Pion Capture and Transport for ESSnuSB+

Max Topp-Mugglestone, Ilias Efthymiopoulos

max.emil.topp-mugglestone@cern.ch

ilias.efthymiopoulos@cern.ch

ESS neutrino Super Beam plus

Contents

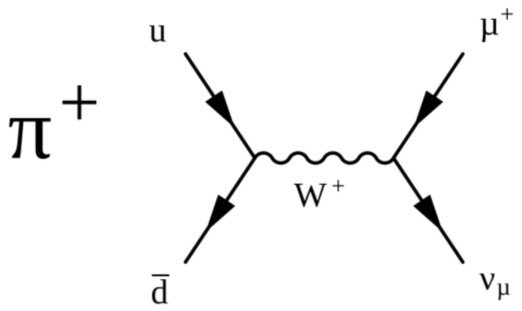
- ESSnuSB and ESSnuSB+ overview
- Facility layout
- Target station
- Muon production & pion momentum choice
- Stochastic injection into LEnuSTORM
- Transfer line design

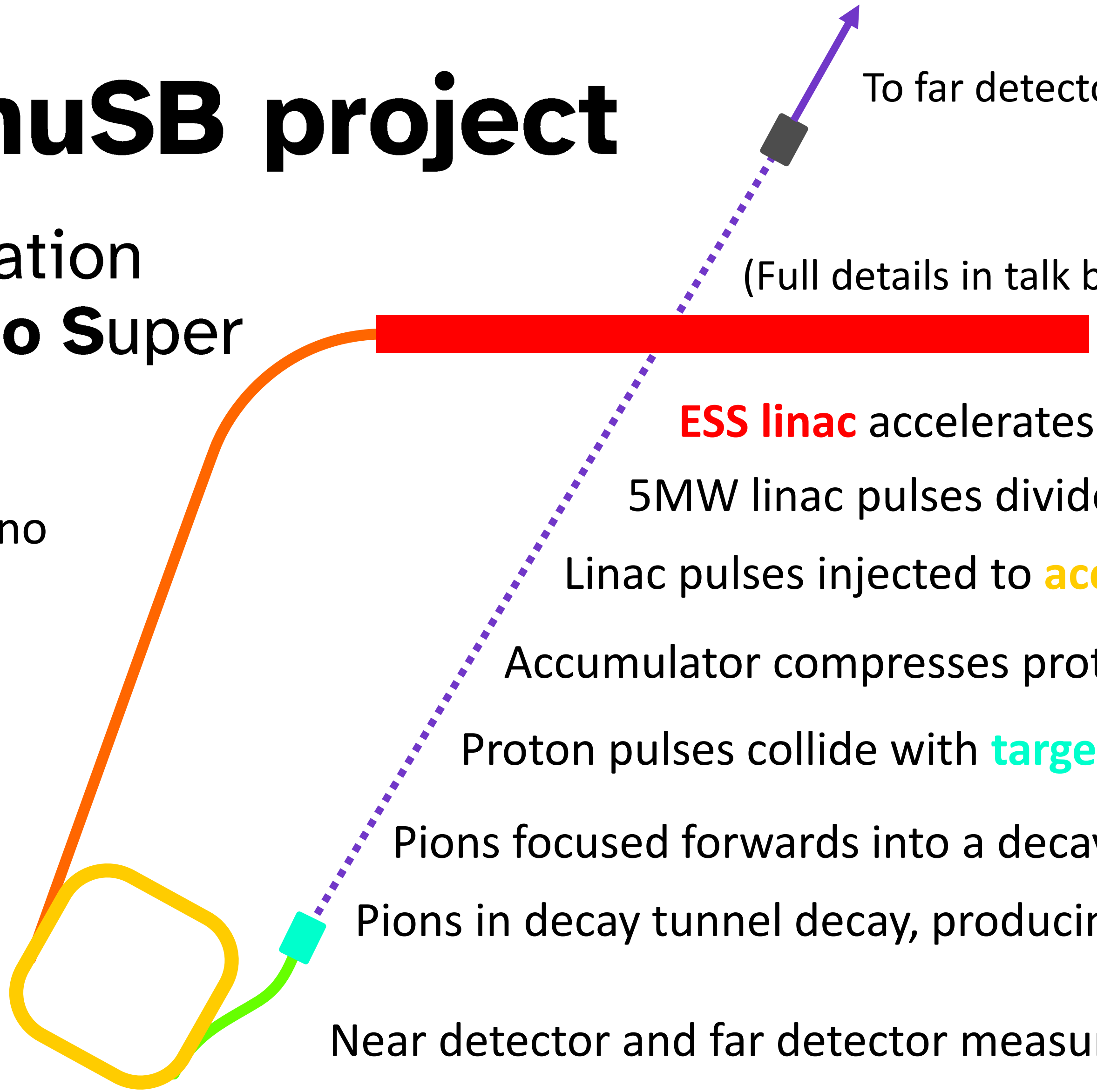
The ESSnuSB project

European **S**pallation **S**ource **Neutrino S**uper **B**eam

Goals:

- Generate intense neutrino beam for long-baseline experiment
- Study neutrino flavour oscillations





To far detector (+350km)

(Full details in talk by E. Baussan tomorrow morning)

ESS linac accelerates H- to 2.5 GeV

5MW linac pulses divided into 4 batches

Linac pulses injected to **accumulator ring**

Accumulator compresses proton pulses from 2.9ms to 1.3μs

Proton pulses collide with **targets** to produce pions

Pions focused forwards into a decay tunnel using a magnetic horn

Pions in decay tunnel decay, producing **muon neutrino beam**

Near detector and far detector measure populations of ν_μ, ν_e

The ESSnuSB+ project

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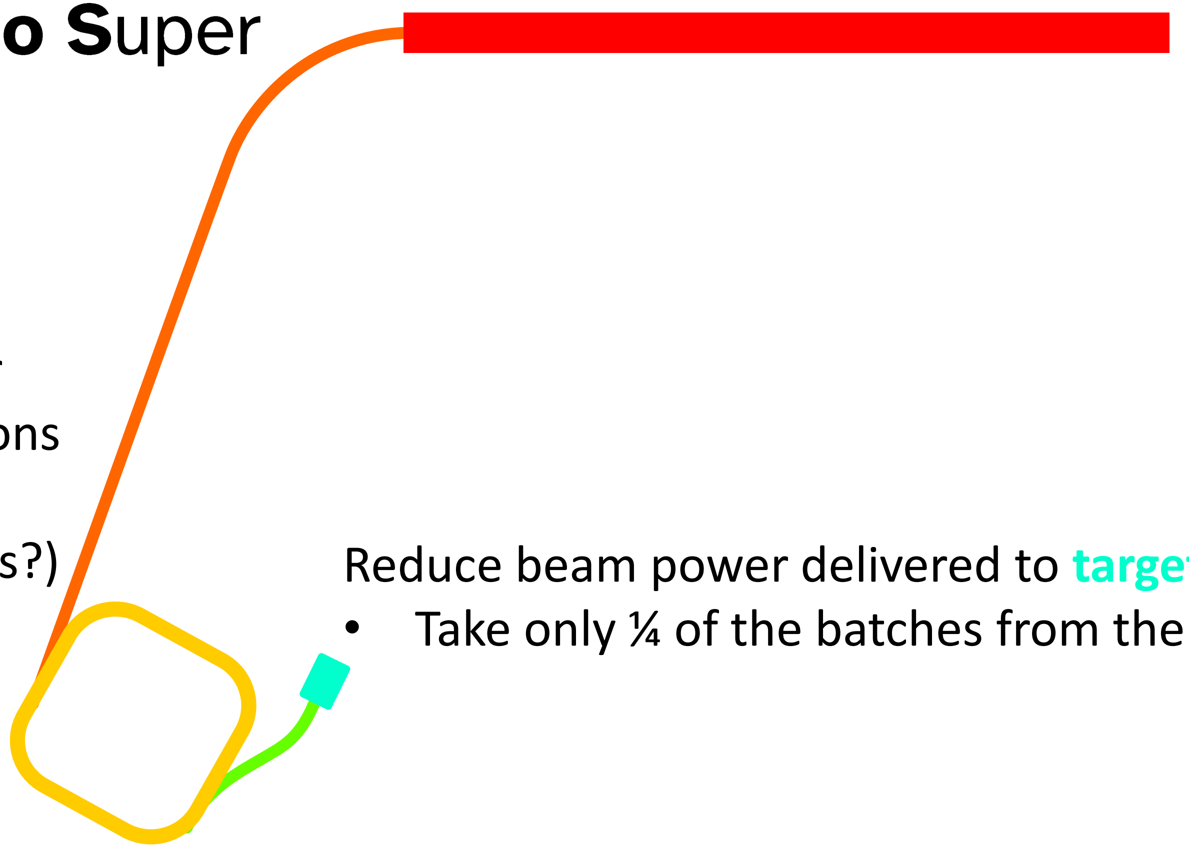
(Full details in talk by E. Baussan tomorrow morning)

Goals:

- Generate intense neutrino beam
- Study neutrino/matter interaction cross sections at low energy
- (Study sterile neutrinos?)



Reduce beam power delivered to **target**

- Take only ¼ of the batches from the linac (1.25 MW beam power)

The ESSnuSB+ project

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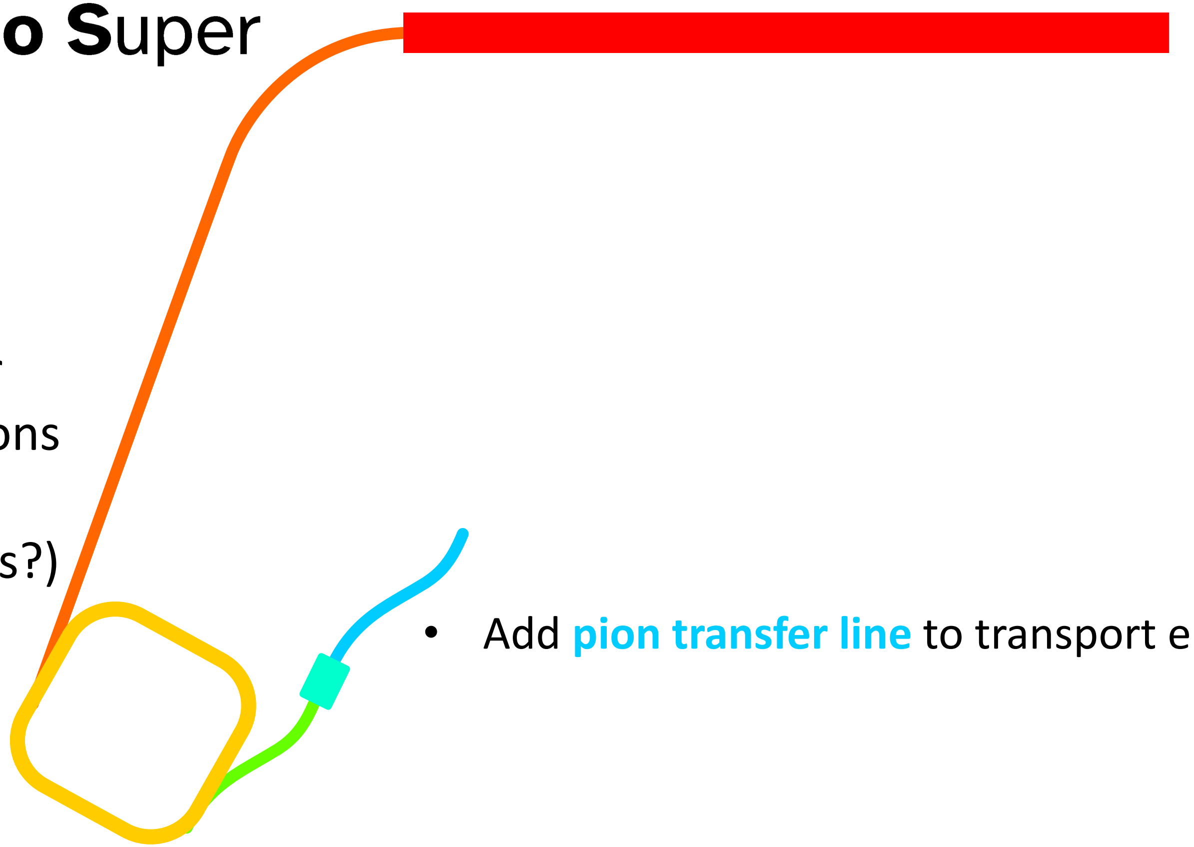

