NuSTORM accelerator: Challenges and opportunities

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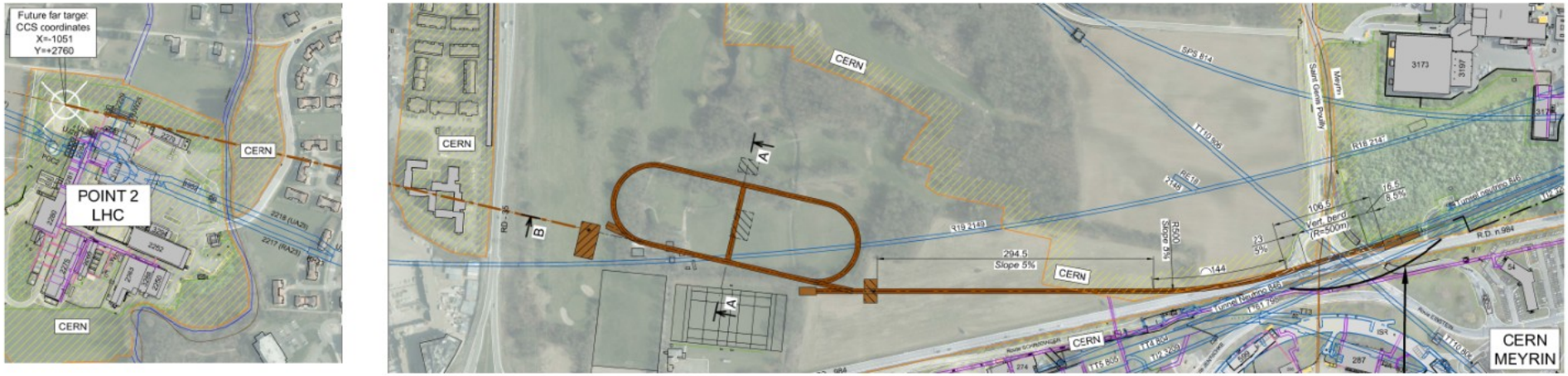
NuSTORM accelerator challenges

- nuSTORM facility is a unique facility for
  - High muon rate
  - Well-characterised neutrino beam
- Several applications
  - Measurement neutrino scattering cross sections
  - Search for sterile neutrinos and other BSM physics
  - Provide a technology test-bed for the muon collider
- What is the nuSTORM facility?
- What is the physics reach?
- How can it provide a test-bed for the muon collider?

nuSTORM facility

- What is the nuSTORM facility?

