MICE And nuSTORM

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Rencontres du Vietnam: Flavour Physics Conference
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Overview

- The MICE Experiment
  - Purpose
  - Stages of development and hardware implementation
  - Analysis so far (beam)
  - Timeline
- The nuSTORM Experiment
  - Physics goals
  - Facility design
  - Decay ring options
  - Simulations

Muon Ionisation Cooling Experiment MICE

- Ionisation cooling is the process of reducing the beam emittance (phase space) while maintaining the longitudinal momentum of the beam.
- Necessary for a Neutrino Factory or Muon Collider.
- Short lifetime of muon means that
  - traditional beam cooling techniques which reduce emittance cannot be used.
  - ionisation cooling is the only practical solution to preparing high intensity muon beams for use in these facilities.
- Half of a neutrino factory cooling cell will be built.

MICE

*Muon beam loses both transverse and longitudinal momentum by ionisation cooling when passed through an 'absorber'.

*Longitudinal momentum is restored by four 200 MHz RF cavities.

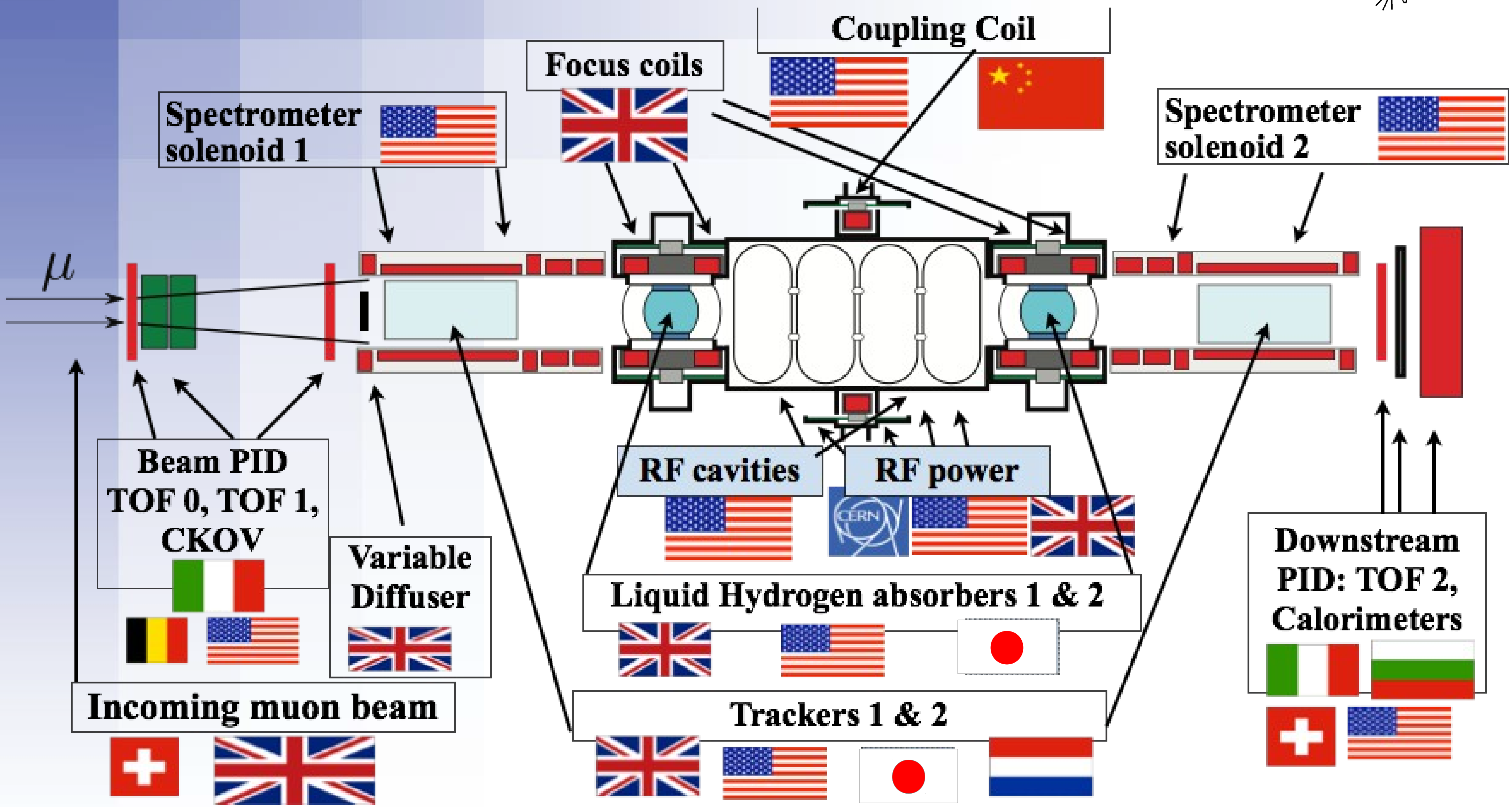
$$\frac{d\epsilon_n}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}$$

$D\epsilon_n/ds$ is the rate of change of normalised-emittance within the absorber;
β, E_μ and m_μ the muon velocity, energy, and mass respectively;
$\beta_\perp$ is the lattice betatron function at the absorber; and
L_R is the radiation length of the absorber material.

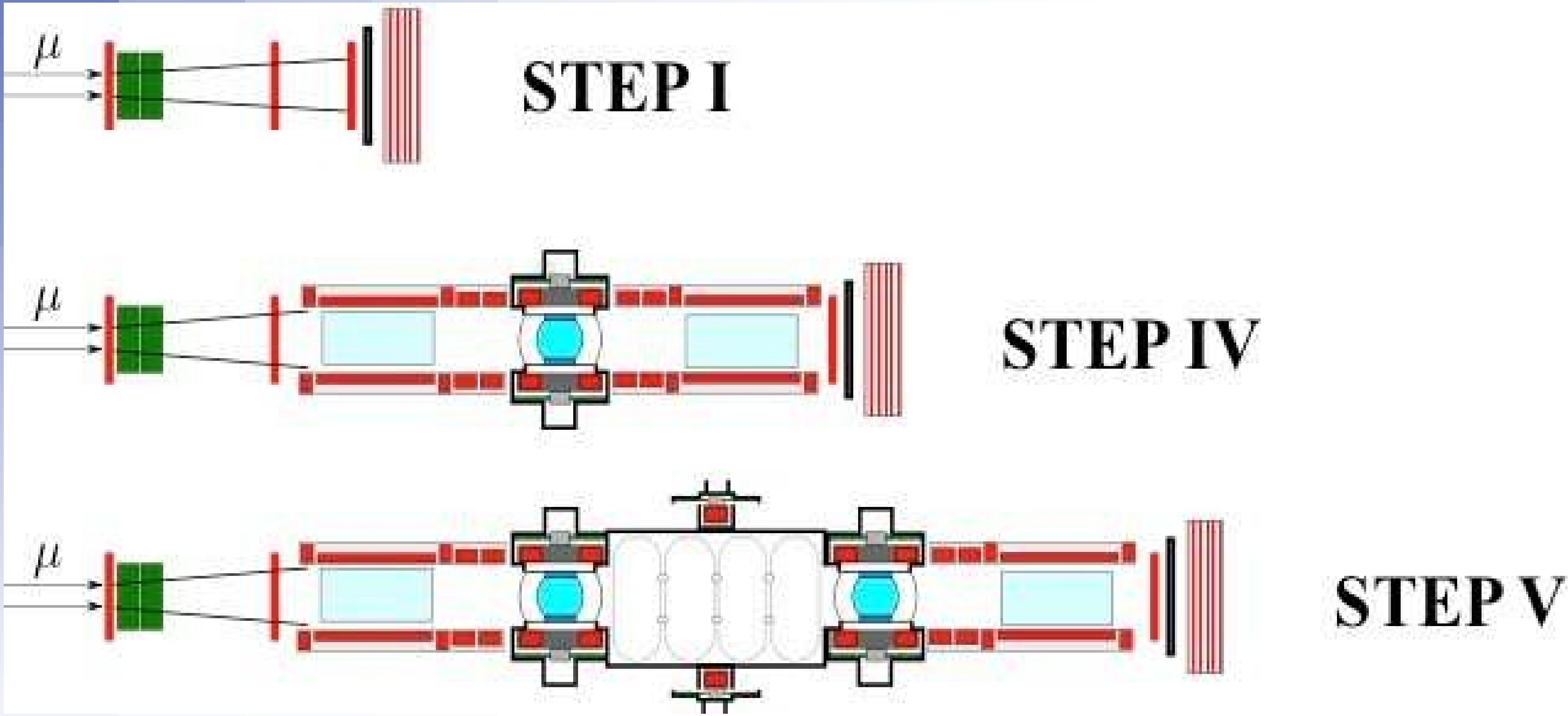
*Heating through multiple scattering

MICE aims to reduce the transverse emittance of the beam by 10% and measure it to an accuracy of 0.1%.