- Add **pion transfer line** to transport energy/sign-selected pions

The ESSnuSB+ project

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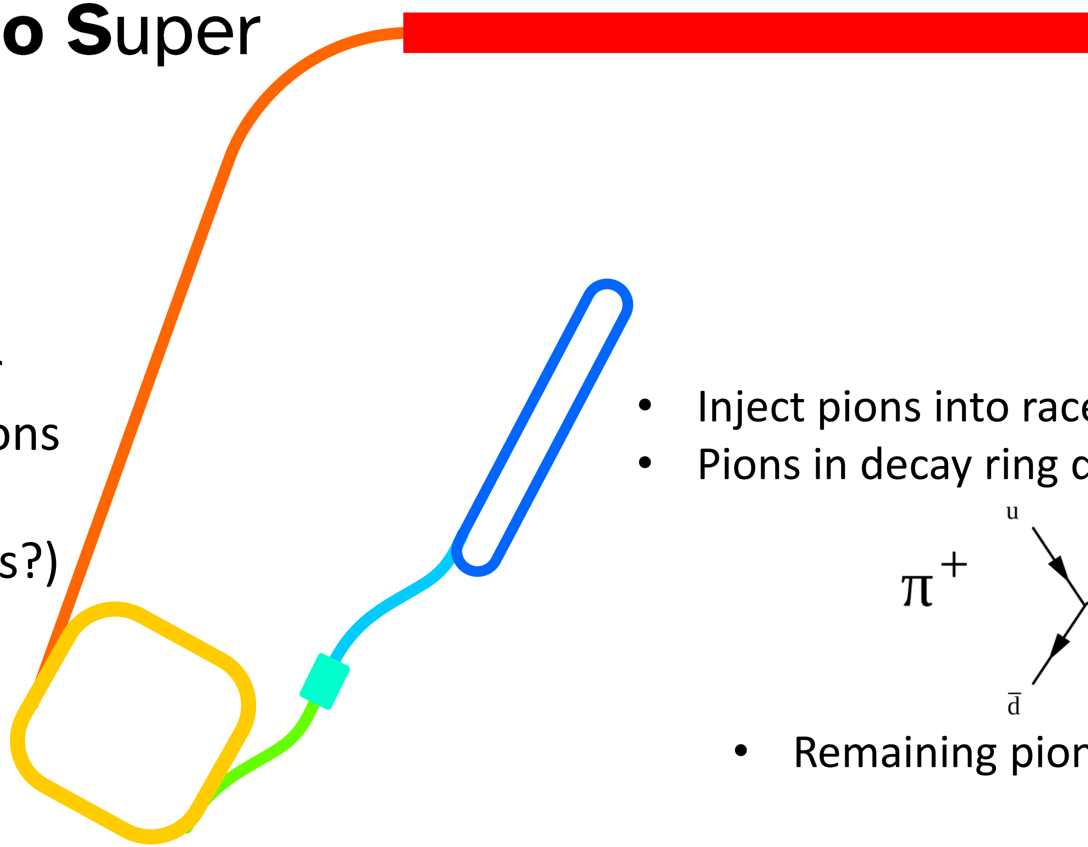
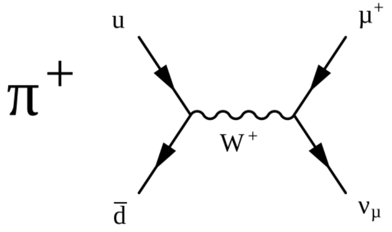


- Inject pions into racetrack **decay ring** (LEnuSTORM)
- Pions in decay ring decay into muons in first straight



- Remaining pions are dumped

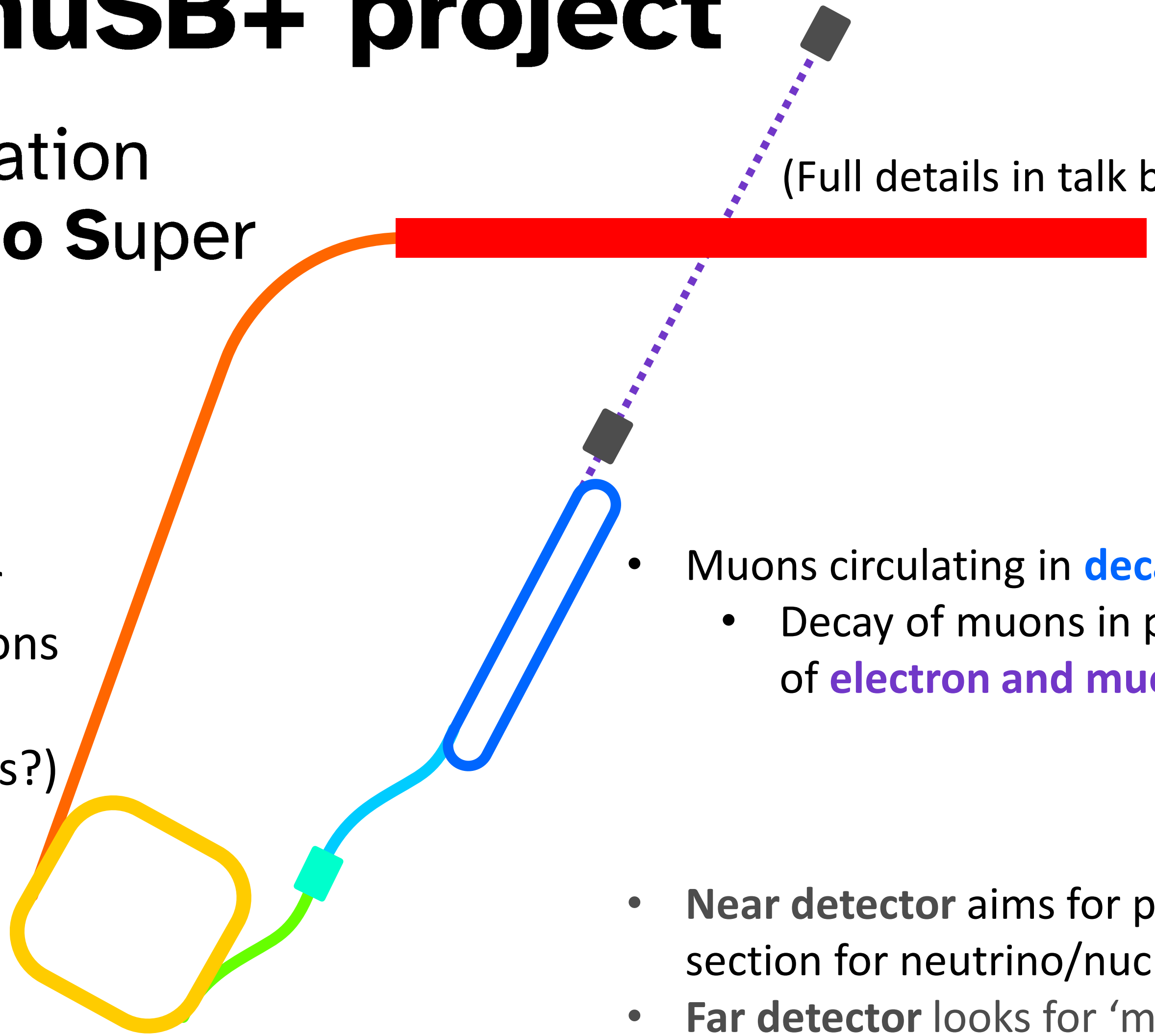
The ESSnuSB+ project

European **S**pallation
Source **Neutrino S**uper
Beam **+**

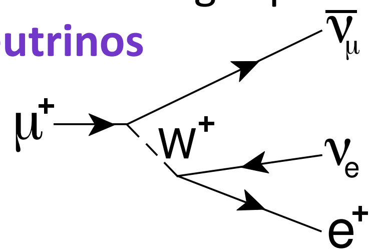
Goals:

- Generate intense neutrino beam
- Study neutrino/matter interaction cross sections at low energy
- (Study sterile neutrinos?)

(Full details in talk by E. Baussan tomorrow morning)

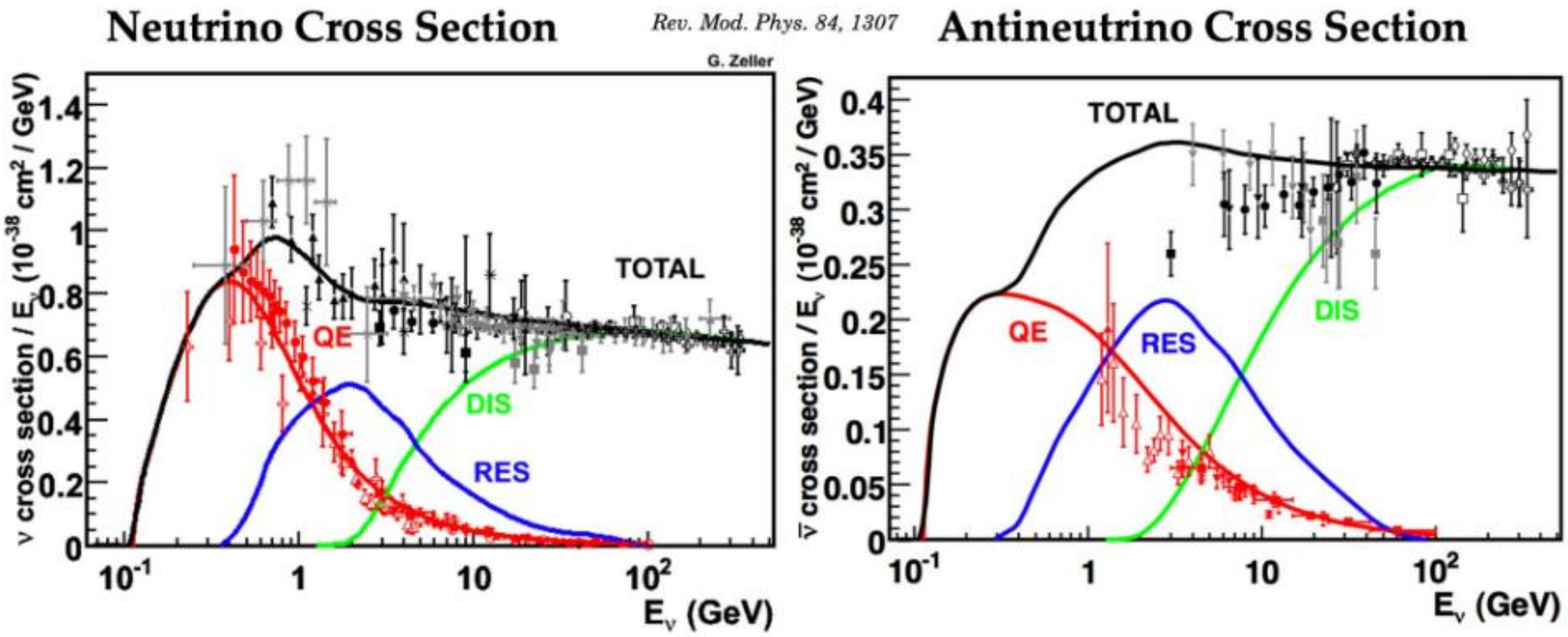


- Muons circulating in **decay ring** undergo decay processes
  - Decay of muons in production straight produces beam of **electron and muon neutrinos**



- **Near detector** aims for precision measurements of cross section for neutrino/nucleus interactions
- **Far detector** looks for 'missing' ν_e

Muon energy



- Very limited data on low energy (<600 MeV) neutrino cross sections -> 600 MeV/c is a good design momentum for a muon storage ring

Layout considerations

- The ESSnuSB project needs a decay tunnel in front of the target station, aimed at a far detector
  - Decay ring cannot intersect the decay tunnel or its shielding
- The LEnuSTORM decay ring shares the same detector
  - Production straight must be aimed at the detector
- Pions decay in flight
  - Transfer line must be as short as possible
- Target station is a megawatt-class radiation environment