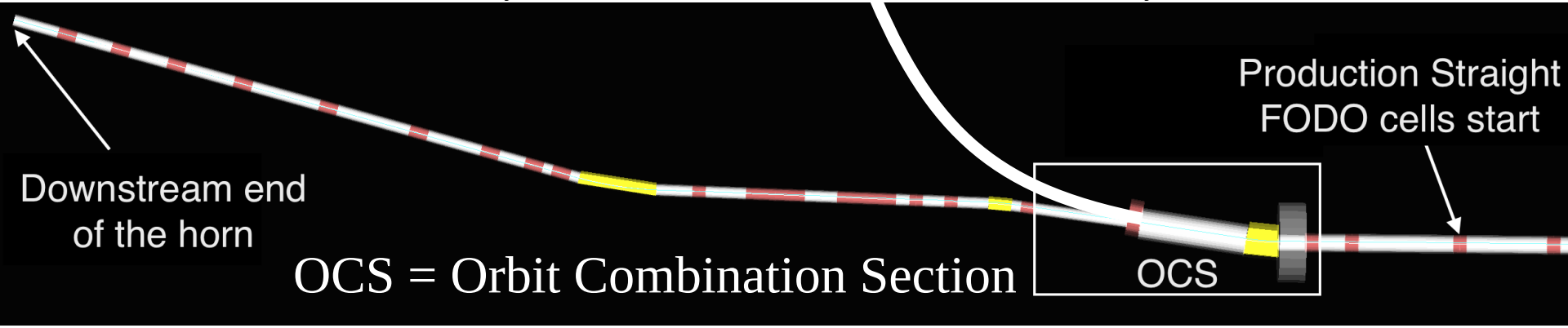


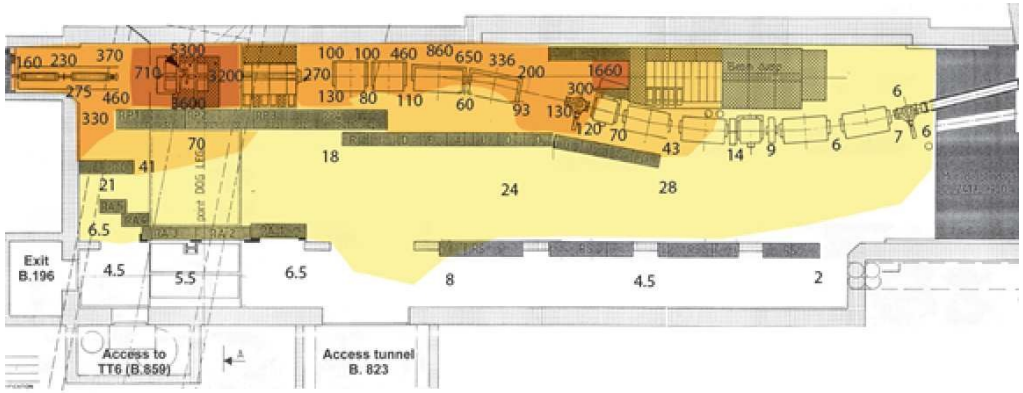
nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - Option for conventional FODO ring or high aperture FFA ring

Target and Pion Transport Line

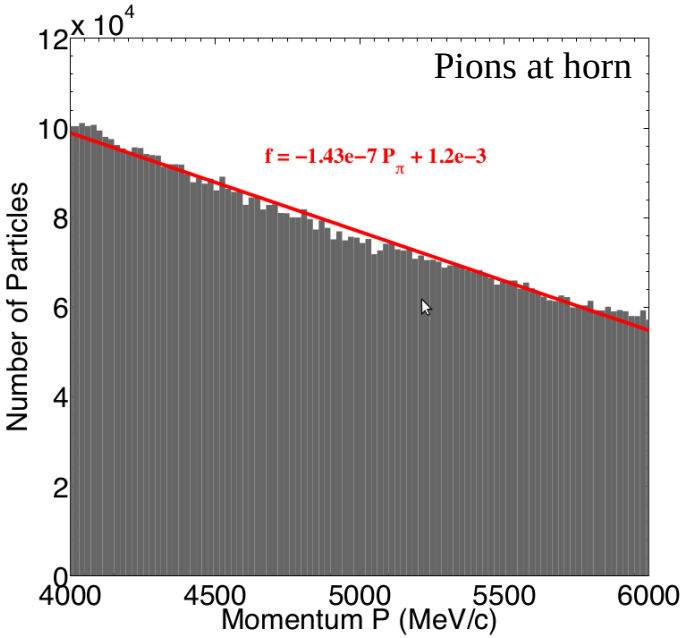
A. Liu et al, Design and Simulation of the nuSTORM Pion Beamline, NIM A, 2015
D. Adey et al, Overview of the Neutrinos from Stored Muons Facility – nuSTORM, JINST, 2017

