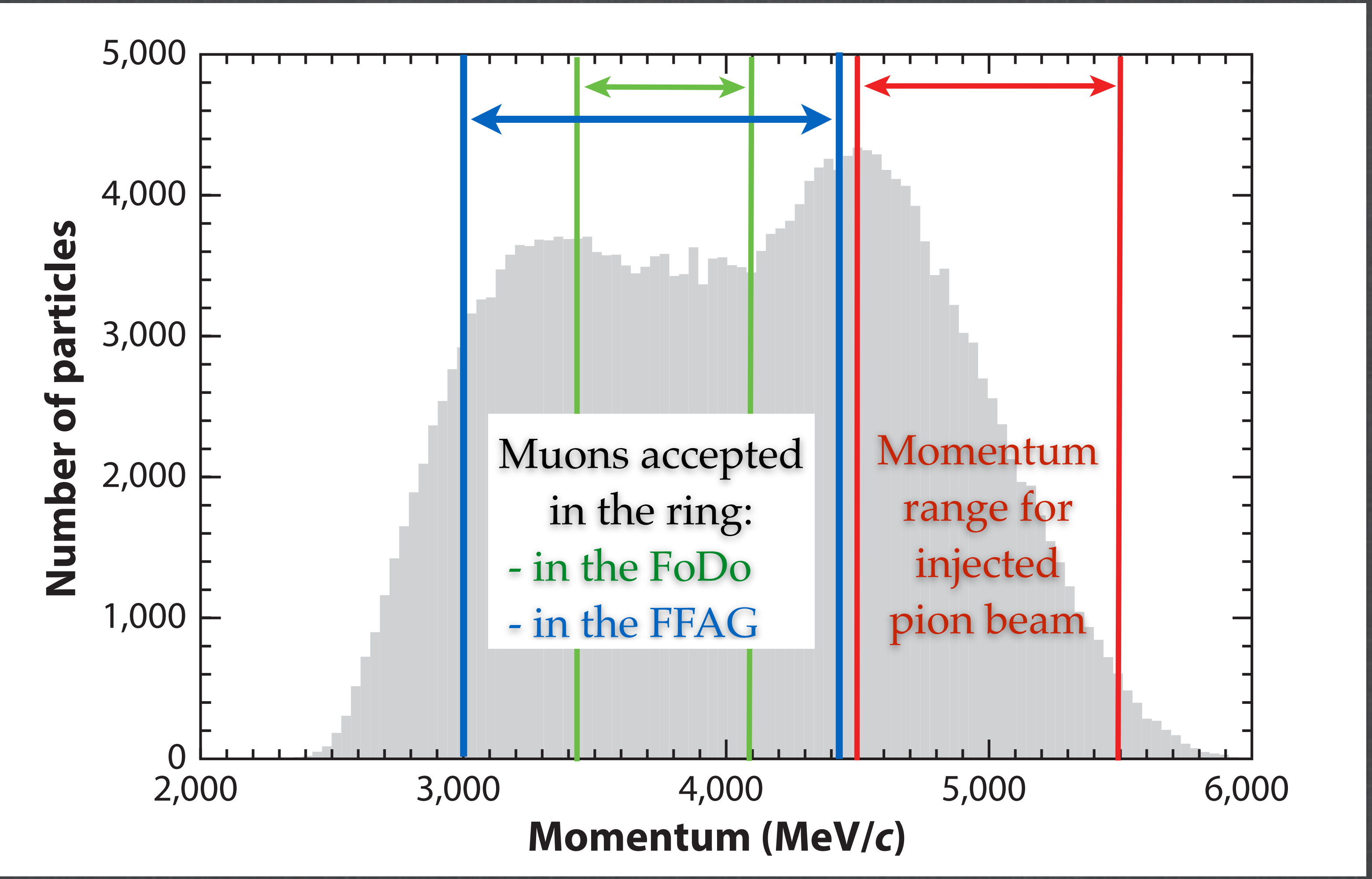
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

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





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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.

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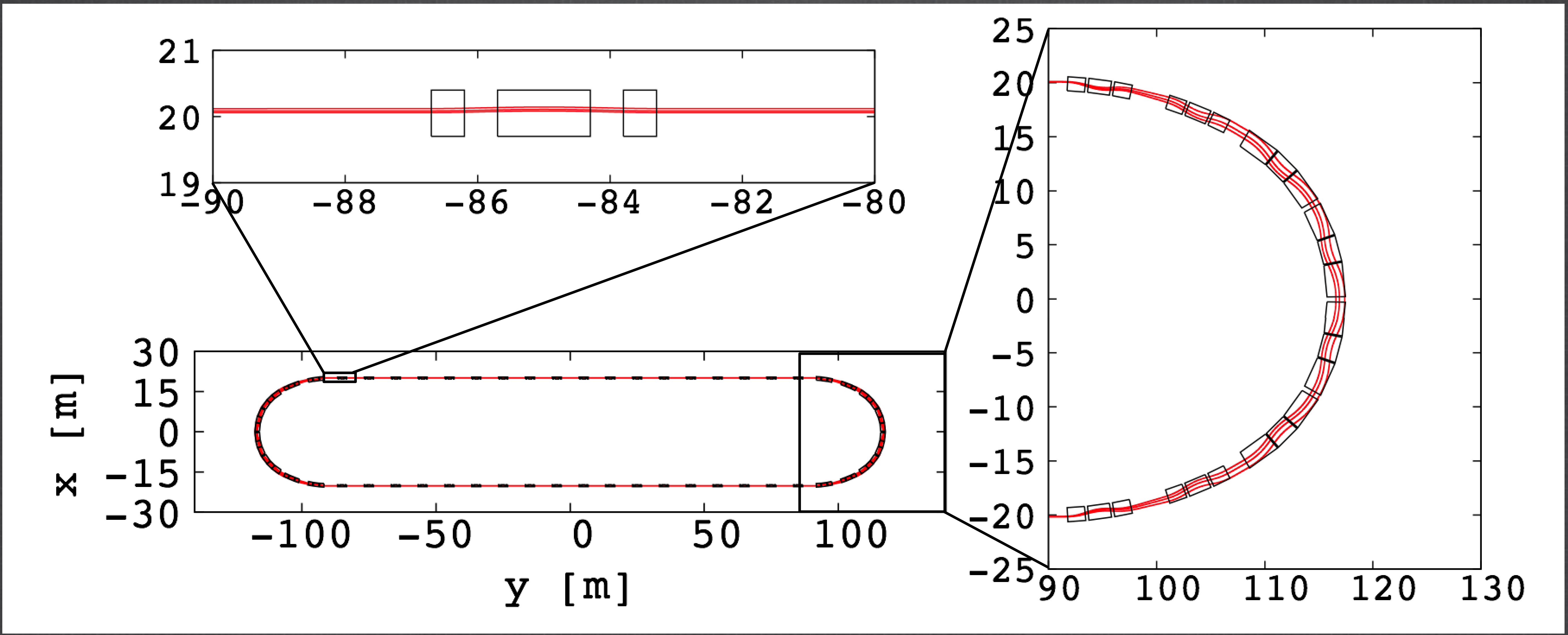
Triplet solution



J.-B. Lagrange et al., "Progress on the Design of the Racetrack FFAG Decay Ring for nuSTORM", WEPWA043, IPAC15, Richmond, USA (2015)

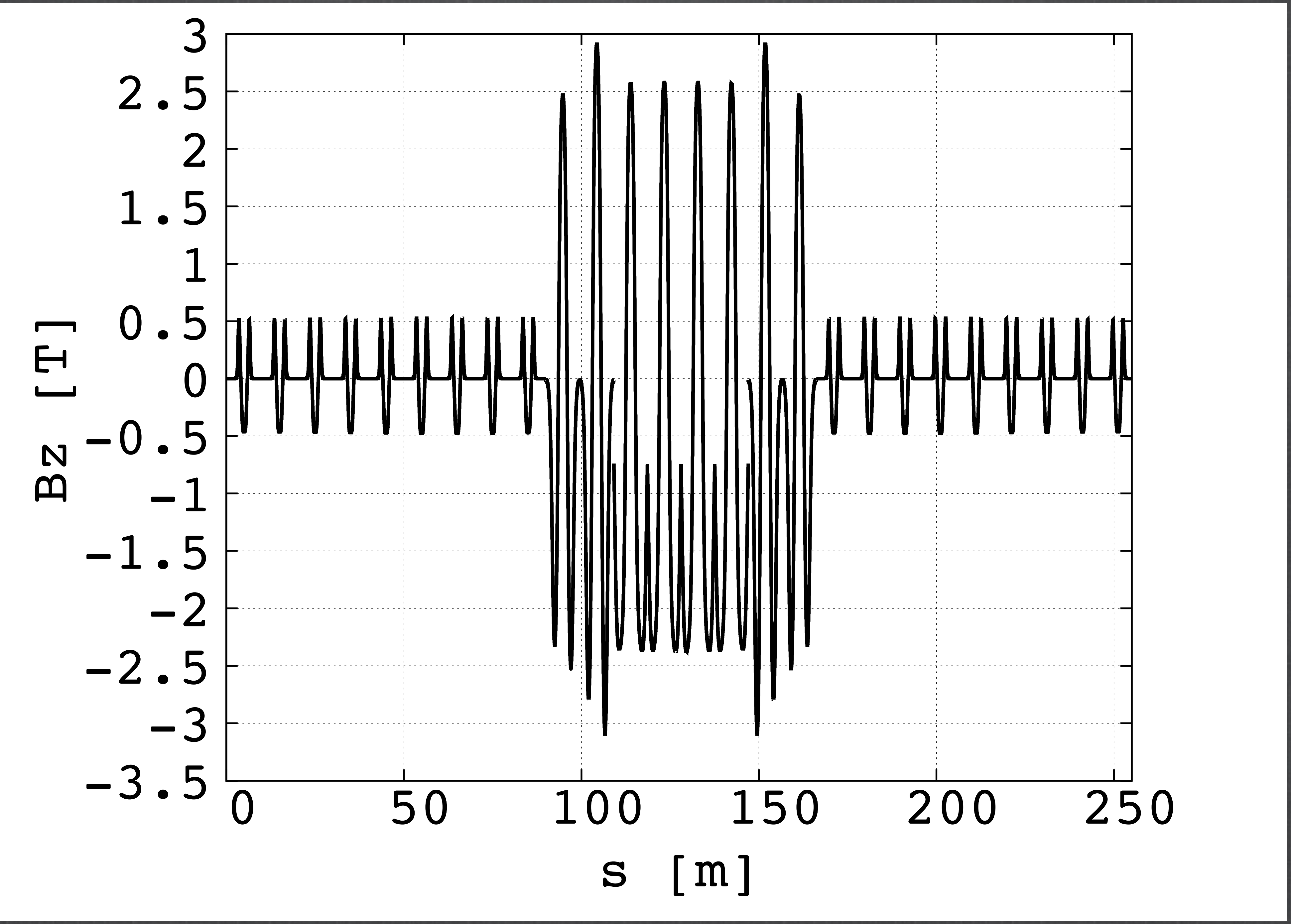
Triplet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.6	36.2	10
Opening angle [deg]	30	15	
k-value/m-value	6.057	26.	5.5 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.5	3.3	1.5
horizontal excursion [m]	1.3	1.1	0.6
Full gap height [m]	0.45	0.45	0.45
Average dispersion /cell [m]	2.5	1.3	0.18
Number of cells /ring	4×2	4×2	36×2

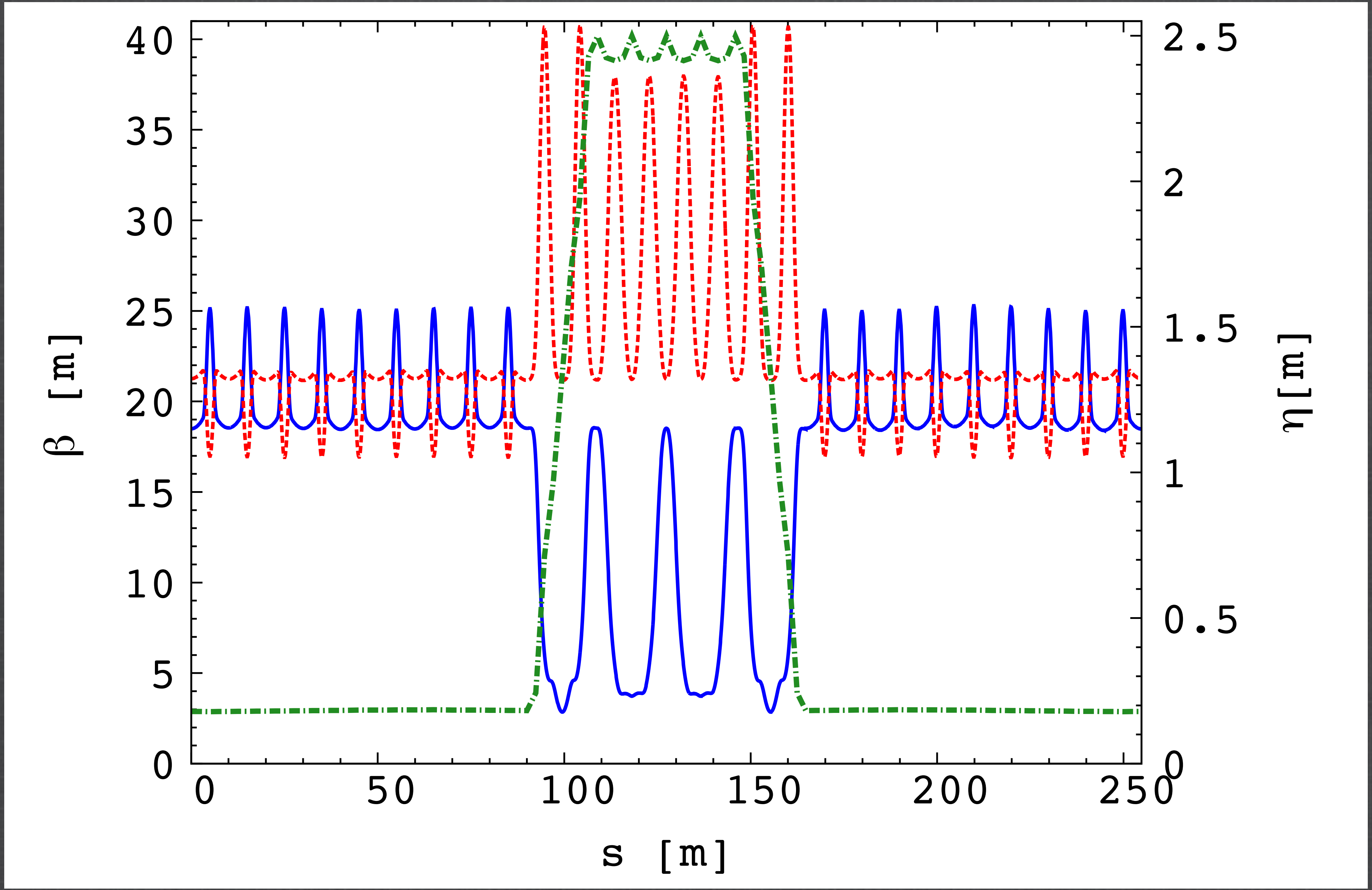
Triplet solution

Magnetic field for P_{max} (+16%)



Triplet solution

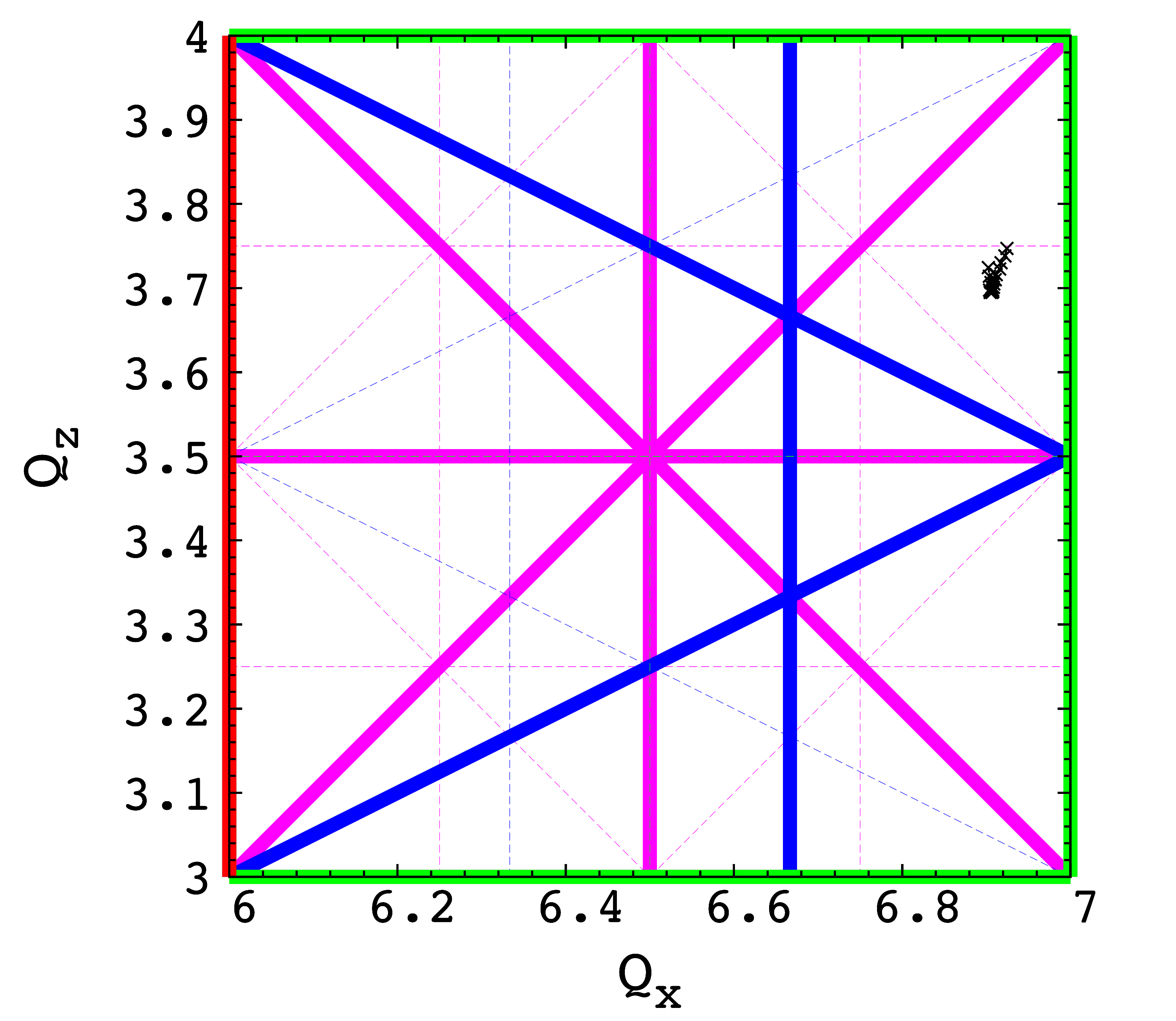
Beta-functions and dispersion at matching momentum