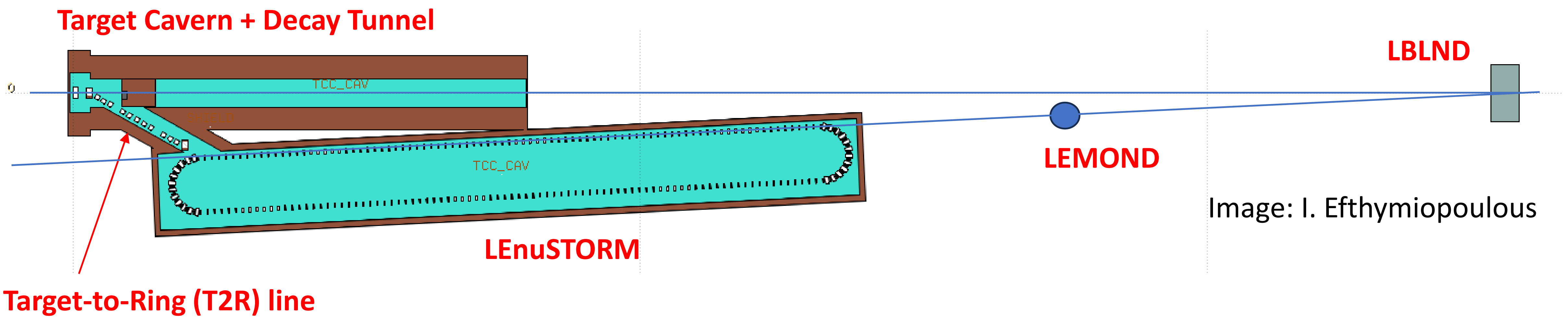
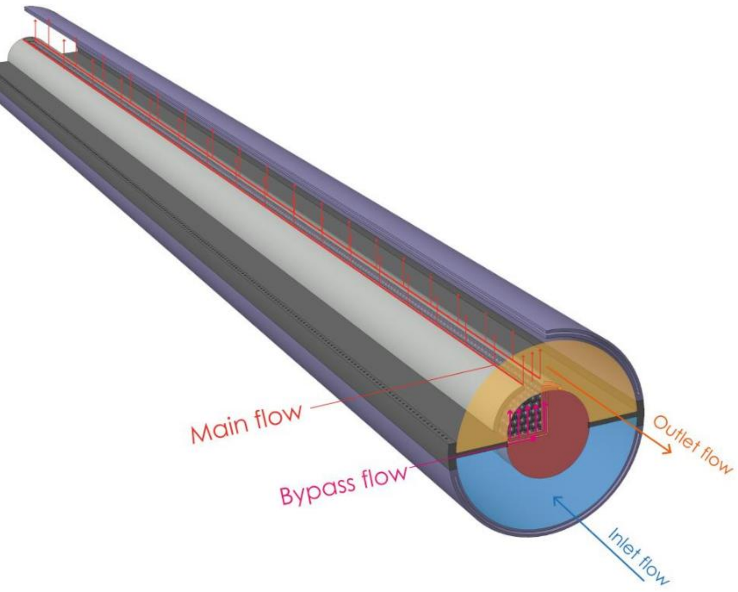