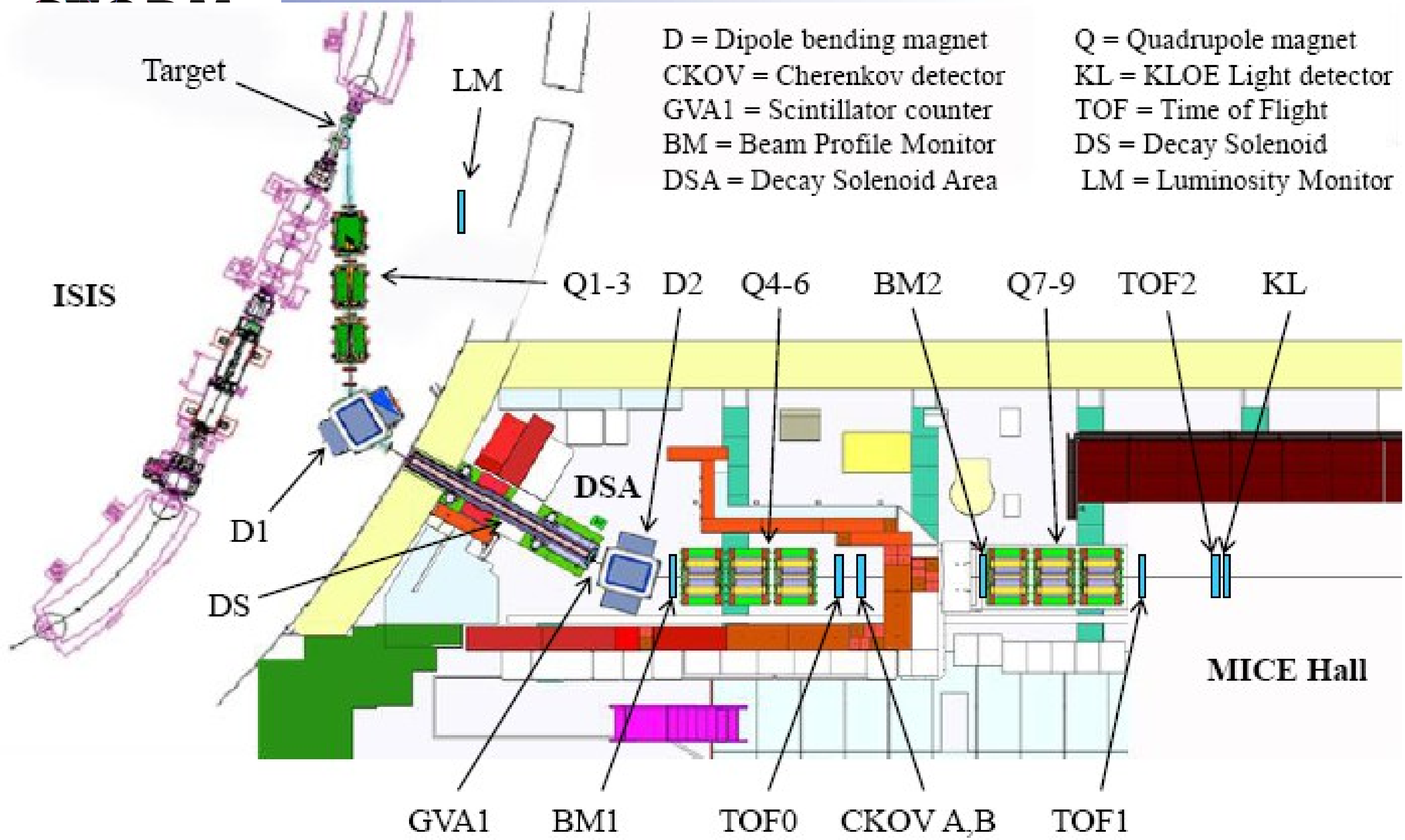
MICE


Coupling Coil
Focus coils
Spectrometer solenoid 1
Spectrometer solenoid 2
μ
Beam PID TOF 0, TOF 1, CKOV
Variable Diffuser
RF cavities
RF power
CERN
Liquid Hydrogen absorbers 1 & 2
Downstream PID: TOF 2, Calorimeters
Incoming muon beam
Trackers 1 & 2

Staged Implementation



MICE



Far left shows part of the ISIS accelerator which serves as a proton driver, with a titanium target used to generate pions by intercepting the circulating proton beam.

Step I

νSTORM

Muons per MICE target dip (spill) as a function of ISIS beam loss

μ^-

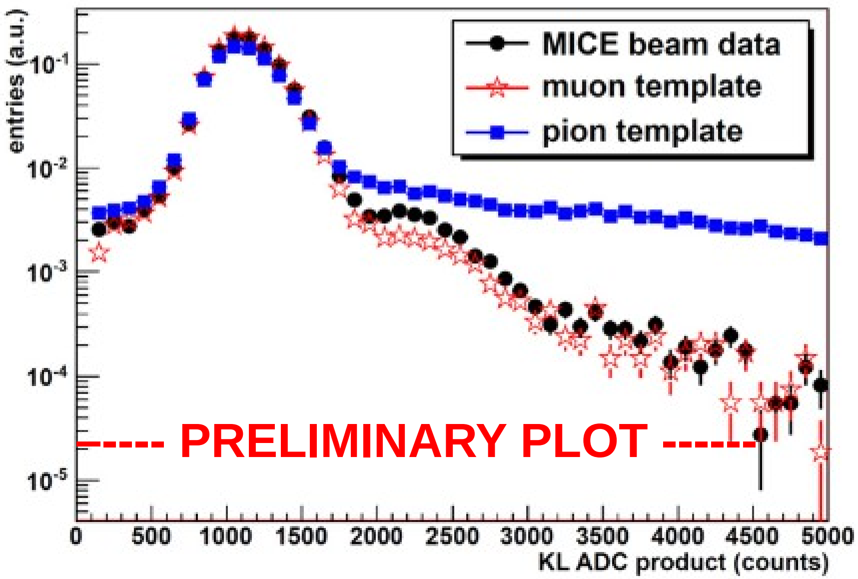
ε_N (π mm · rad)	μ^- rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	4.1±0.2	6.3 ±0.2	4.9±0.2
6	4.1±0.4	4.8±0.2	4.5±0.2
10	4.6 ±0.2	5.4±0.2	4.4±0.1

μ^+

ε_N (π mm · rad)	μ^+ rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	16.8±1.8	33.1±3.2	33.0±2.6
6	17.8 ±1.8	31.0±2.0	31.7±2.0
10	21.6±2.2	34.0±2.5	26.1±1.5

- Observed particle rates in TOF0 and TOF1 detectors were recorded and time-of-flight used to select good μ tracks.
- The rates are found to be linear with the ISIS beam loss/target depth.
- Errors mainly due to the time-of-flight cuts used to define a muon.
- Muons per spill is presently limited by the tolerance of the irradiation caused in ISIS by protons and secondary particles produced in the MICE target.
- Rates obtained are sufficient to collect the ~10^5 muons necessary to perform a relative measurement of cooling with a precision of 1%, in maximum one day.

Ref. ArXiv:1203.4089

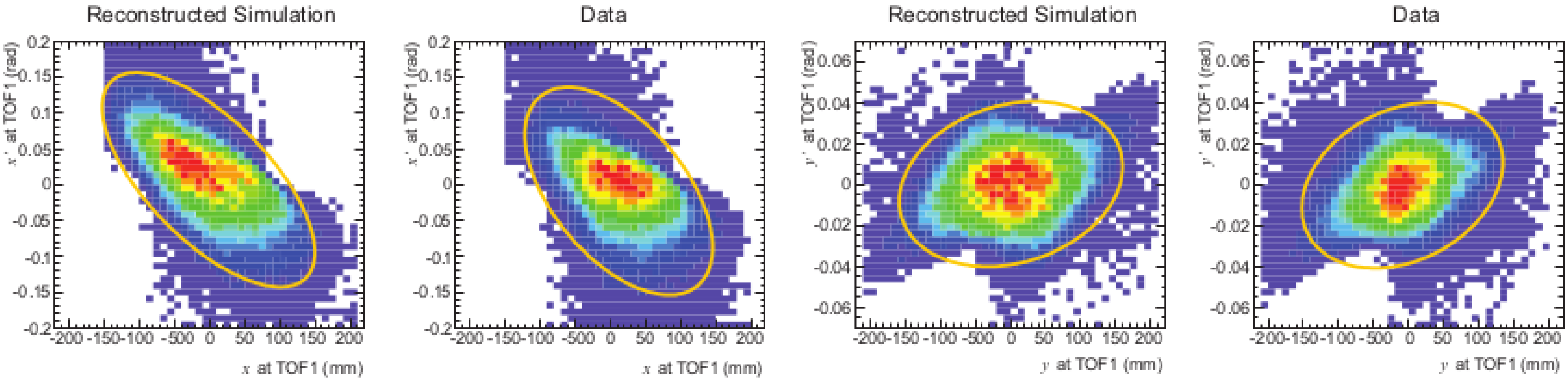


MICE Muon beam contamination

- Determination of MICE muon beam purity using the KL detector. A pion contamination in the muon beam at or below the 1% level (<5% for μ^+) is determined.

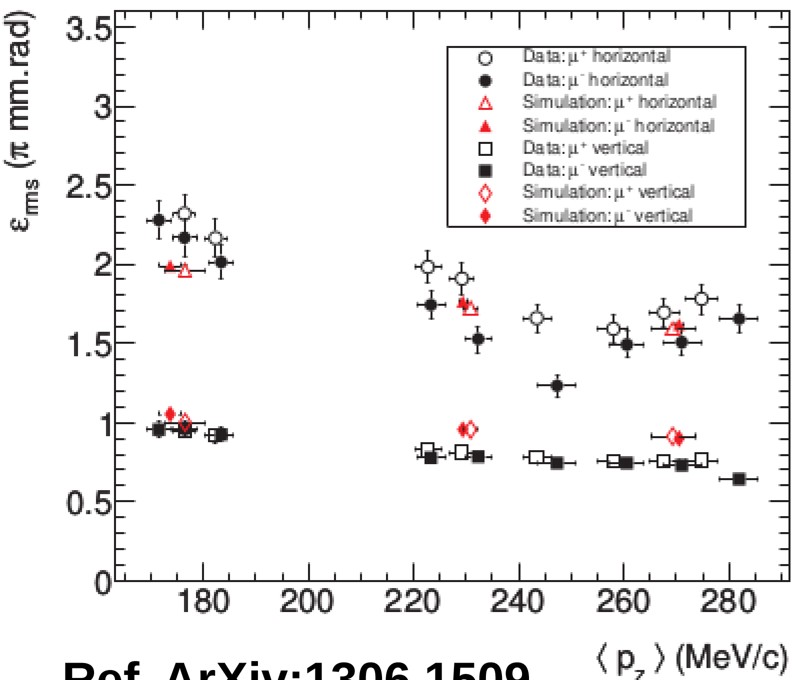
Step I

Reconstructed horizontal and vertical trace-space in simulation and data.