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

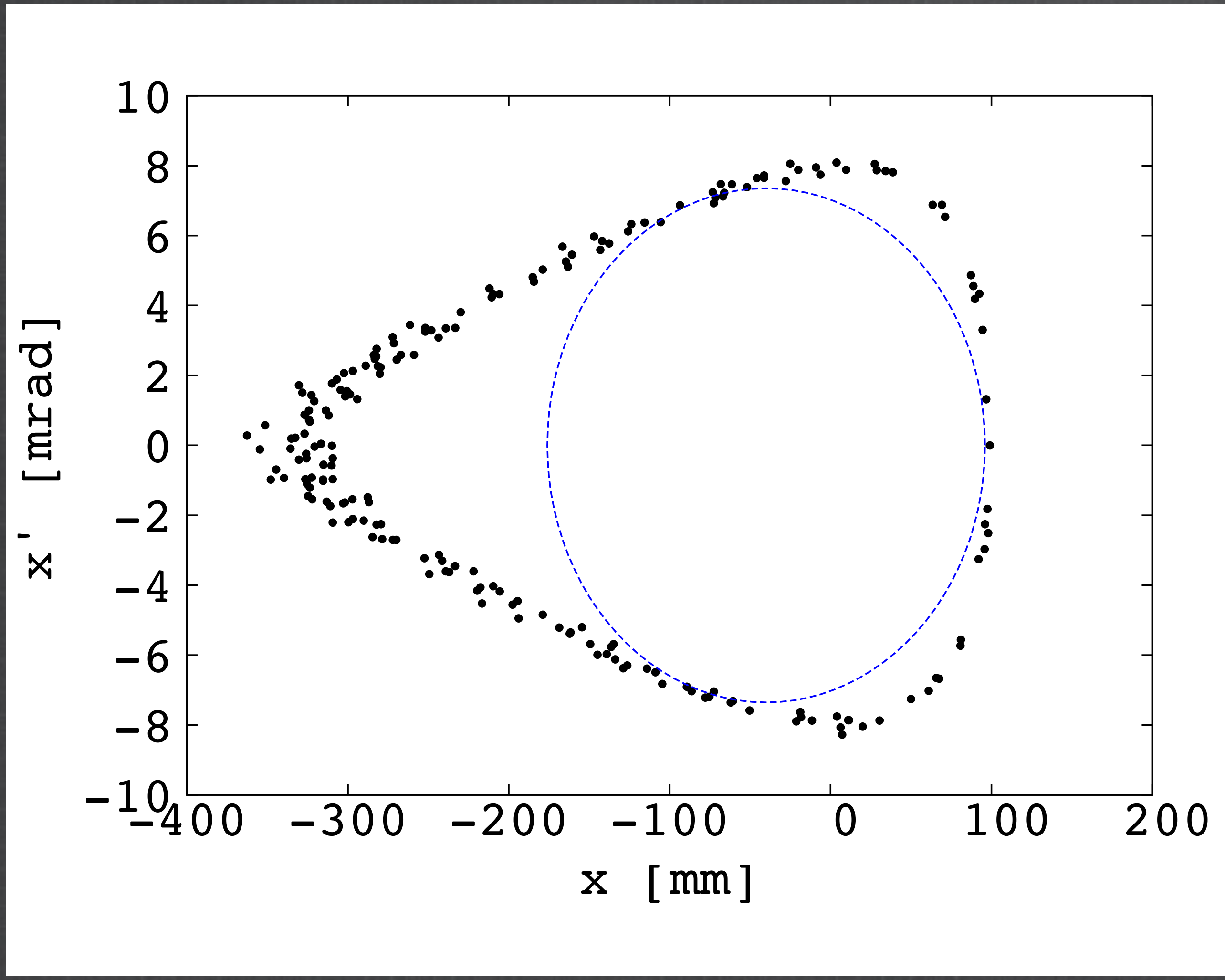
Triplet solution

Tune diagram $\frac{\Delta P}{P} = \pm 16\%$

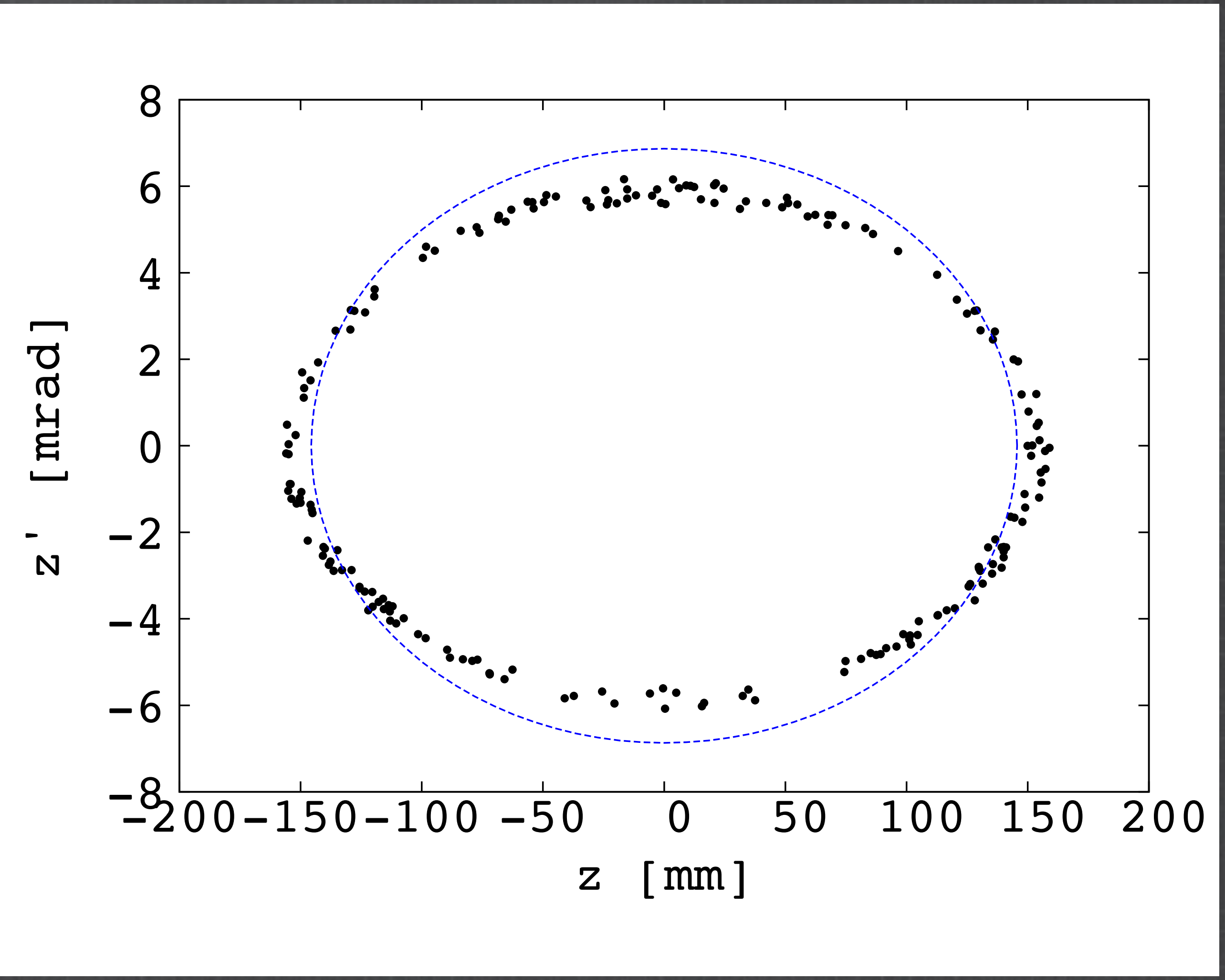


Triplet solution

Transverse acceptance



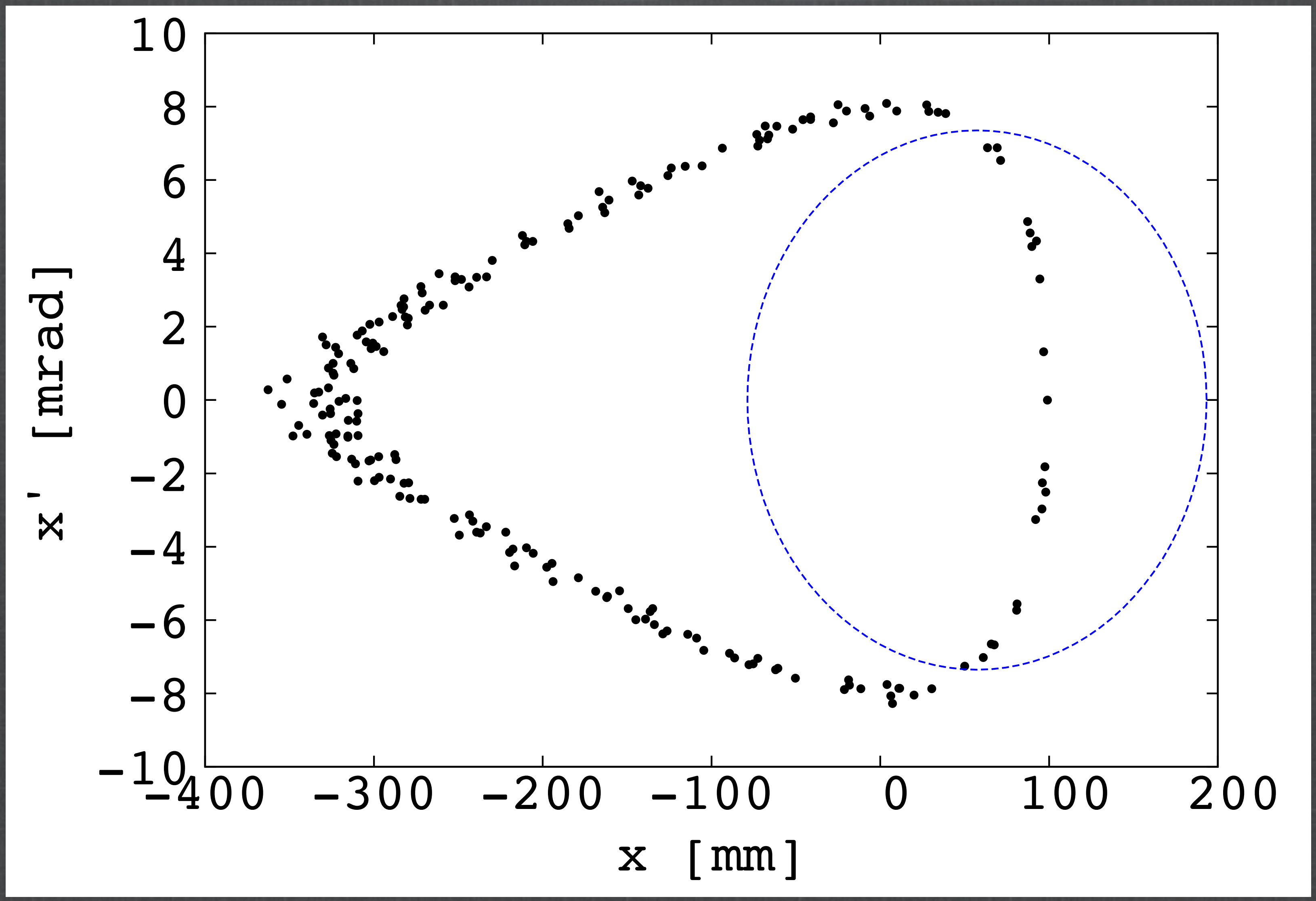
Maximum horizontal stable amplitude over 100 turns



Maximum vertical stable amplitude over 100 turns

Triplet solution

Muon capture efficiency



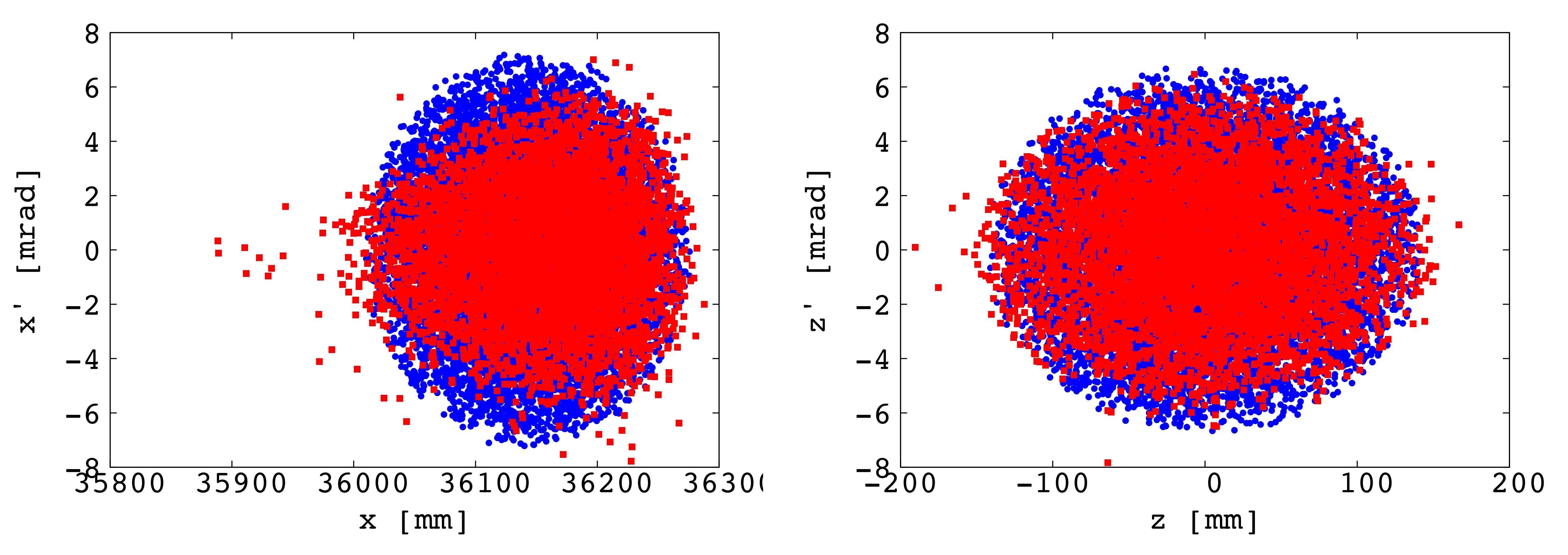
Maximum vertical stable amplitude over 100 turns

(Dotted ellipse represents 1 π.mm.rad 5 GeV/c pion beam position)

Triplet solution

Multi-particle tracking without dispersion matching.

10000 particles with a Waterbag distribution. Unnormalized emittances are 1000 π mm.mrad in transverse planes. Momentum uniformly distributed around 3.8 GeV/c ±16%.

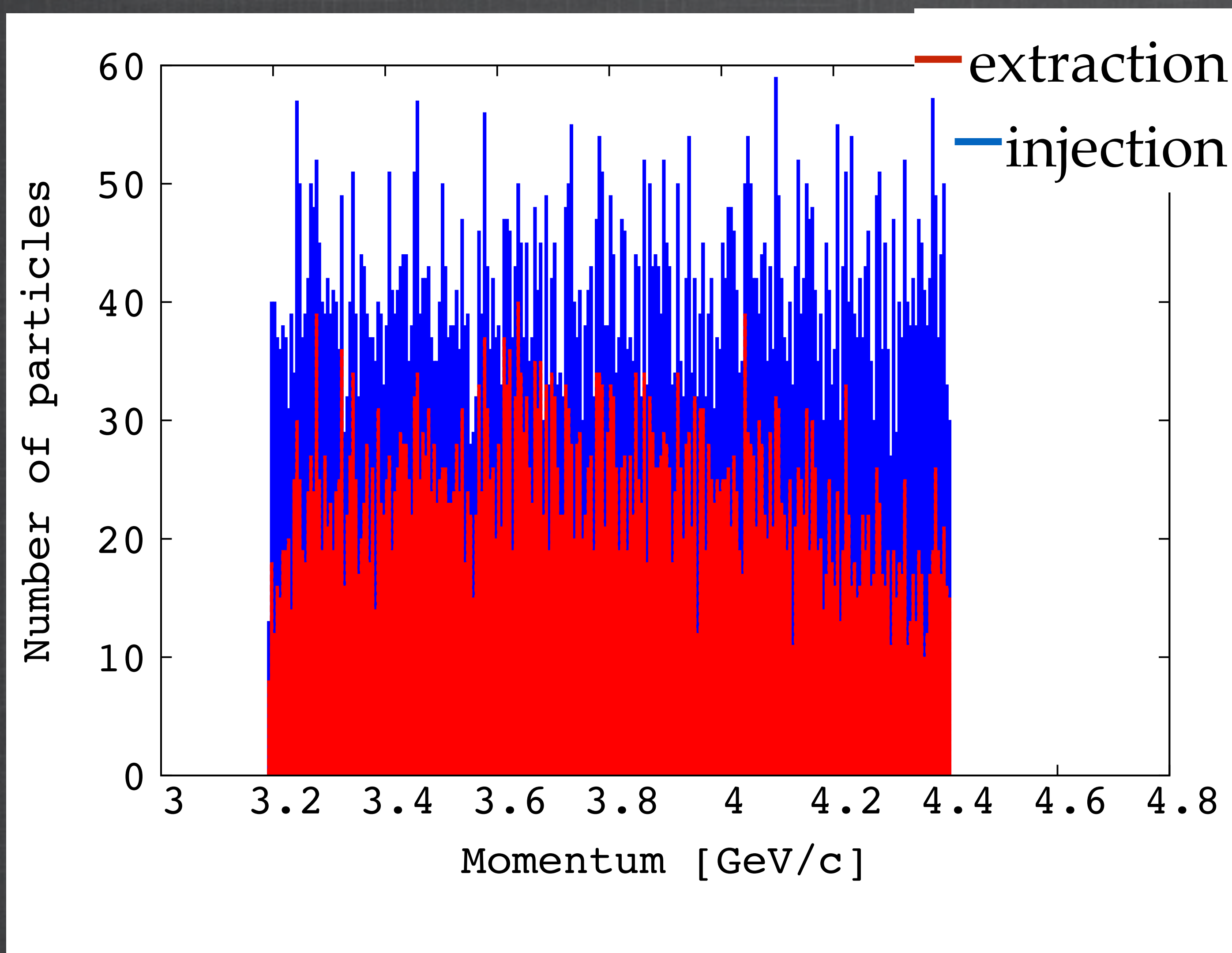


Results in the horizontal (left) and vertical (right) phase spaces

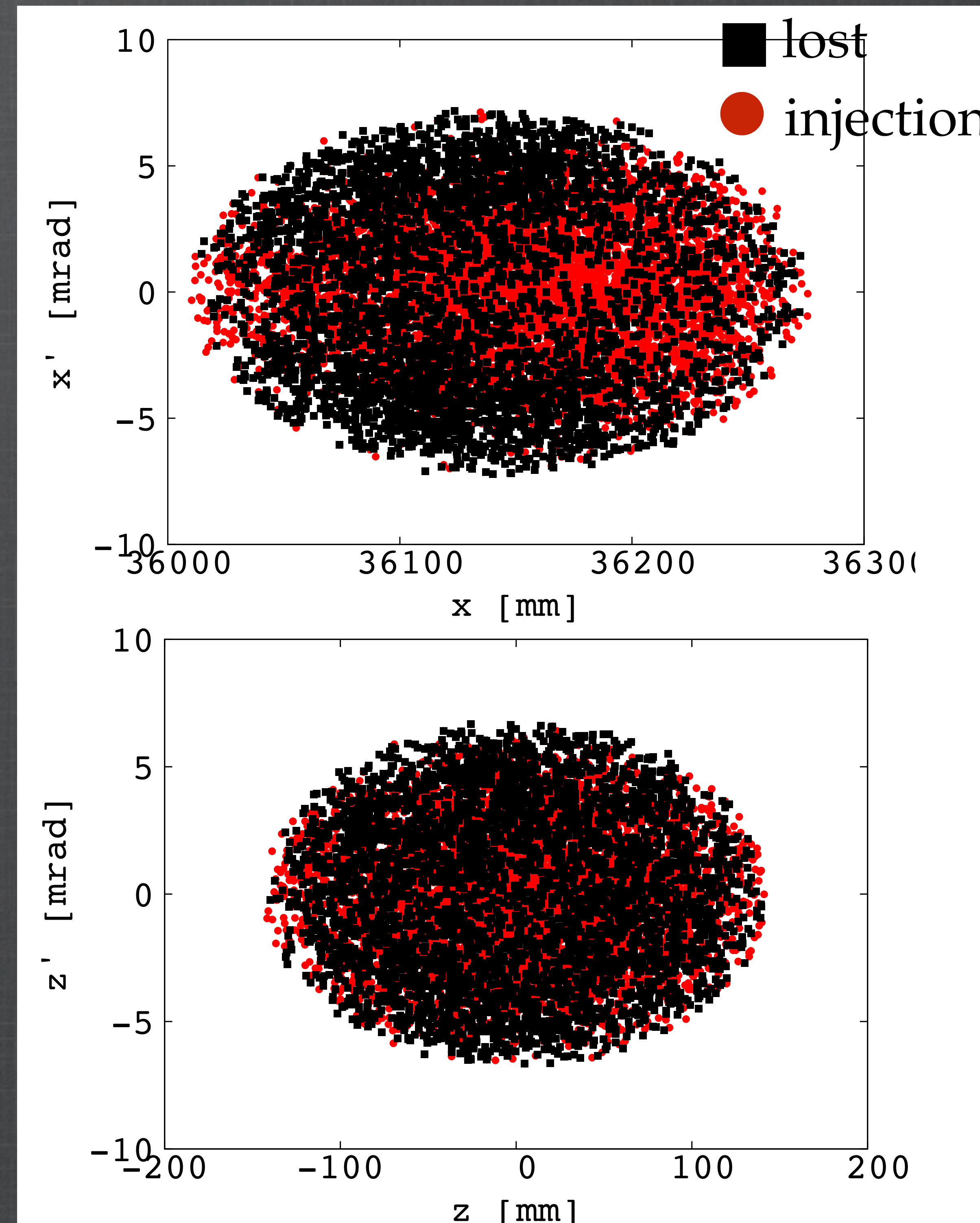
■ extraction
● injection

Triplet solution

Loss after 100 turns: 41%!



Momentum range at the injection (blue) and for the surviving particles after 100 turns (red).



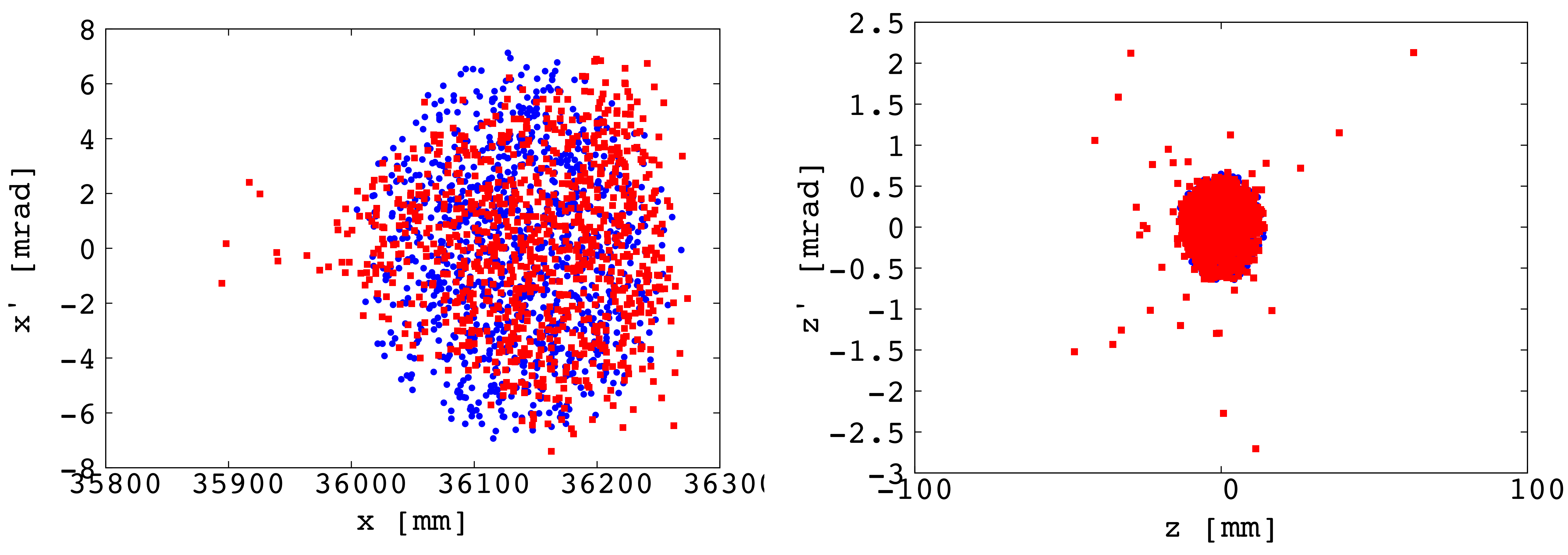
Results in the horizontal (top) and vertical (bottom) phase spaces

Triplet solution

Multi-particle tracking without dispersion matching.

1000 particles with a Waterbag distribution. Unnormalized emittances are 1000/10 π mm.mrad in horizontal/vertical planes.

Momentum set to 3.648 GeV/c.



Results in the horizontal (left) and vertical (right) phase spaces

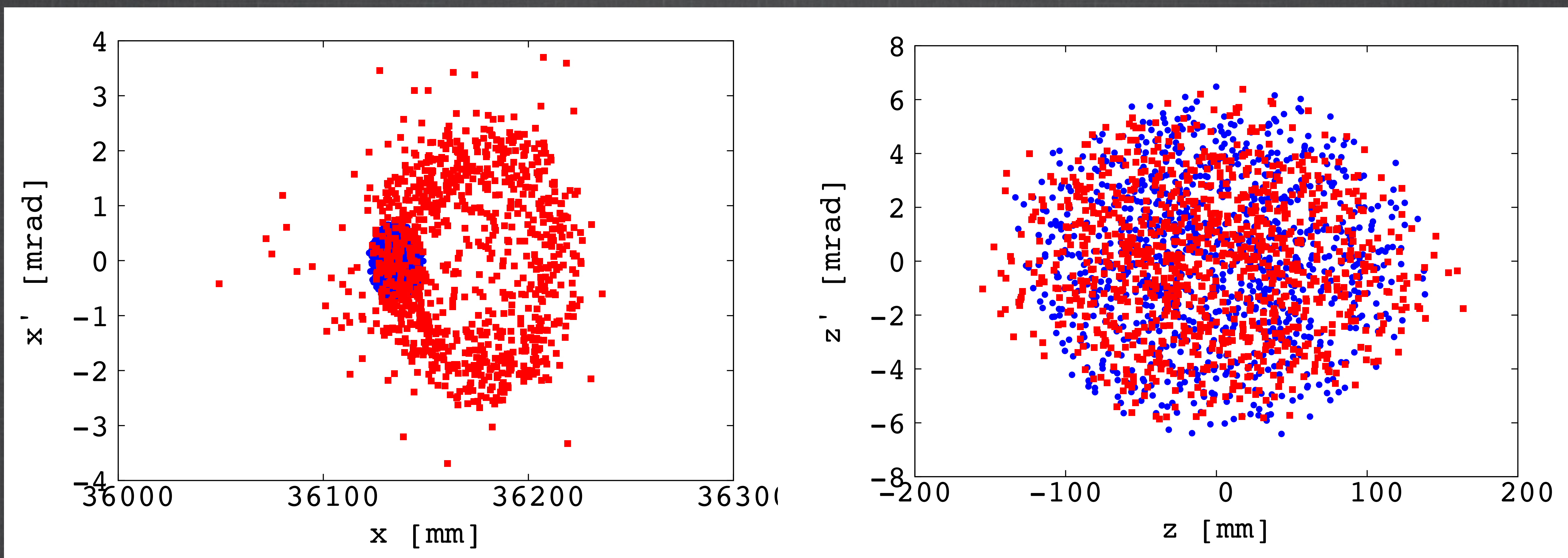
extraction
injection

Triplet solution

Multi-particle tracking without dispersion matching.

1000 particles with a Waterbag distribution. Unnormalized emittances are 10/1000 π mm.mrad in horizontal/vertical planes.

Momentum set to 3.648 GeV/c.



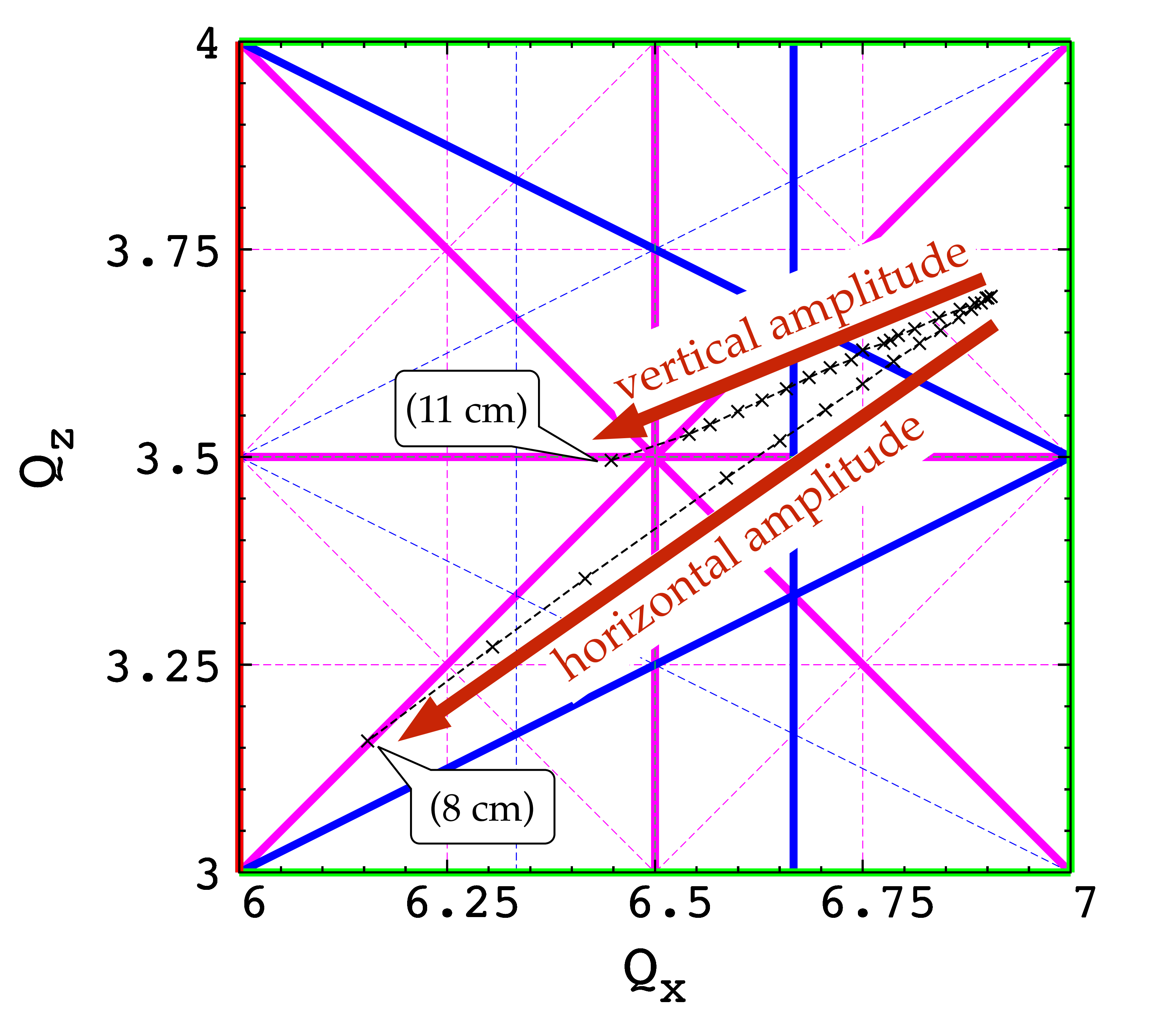
Results in the horizontal (left) and vertical (right) phase spaces

extraction

injection

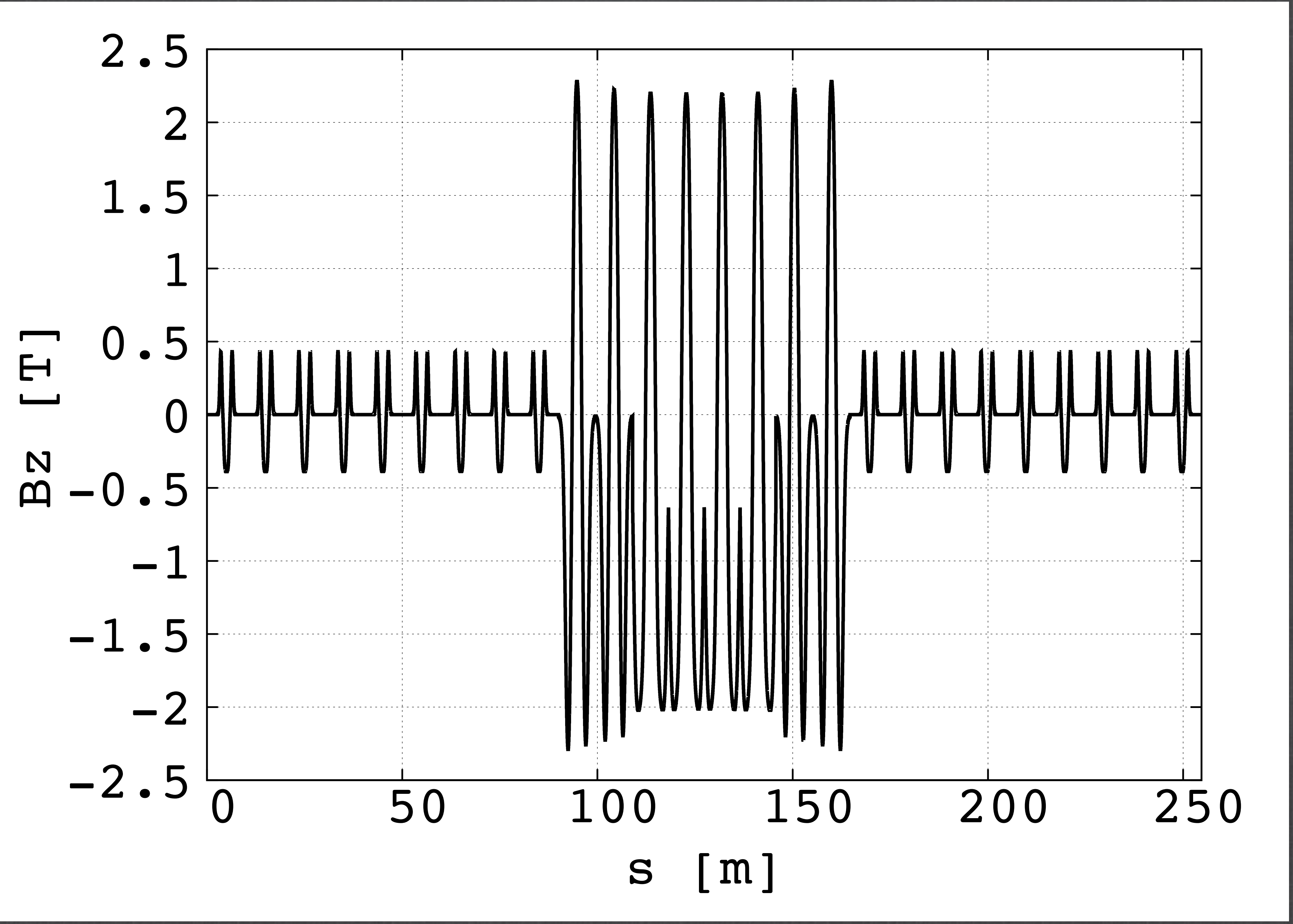
Triplet solution

Amplitude detuning obtained from FFT (1024 paths)