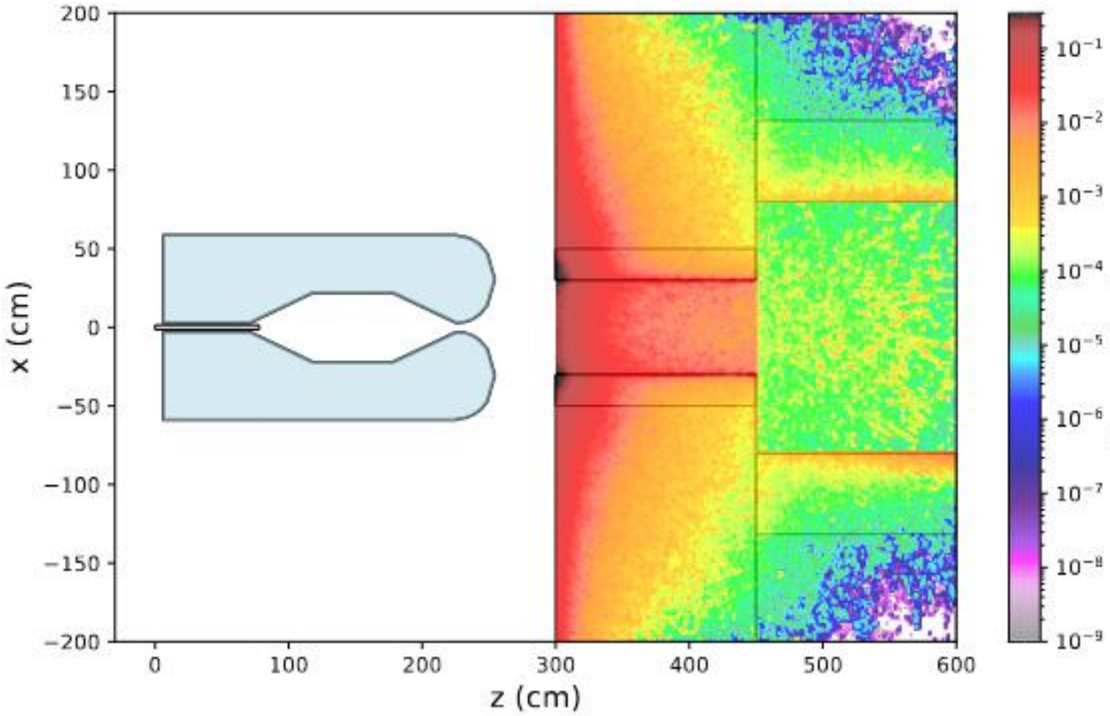
Image: I. Efthymiopoulous

Target Station

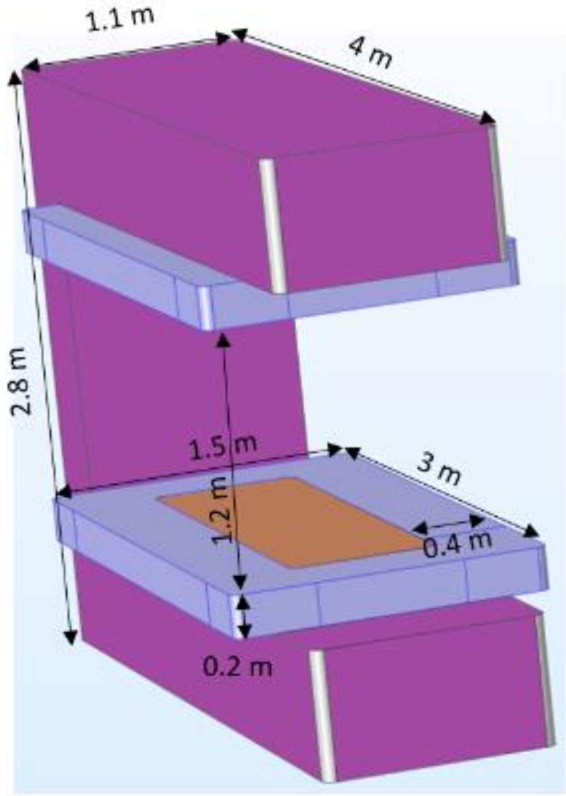
- Titanium sphere target, magnetic horn



Target schematic
Credit: J. Aguilar

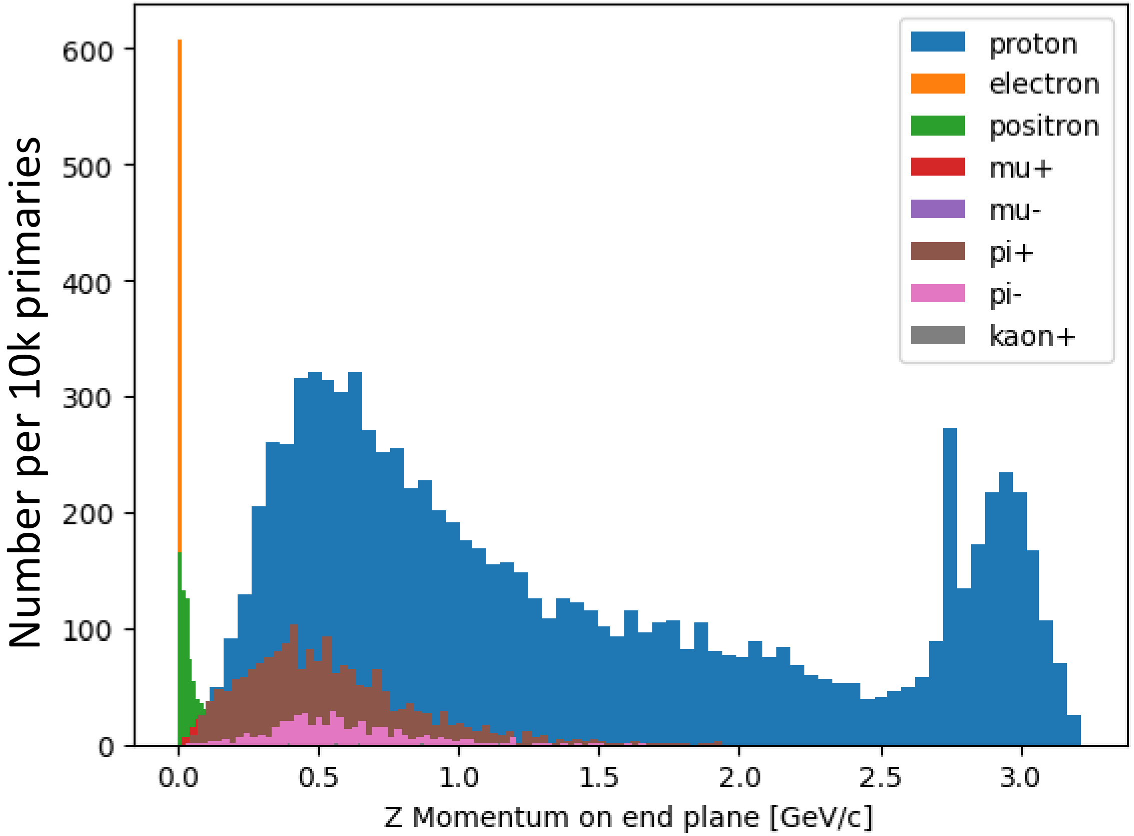


Horn + target station radiological simulation in FLUKA
Credit: E. Baussan

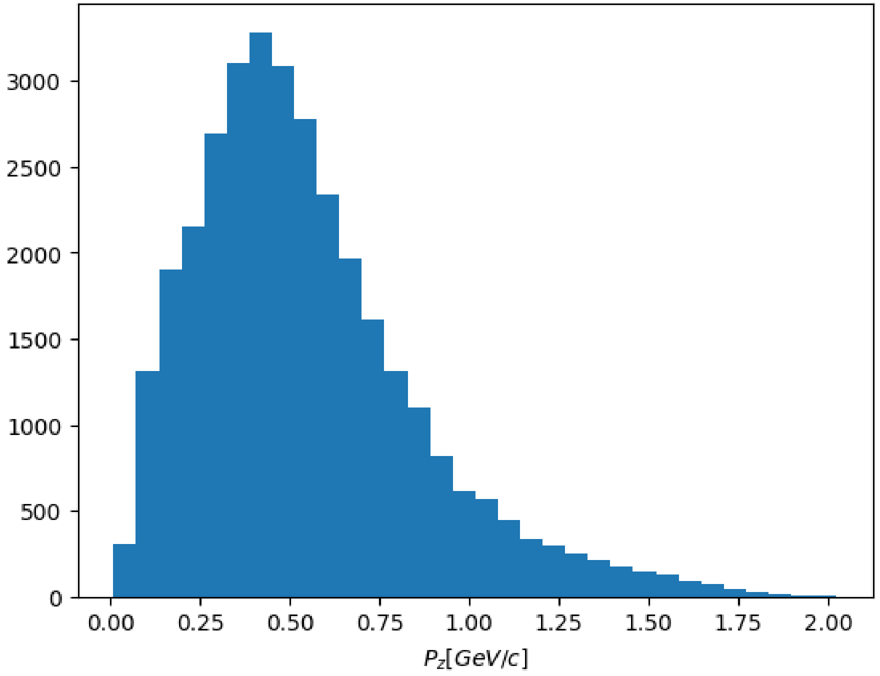


Preliminary dipole design
Nominal strength: 0.79 T
Credit: T. Tolba

Secondary beam



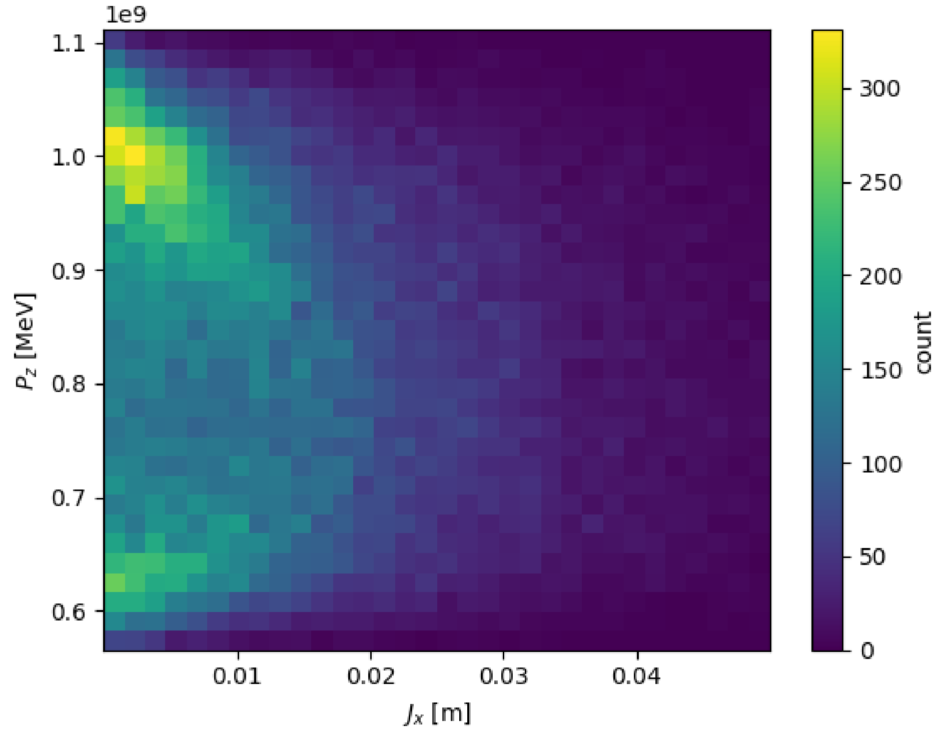
- Output from horn



- Pion spectrum (200k primaries)

Muon Production

- Muons are produced from pions traversing the production straight of the decay ring
- Muons are produced in all directions isotropically in the rest frame of the pion
- Lorentz-boosting to the lab frame concentrates muon decays in forwards and reverse directions
- Only muons with a small transverse amplitude can be captured



Example muon production in LEnuSTORM production straight, assuming matched Gaussian pion beam, N = 1e4, horizontal emittance 3 mm

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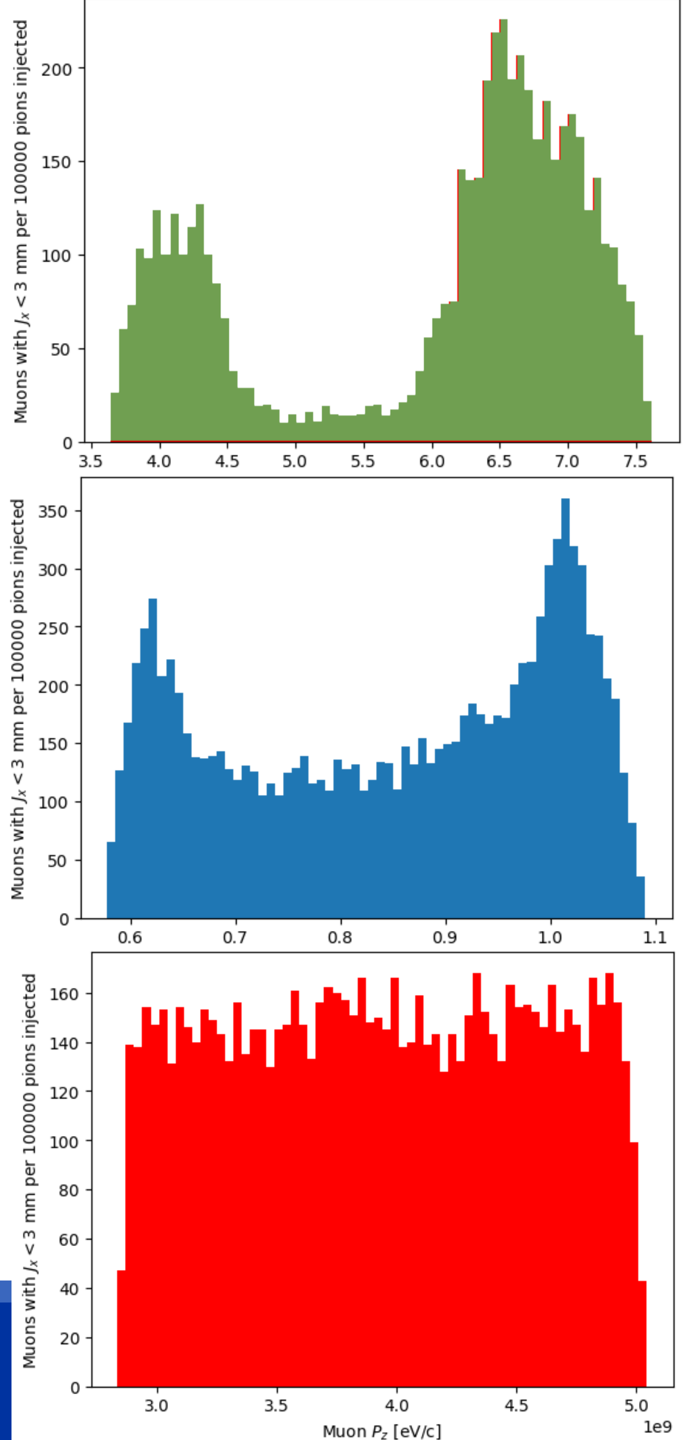


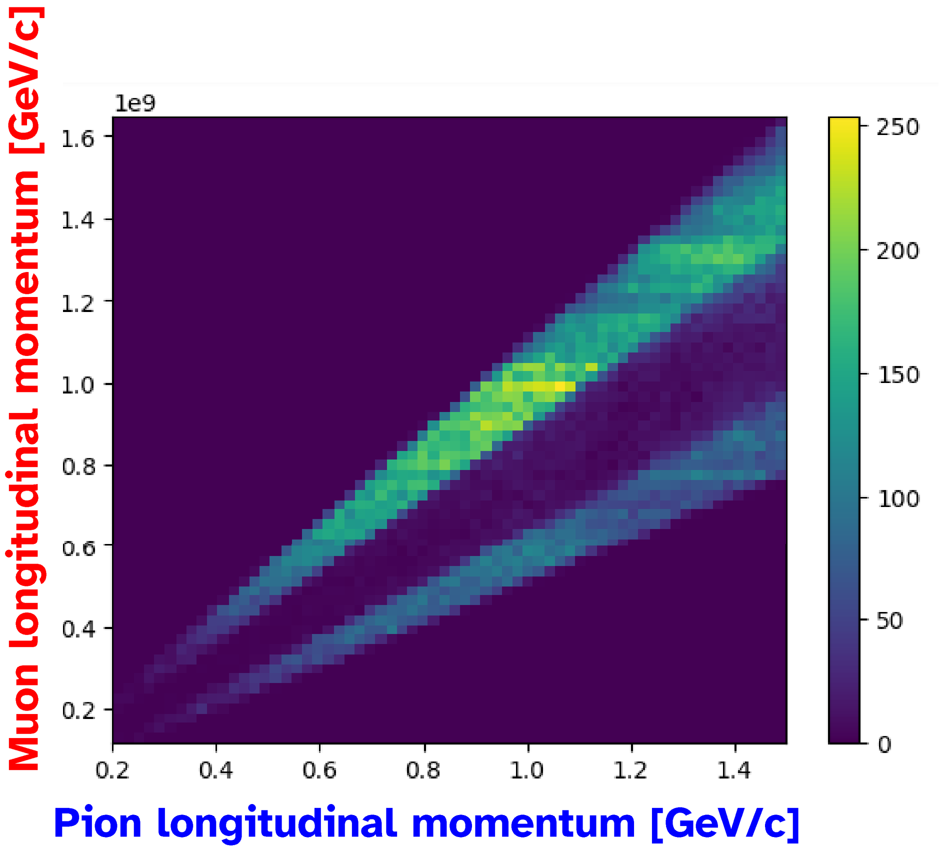
LEnuSTORM Pion momentum = 700 MeV/c

LEnuSTORM Pion momentum = 1050 MeV/c

nuSTORM Pion momentum = 5 GeV/c

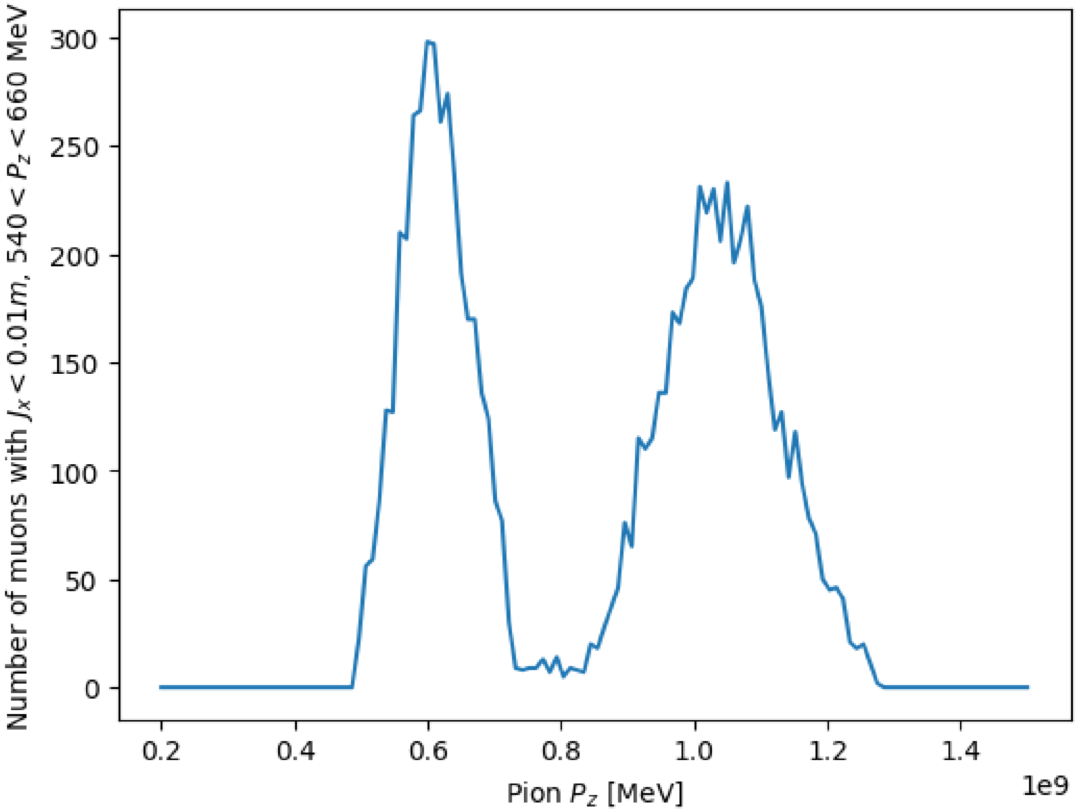
Pion momentum selection

- Select momentum slice from horn output, width ±10%
- Simulate one pass of selected pions through the production straight
  - Assuming a 40 cm diameter aperture on each element
  - Assuming initial decays corresponding to a transfer line of 25m
- Evaluate muon distribution within 0.01 m emittance at the end of the production straight