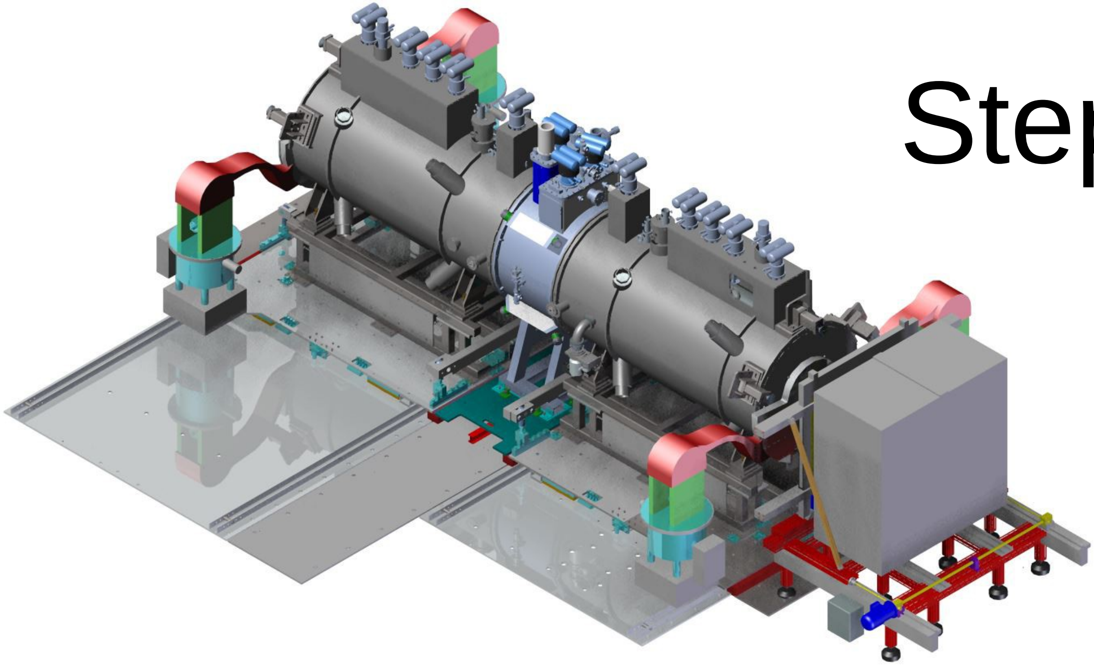


Horizontal and vertical RMS emittance in data and simulation.

A novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 π mm-rad, with central momenta from 170–280 MeV/c, and momentum spreads of about 25 MeV/c.

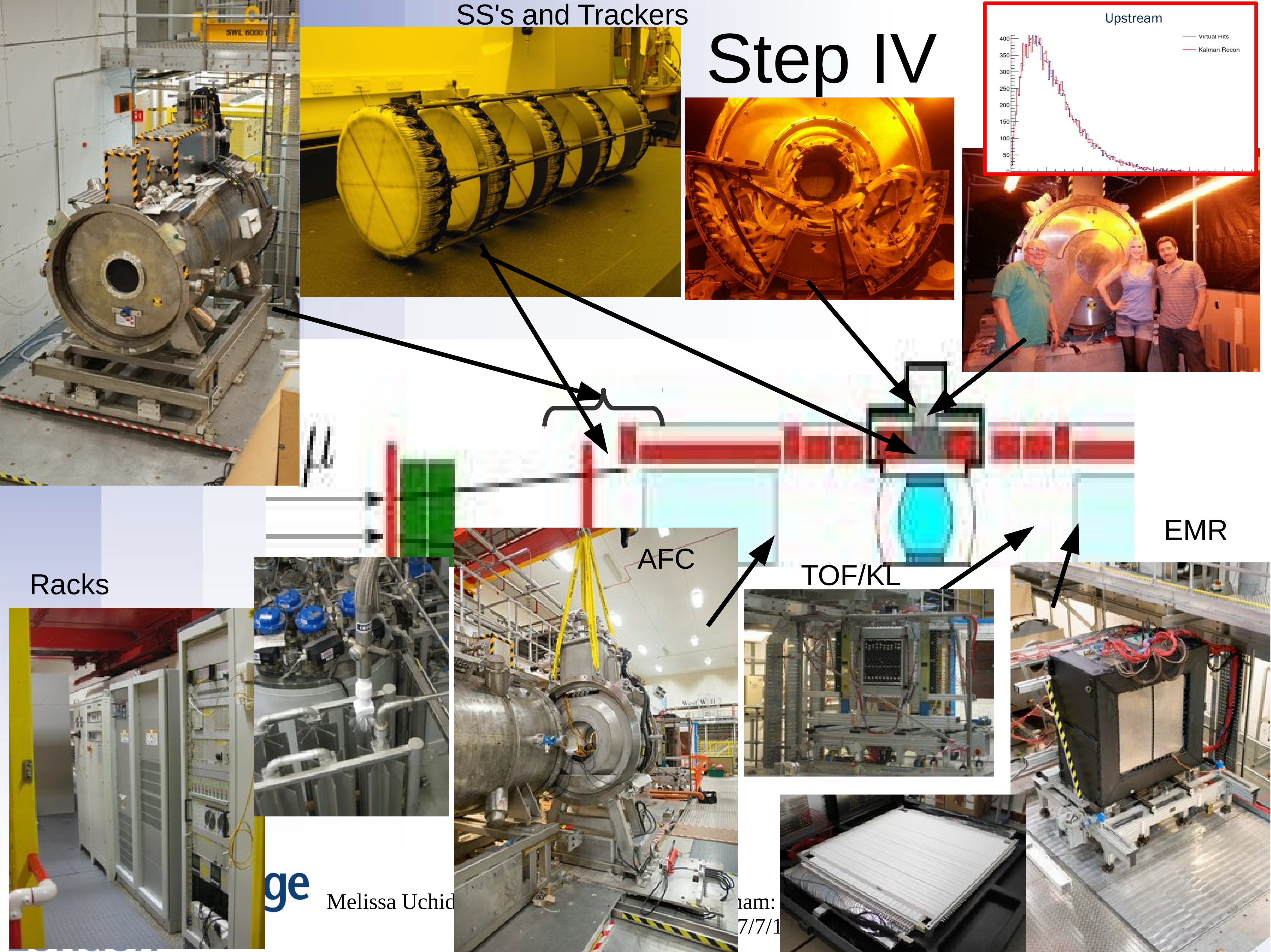


Ref. ArXiv:1306.1509

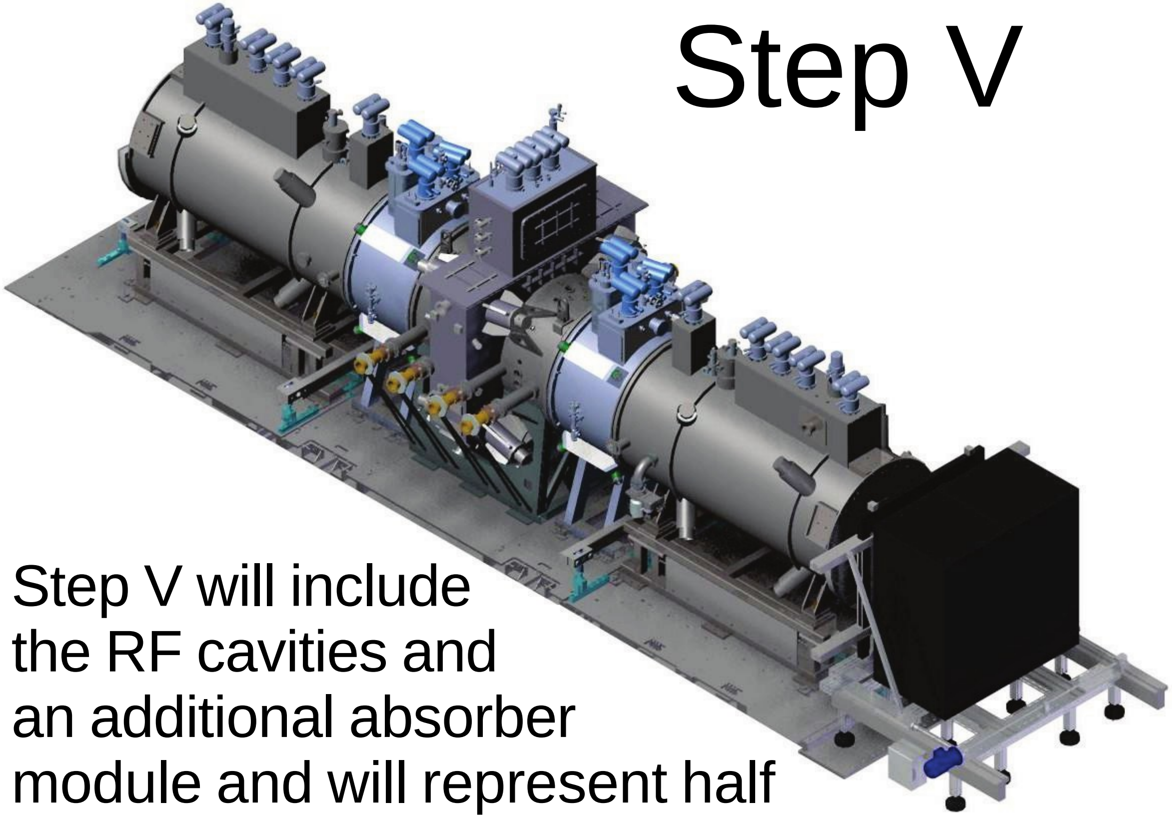


Step IV

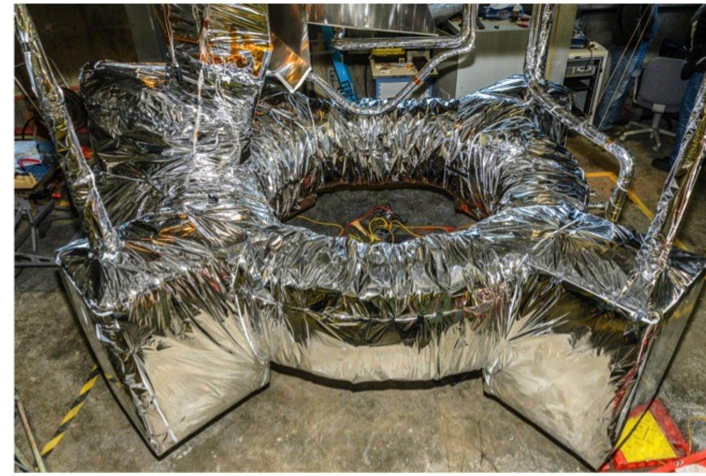
- Is currently in the advanced stages of construction and commissioning.
- It will test the system without RF cavities to re-accelerate the beam.
- Will test beam propagation in the magnetic system and allow precise measurement of ionisation cooling related properties of absorbers (H2, LiH, and possibly more) with great precision (reduction of transverse and longitudinal beam emittance which means it will not be sustainable cooling).
- Data taking is on target to begin in 2015.