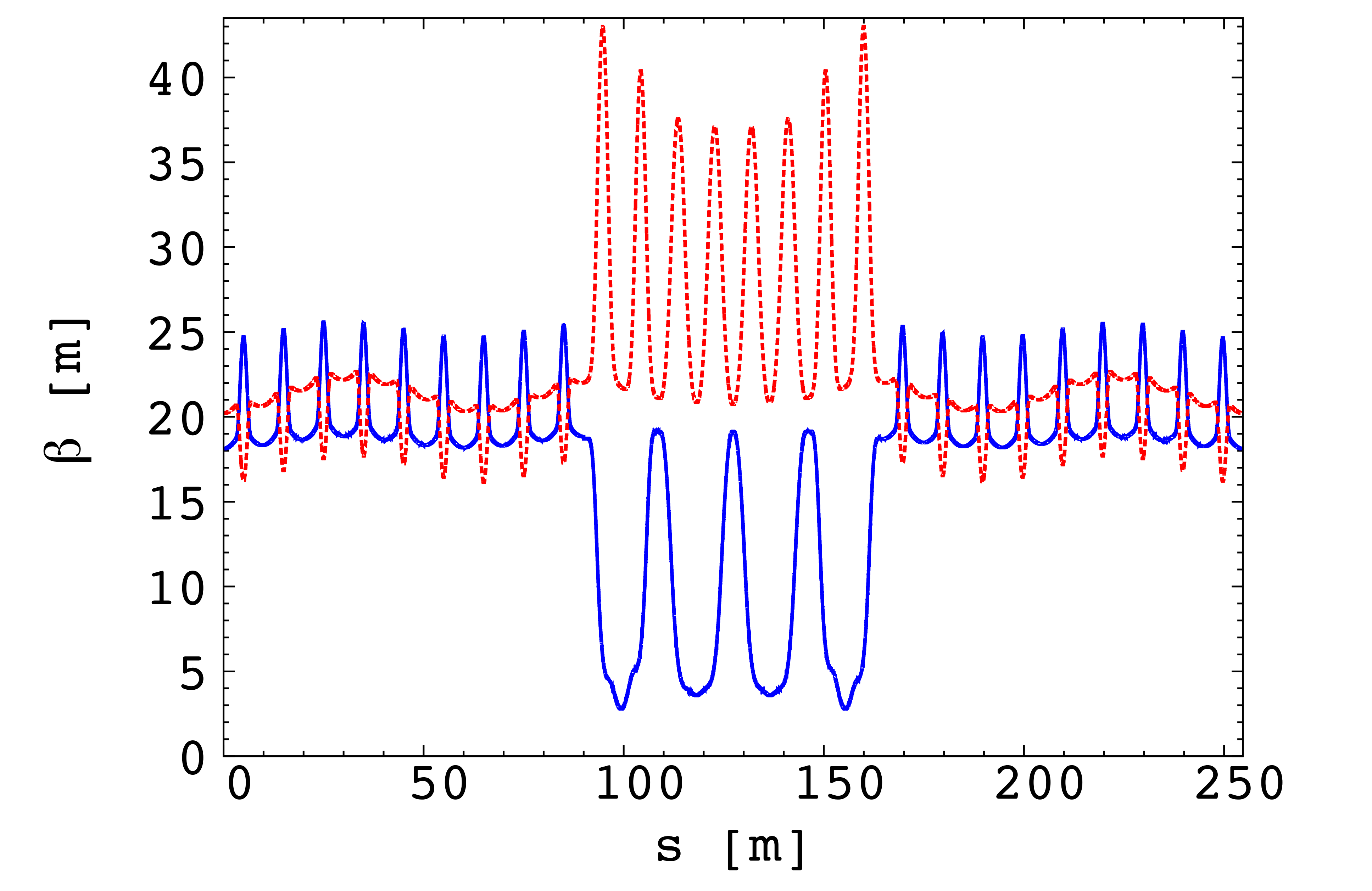
Triplet solution

Cross-check with pyzgoubi:
Magnetic field for matched momentum



Triplet solution

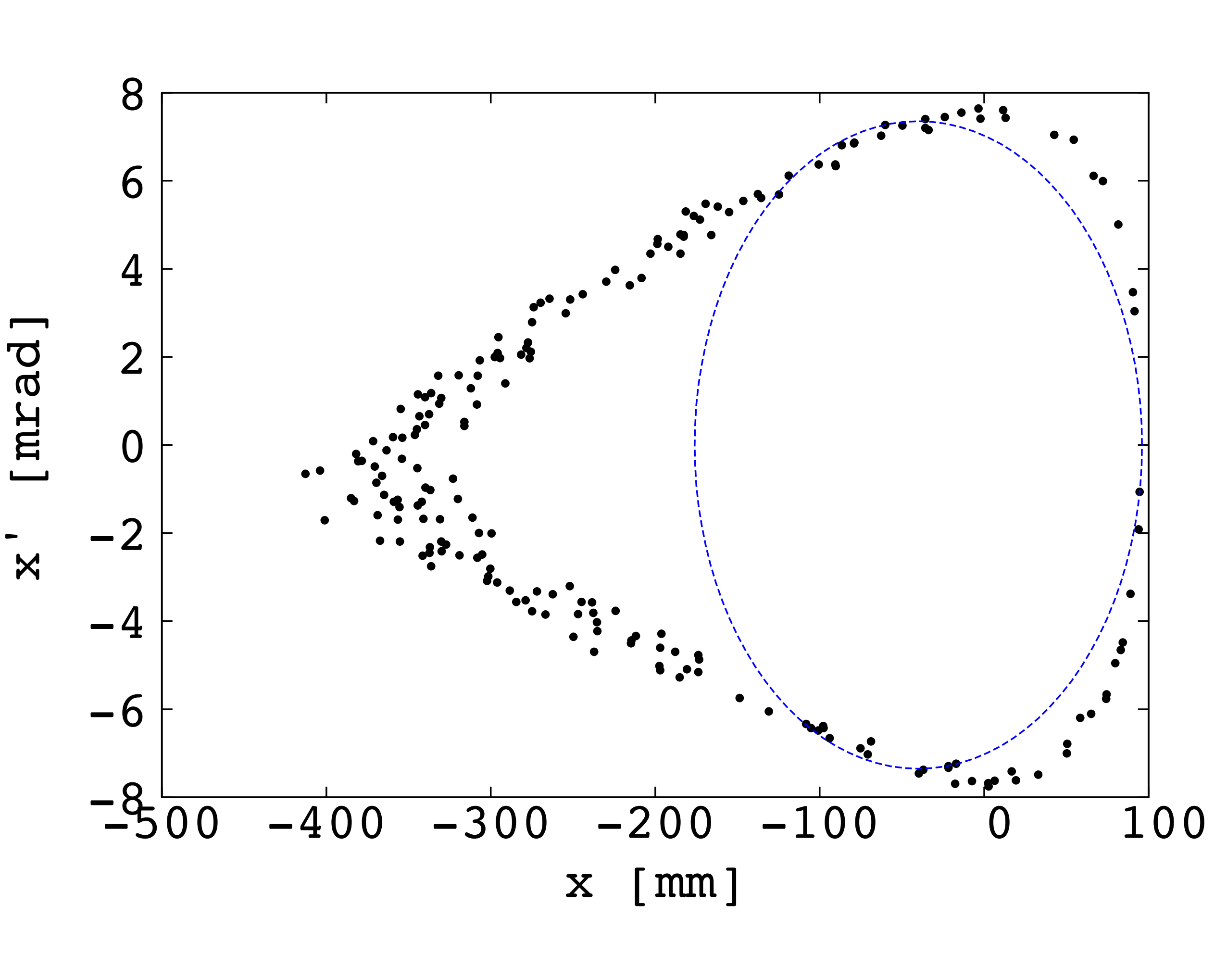
Cross-check with pyzgoubi:
Magnetic field for matched momentum



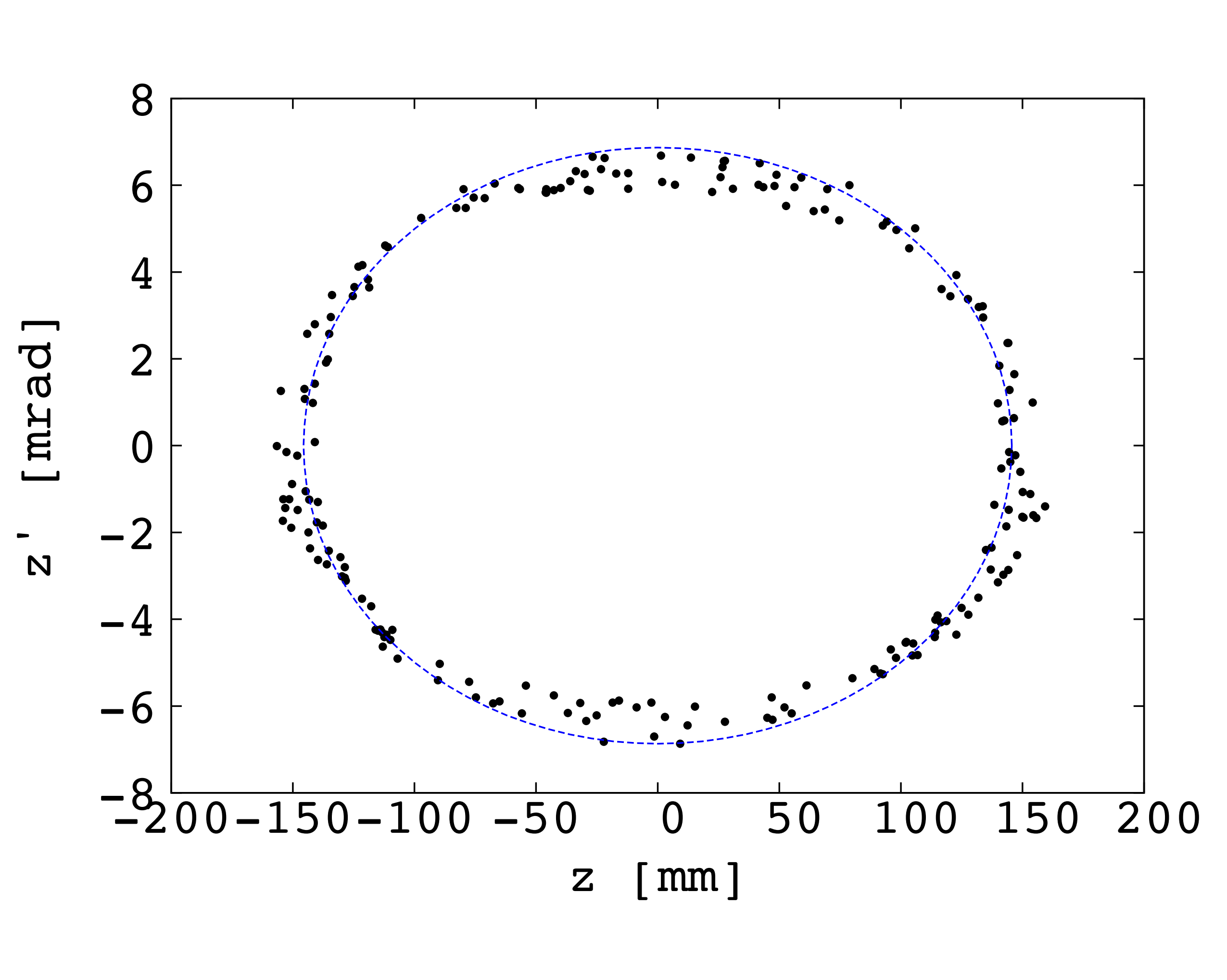
Horizontal (plain blue), vertical (dotted red) beta-functions for half of the ring.

Triplet solution

Cross-check with pyzgoubi: transverse acceptance



Maximum horizontal stable amplitude over 100 turns



Maximum vertical stable amplitude over 100 turns

Good agreement

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νSTORM

Changes in the design

- Increase momentum acceptance
-> from 3.8 GeV/c ±16% to 3.7 GeV/c ±19% (accept lower momentum)

- Beam emittance increases 1 π.mm.rad to 2 π.mm.rad
-> increase the DA (reduce the gradient in the straight section).

- Triplet cell has few parameters for adjustments and 2 kinds of magnet design
-> Quadruplet cell, all magnets identical.

- Long cell is better: few magnets, not dominated by fringe fields.

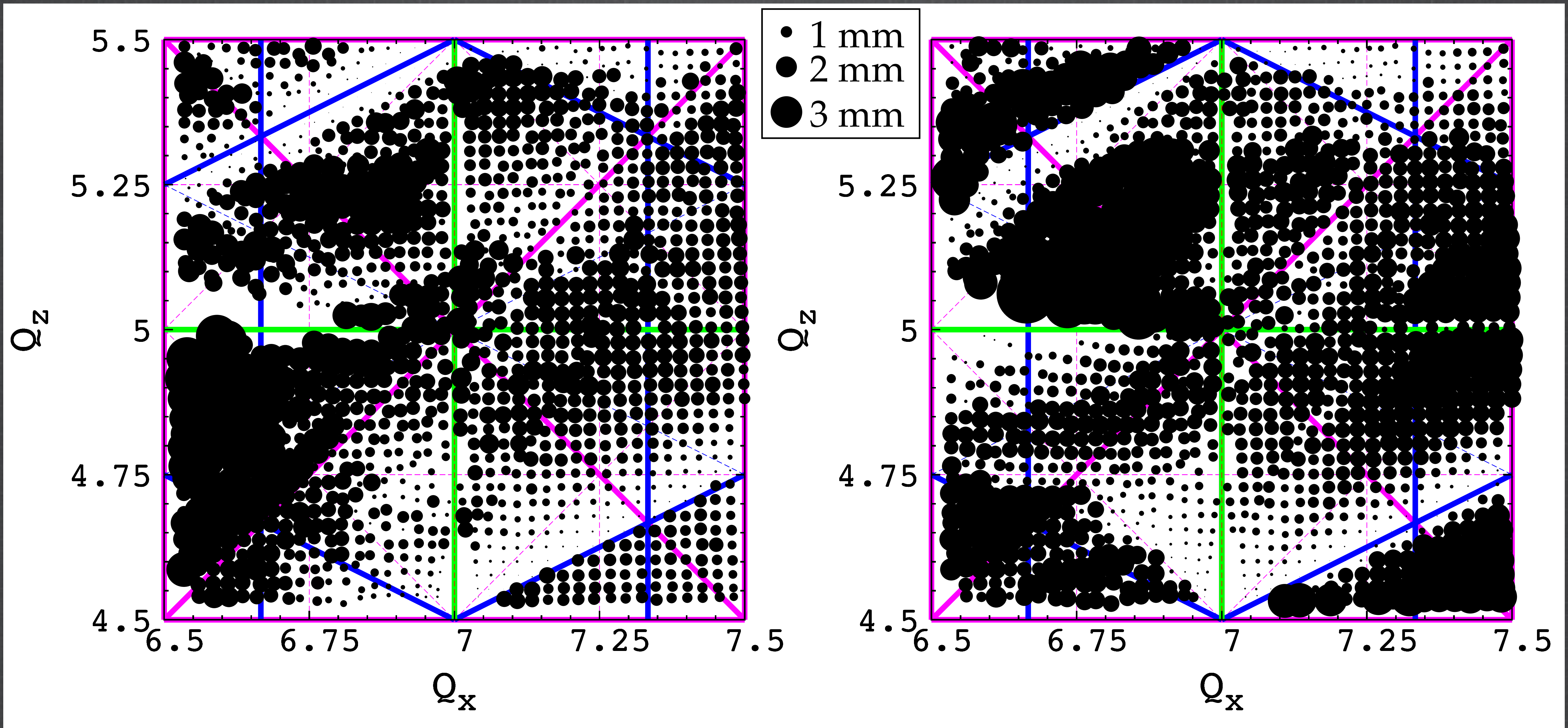
Changes in the design (2)

→ Consequences of low gradient in the straight section:

- PROS:
  - increase the DA.
  - reduce the maximum dispersion in the arc.
- CONS:
  - reduce the efficiency of muon capture.

Quadruplet: tune optimization

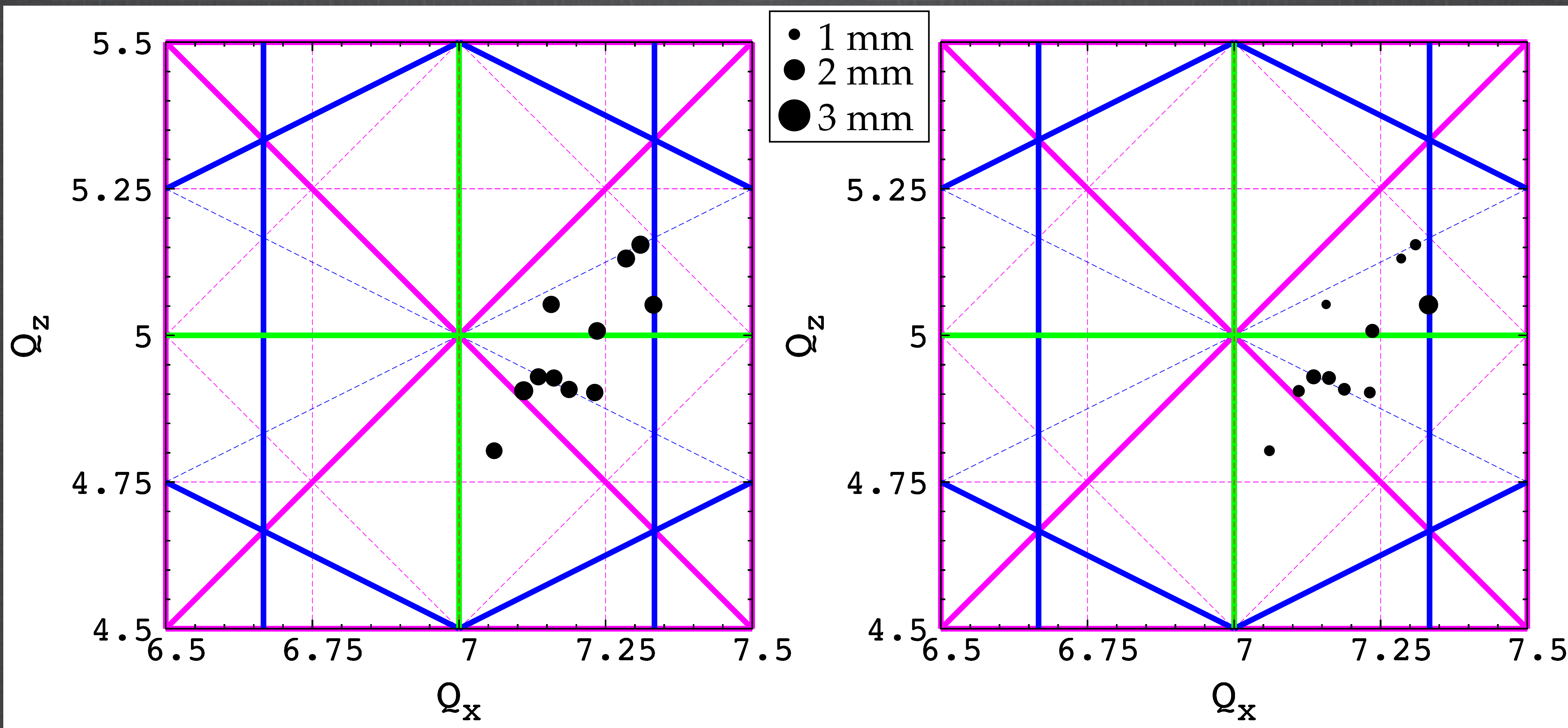
Tune diagram



DA study in horizontal (left) and vertical (right)