Pion momentum selection

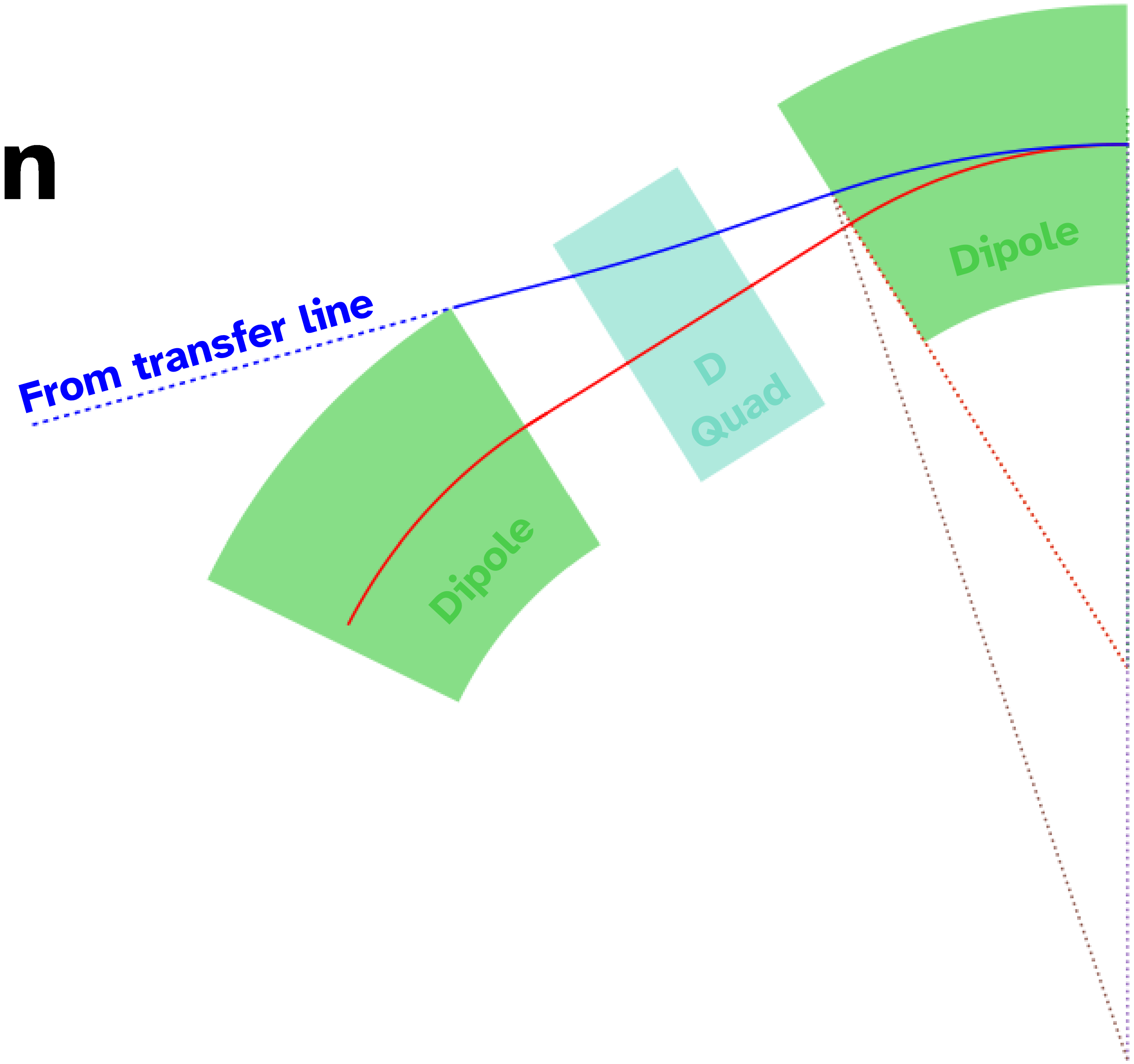
- If 600 MeV/c is the desired muon energy
  - Forward-decaying muons can be taken from pions around 600 MeV/c
  - Rearward-decaying muons can be taken from pions around 1050 MeV/c
- Production of low-emittance 600 MeV/c muons from other pion momenta is suppressed



Low-emittance muon yields as a function of central pion momentum, using horn output and 25 m transfer line with perfect transverse acceptance

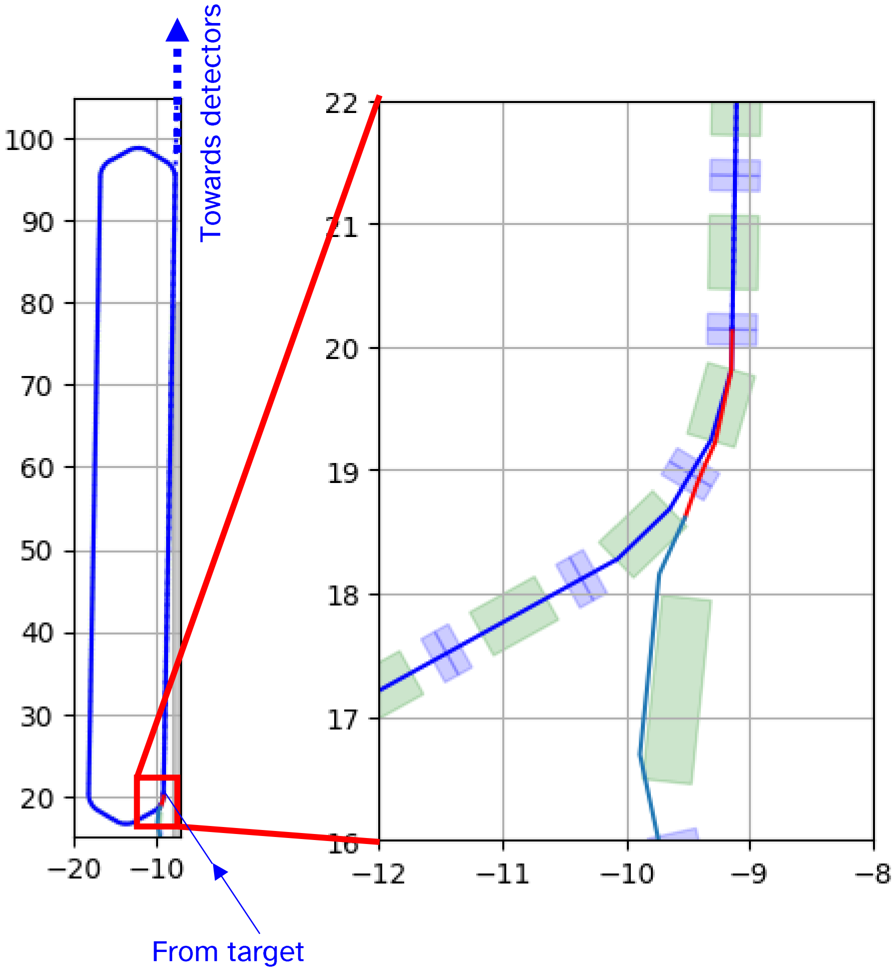
Stochastic Injection

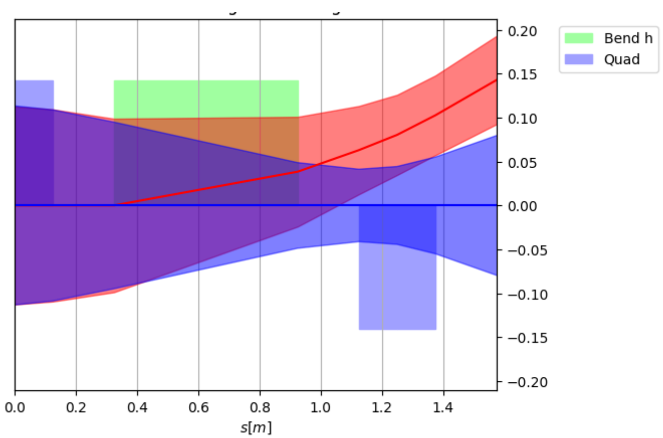
- Assume a circulating **600 MeV/c muon** beam and injected **1050 MeV/c pions**
- Difference in magnetic rigidity enables separation of species in dipoles
- By ensuring sufficient dispersion in the lattice that the circulating muon beam and injected pion beam can be divided by a septum, we can achieve a passive injection



Stochastic injection

- Dispersion of baseline ring is not sufficient – modification will be required
- One possibility – replace ring arcs with a 3-bend ‘missing bend’ configuration

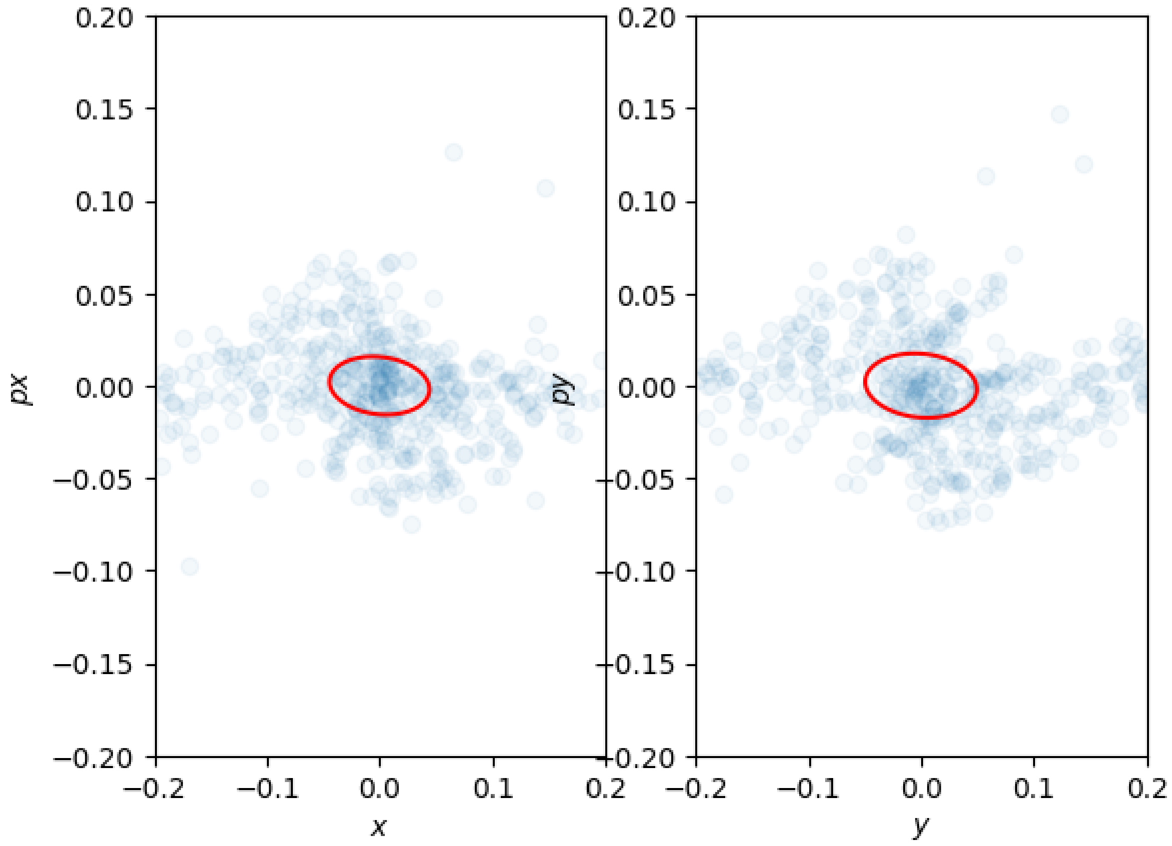




Beam profiles assuming 3mm emittance, 10% momentum spread

Pion beam characterisation

- Horn is optimized to produce a parallel, axisymmetric pion beam
- Culling all particles outside of an initial 40 cm wide rectangular aperture, and restricting to 1050 MeV/c (+- 10%) we find an initial emittance of 2.2 mm in both planes



Measured $\beta_{x,y}$: 2.8m, measured $\alpha_{x,y}$: -0.13

Transfer line goals

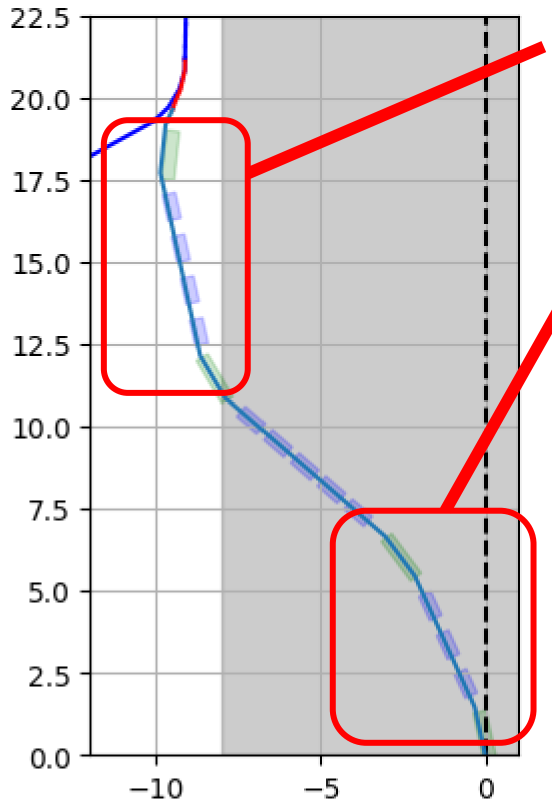
- Transport pions laterally through shielding between high-radiation target station environment, low-radiation decay ring environment
- Minimise line length
- Maximise transverse acceptance
- Maximise momentum acceptance
- Start and end with 0 dispersion*
- Match horn optics to production straight pion optics