SS's and Trackers
Step IV
Upstream
Virtual Hits
Kalman Recon
400
350
300
250
200
150
100
50
μ
AFC
TOF/KL
EMR
Racks

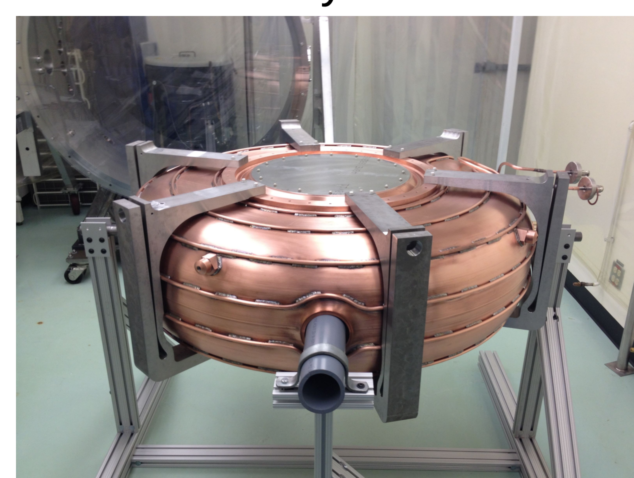
Step V



Step V will include the RF cavities and an additional absorber module and will represent half of a full lattice cell of the Neutrino Factory Feasibility Study II (FS-II) cooling channel. The Step V configuration will allow the essential demonstration of ionisation cooling with re-acceleration. Construction of Step V is scheduled for completion in 2017/2018.



The 2.5 T superconducting CC magnets located around the RF cavity assemblies and cryostats have been designed by a collaboration from the US and China. It has been built and is currenty undergoing testing and training at the Solenoid Test Facility in Fermilab. Assembly of the RF control and power distribution systems is under way at LBNL and Daresbury Lab.



All RF cavities have been fabricated and the first is being readied for testing in the Fermilab MuCool Test Area (MTA).

nuSTORM

nuSTORM

- Designed to deliver beams of $\nu_e(\bar{\nu}_e)$ and $\bar{\nu}_\mu\ (\nu_\mu)$ from the decay of a stored $\mu^\pm$ beam with a central momentum of several GeV/c and a momentum acceptance of 10%.
- The facility has three primary physics objectives:
  - Serve future long- and short-baseline neutrino-oscillation programs by providing definitive measurements of $\nu_e(\bar{\nu}_e)$N and $\nu_\mu(\bar{\nu}_\mu)$N scattering cross sections with sub-percent level precision;
  - Allow searches for eV sterile neutrinos (LSDN-like) with exquisite sensitivity (appearance and disappearance); and
  - Constitute the first operational use of a muon storage ring as a neutrino source—a great step for R&D on muon accelerators as a powerful new technique for particle physics.
- The nuSTORM facility represents the simplest implementation of the Neutrino Factory concept.

nuSTORM

Precision cross section measurements are essential to neutrino oscillation experiments

- Flux and cross sections must be known to <<5%
- Hadron production experiments (NA61 CERN)+ near detectors measure cross sections to 5%.
- To measure cross sections ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$, to 1% a mini ν factory is needed (1st step is a μ storage ring).

Event Rate per 10^{21} POT, 100 tonnes at 50 m

μ^+ Channel	μ^+ N_{evts}	μ^- Channel	μ^- N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

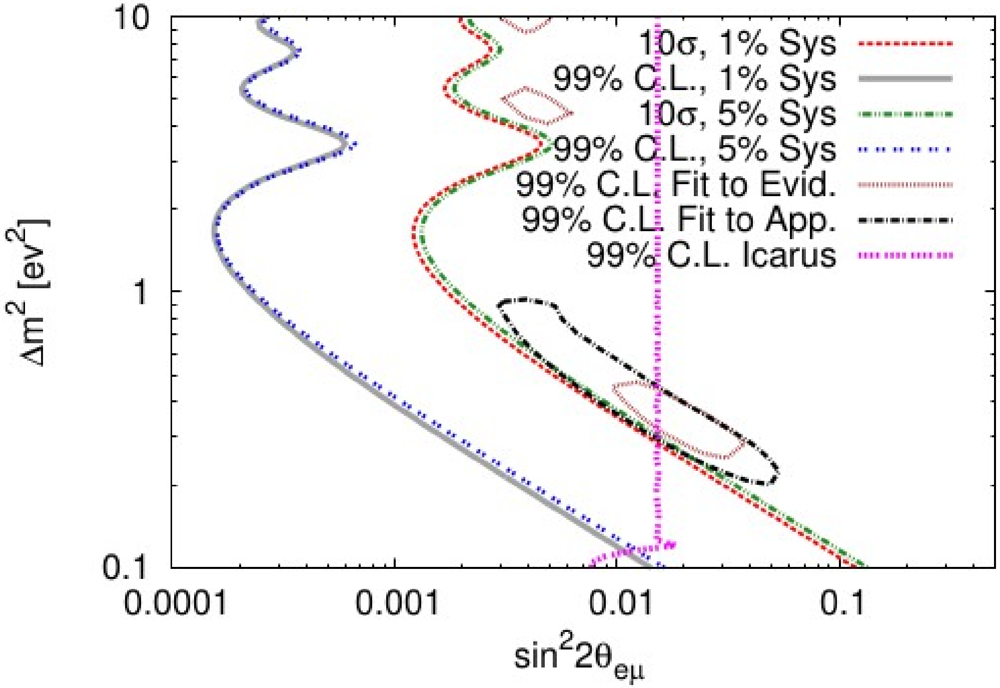
From a full simulation of the decay straight. NuSTORM measurements limited by detector systematics.

Experiment	Flux Error
MiniBooNE	6.7—10.5%
T2K	10.9%
Minerva	12%
nuSTORM	<1%

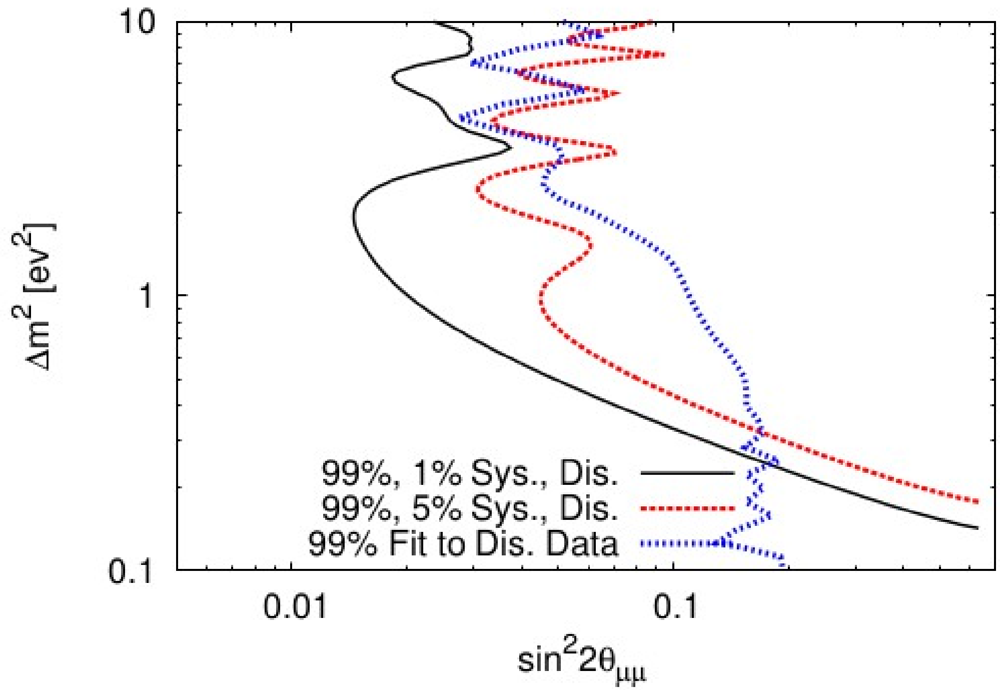
D. Adey et. al. **Phys.Rev.D89,071301(R)**

Sterile ν Search

$\nu_e \rightarrow \nu_\mu$ Appearance Search



$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Disappearance Search



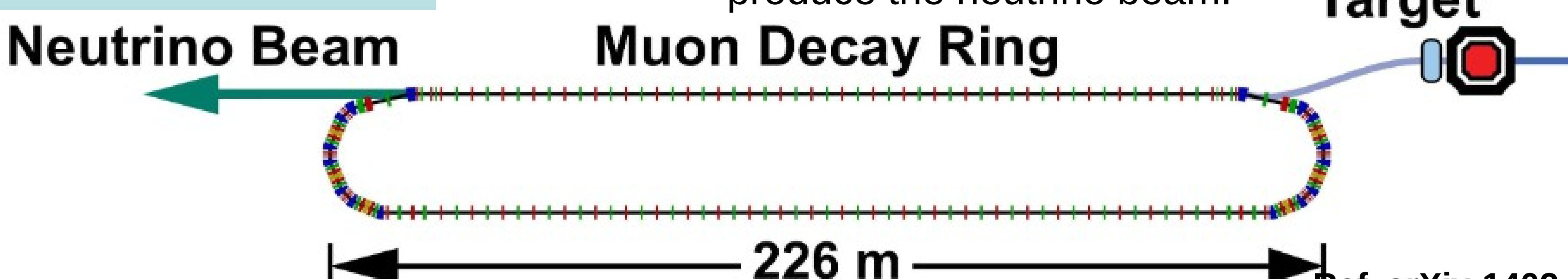
- Studies of sterile neutrino discovery potential completed.
- Assume:
  - 3+1 model
  - sample of 1.8×10^{18} useful μ^+ decays.
- 1.3 kTon iron-scinitillator calorimeter detector.
- Assume a 0.5% rate and 0.5% cross-sectional systematic.

Facility

- The components of nuSTORM consist of 5 major elements:
  - Primary proton beam line (10^{21} POT ~4-5 yrs 2.6×10^{18} useful π decays),
  - Target station (100 kW designed for 400 kW) with horn to select $\pi^+\pi^-$,
  - Pion transport line (chicane to select charge of πs & stochastic injection),
  - Muon decay ring and
  - Detector halls.