Quadruplet: tune optimization

Tune diagram

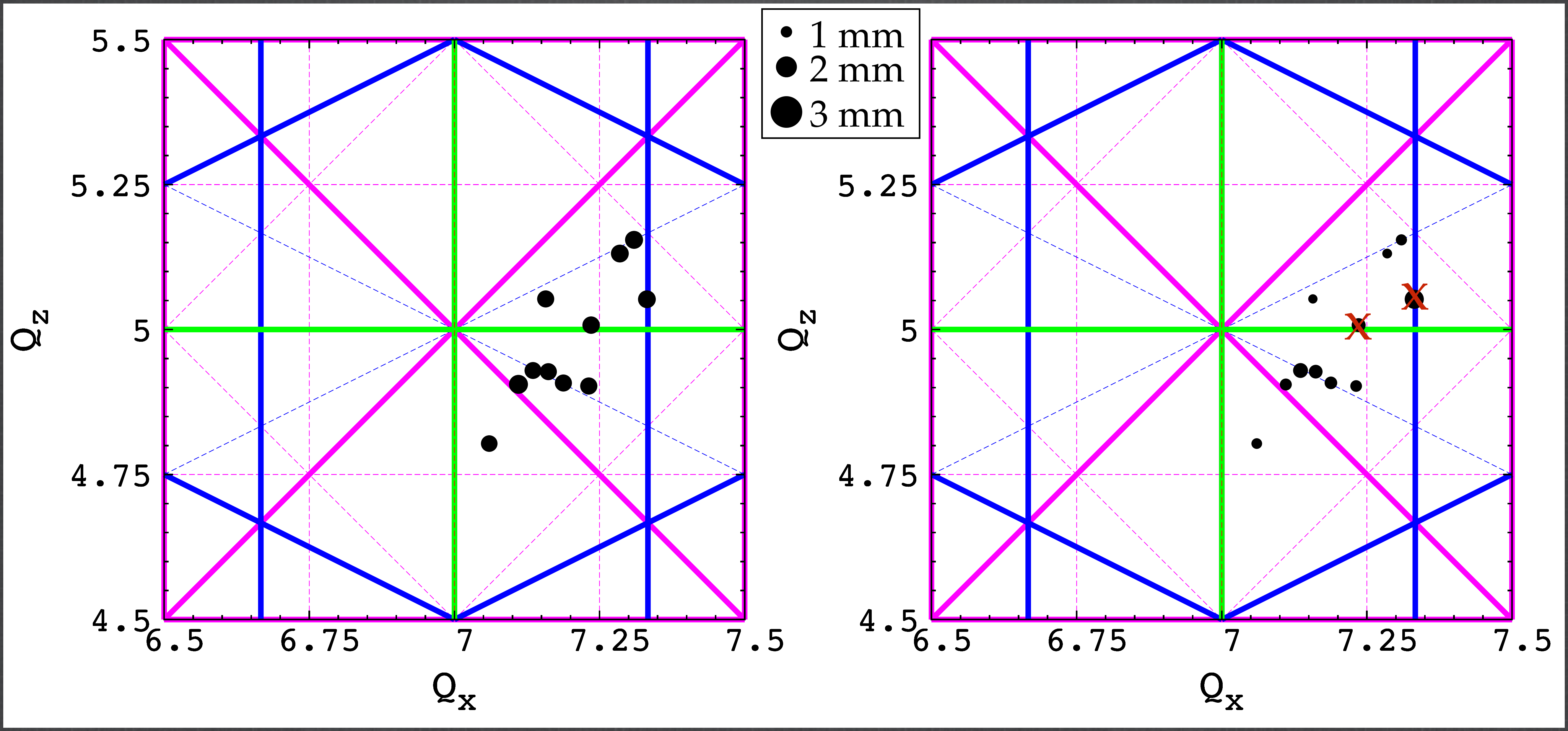


DA study in horizontal (left) and vertical (right)

max. amp > $\frac{\ln\left(\frac{P_{pion}}{P_{matched}}\right)}{m}$

Quadruplet: tune optimization

Tune diagram



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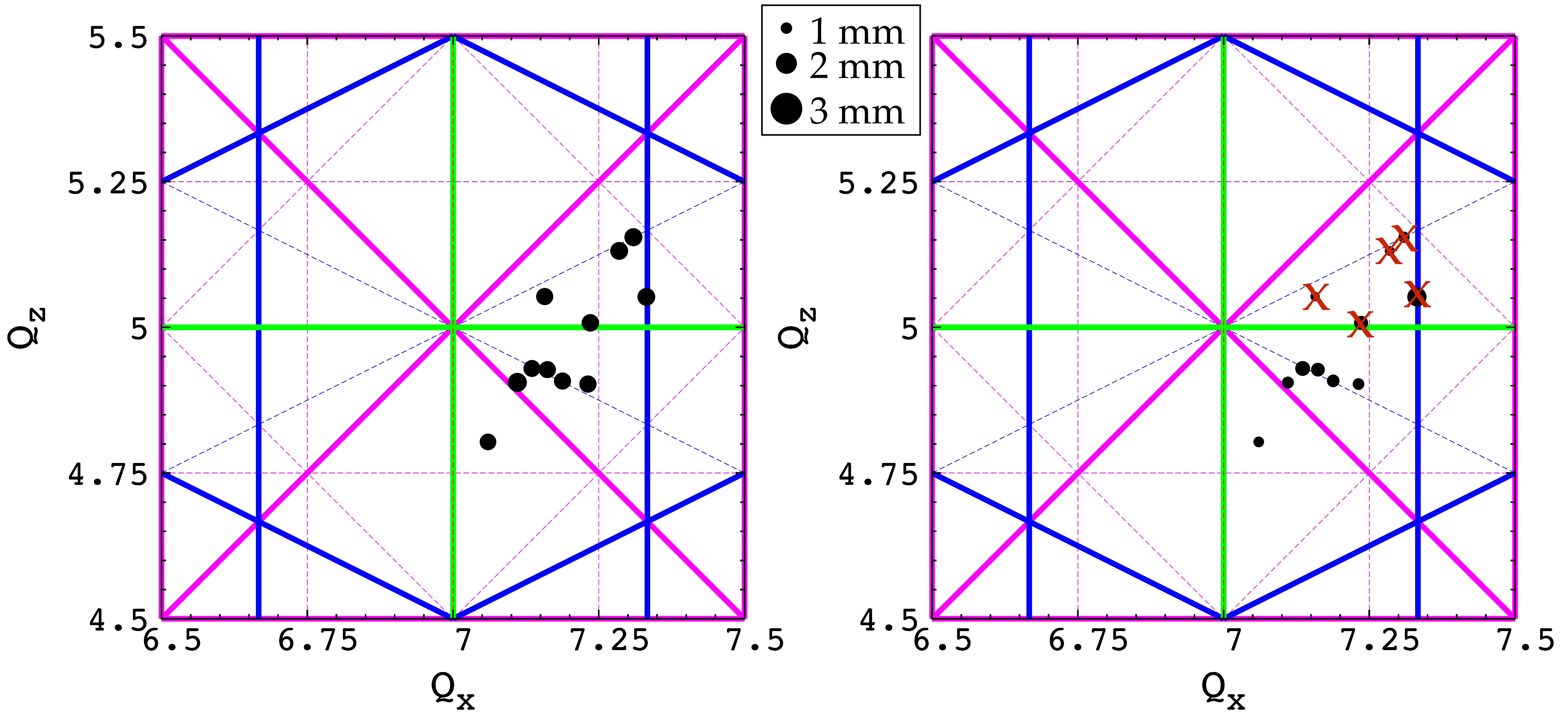

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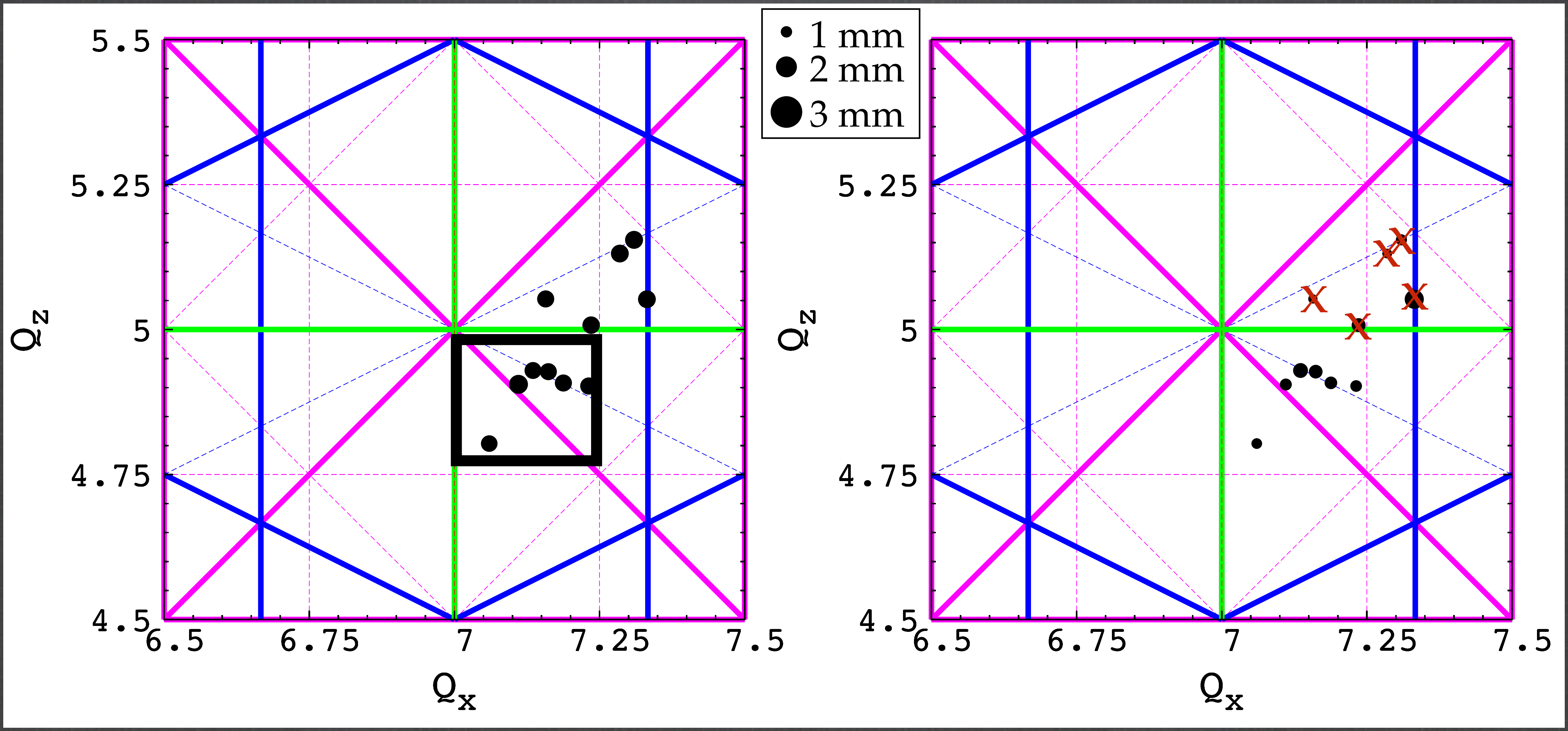
Quadruplet: tune optimization

Tune diagram



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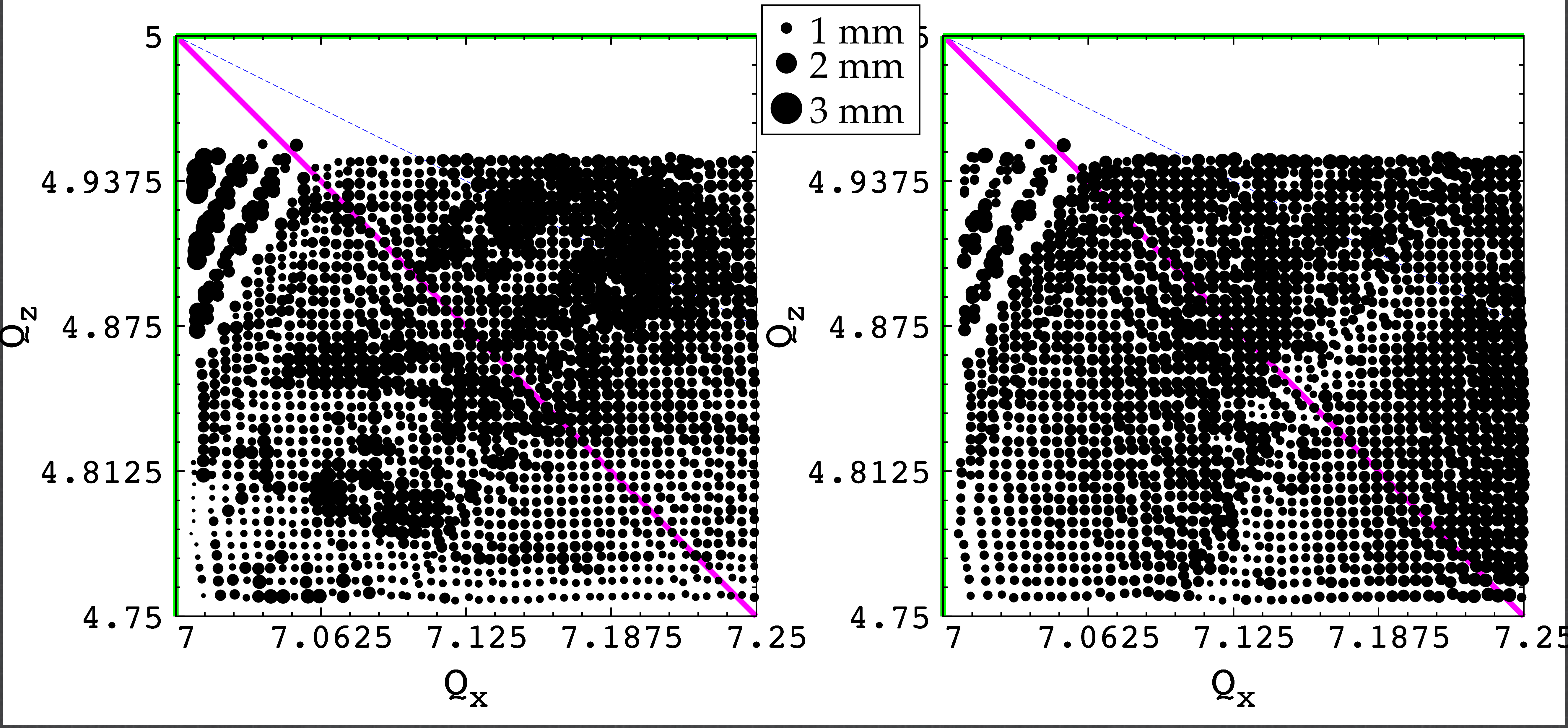
Quadruplet: tune optimization

Tune diagram



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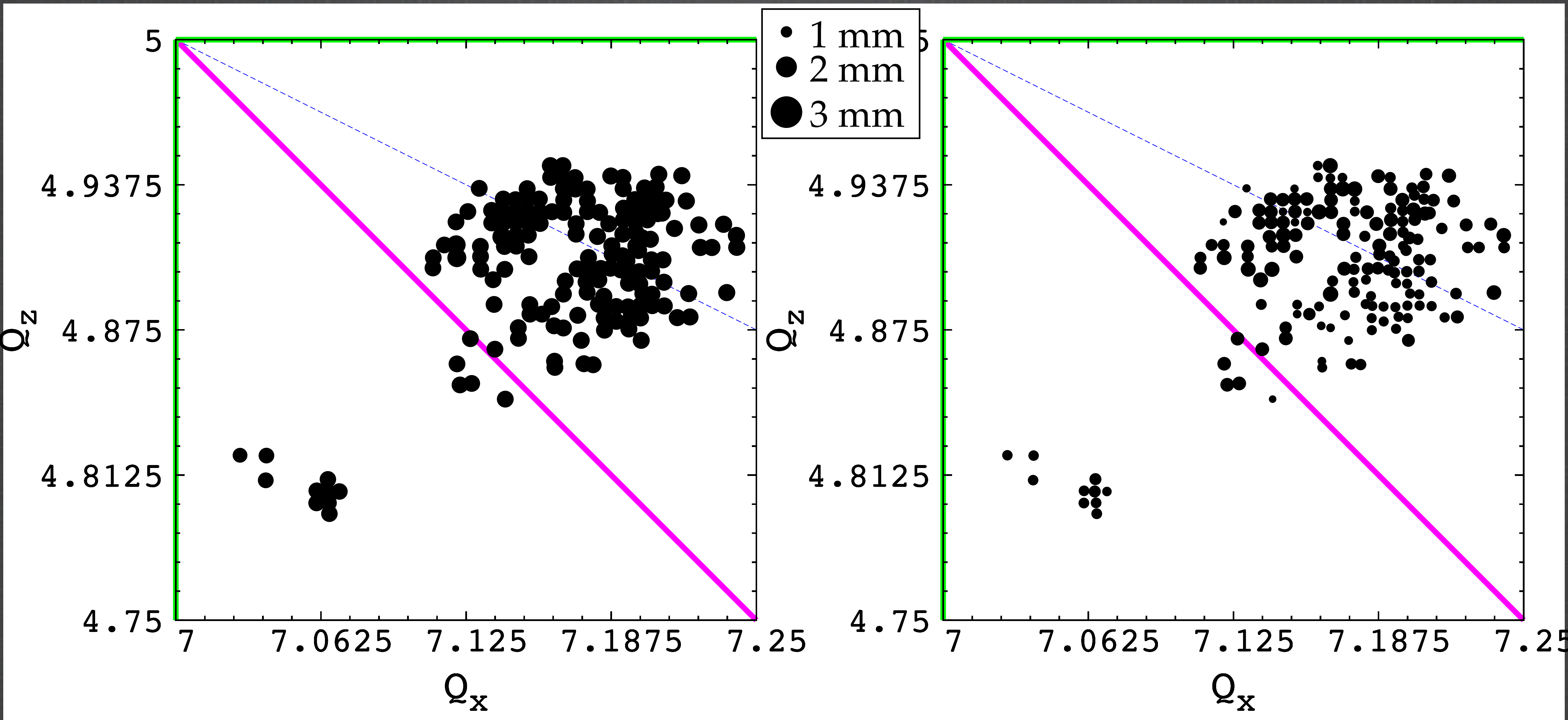
Quadruplet: tune optimization

Tune diagram



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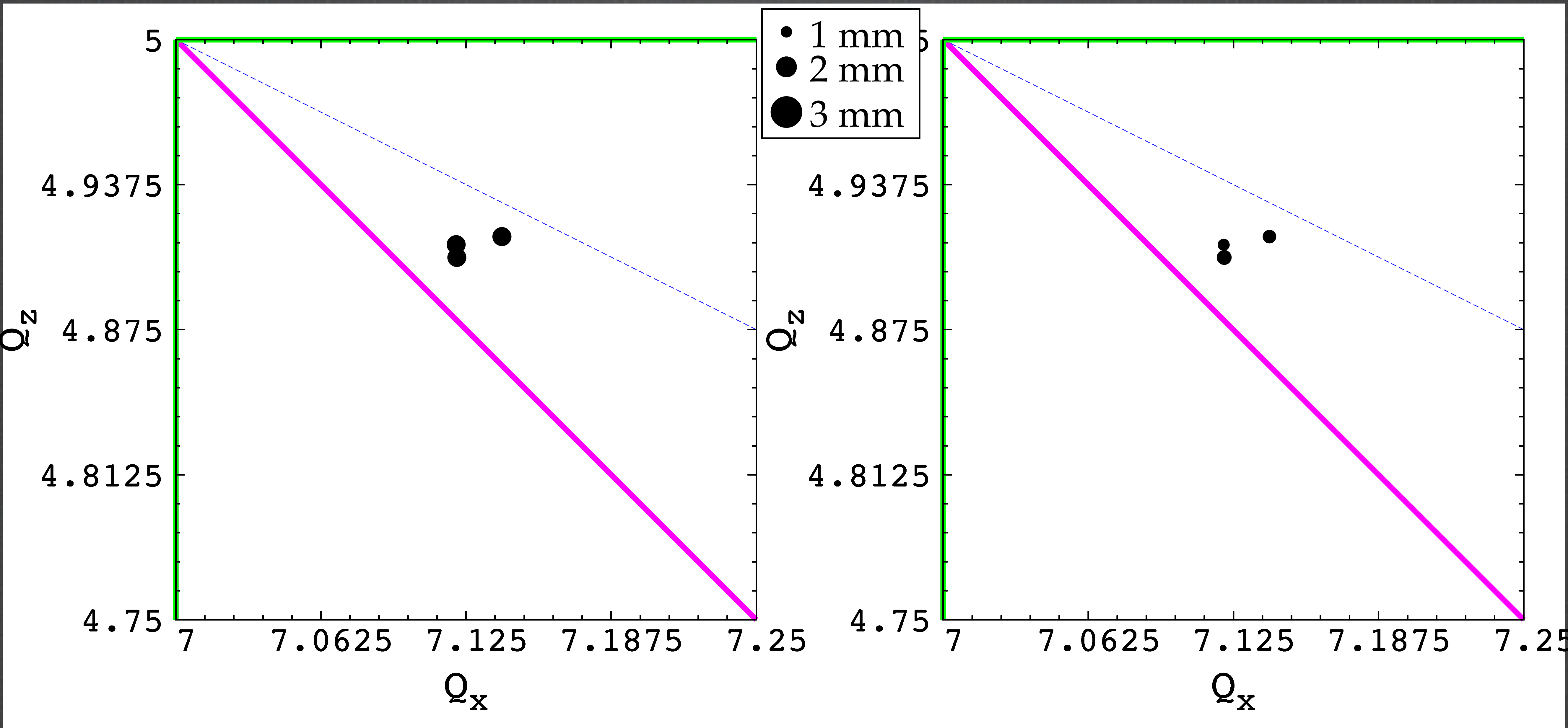
Quadruplet: tune optimization

Tune diagram

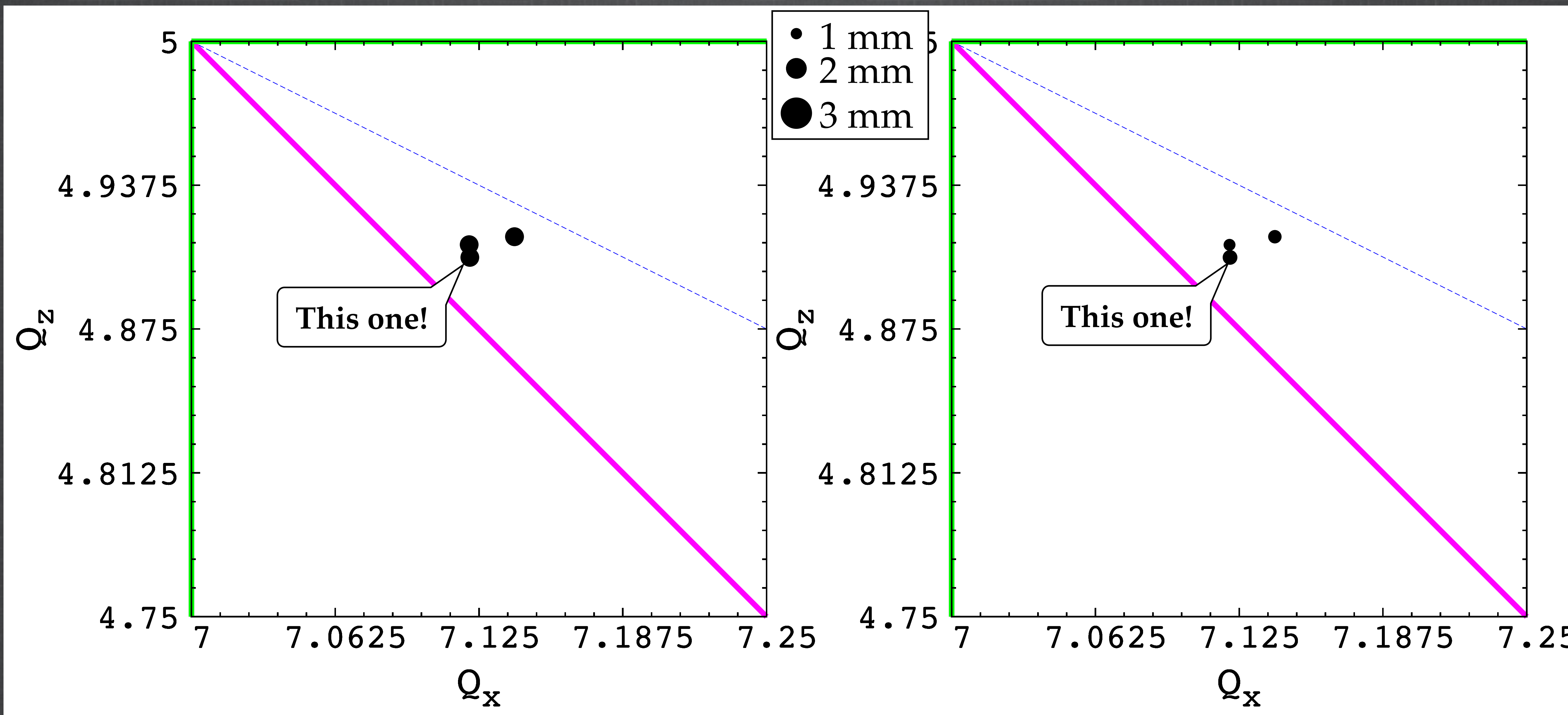


DA study in horizontal (left) and vertical (right)

$\varepsilon_H > 2$ mm.mrad

Quadruplet: tune optimization

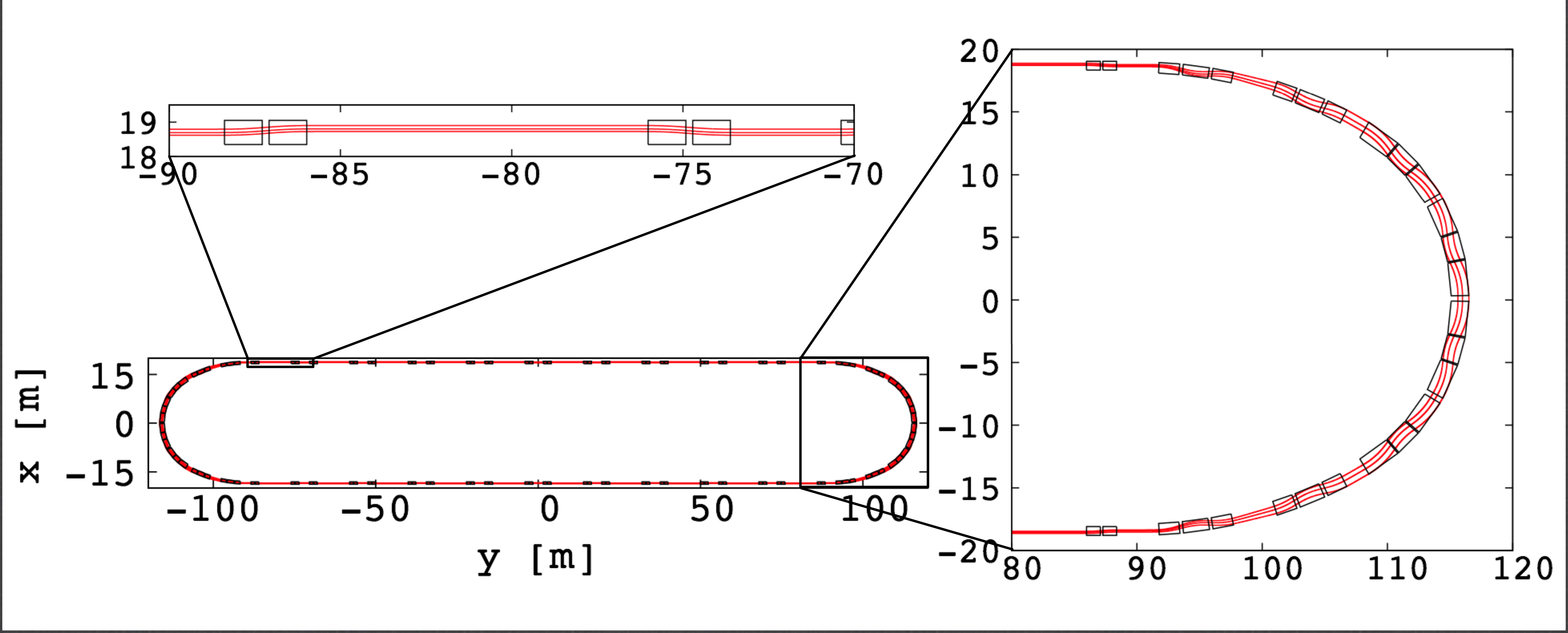
Tune diagram



DA study in horizontal (left) and vertical (right)