*Zero dispersion condition must be satisfied at beginning of production straight

Transfer line design

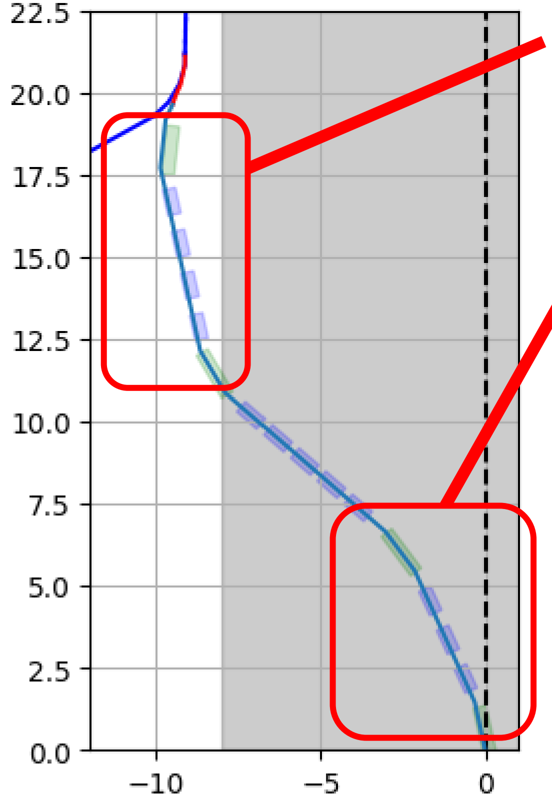
- Compute pion beam parameters on horn end plane
  - Propagate through initial target station dipole
- Compute Courant-Snyder parameters of production straight for 1050 MeV/c pions
  - Propagate these in reverse direction through stochastic injection section

Transfer line design



- Two independent closed-dispersion arcs based on linear optics
  - Target station contains only robust, simple magnetic components (large aperture dipole, quadrupole)
    - Identical copy of LADM is used as the second bend for simplicity
- Linked with shortest possible straight
- Symmetry of second arc is broken to match dispersion of stochastic injection system
- Quad strengths in straight are tuned to ensure matching of injection optics to horn output

Transfer line design



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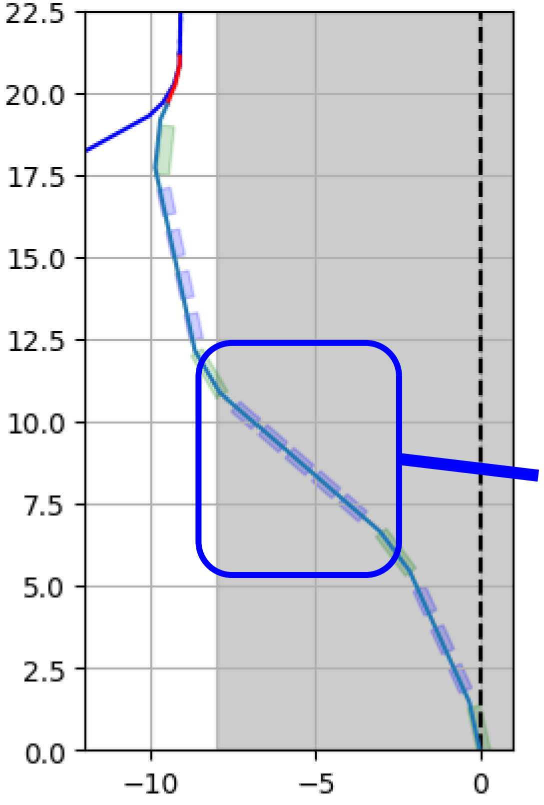
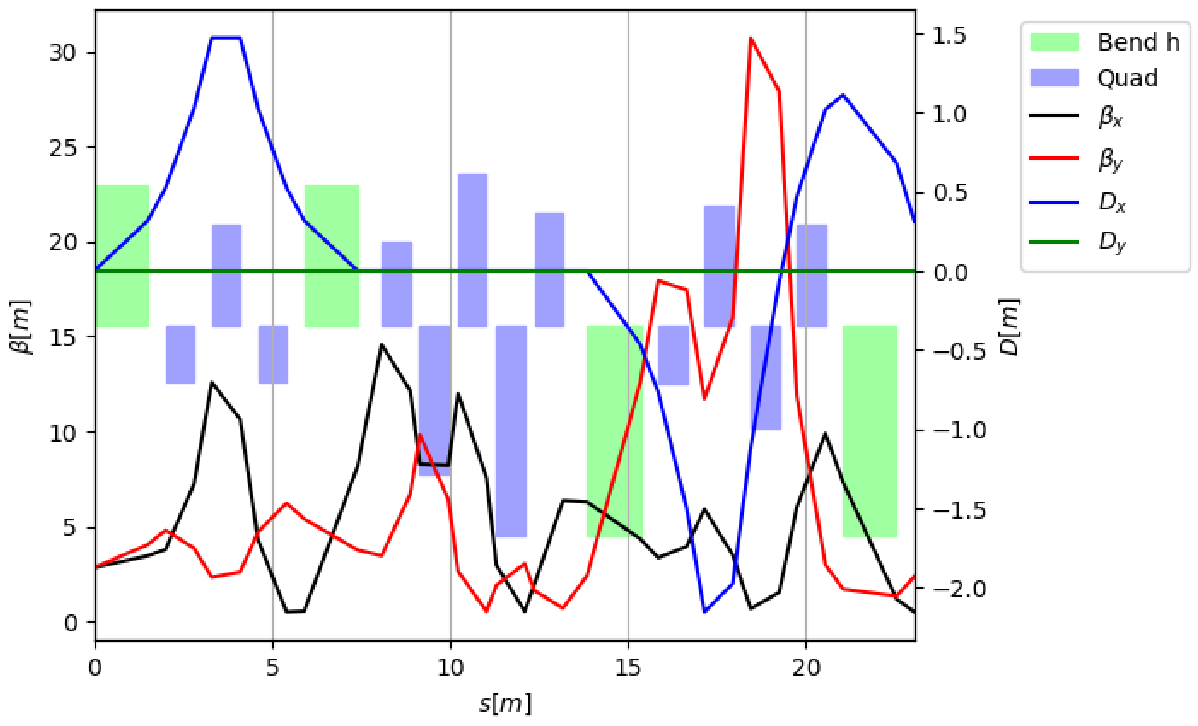
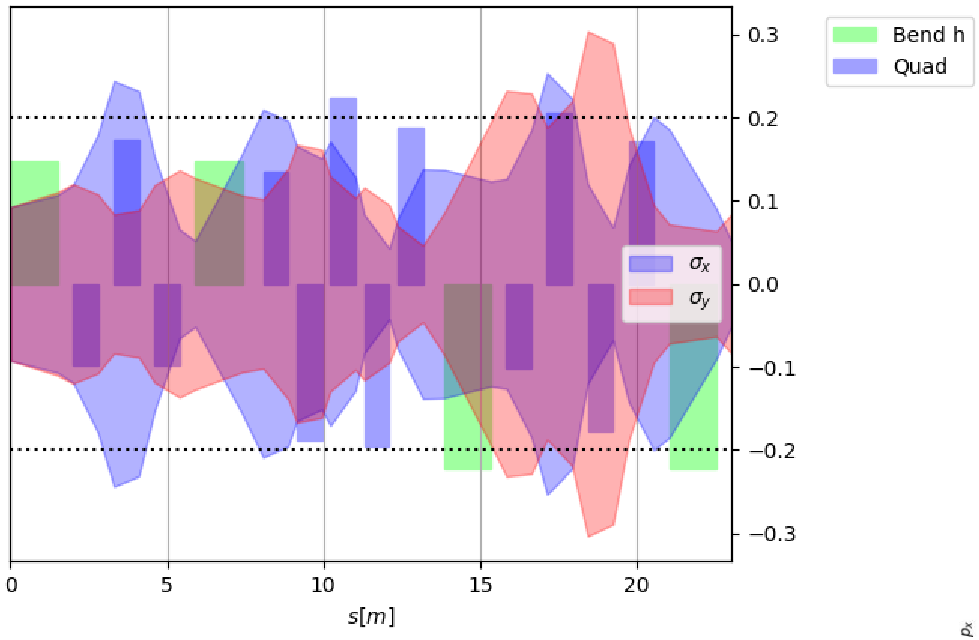
Transfer line design – Linear Optics



- Successful matching of target station to ring optics using linear optics
- Straight section of transfer line with zero first-order dispersion

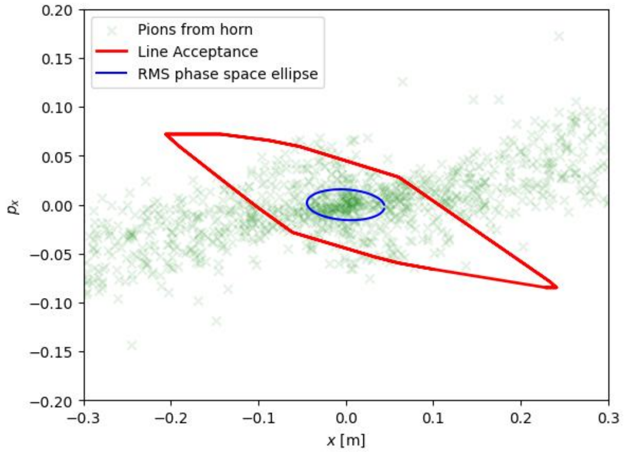


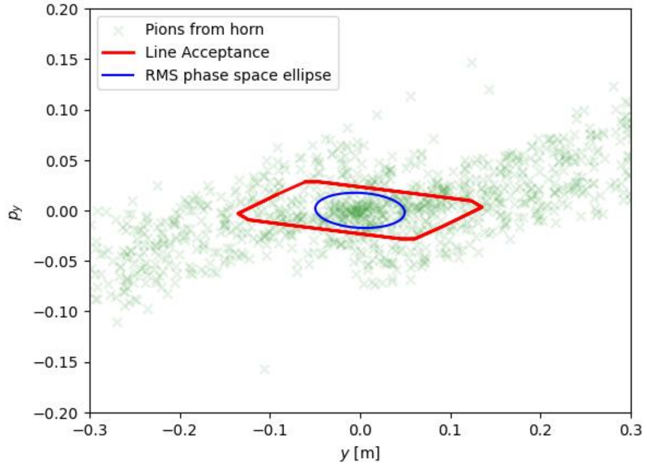
Transfer line design - Linear Optics



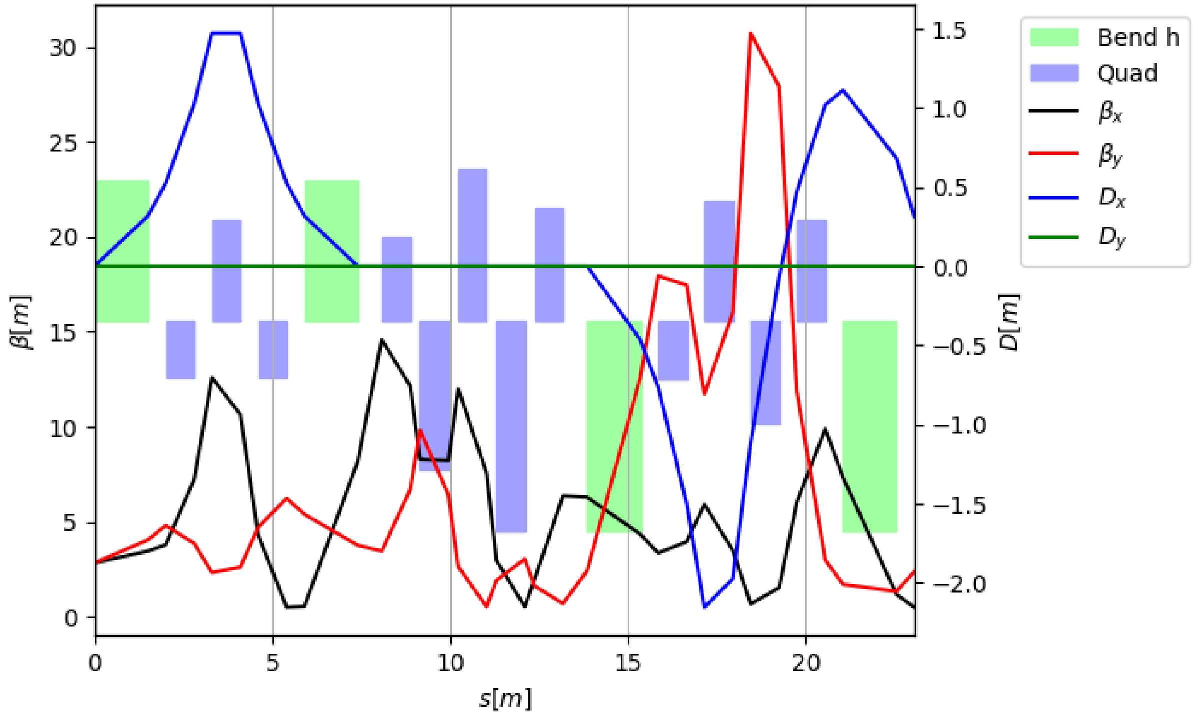
Horizontal and vertical projections of beam, assuming 2.2 mm emittance computed from horn and 10% momentum spread