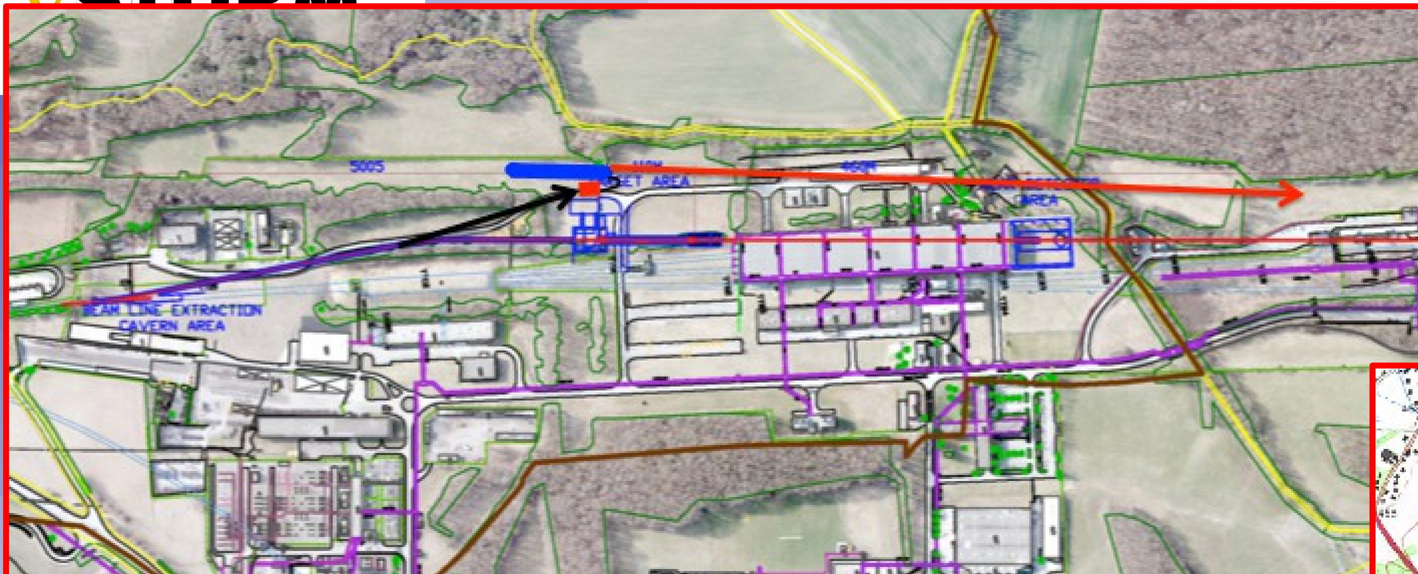
$$\mu \rightarrow e + \bar{\nu}_{\mu} + \nu_{e}$$

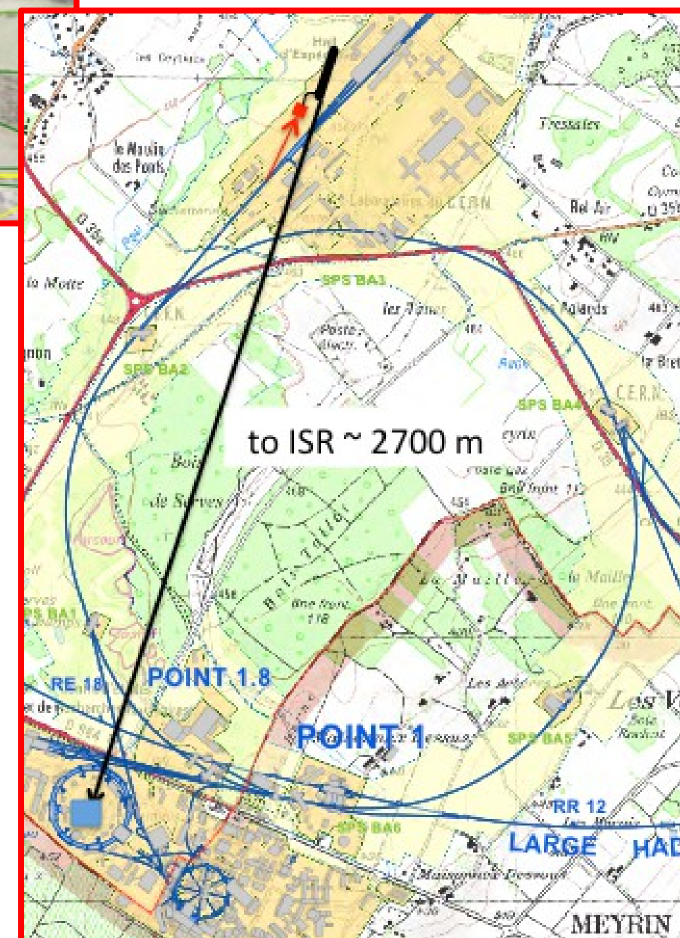
A schematic of the storage ring configuration. Pions are injected into a straight section and must decay into muons before the first bend or be ejected from the ring. Muons that decay in the injection straight during subsequent turns produce the neutrino beam.



Ref. arXiv:1402.5250

Implementation at CERN





- **Principle Issue:**
  - SPS spill is 10μs:
    - Implies bend for p extraction or π beam or development of fast extraction.
- **Two options:**
  - North Area implementation:
    - Possible exploitation of synergies with ICARUS/NESSiE
  - North Area to West Area implementation:
    - Advantage is p/π bend isn't required
    - Longer baseline must be tuned to larger muon energy (possibly an advantage too)

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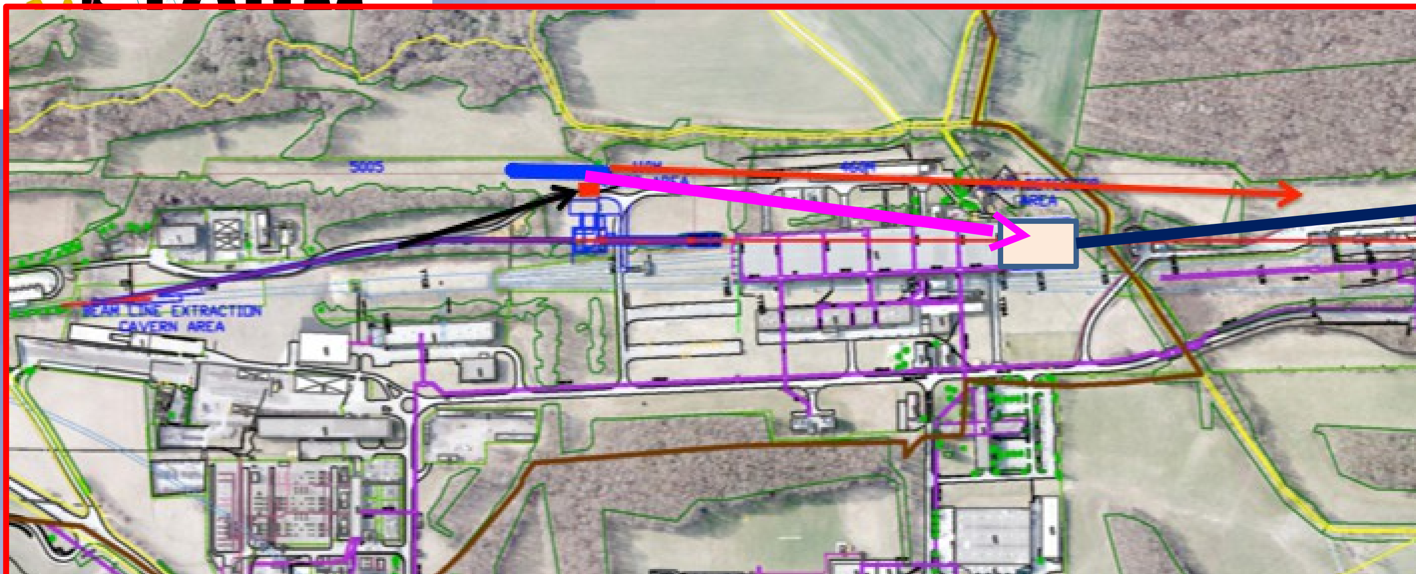
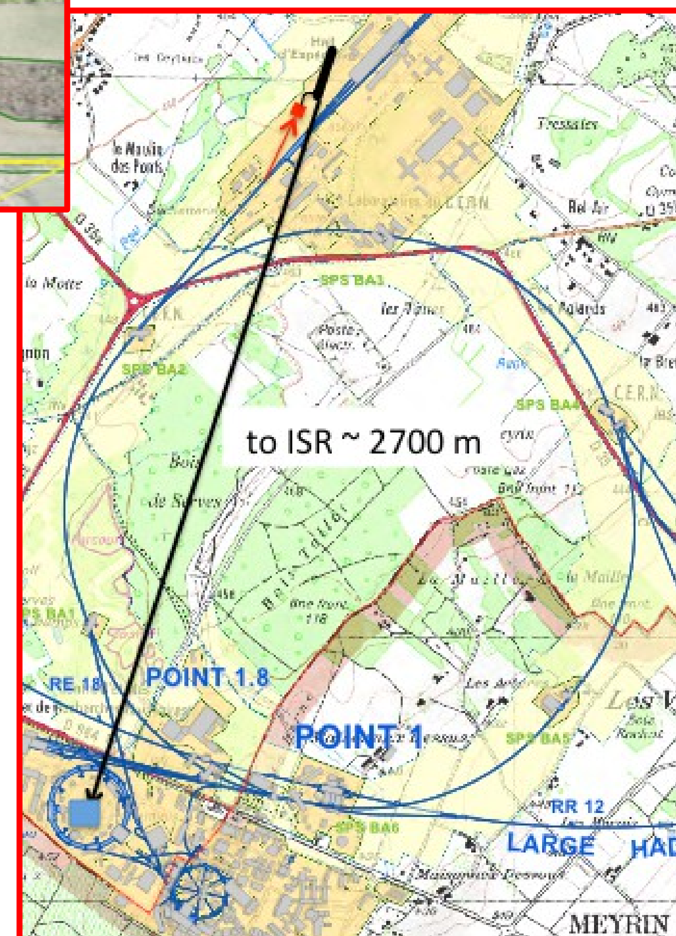