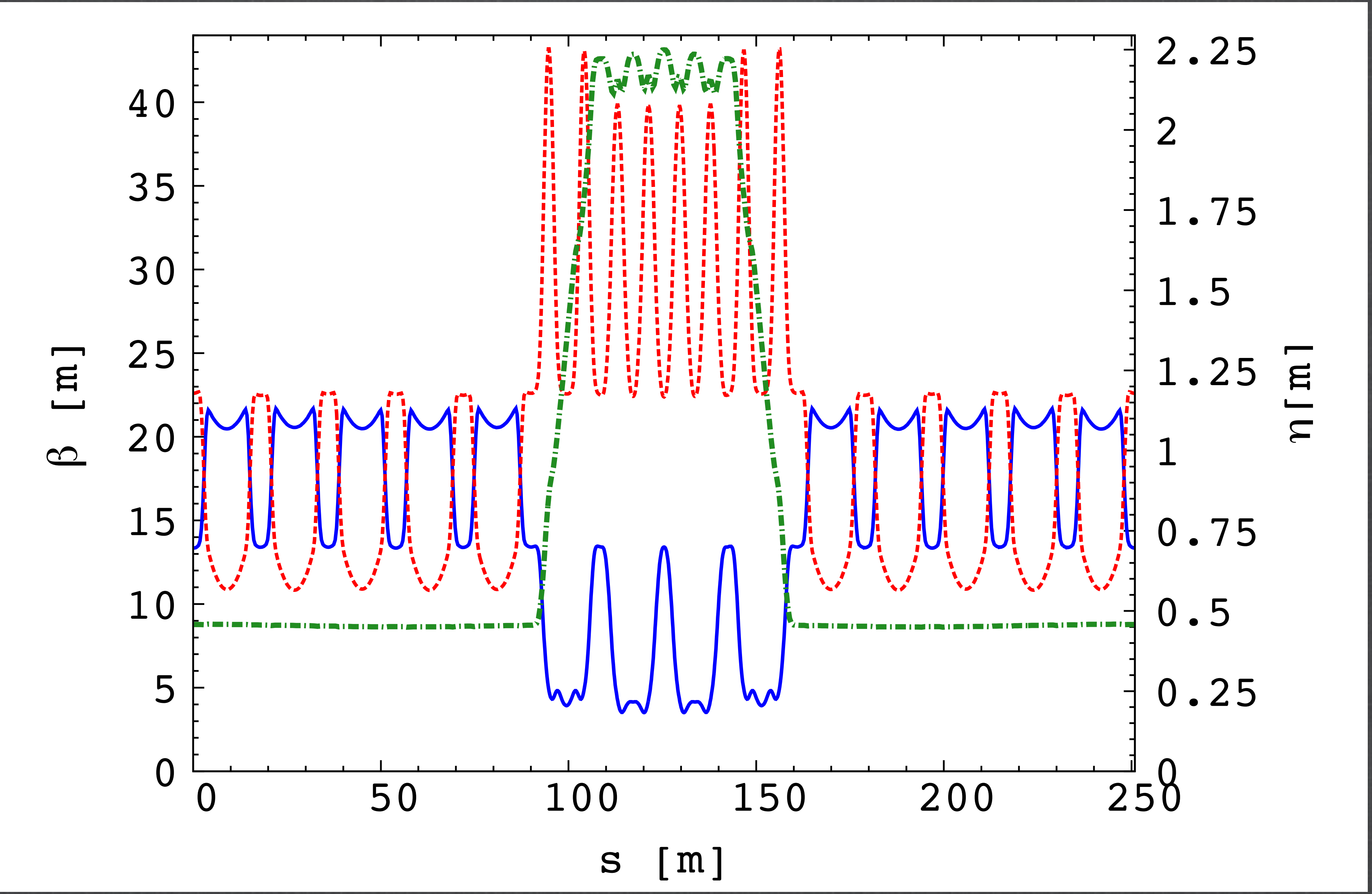
$\varepsilon_H > 2$ mm.mrad

Quadruplet solution



Quadruplet solution

Beta-functions and dispersion at matching momentum



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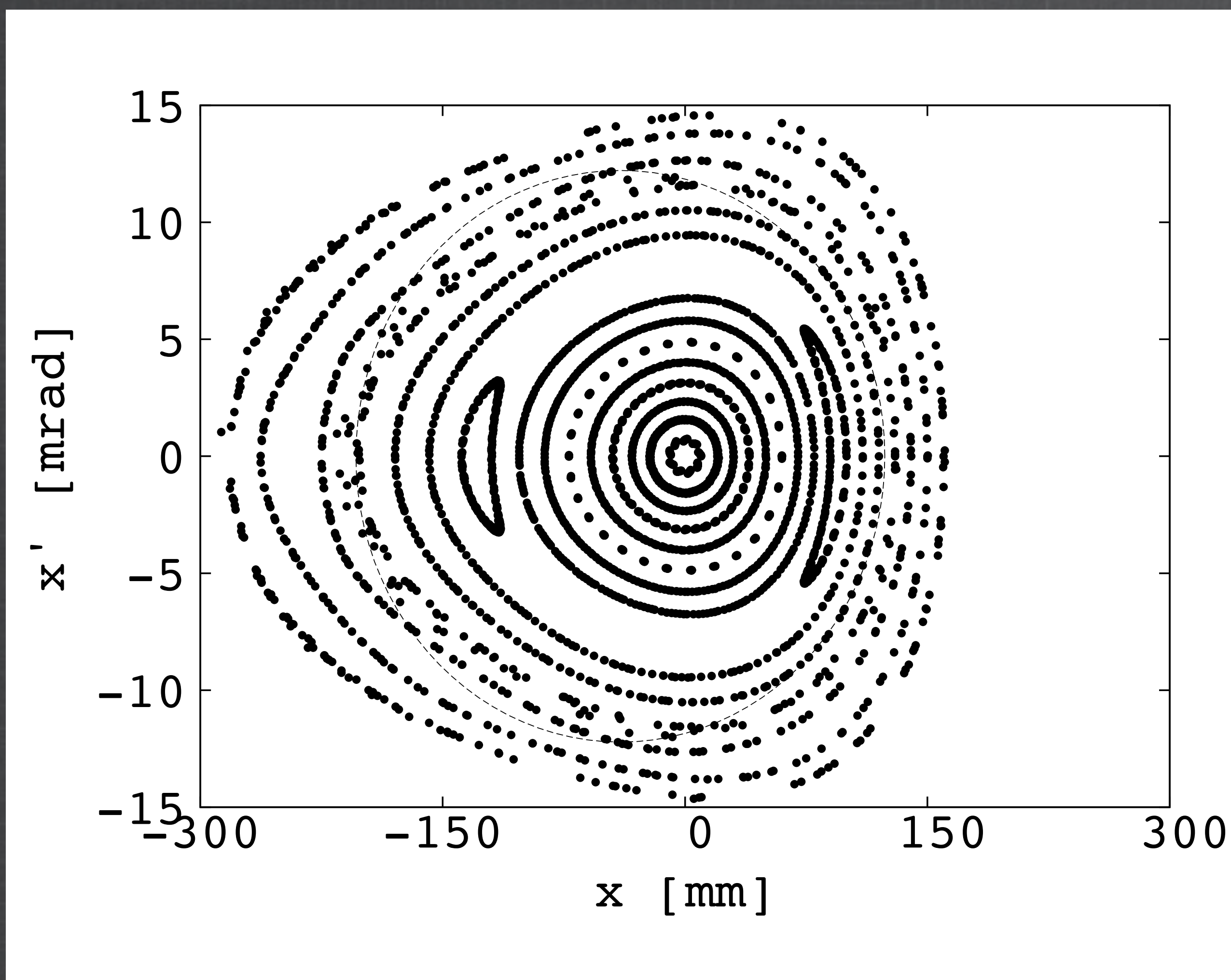
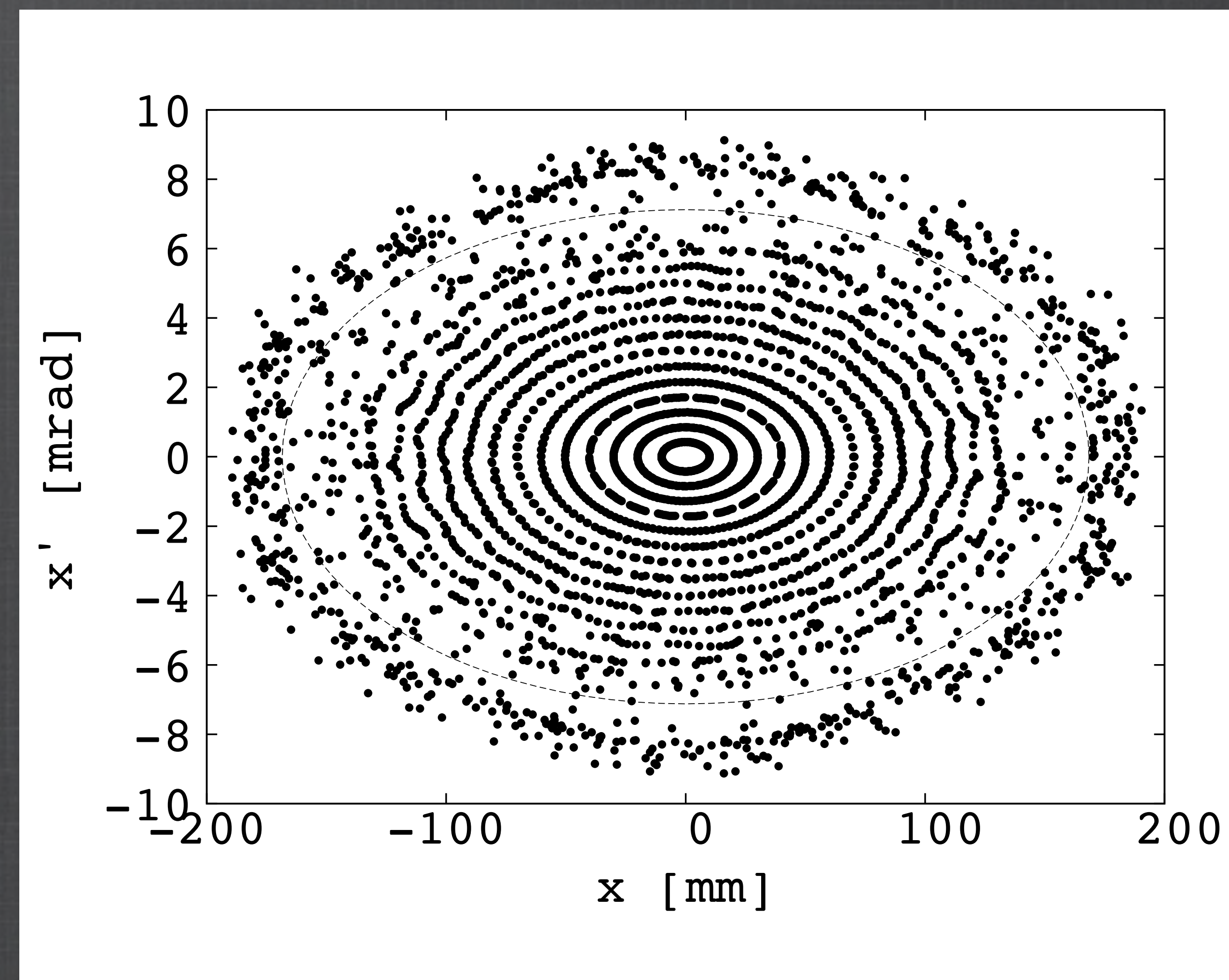
Quadruplet solution

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns

(Dotted ellipse represents 2 π.mm.rad)

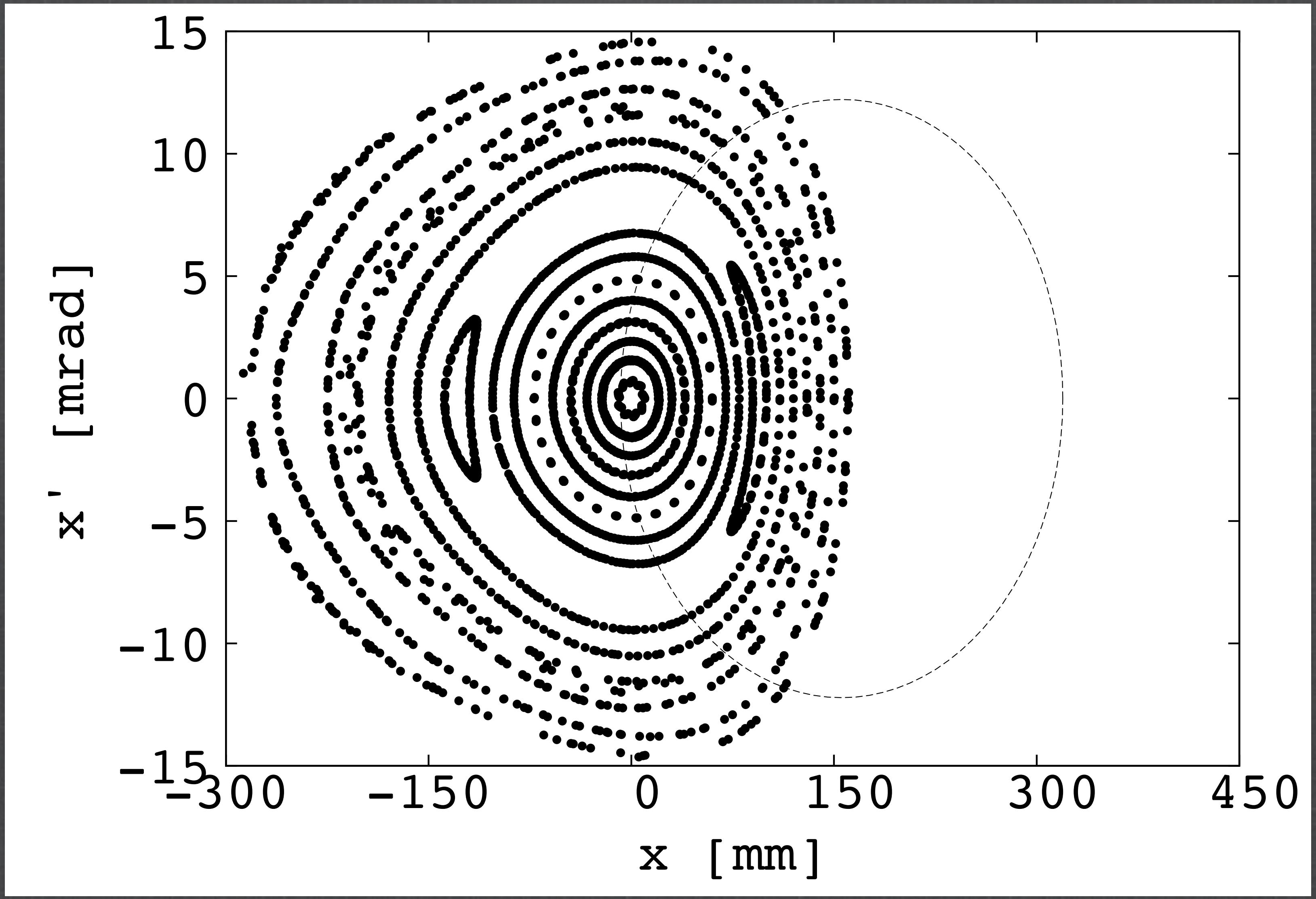


Maximum vertical stable amplitude over 100 turns

(Dotted ellipse represents 1.2 π.mm.rad)

Quadruplet solution

Muon capture efficiency



Maximum vertical stable amplitude over 100 turns

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

nuSTORM Summary

- nuSTORM produces a new type of conventional neutrino beam from pion decay and muon decay
- Facility with strong physics interest (Sterile neutrino search, Cross-section measurements, long-baseline oscillation search), and accelerator and detector R&D test bed.
- New zero-chromatic FFAG decay ring designs with large DA, large momentum acceptance. Lattice optimised with a DA scan in the tune diagram.

nuSTORM Future plans

- Multi-particle tracking to confirm the DA.
- Study of tolerance to errors (field error and misalignment) in FFAG and FoDo lattices.
- Investigation of a zero-dispersion (chromatic!) straight capture section with FFAG arcs to increase muon capture efficiency and reduce chromaticity of FoDo.

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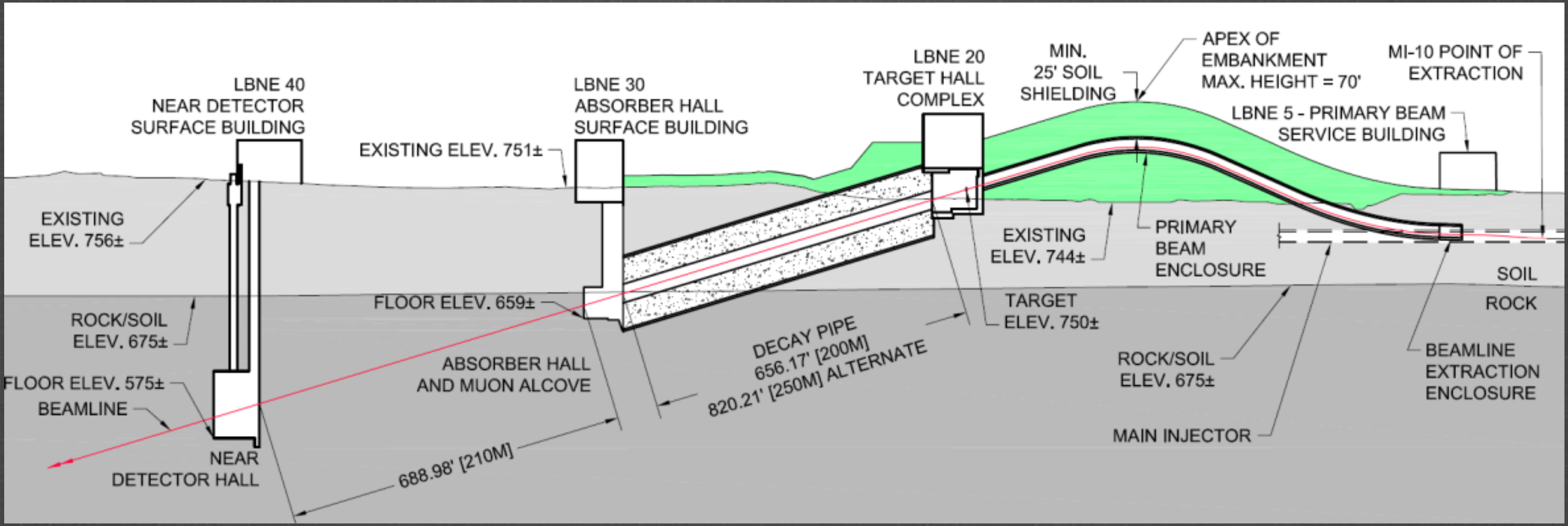
Motivation



(LBNF Letter of Intent, Jan 2015)

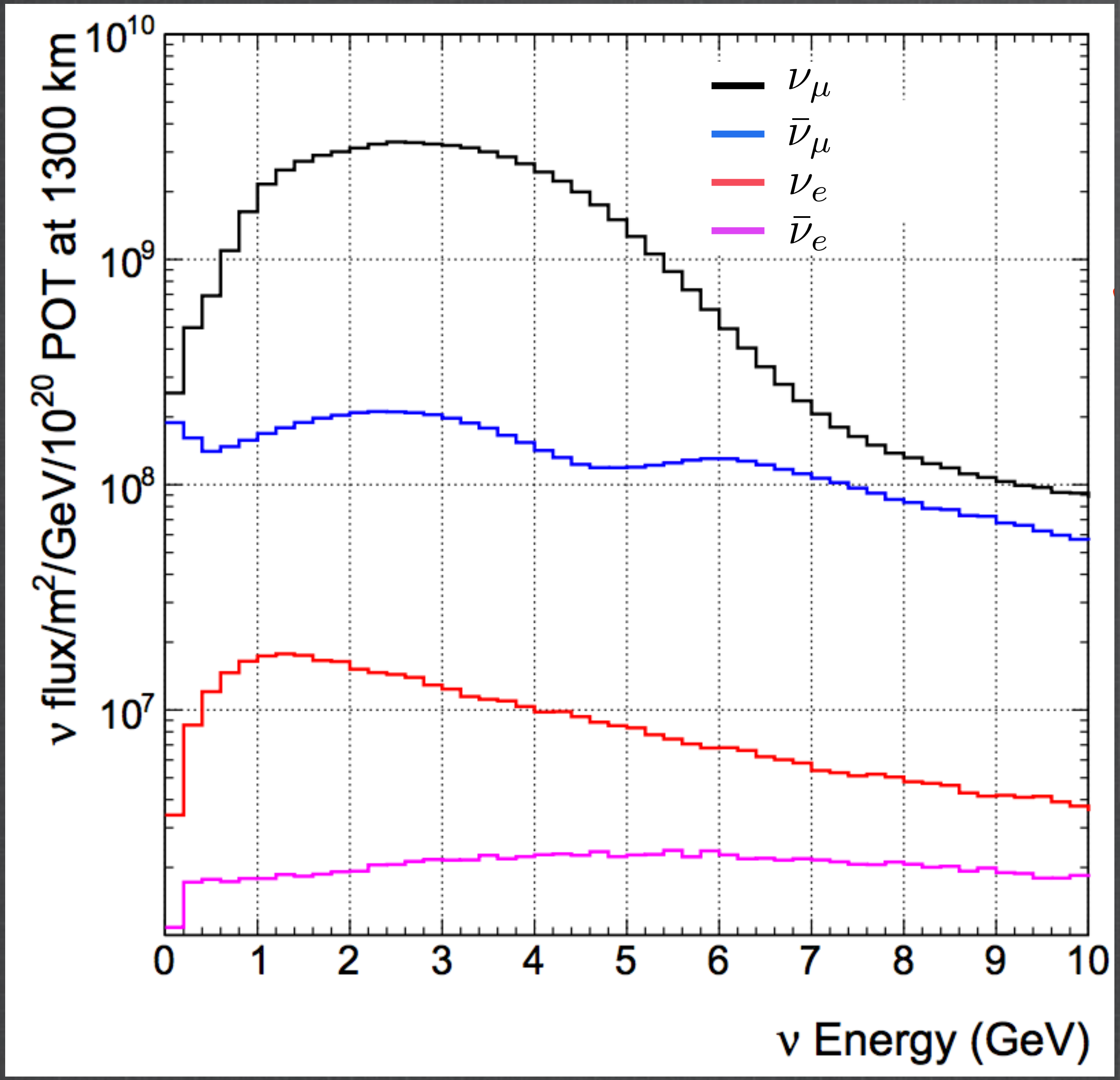
Decay pipe:

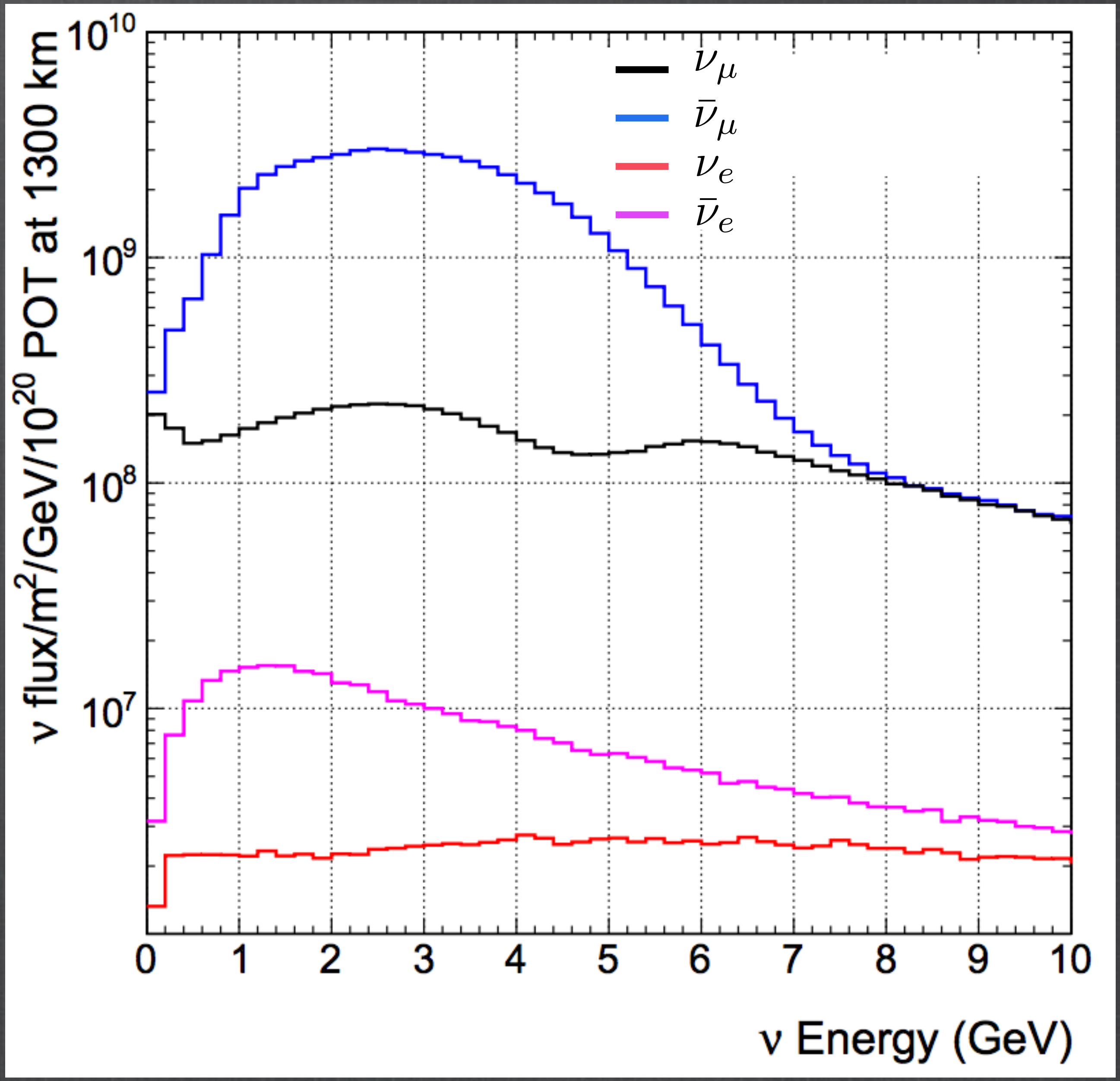
- 6 (4?) m diameter,
- filled with Helium,
- 7 m of concrete around the pipe to shield it.