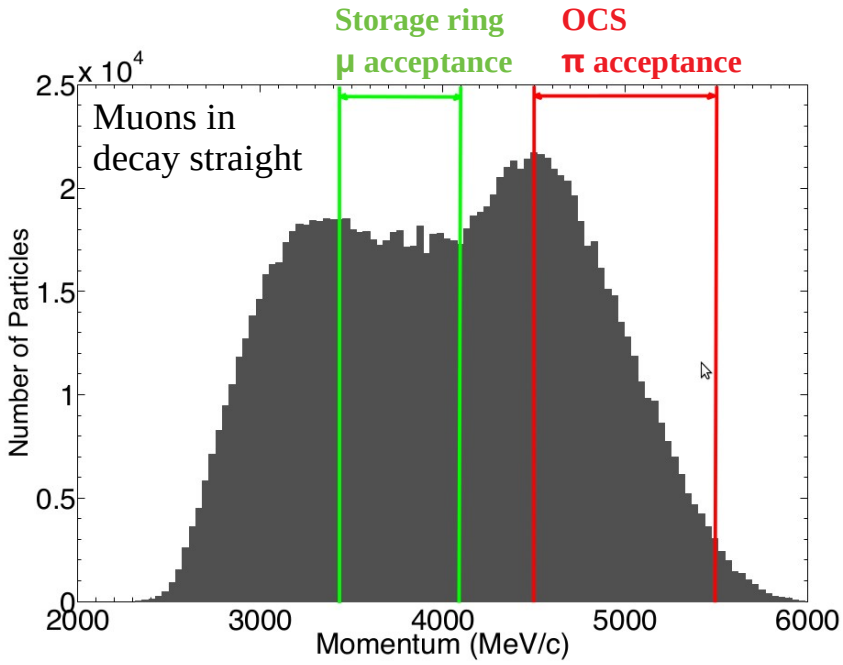




- Conventional 250 kW target horn
- Pion transport line
  - Proton beam dump
  - Momentum selection
  - Active handling

Stochastic Muon Capture

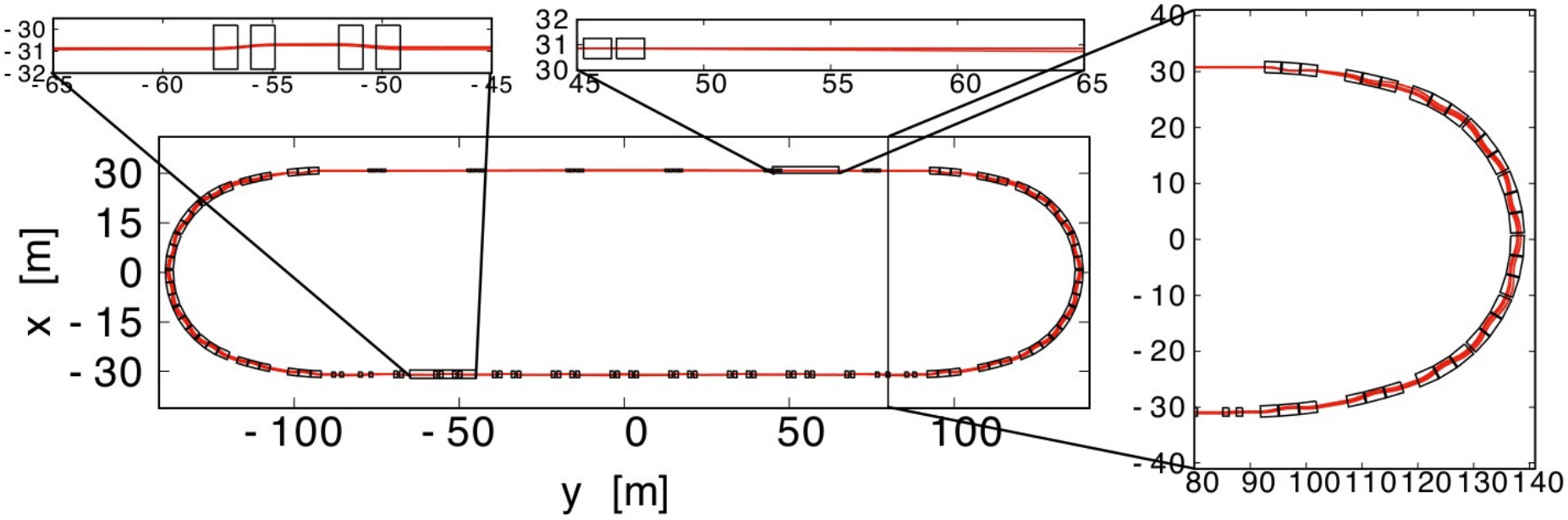




- Pions injected into the decay ring
- Capture muons that decay backwards in pion CoM frame
- Undecayed pions and forwards muons diverted into muon test area
  - Extraction line at end of first decay straight