North area extension



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Decay Ring

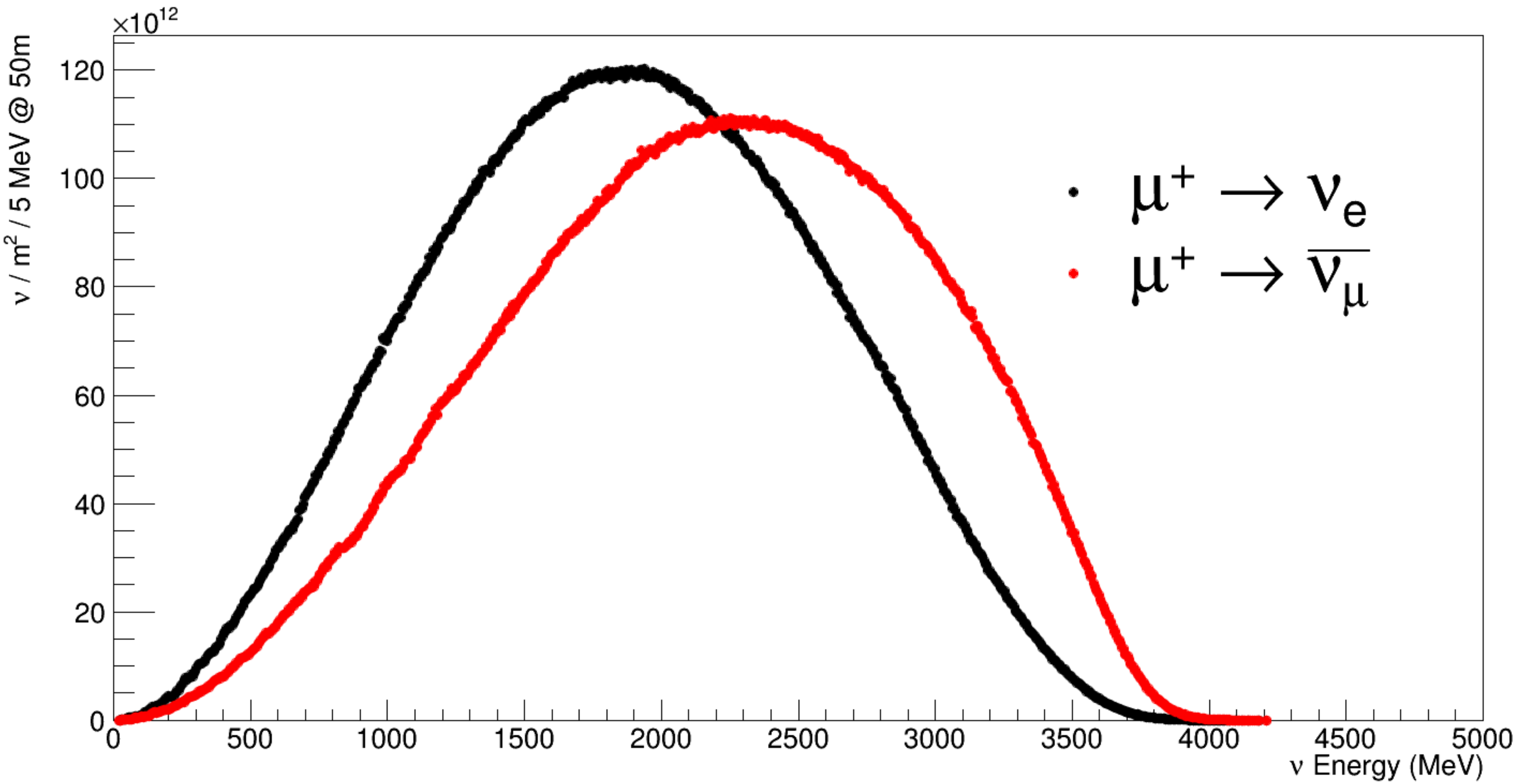
The decay ring could be built from:

- **FODO** (Focusing Defocussing) magnets or
- **FFAG** (Fixed Field Alternating Gradient) magnets.

The momentum acceptance is ±10% (total 20%) in the FODO, ±16% (total 32%) in the FFAG solution.

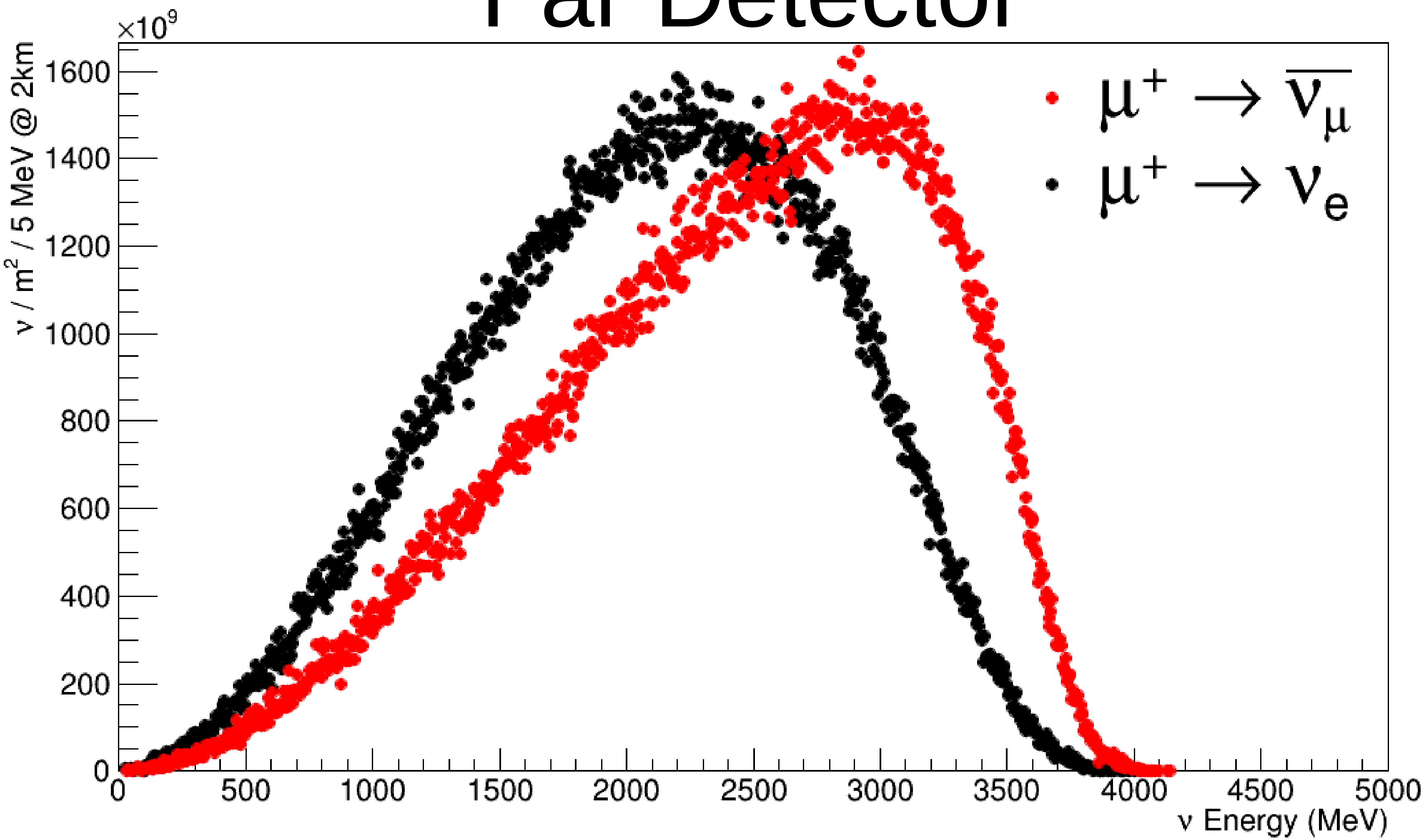
A full study of both possibilities is under way to determine the benefits and disadvantages of both.

Flux from Muon Decays at Near Detector



50 m from the end of the decay straight with a 3m radius.

Flux from Muon Decays at Far Detector



Far detector performance for sterile neutrino searches:Light sterile neutrino sensitivity at the nuSTORM facility. **Ref. Phys. Rev. D 89, 071301(R)**

2 km from the end of the decay straight with a 3 m radius. Full muon simulation and decays. Shifts to higher energy due to kinematics effect.

Conclusions

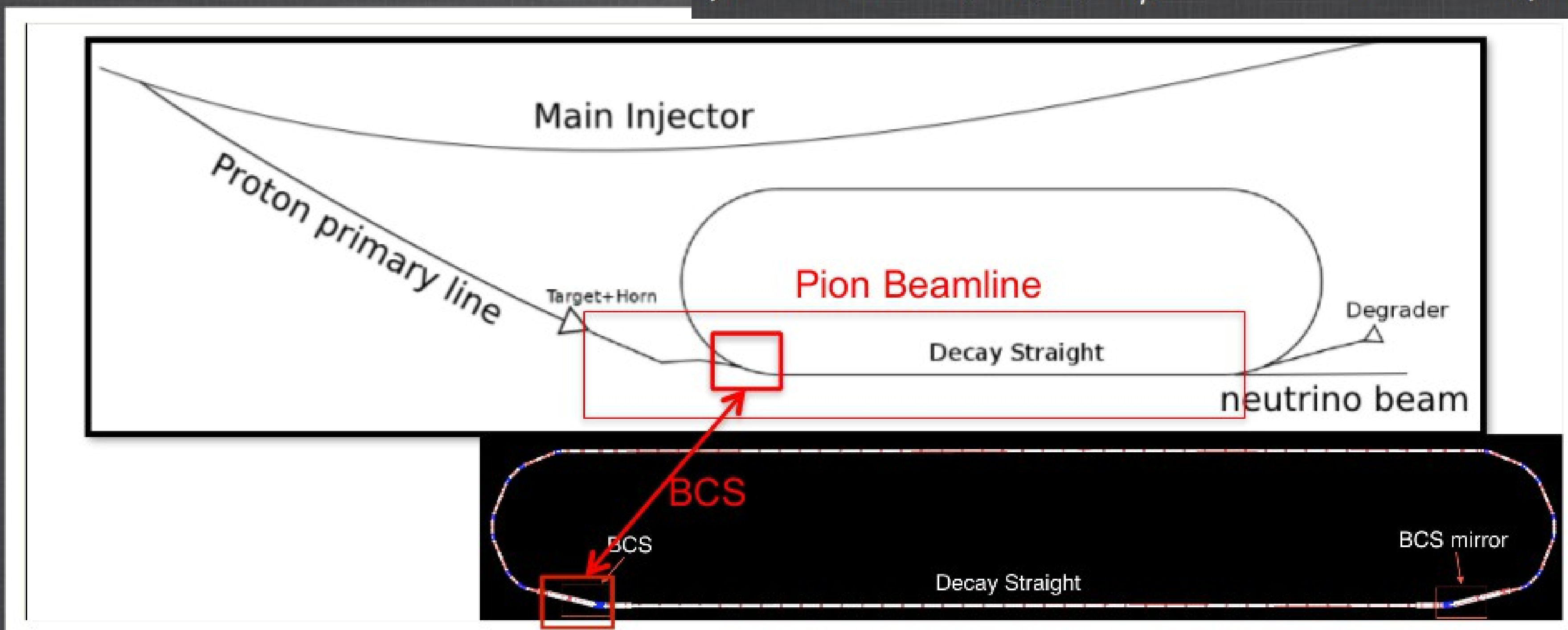
- **MICE**
  - The MICE experiment aims to reduce the emittance of a muon beam by 10% and to measure it with an accuracy of 0.1%.
  - Has already shown that it is using a suitable beam and instrumentation to achieve its physics goals.
  - Step IV will demonstrate ionisation cooling but without beam re-acceleration. Construction is well underway and data taking is on target to begin in 2015.
  - Step V and beyond will demonstrate transverse ionisation cooling. Construction is scheduled for completion in 2017/2018.
- **NuSTORM**
  - Will create a neutrino beam from a stored $\mu^{\pm}$ beam with a central momentum of a few GeV/c and a momentum acceptance of 10%. It will
  - allow searches for sterile neutrinos;
  - Measure scattering cross sections with percent-level precision;
  - Constitute the crucial first step in the development of muon accelerators;
  - And represents the simplest implementation of the Neutrino Factory concept.
  - Design studies, simulations and physics studies are well advanced.