→ 20 m diameter tunnel!

Neutrino Flux at DUNE

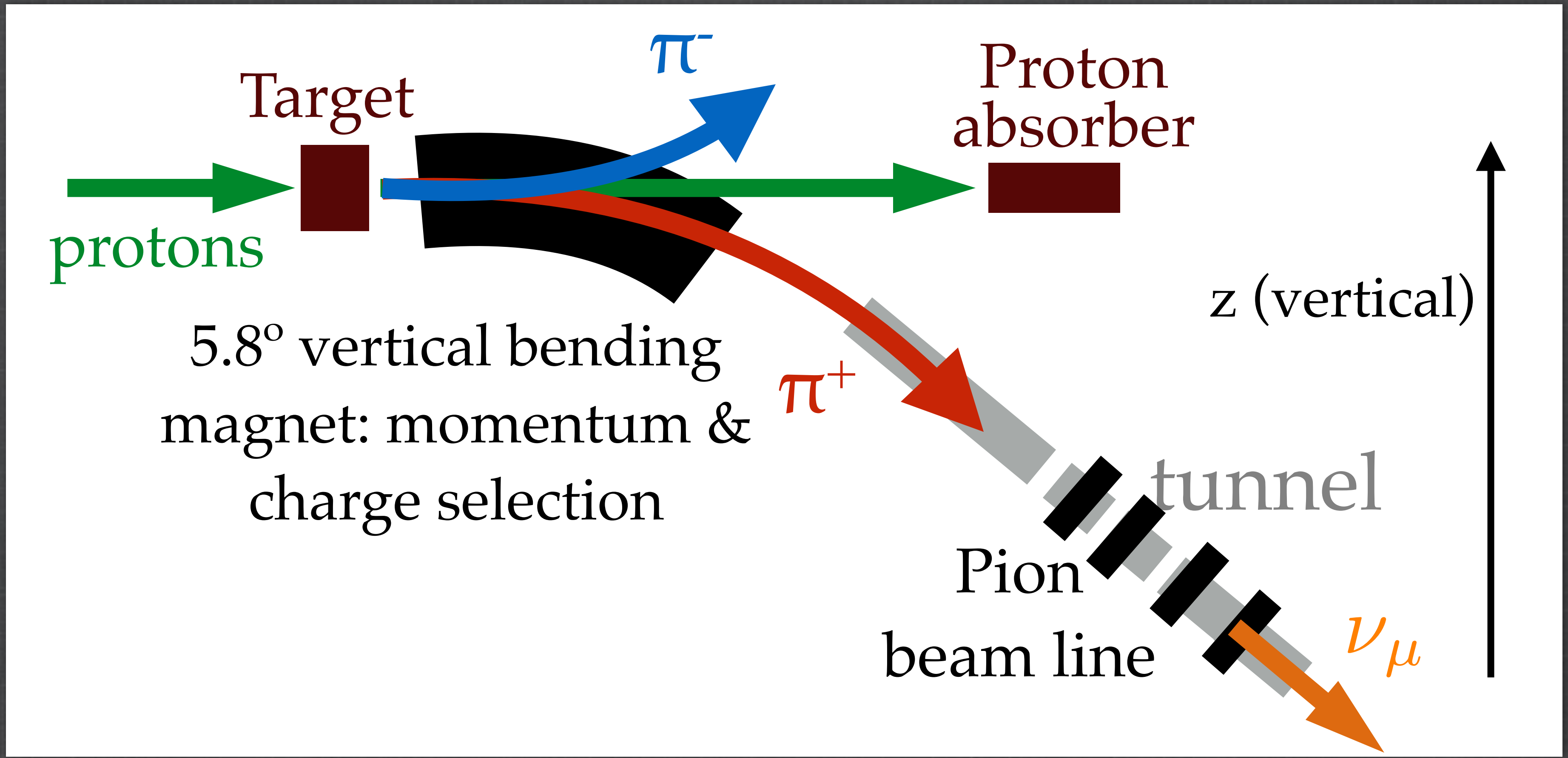
(CDR-Physics Volume)





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

General Concept



Pion beam line

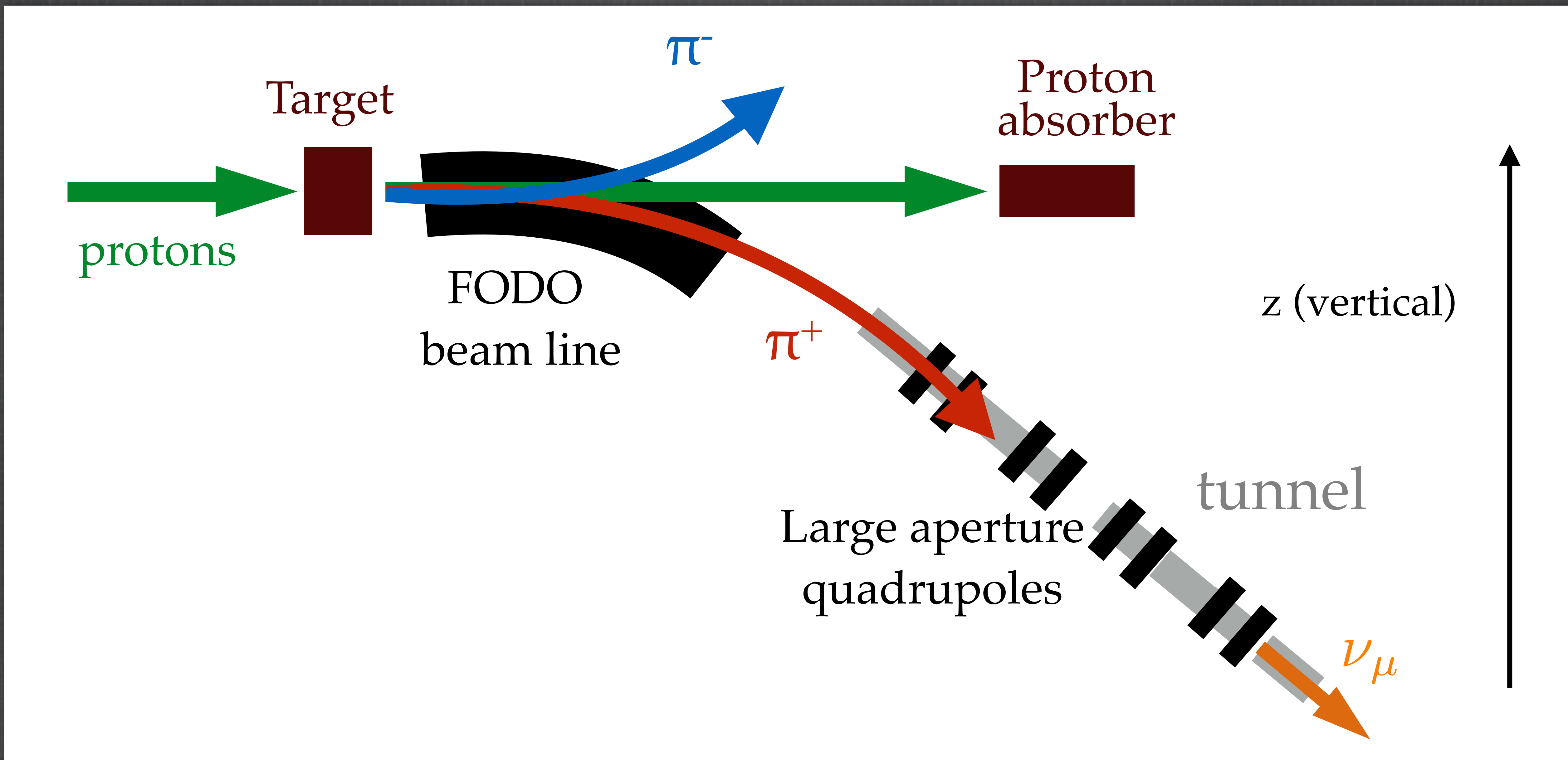
- clean, well known flux
- smaller tunnel (conventional pion beam line)
- Detector does not need to be magnetised

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

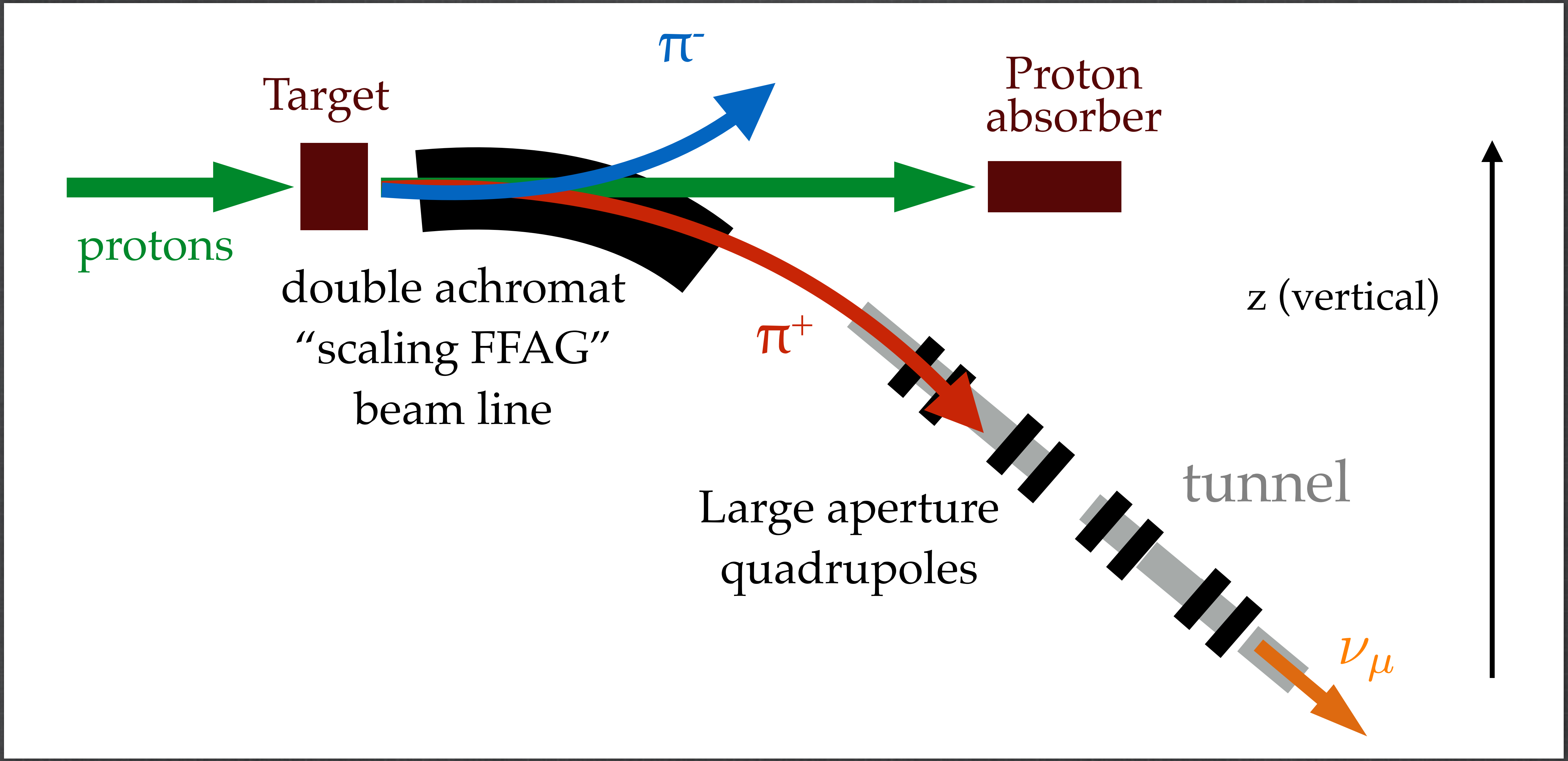
General Parameters

- Pions 7 GeV/c ± 50%
- Normal conducting range (KEK radiation hard coils)
- C-shape magnet

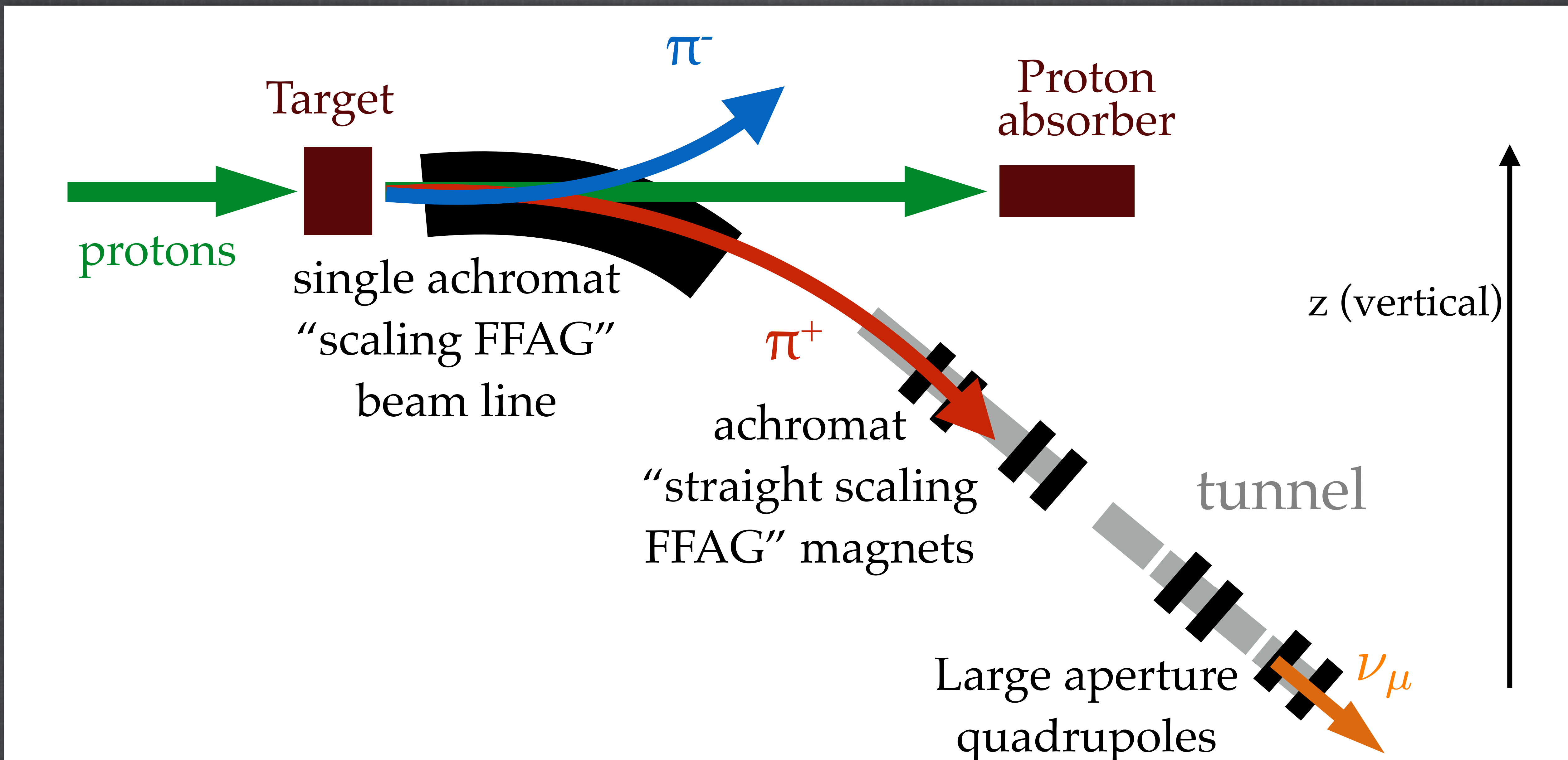
First design concept



Second design concept



Third design concept



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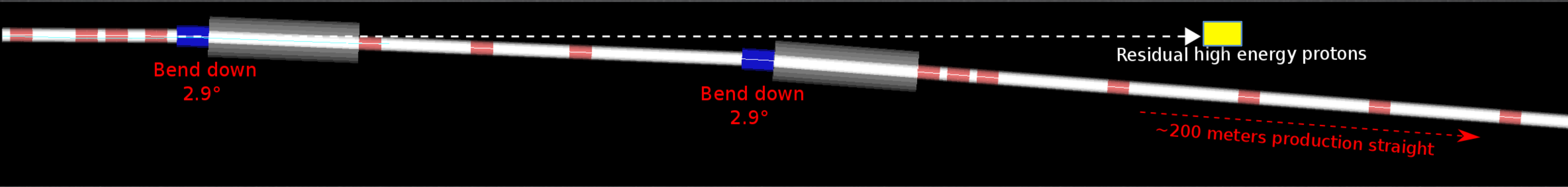
Preliminary results

No optimization yet

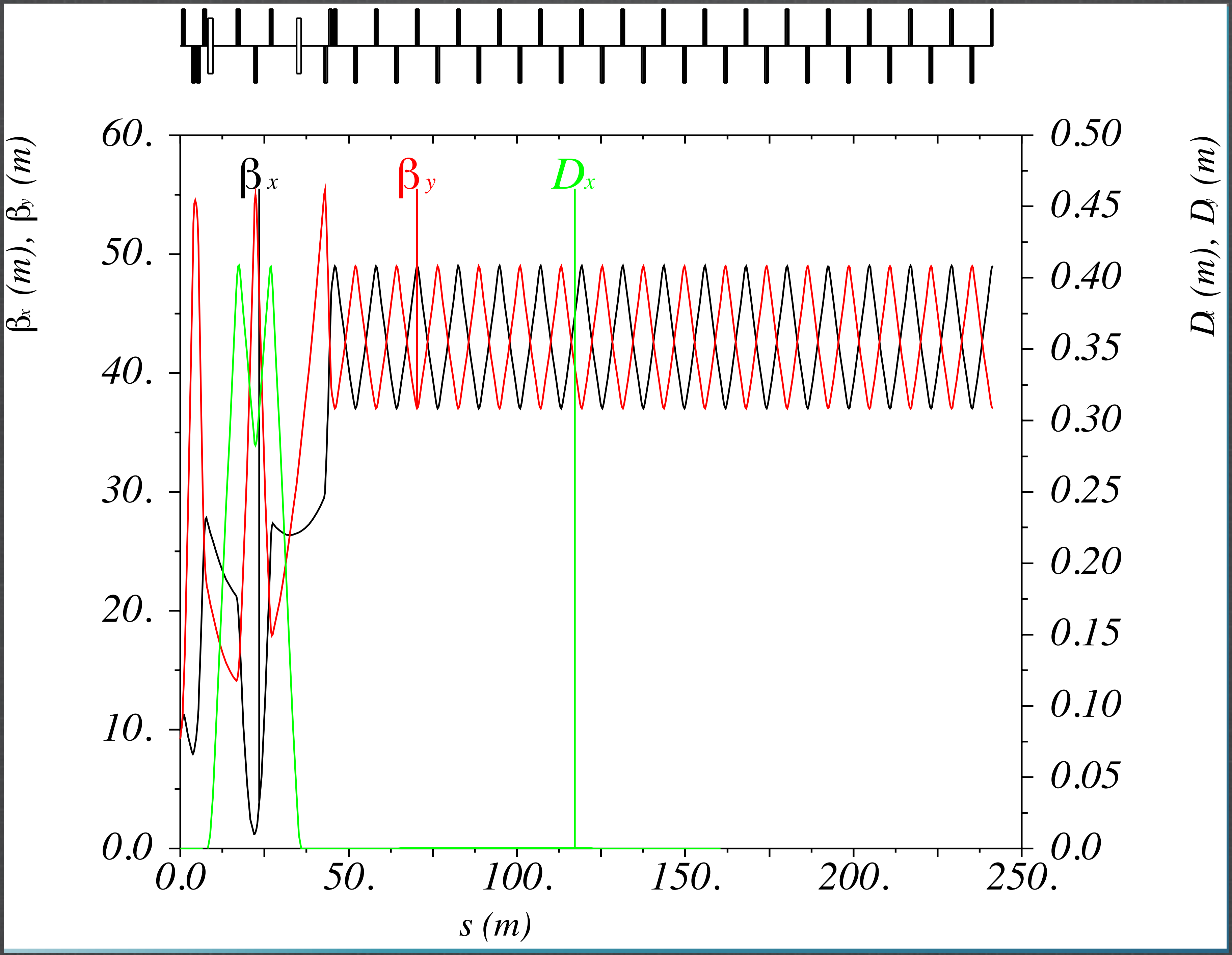
FODO beam line



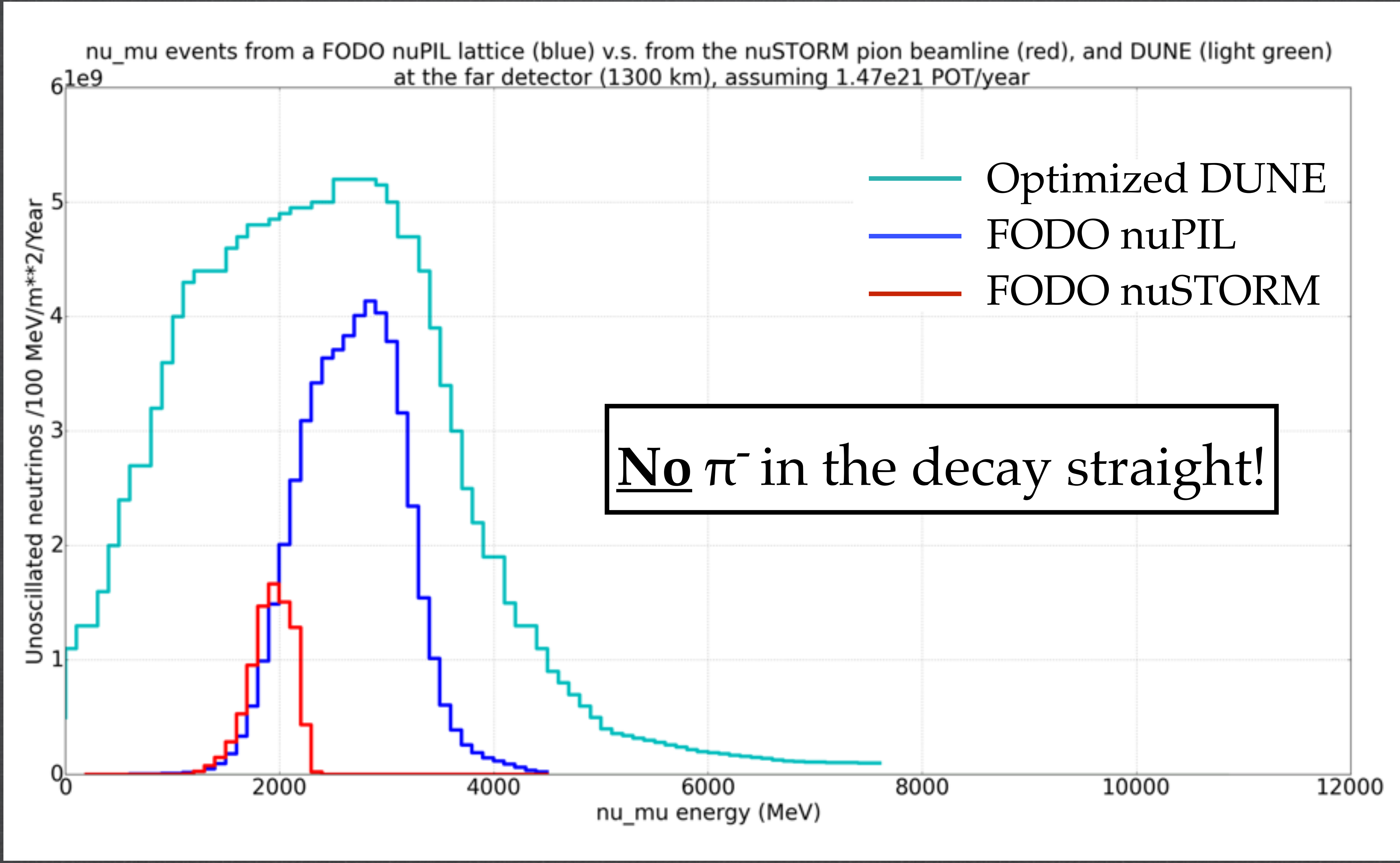
Total length 240 m.