Storage Ring

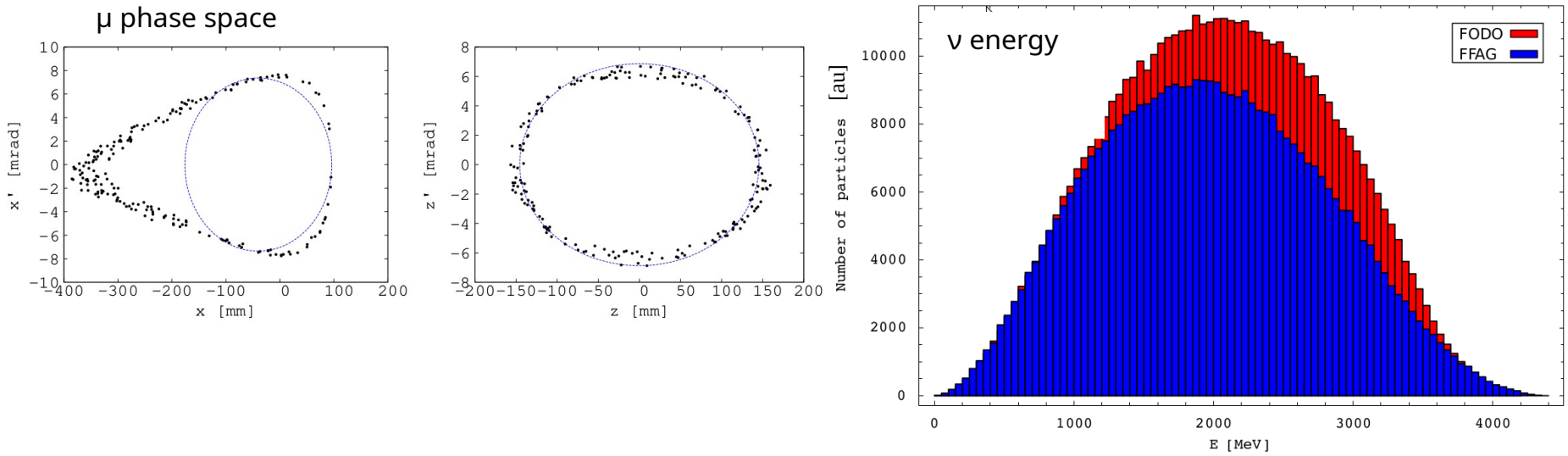
nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020



- Storage ring technologies:
  - Conventional FoDo ring
  - High acceptance FFA ring

Storage Ring

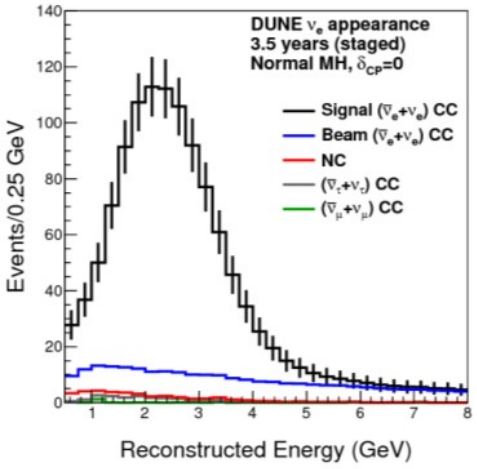
Lagrange et al, Racetrack FFAG muon decay ring for nuSTORM with triplet focusing, J. Inst 13 (2018)