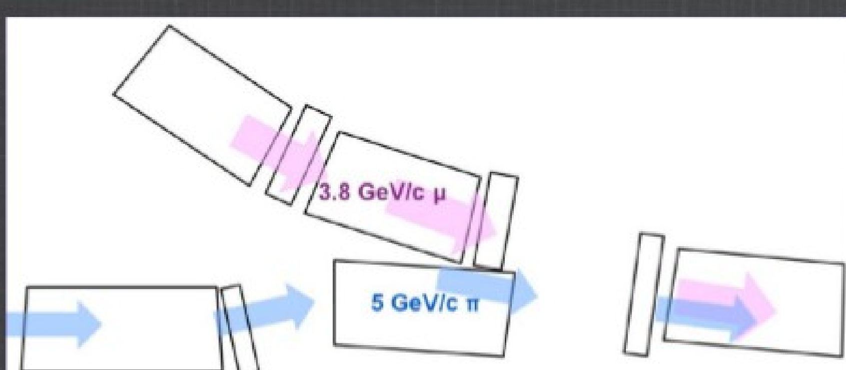
Stochastic Injection

Stochastic injection gives access to a pion beam decaying in the straight section as well as muon beam decay.

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

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





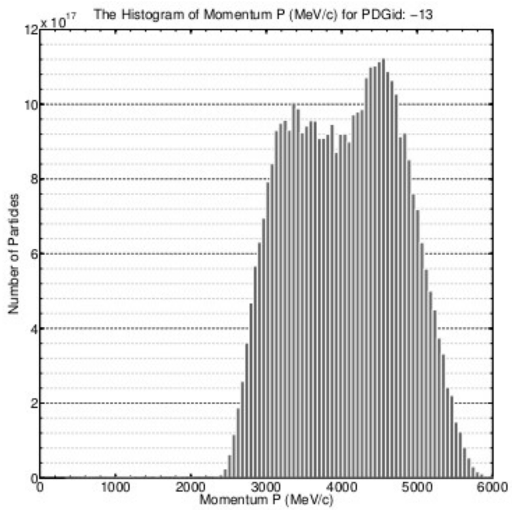
- concept from D. Neufer*: injection of pions at the Beam Combination Section (BCS) that decay in the straight section in muons.
- No kicker!

*Telmark Conference on neutrino mass, 1980

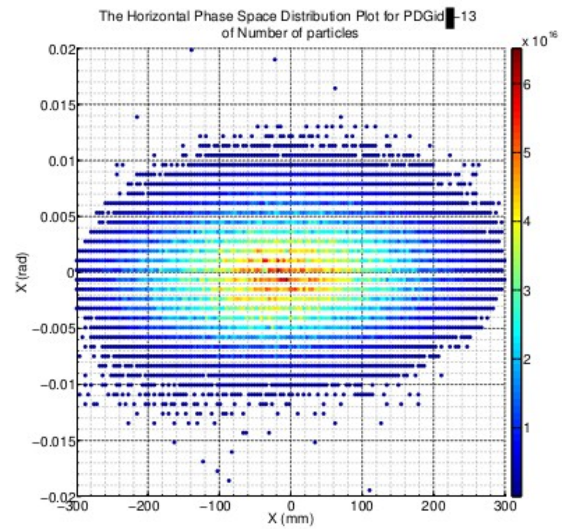
FODO Ring Simulations

Beam Structure

μ^+ Distribution



p_x/p_z versus x



Full simulation of FODO run developed with G4beamline.

Tracks secondaries ($K^\pm$, $\mu^\pm$, $\pi^\pm$) from 10^{21}POT.

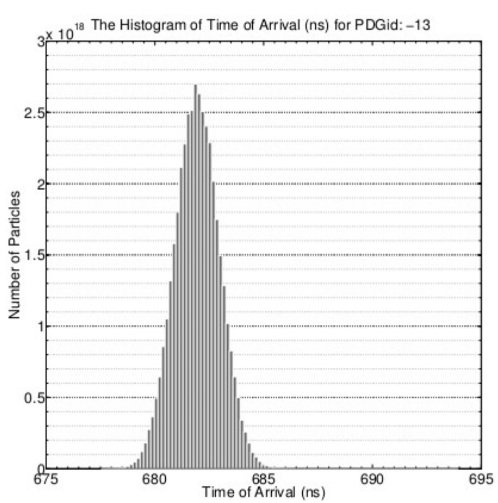
Precise profiles of momentum beam extracted.

Beam structure well defined

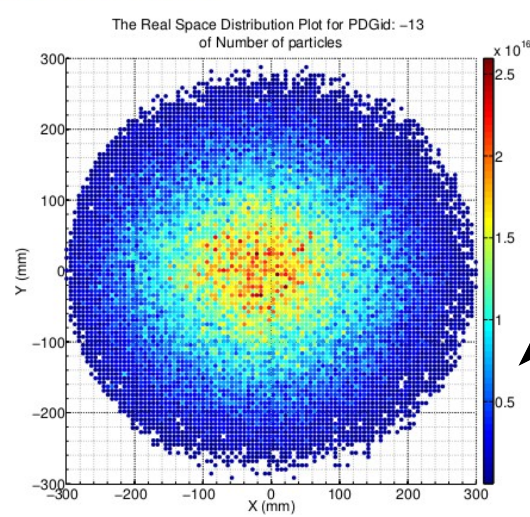
Supplies knowledge of neutrino timing.

Muon Momentum

Time distribution



Beam Profile



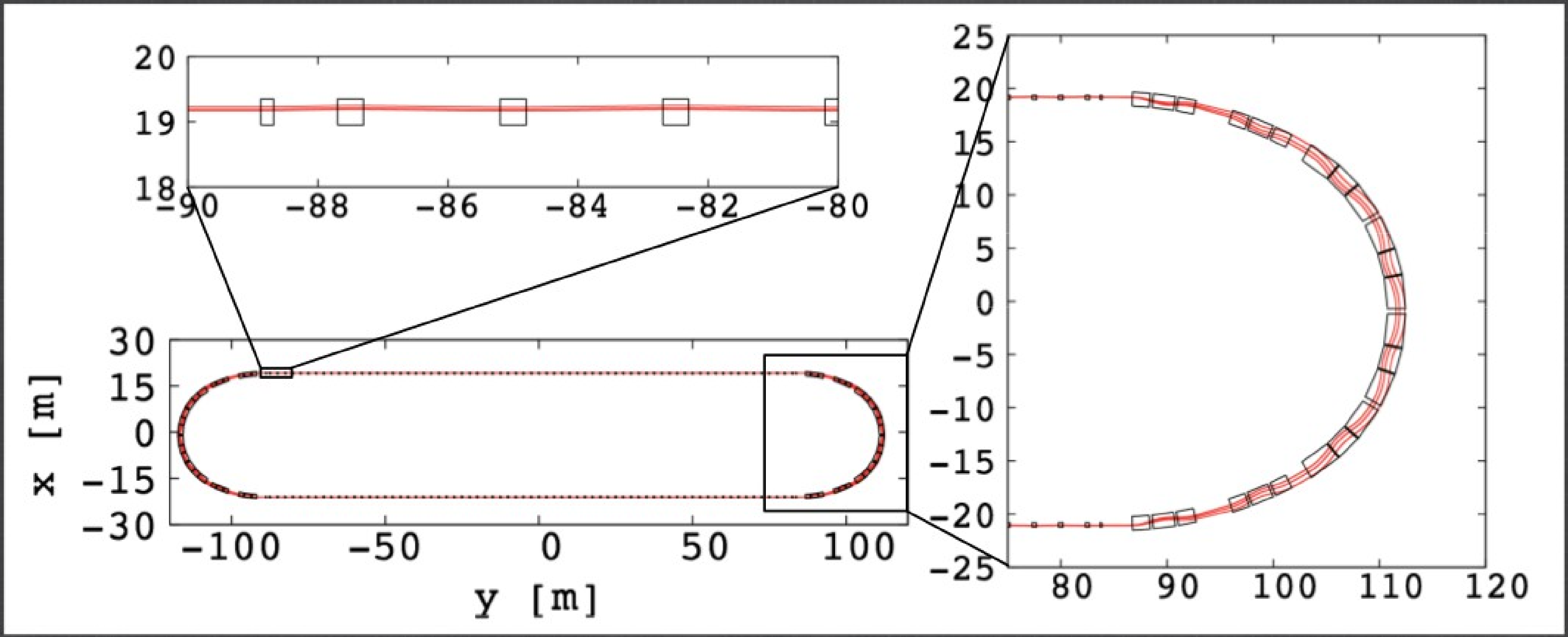
- Uniform decays in straight.
- Integrate over decay positions to produce ν beams.