- Assume 0.4 m rectangular aperture on all magnets
- 1-sigma projection of pion beam mostly within these limits





Future

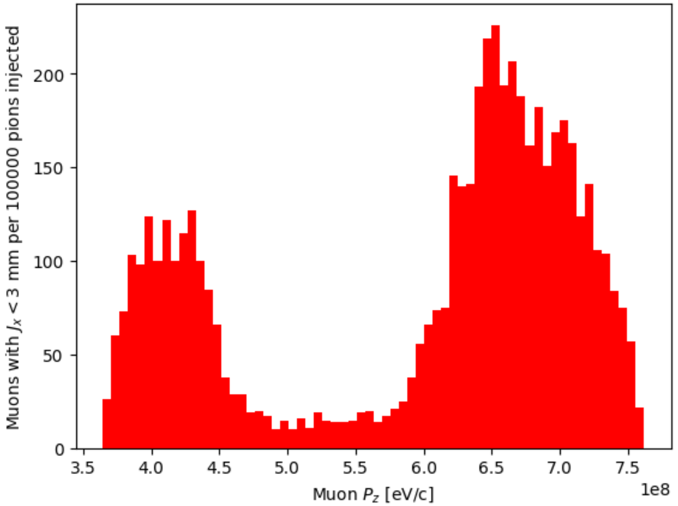


- Add multipole components in straight to improve off-momentum matching

- Horizontal acceptance limited largely by simultaneous dispersion and beta-function peak
  - Reoptimisation of horn for a focal point in the first arc?
- Distribute bend of second arc to limit max. dispersion?
  - Shortening final dipole would enable reduction of β_y
- Study gains from a CF magnet approach (/FFA-style optics)

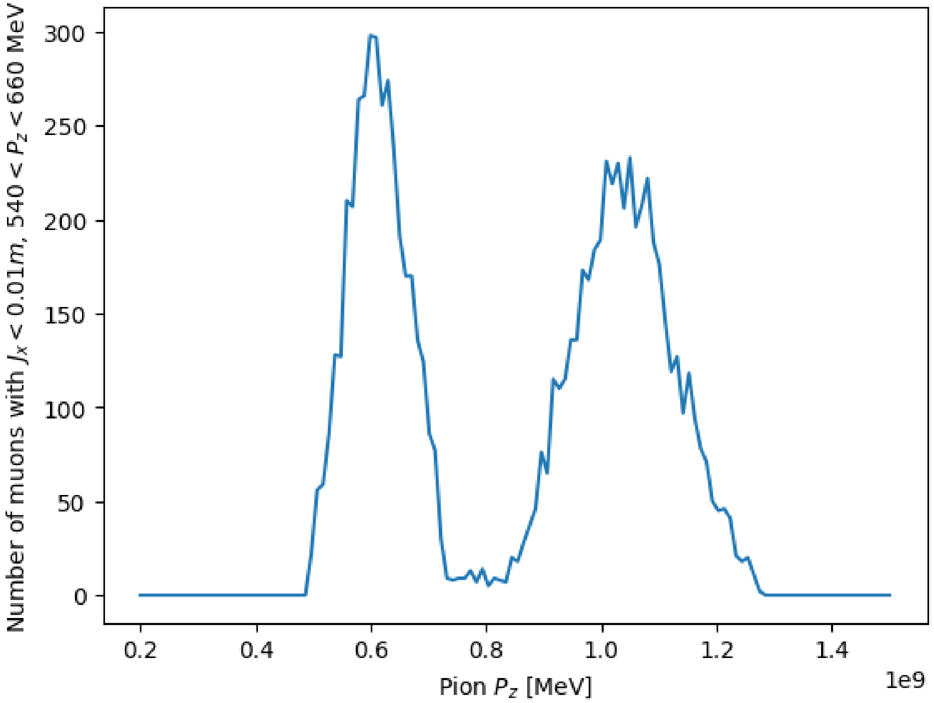
Backup

Muons from forward decays



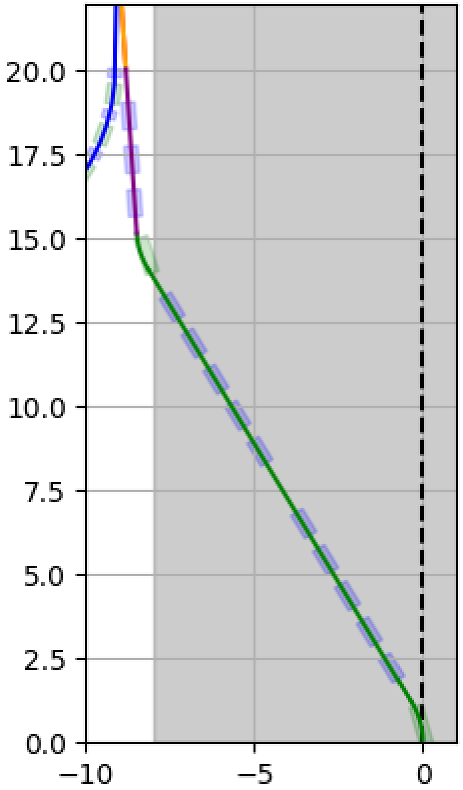
Muon spectrum from 700 MeV/c pion beam

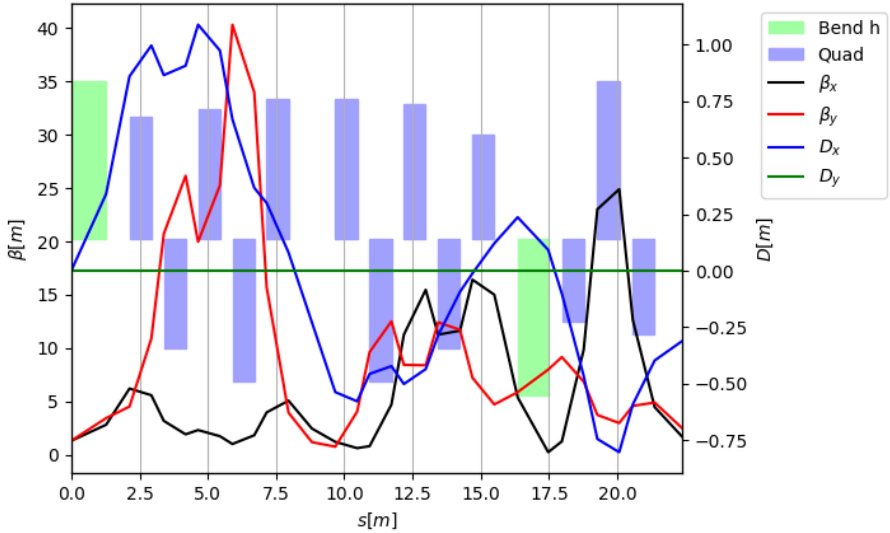
Yield of low-emittance 600 MeV/c muons as a function of pion momentum



- Forward production efficiency is greater than reverse production efficiency for a given pion momentum
- Horn spectrum contains more muons close to 600 MeV/c than 1050 MeV/c
- Pion and muon optics would be the same -> muons from decays in transfer line could be transported to production straight

600 MeV/c pion transfer line



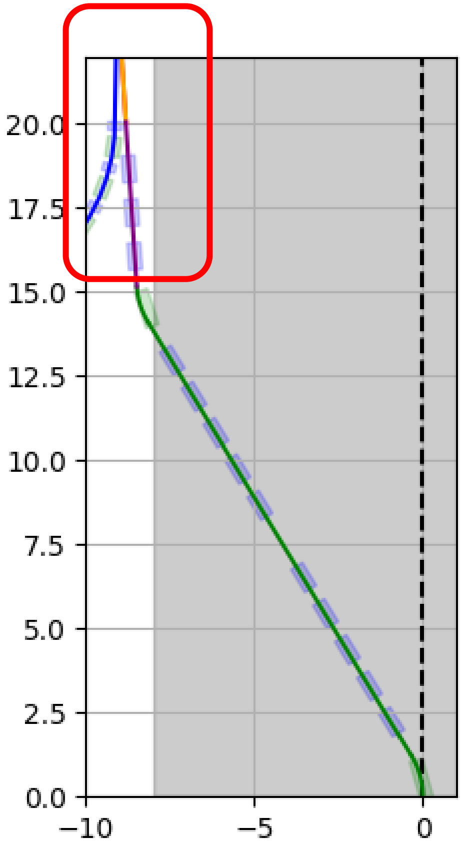


Courant-Snyder parameters of 600 MeV/c transfer line

Matched to ring optics*

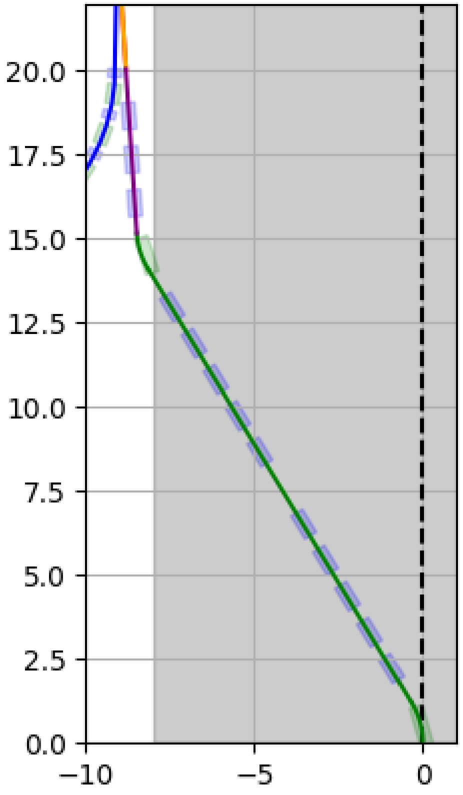
- Simple line optics have been designed for a 600 MeV/c muon transfer line

600 MeV/c pion transfer line



- If $P_\mu \approx P_\pi$, stochastic injection is not possible.