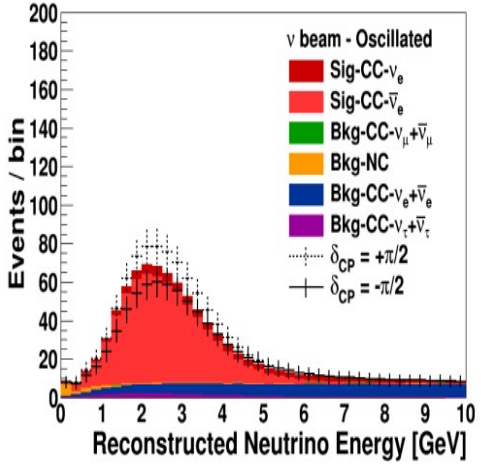


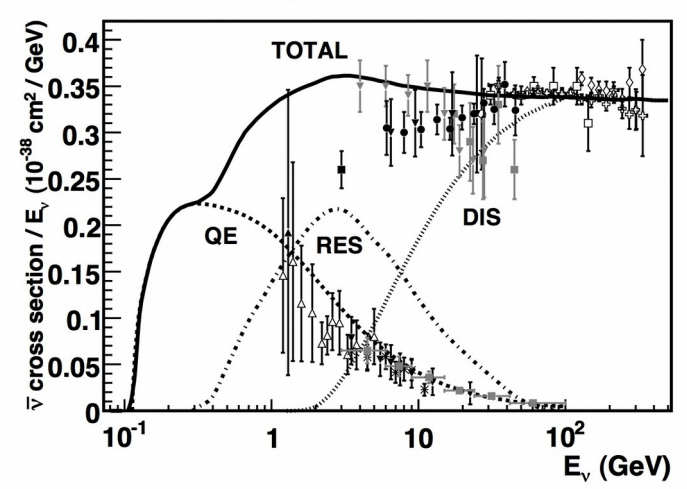
- Neutrinos momentum range up to 4 GeV
- Tunable ring energy under investigation
  - Optimisation so far has focused on 3.8 GeV μ
  - Higher energy would give more reach to cross section measurements
- Optimisation of storage ring to give improved neutrino flux
  - Hybrid FoDo straights with high acceptance FFA bends

Cross Section Measurement

J. A. Formaggio and G. P. Zeller.
From eV to EeV: Neutrino Cross Sections Across Energy Scales
Rev. Mod. Phys. 84 (2012)







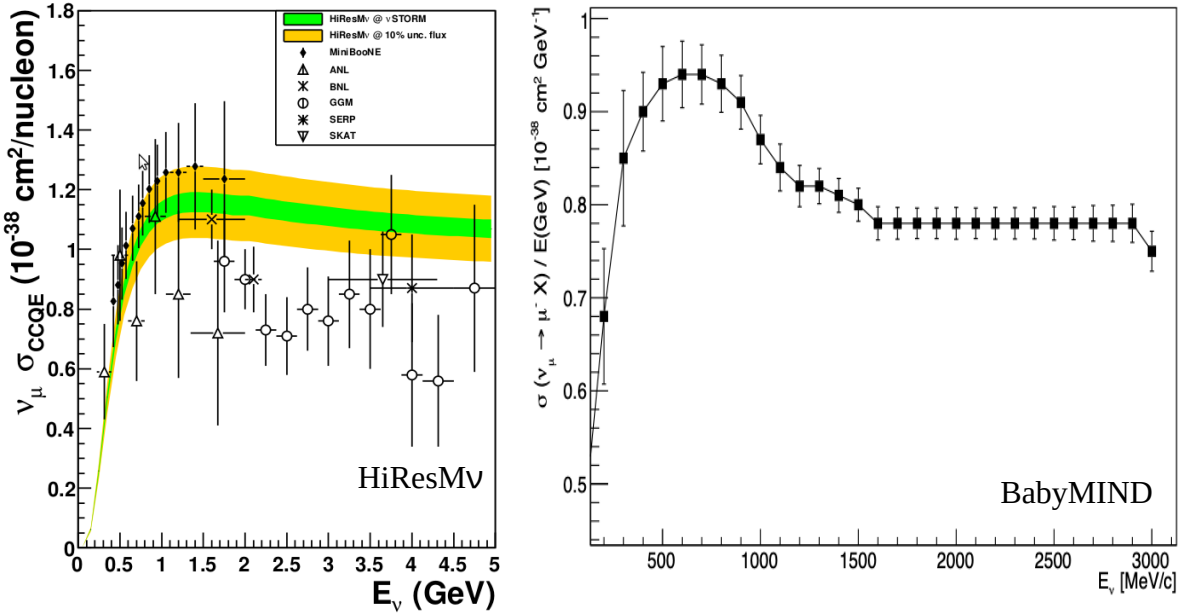
- DUNE and T2K ν energy spans QE and DIS
- Major contributor to systematic uncertainty
- See talk this afternoon!

Science & Technology Facilities Council
ISIS Neutron and Muon Source

Cross Section Measurement

S.-P. Hallsjö, CCQE Muon Neutrino Interactions in the Baby MIND Detector, PhD thesis, University of Glasgow, 2018.