Tracked in G4BL.

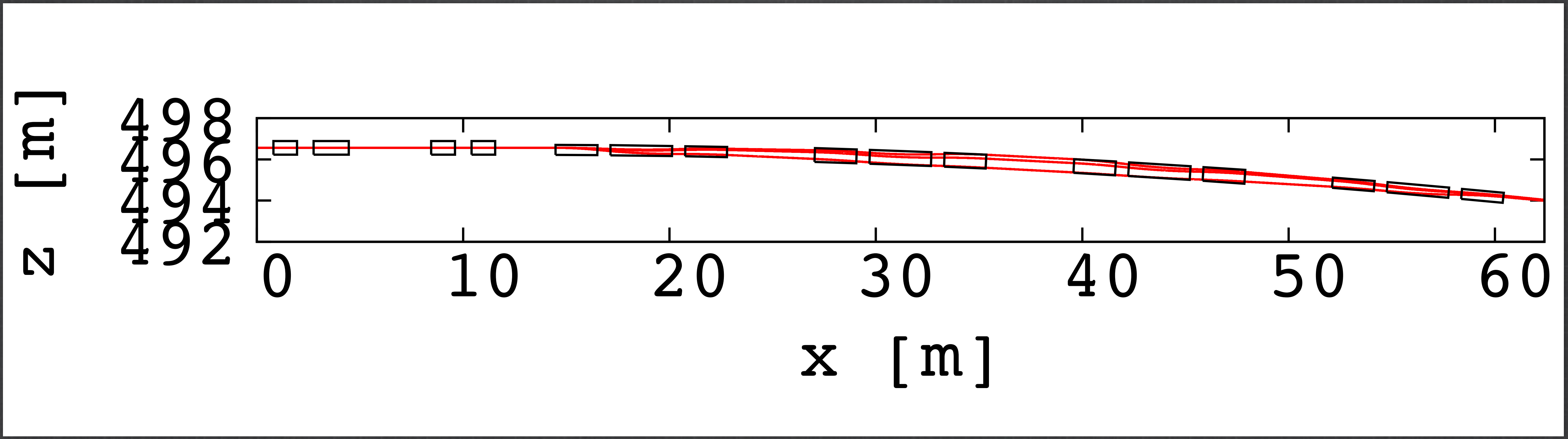
FODO beam line
Beam optics



FODO beam line
Flux

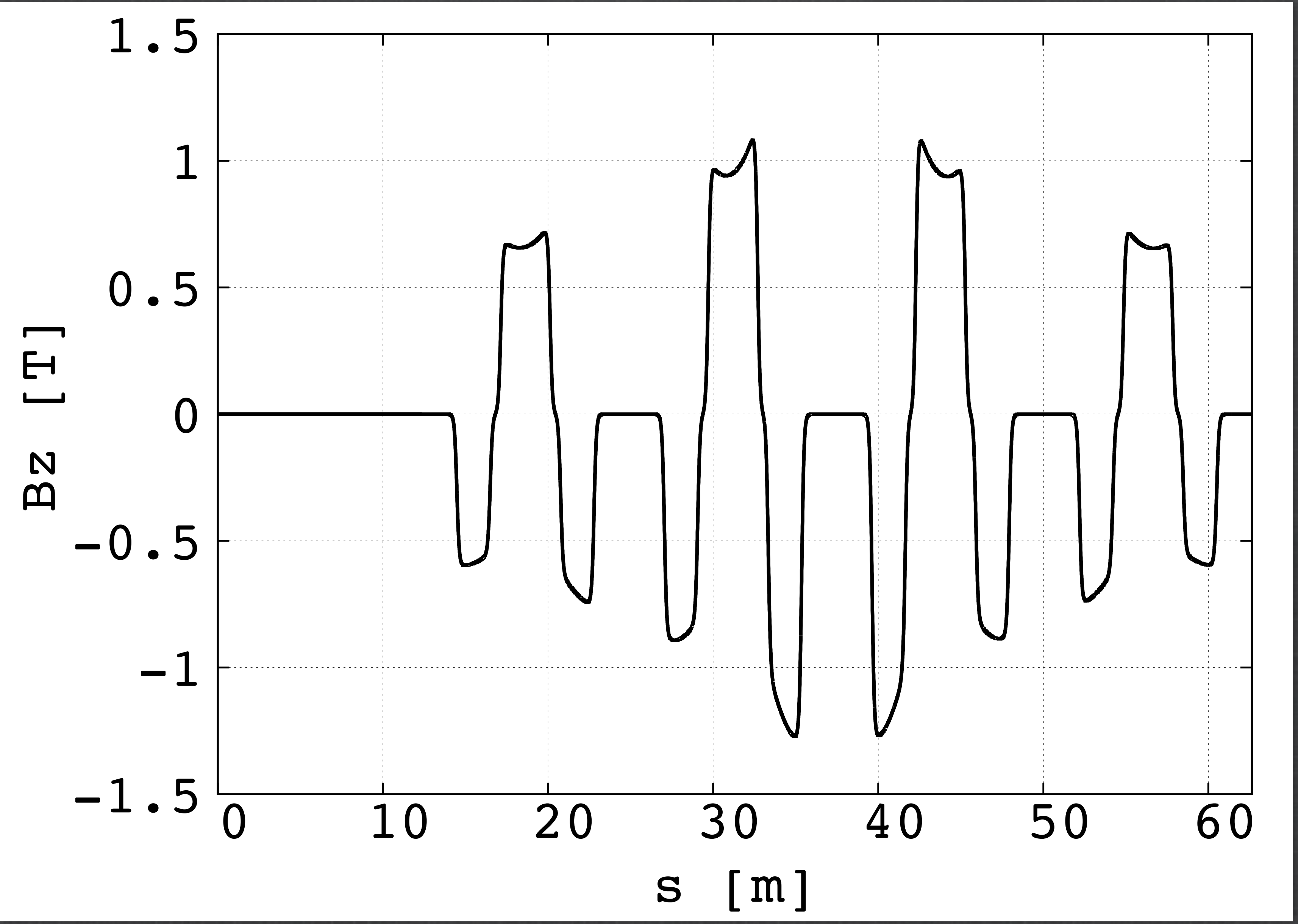


Double achromat FFAG beam line



- 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.

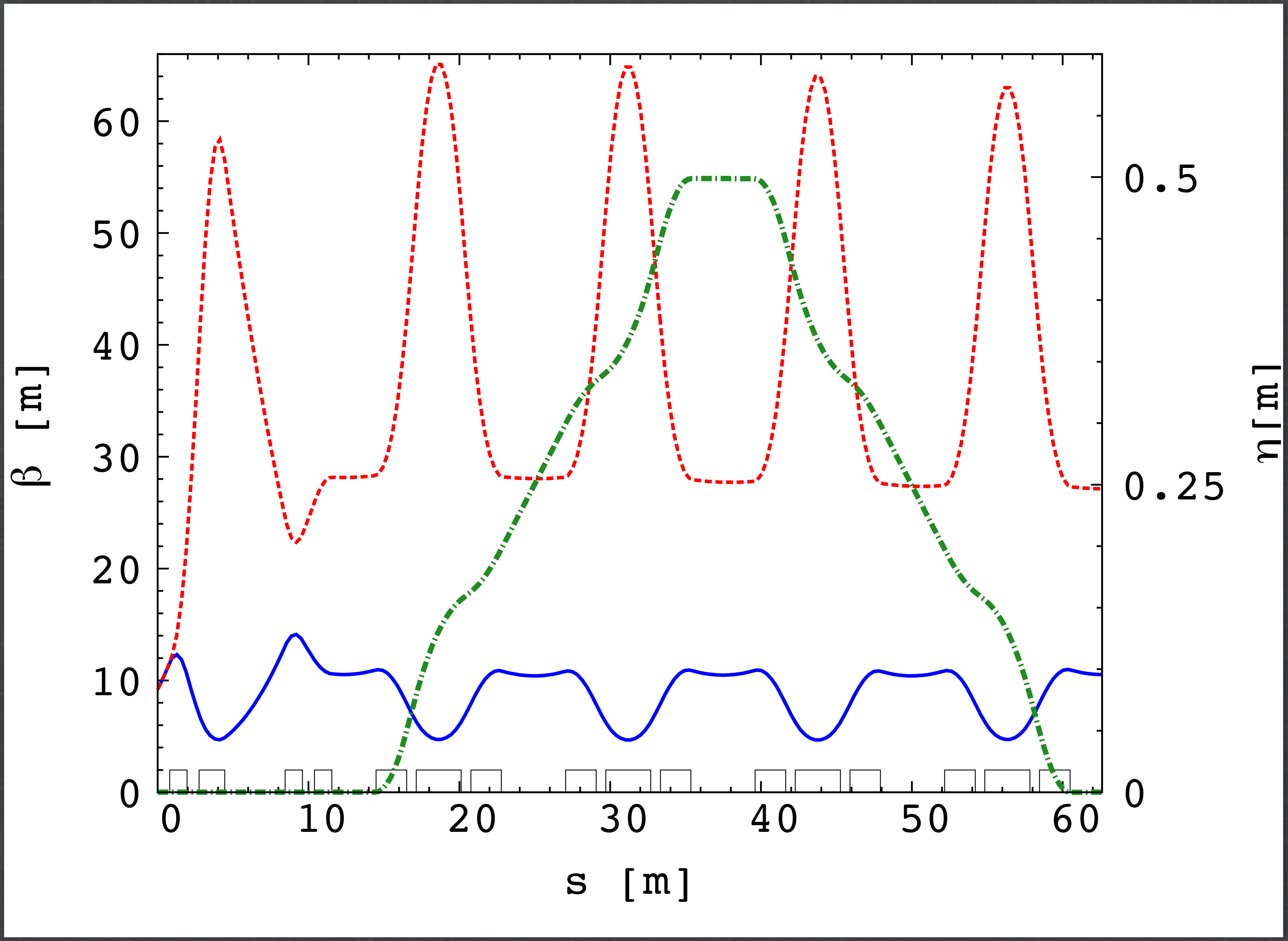
Double achromat FFAG beam line



Magnetic field for P_{max} (10.5 GeV/c)

double achromat FFAG beam line

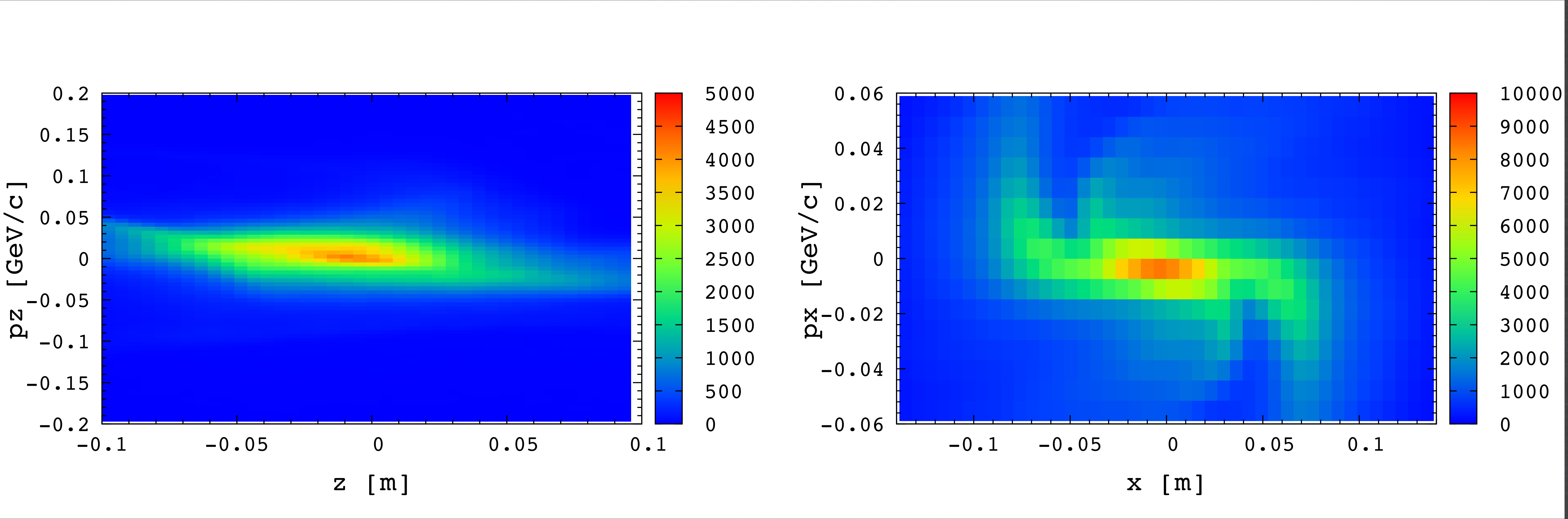
Beta-functions and dispersion at matching momentum



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

double achromat FFAG beam line

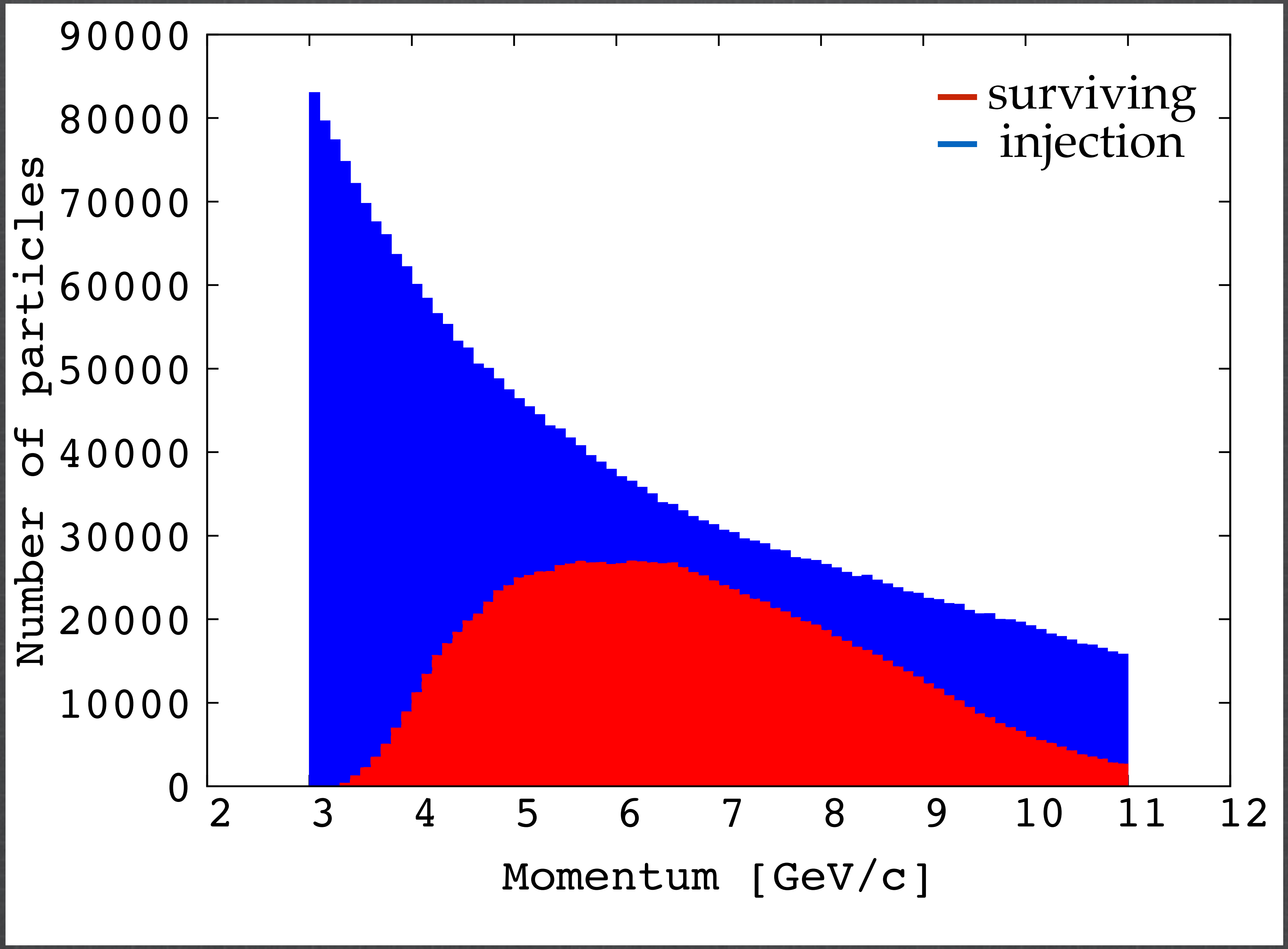
~2.9 10^6 particles (distribution from the horn) → 42.6% survival



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

double achromat FFAG beam line

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

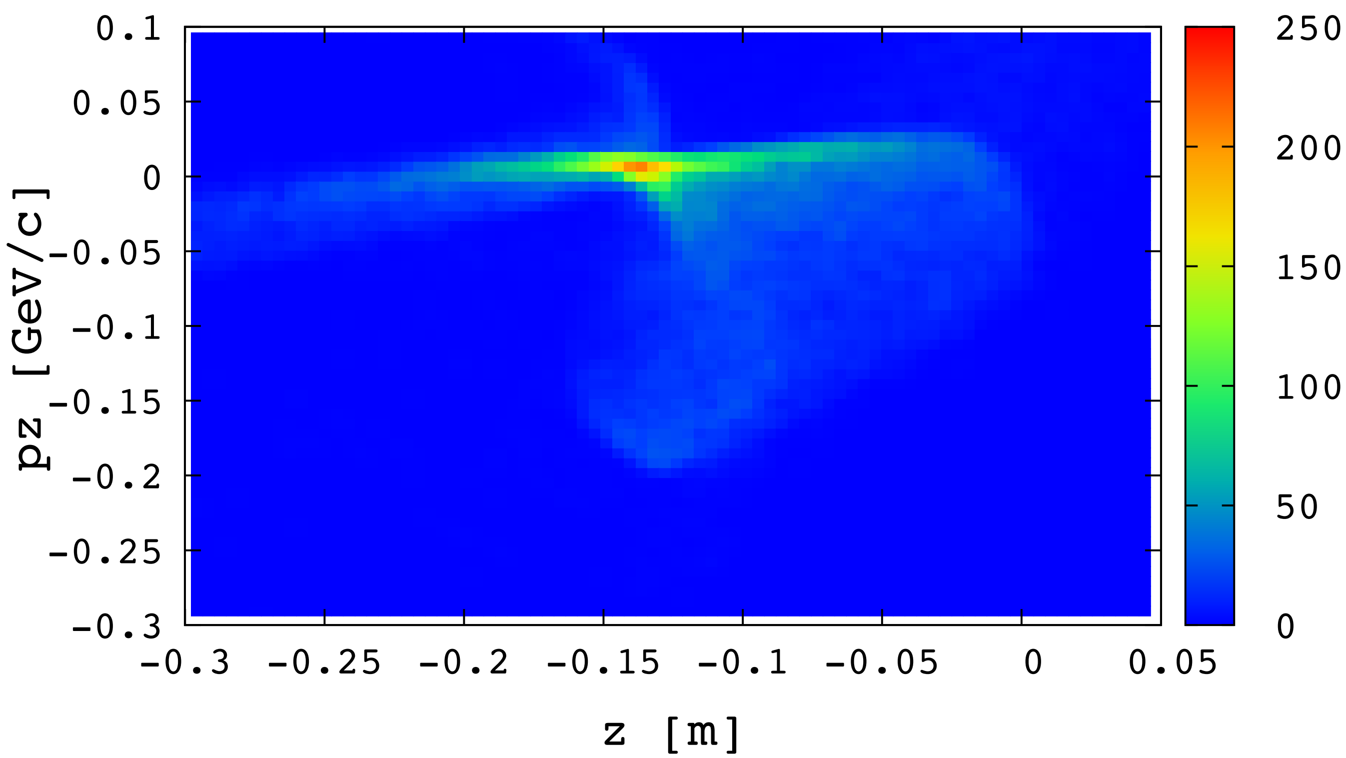


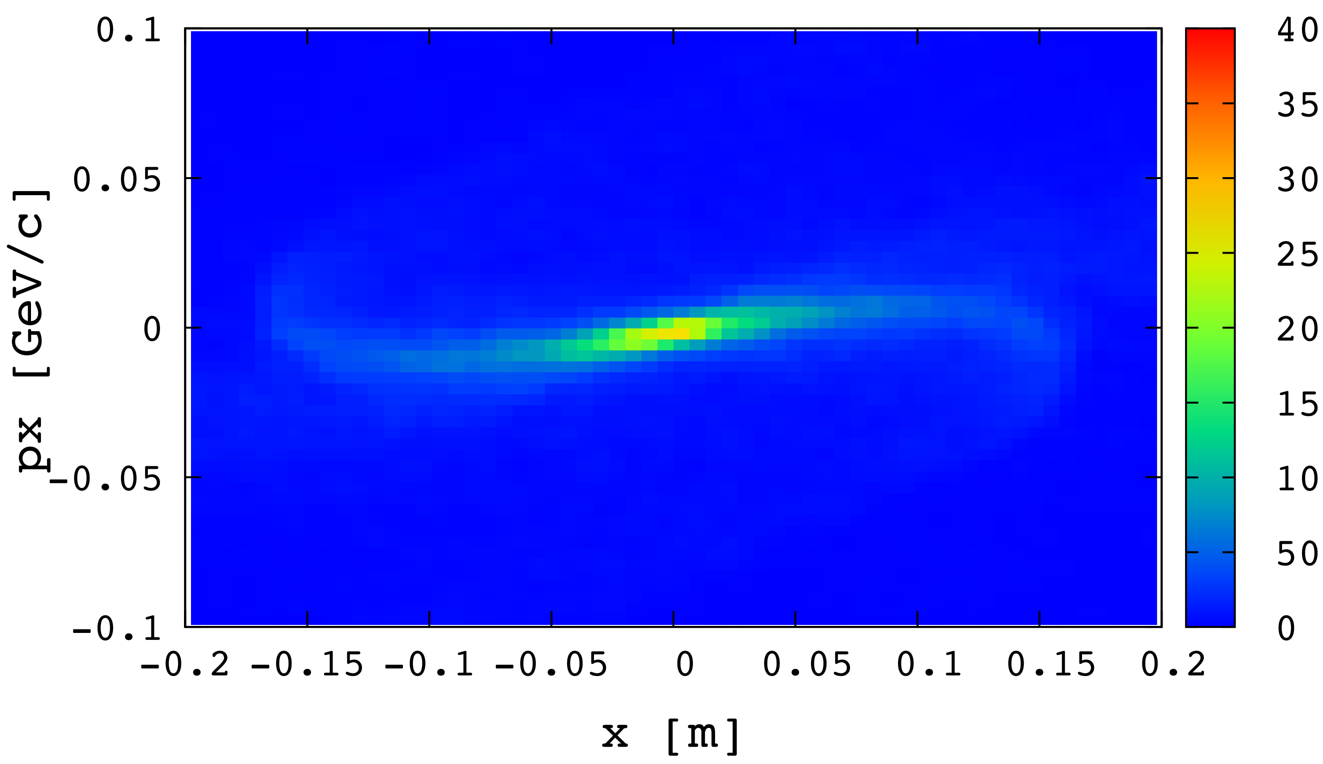
Momentum range at the injection (blue) and for the surviving particles (red) after tracking.