For full details see Talk by JB LAgrange - ICHEP 14 - July 14

Decay Ring FFAG

muon 3.8 GeV/c ± 16% (zero-chromatic system)

Circumference: 500 m, straight section length: 175 m



Neutrinos from STORed Muons

Proposal to the Fermilab PAC

Event rates per 10~ton
at the near detector station

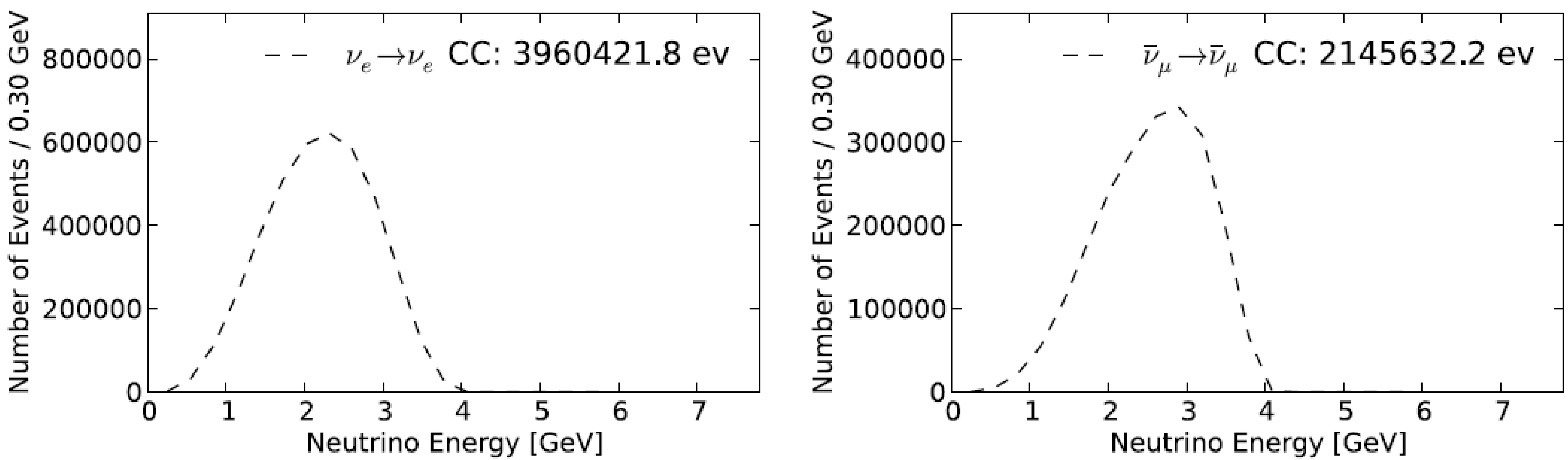


Figure 102. ν_e spectrum at near detector (Left), $\bar{\nu}_\mu$ (Right).

The precise leading edge of neutrino flux allows calibration of the neutrino energy reconstruction.

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

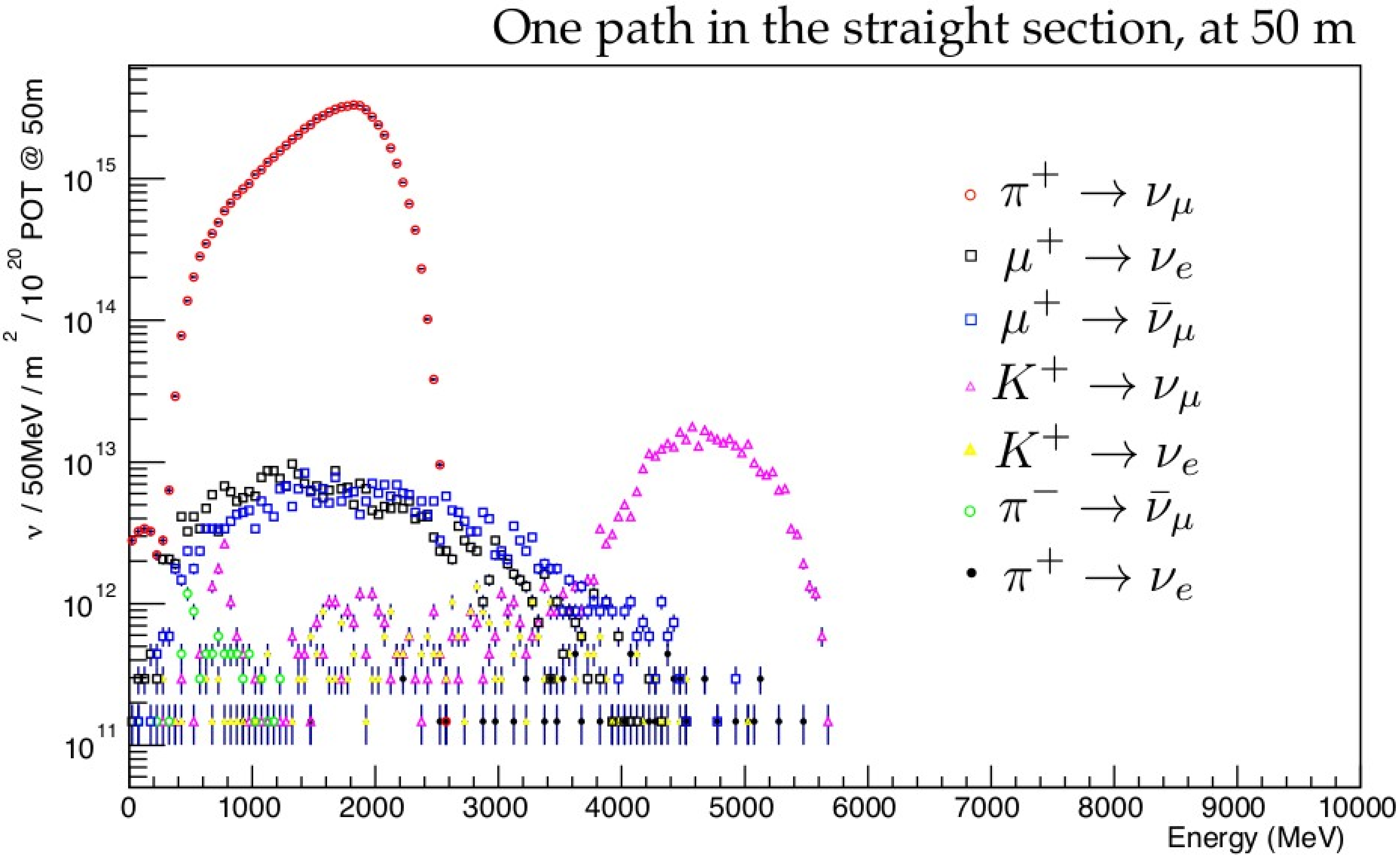
Table XXI. Event rates at near detector (for 100T) with μ^+ stored

Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

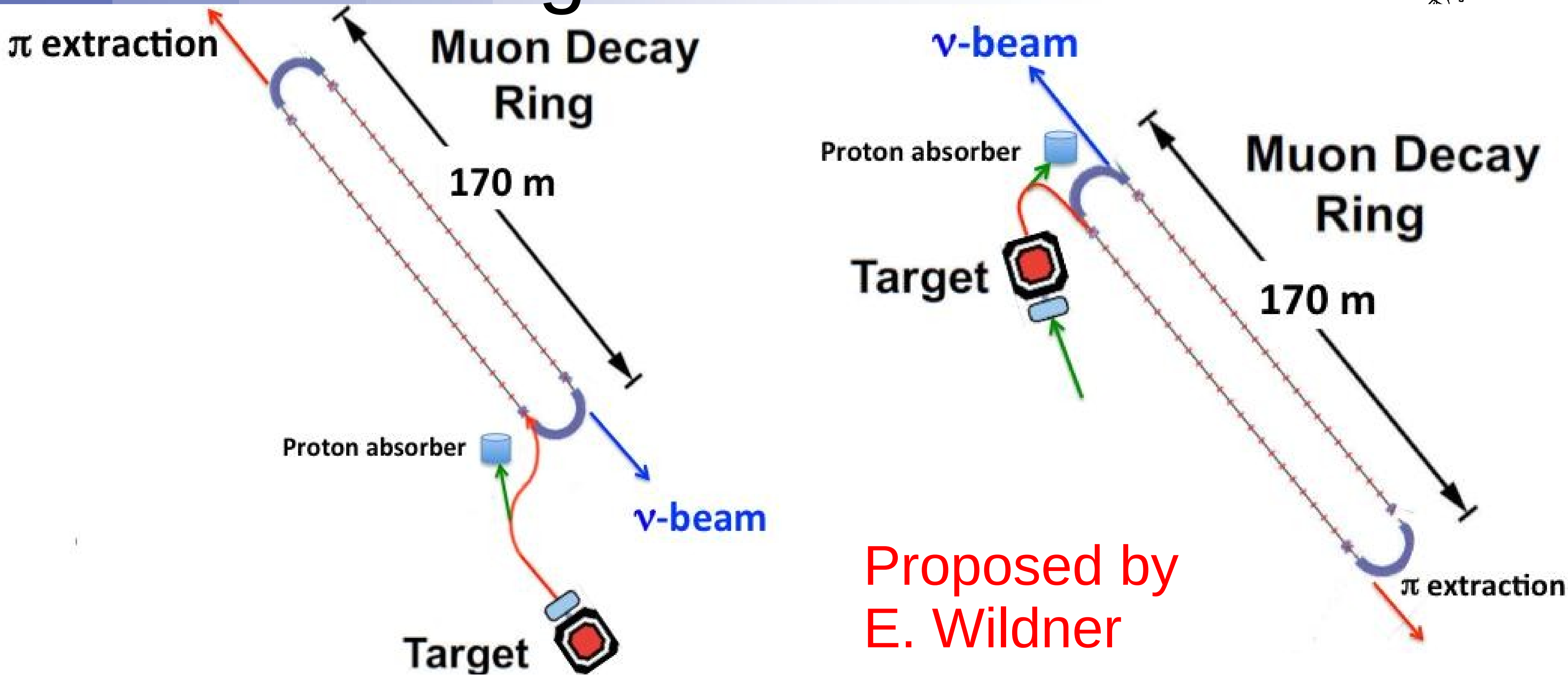
Table XXII. Event rates at near detector (for 100T) with μ^- stored

arXiv:1308.6822v1

Near detector flux from Pion/Kaon decay



Possible Decay Ring Configurations at CERN



Proposed by
E. Wildner

NB// The scheme shown on slide 23 allows to use neutrinos from both from pi and mu decay (with detectors with sufficient time resolution) however, this CERN scheme does not.

νSTORM

Keen sighted Question:

a lot of the numbers for the LOI and proposal for fluxes and sensitivities, are slightly different now and there is some variation in slides and other texts.

This is because of changing assumptions due to optimizations of the facility.
Inconsistency of numbers is less than 10% & due to variations between assumptions.
This does not, however, imply a 10% uncertainty since if we built any of those NuSTORMS, we would still have it instrumented such that we measured everything to 1%.