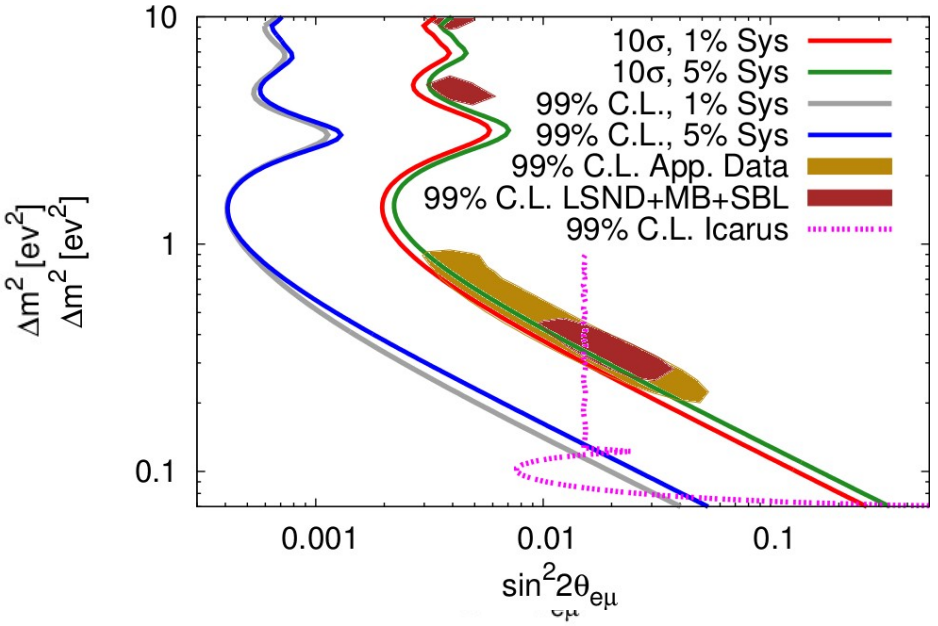
Cross section estimate with a 10 ton detector for 10^{21} POT

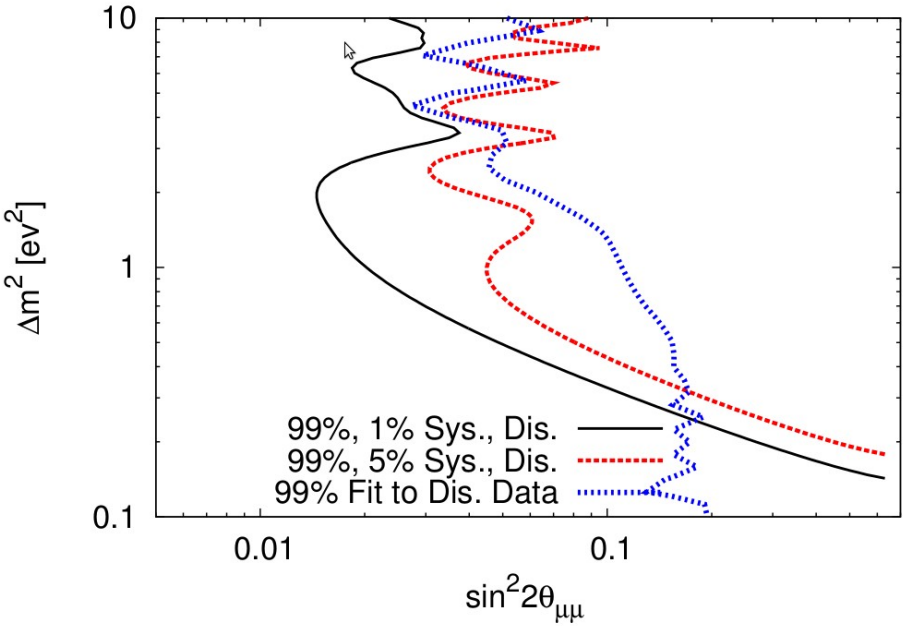


- NuSTORM has excellent sensitivity to CCQE
- Studies of optimal detector geometries ongoing
- Studies of other cross-section sensitivities ongoing
- See talk this afternoon!