double achromat FFAG beam line

Wrong Sign Survival

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



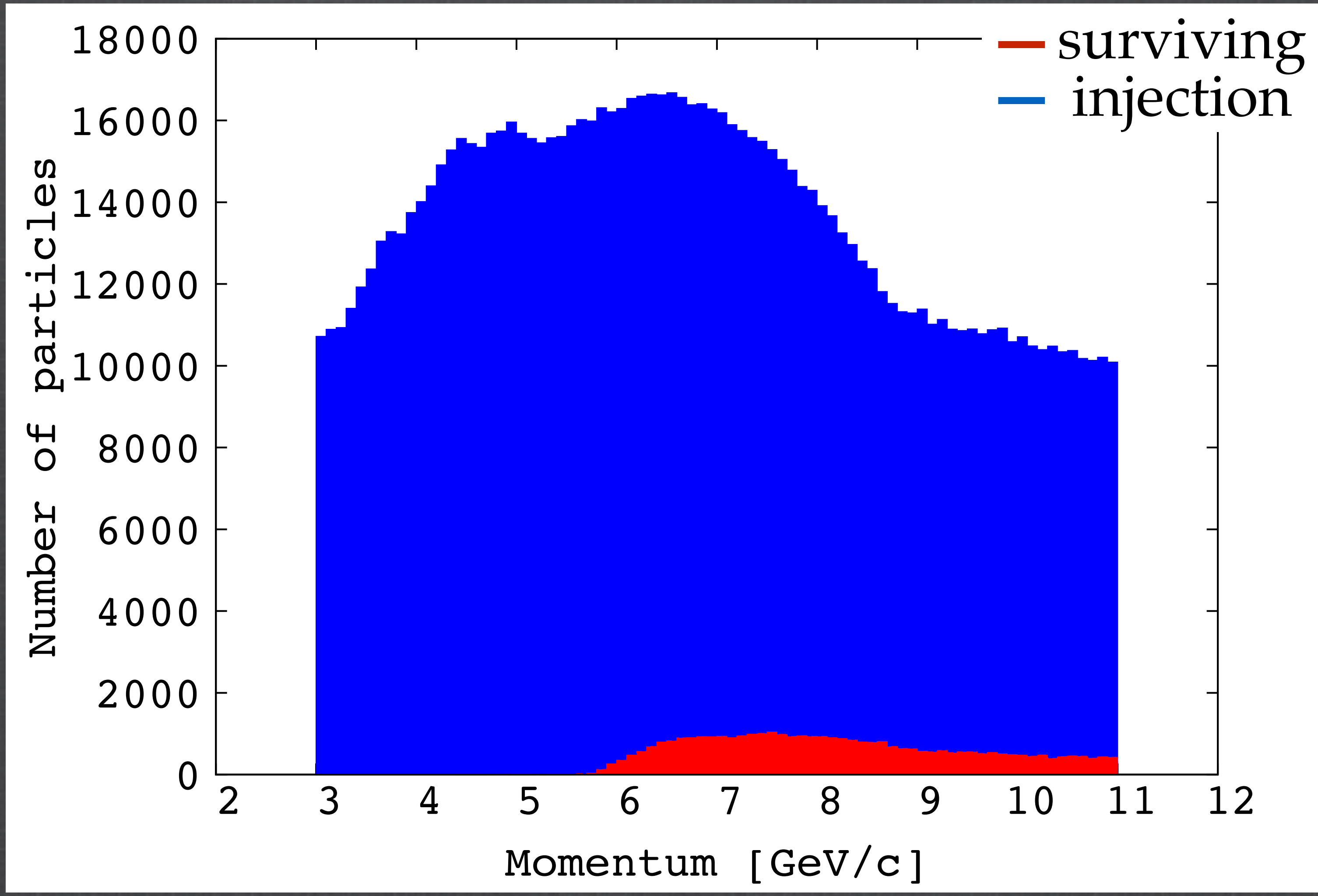


Surviving particles in vertical (left) and horizontal (right) phase spaces

double achromat FFAG beam line

Wrong Sign Survival

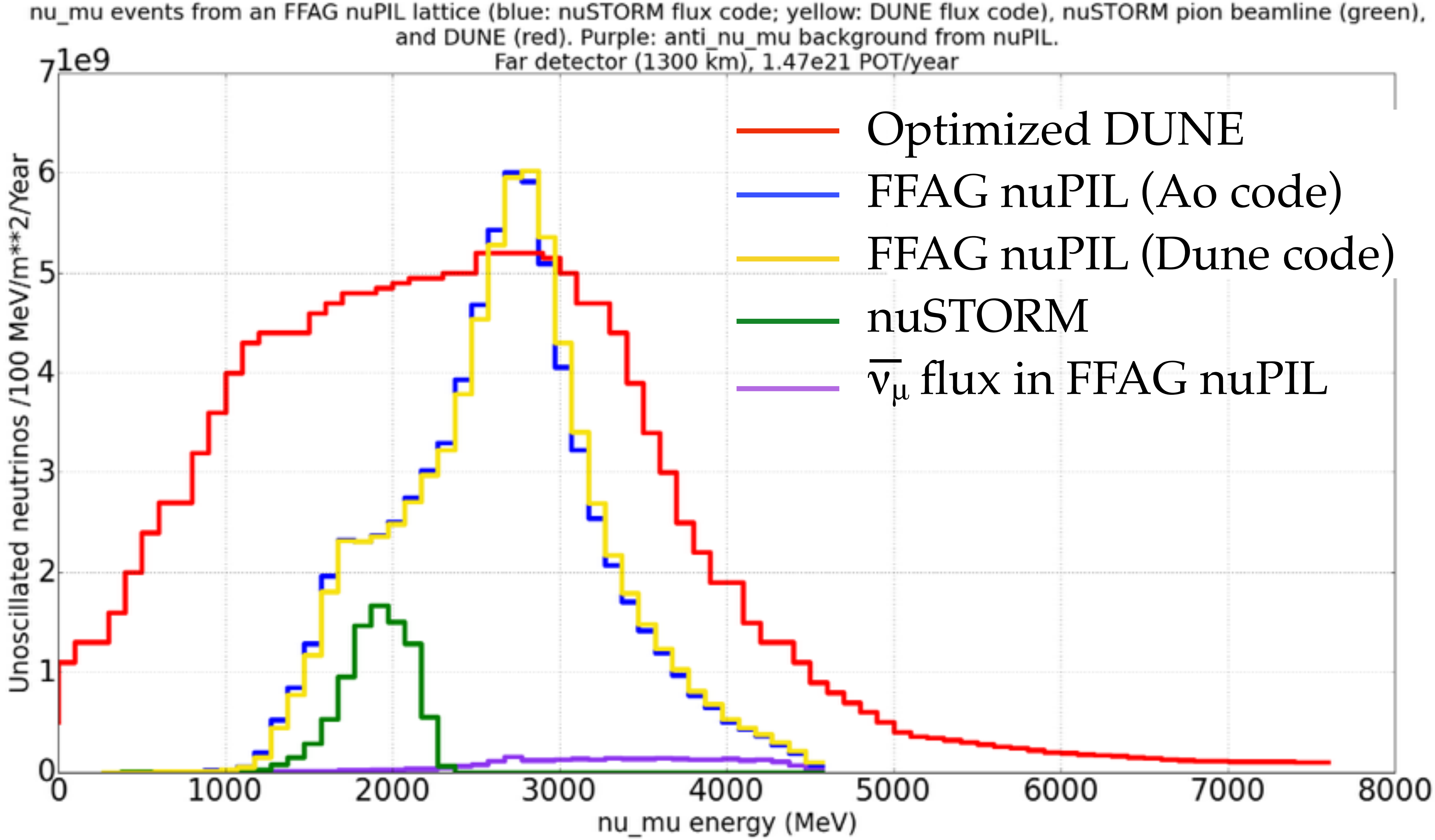
~1.1 10^6 particles (distribution from the horn) → 3.2% survival



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

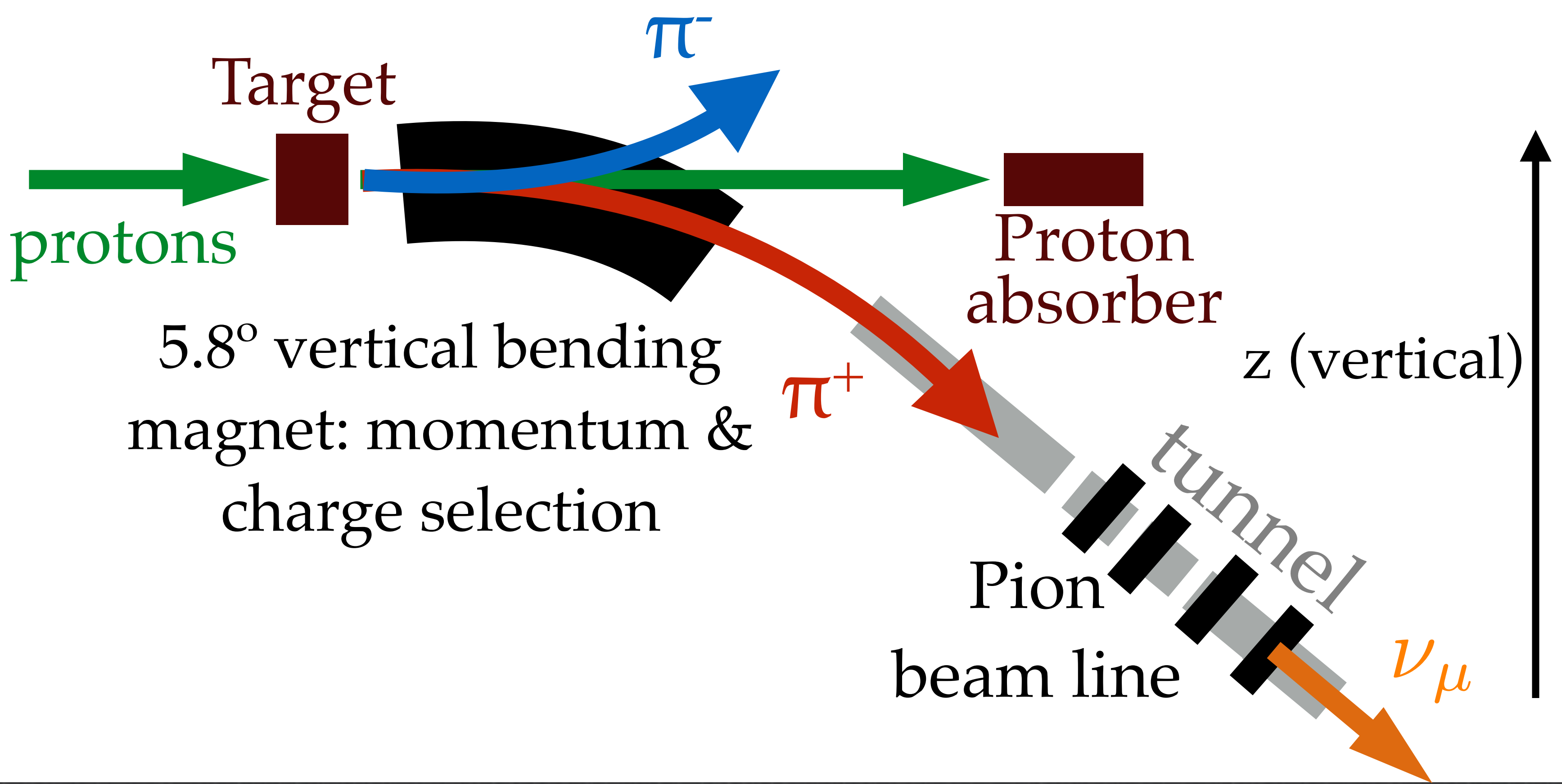
double achromat FFAG beam line

Flux

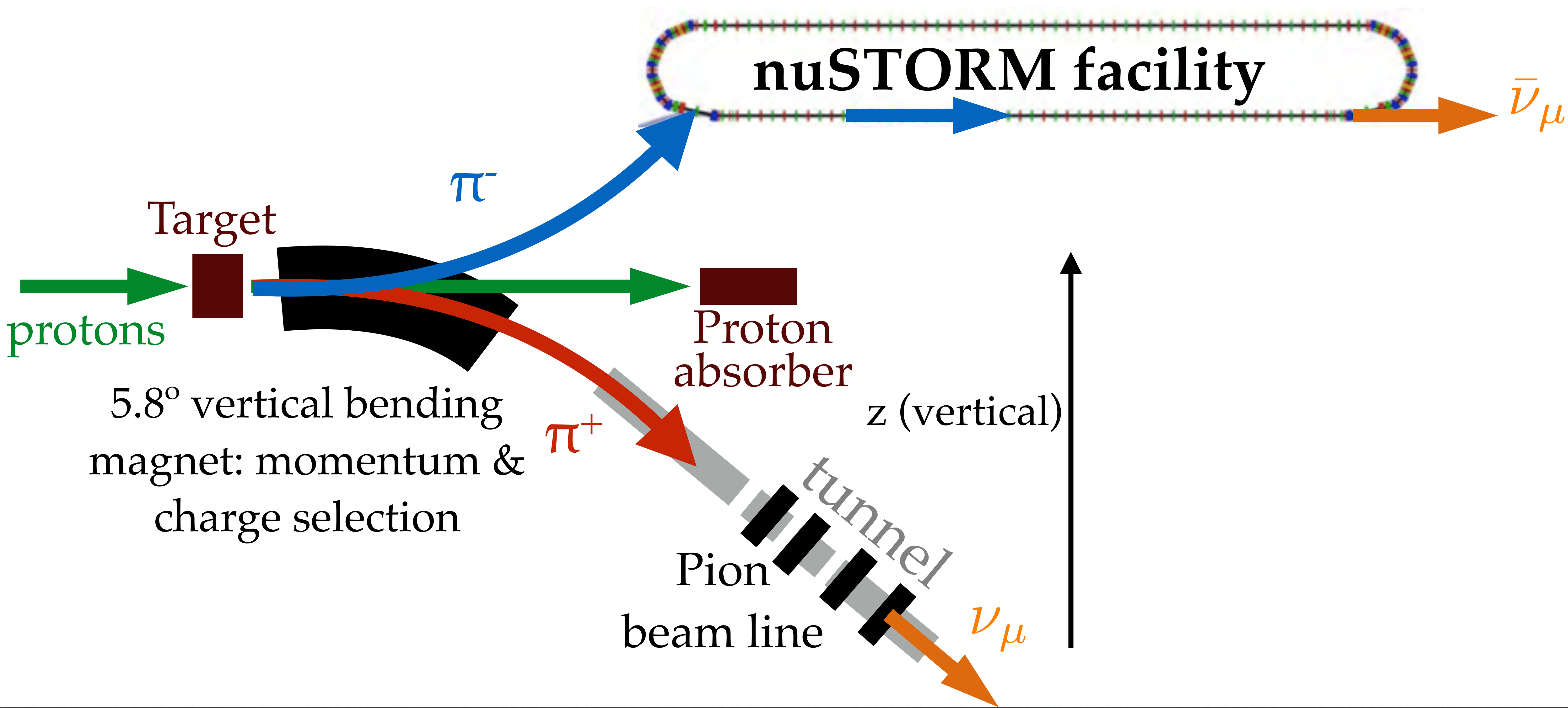


Going further...

Going even further...

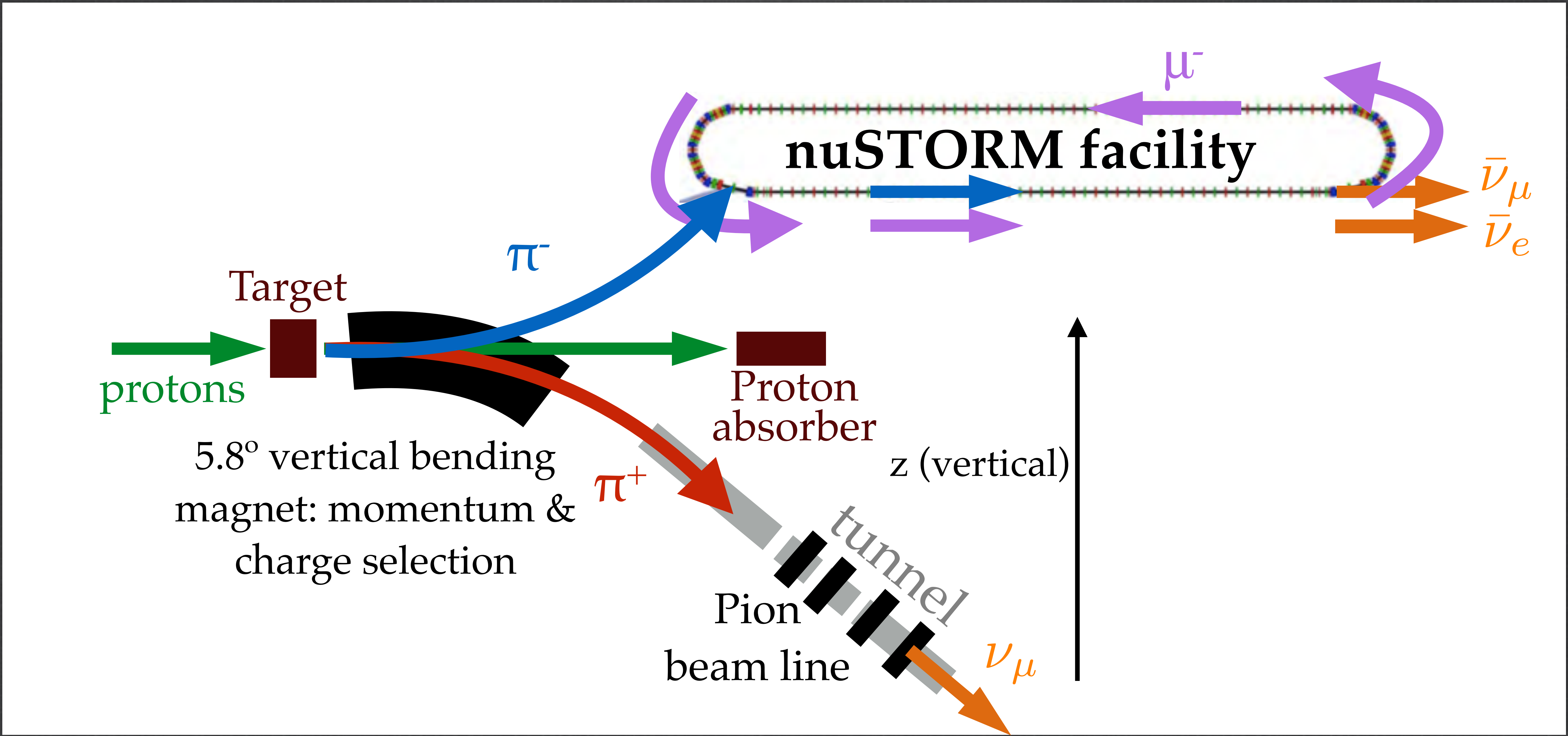


nuPIL AND nuSTORM?



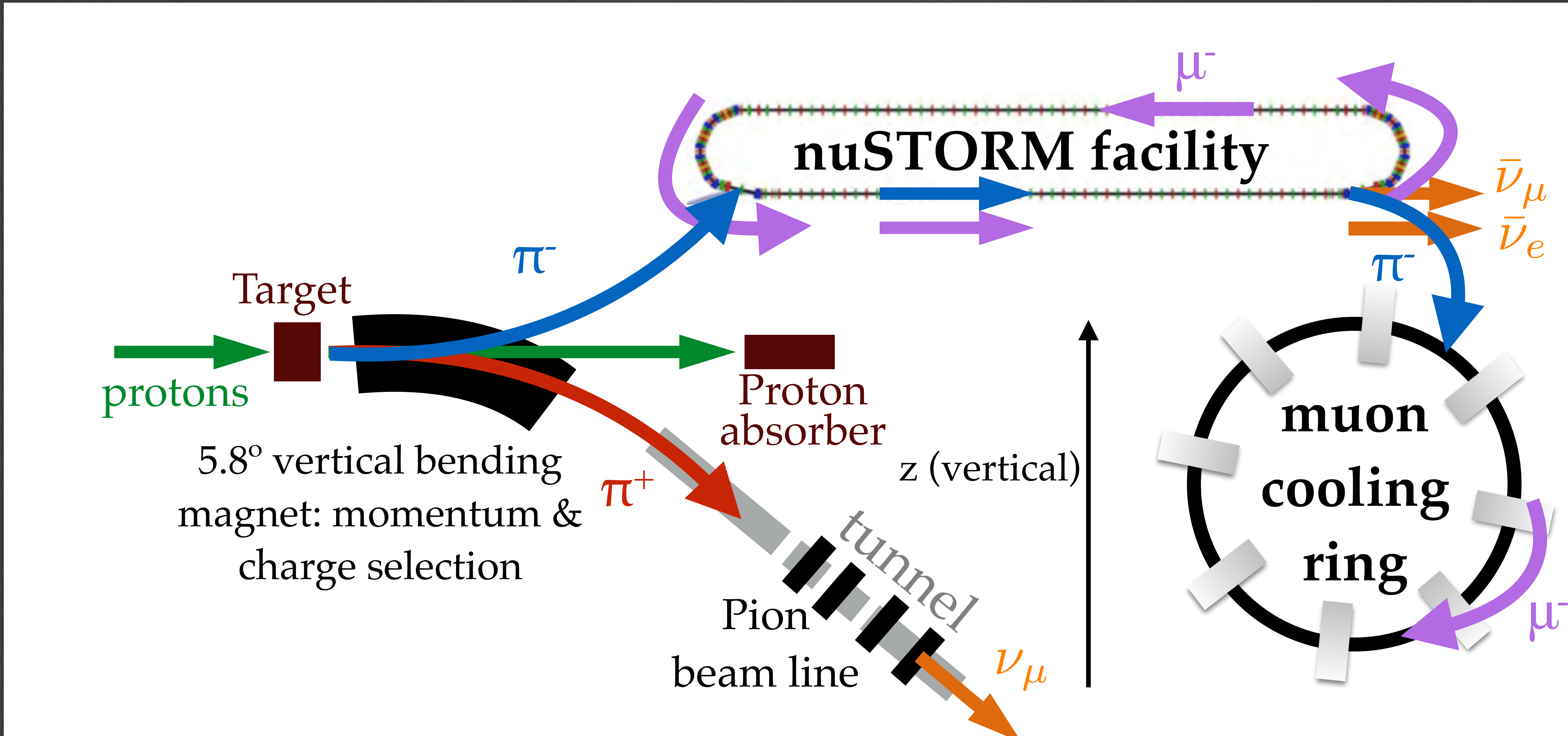
The wrong-sign pions could be used for Short Baseline experiments (i.e. nuSTORM).

nuPIL AND nuSTORM?



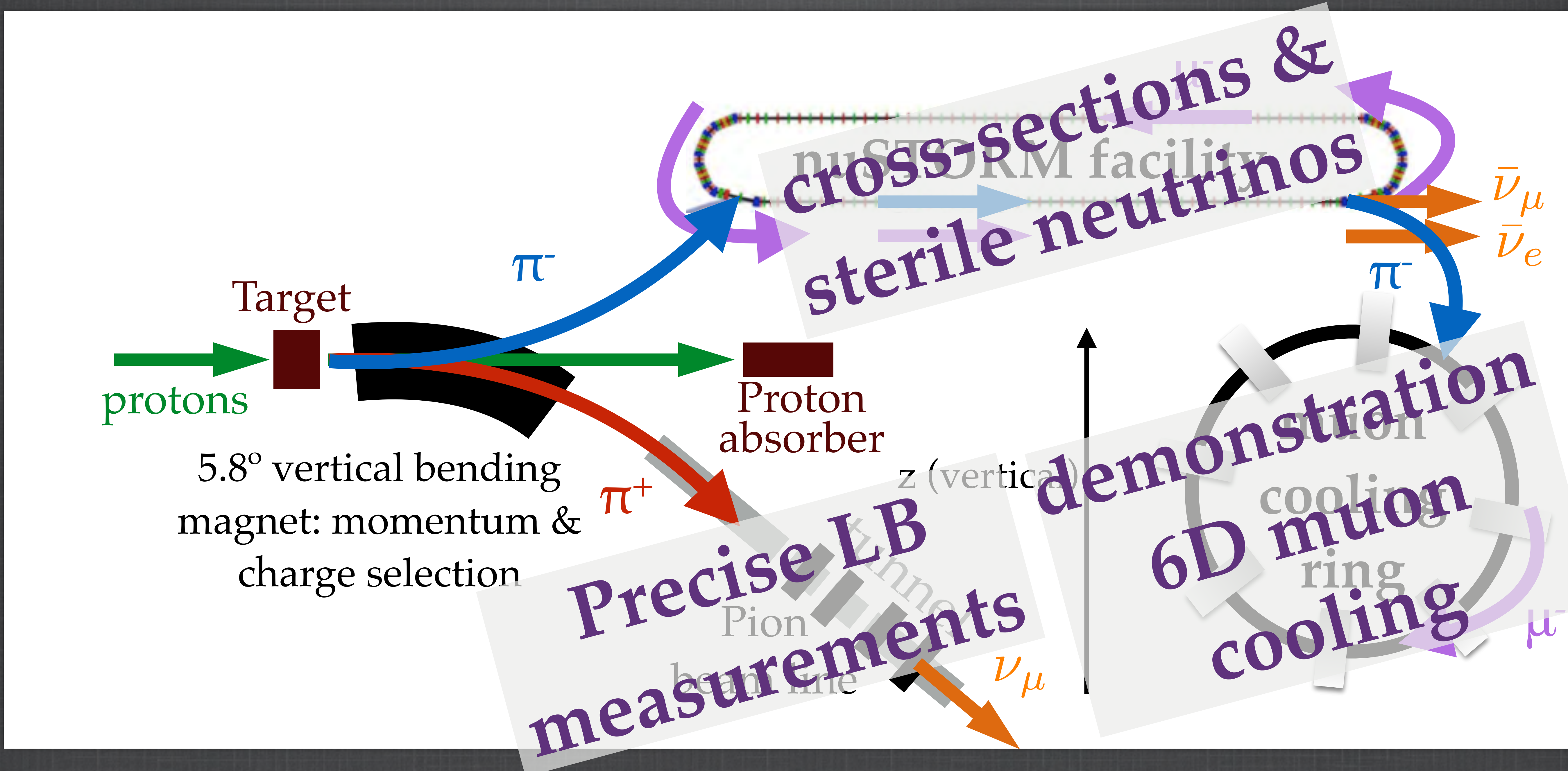
The wrong-sign pions could be used for Short Baseline experiments (i.e. nuSTORM).

Let's be greedy…



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

Let's be greedy…



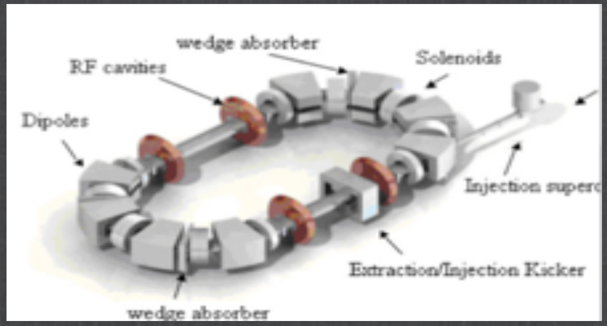
Muon cooling experiment (C. Rubbia's ring) could also be implemented!

nuPIL Summary

- Preliminary results not too bad, but need improvements.
- Large potential for combined experiments: LB, SB and muon cooling ring demonstration
    - **nuPIL**

      +
    - **nuSTORM**

      +
    - **muon cooling ring**



nuPIL Future plans

- Compute the flux from the second design.
- Third design concept to be implemented.
- Optimization for all designs, and compare them regarding the final flux at the detector.
- Investigate beam optics for nuSTORM facility.

Thank you for your attention