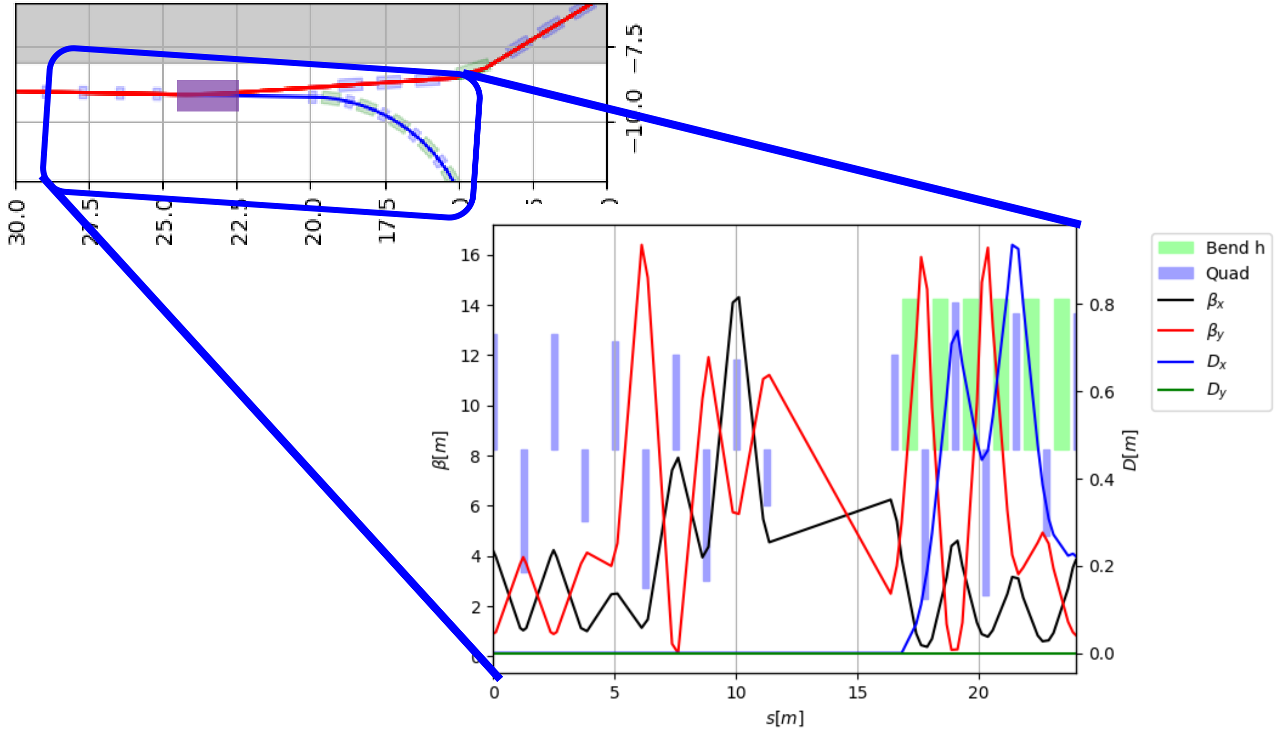
600 MeV/c muon transfer line



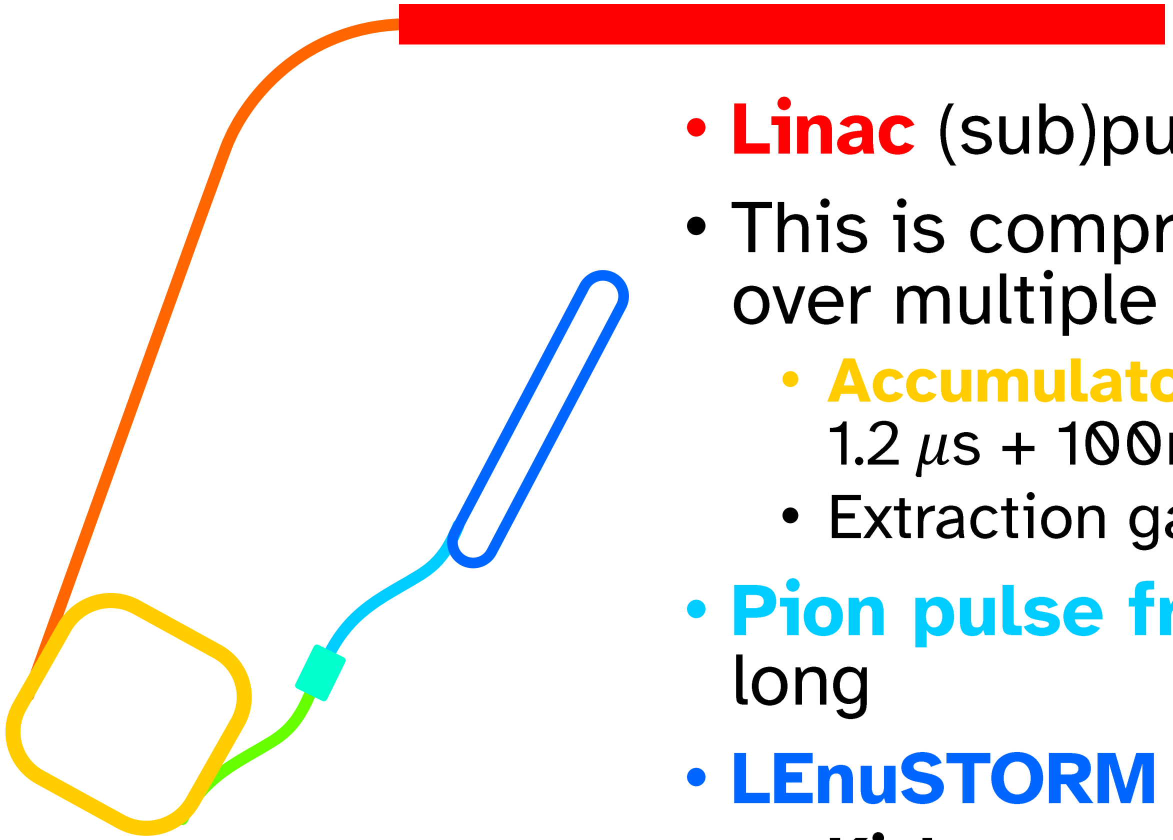
- If $P_\mu \approx P_\pi$, stochastic injection is not possible.

- Modify ring to include a long drift insertion
- Install **kicker magnet** in drift

- **However…**

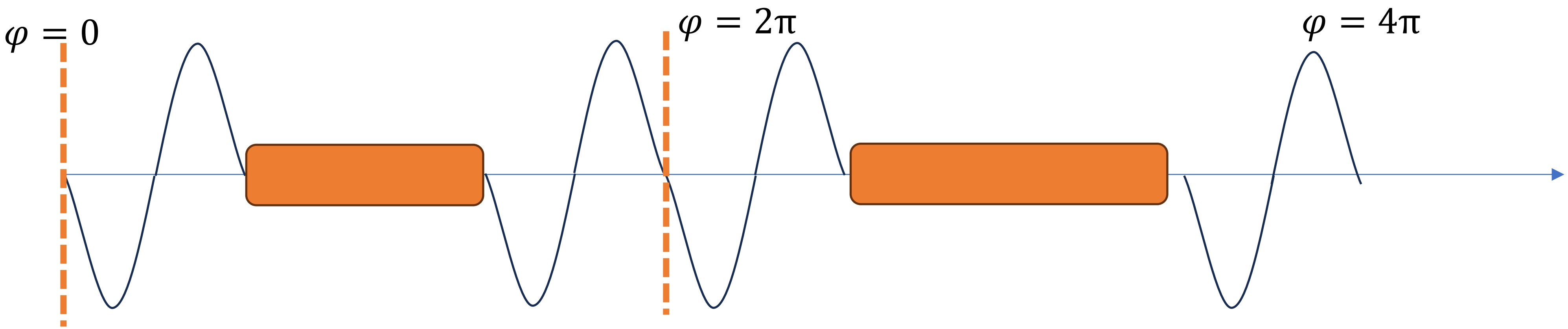


600 MeV/c: the problem



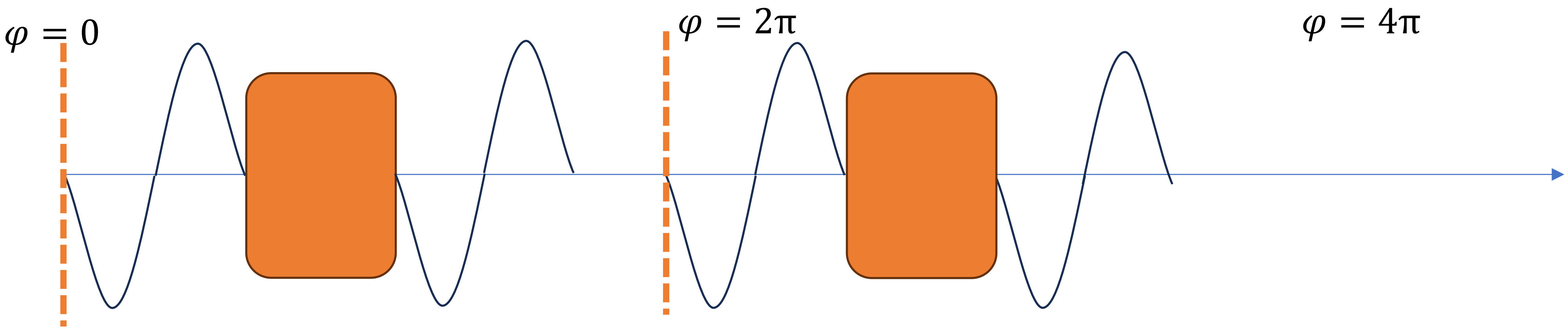
- **Linac** (sub)pulse is ~0.7 ms in length
- This is compressed by injection into **accumulator** over multiple turns
  - **Accumulator ring** is 376 m long (corresponding to 1.2 μs + 100ns extraction gap)
  - Extraction gap preserved by barrier bucket
- **Pion pulse from target** will be 1.2 μs = ~376 m long
- **LEnuSTORM decay ring** is ~ 250m long
  - **Kicker cannot inject entire pulse without destroying circulating beam**

600 MeV/c: the solution?



- Replace single barrier bucket system in **accumulator ring** with double barrier
- Move one barrier towards the other

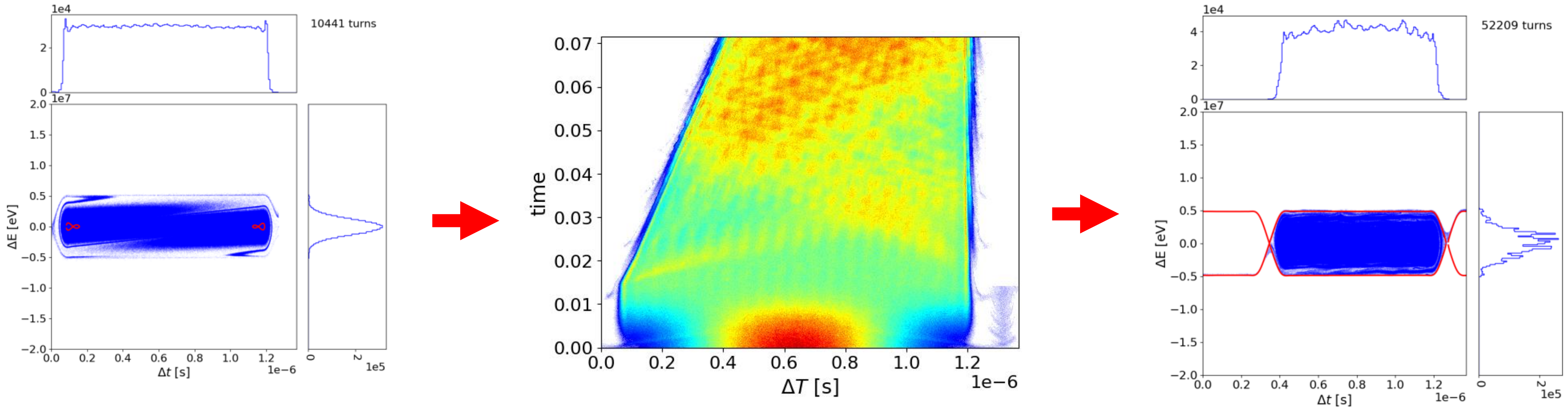
600 MeV/c: the solution?



- Replace single barrier bucket system in **accumulator ring** with double barrier
- Move one barrier towards the other

Barrier bucket compression

- Conventionally, this procedure is done adiabatically
  - Liouville's theorem means increased energy spread - higher barrier voltage will be required
- However, in ESSnuSB compression must be accomplished within 14 Hz linac cycle (~70 ms)
  - This is at the limits of the adiabaticity criteria. There is possibility of non-negligible emittance growth
- We have a 1.25 MW beam -> space charge effects are significant.
- Simulation of bunch compression must be done accounting for space charge and possible non-adiabatic compression



Extremely preliminary longitudinal simulation of a possible compression in the ESSnuSB accumulator

Space charge is not modelled