Sterile Neutrino Sensitivity

D. Adey et al, Light sterile neutrino sensitivity at the nuSTORM facility, PRD 89 (2014)

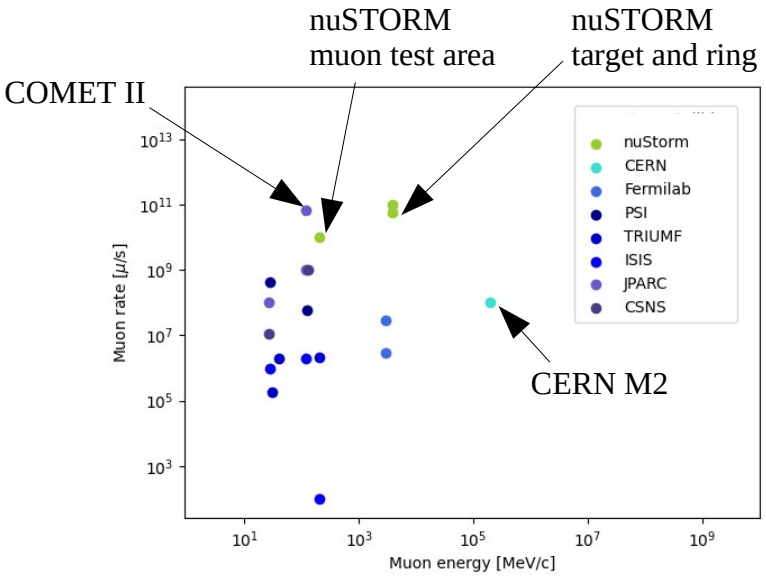




- Sterile neutrino sensitivity
  - Assumes 1.3 kt magnetized iron
  - 1.8 10^{18} useful muon decays
  - Flux known to 0.5 % level
- See talk this afternoon!

Challenges

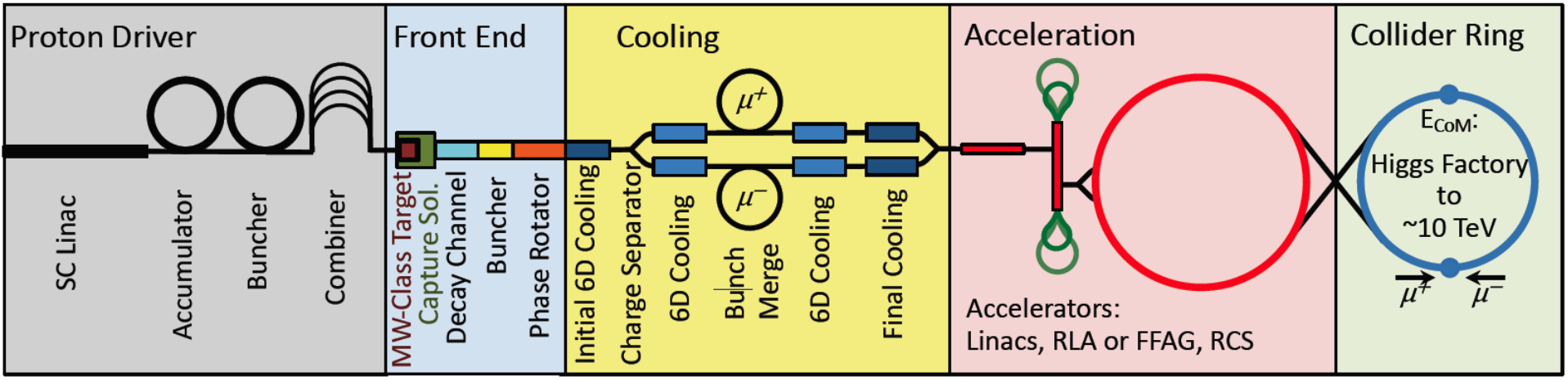
- High current radioactive beam passing active components
  - Normal conducting transport line near target
  - Superconducting combined function dipoles in muon ring
- Containment of tertiary beam (i.e. muons)
  - Large momentum spread and transverse size



Muon Collider

- Why – and how - is nuSTORM related to muon collider?
- **Muon beam physics** highlighted as **high priority initiative** by European strategy update
  - ~10 TeV Muon Collider has **physics reach comparable to FCC-hh**
  - **Footprint** is considerably **smaller**
- CERN-led Muon Collider Collaboration formed in June
- Some discussion of making a “demonstrator”
  - Demonstrate some of the beam physics concepts
  - Address some of the technical issues

Muon Collider Facility

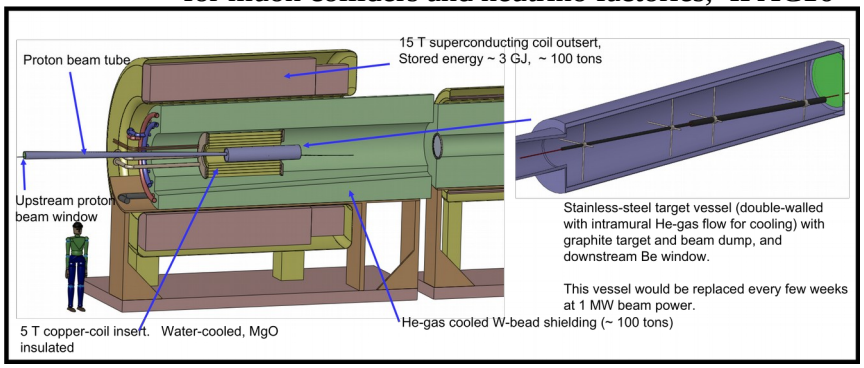


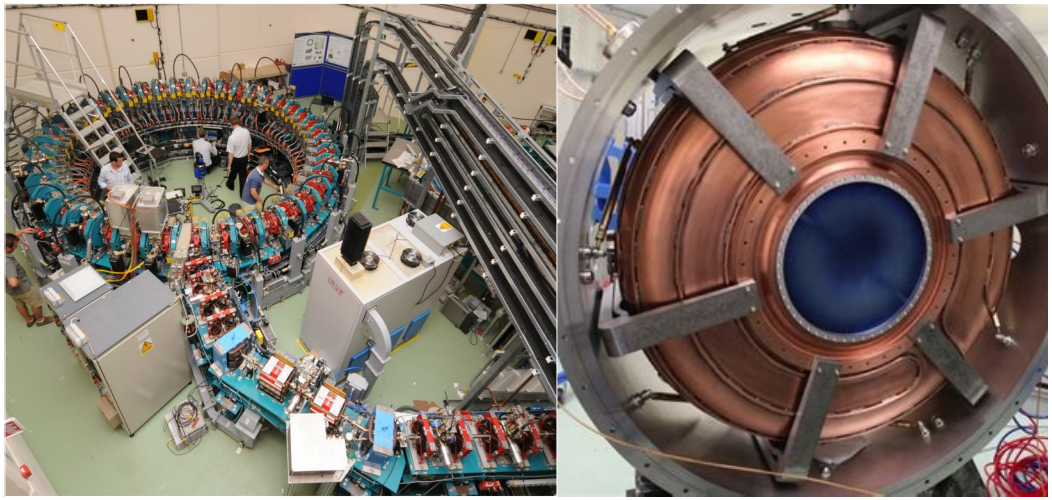
- Proton based Muon Collider (MC) facility
  - Protons on target → pions, muons et al.
  - Transverse and longitudinal capture and cooling
  - Acceleration
  - Collider ring
- Challenges
  - High current radioactive beam passing active components
  - Containment of tertiary beam (i.e. muons)

Technologies

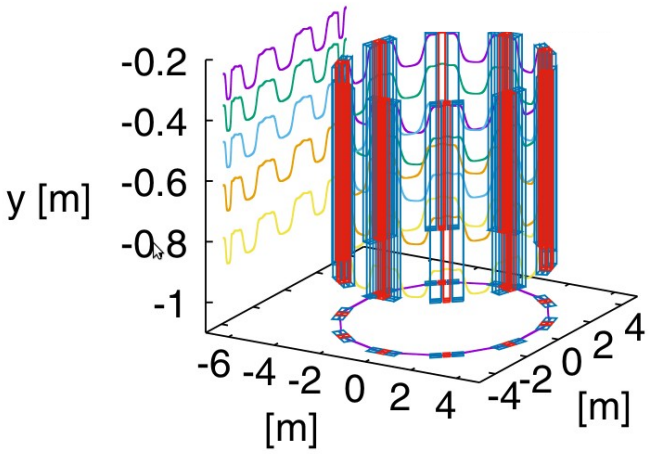
- High power dual-sign ($\mu^+\mu^-$) target
- Capture and ionisation cooling
- Acceleration and storage
  - Either conventional FODO-based Rapid Cycling Synchrotron
  - Or novel FFA

X. Ding et al, Carbon and Mercury target system for muon colliders and neutrino factories, IPAC16

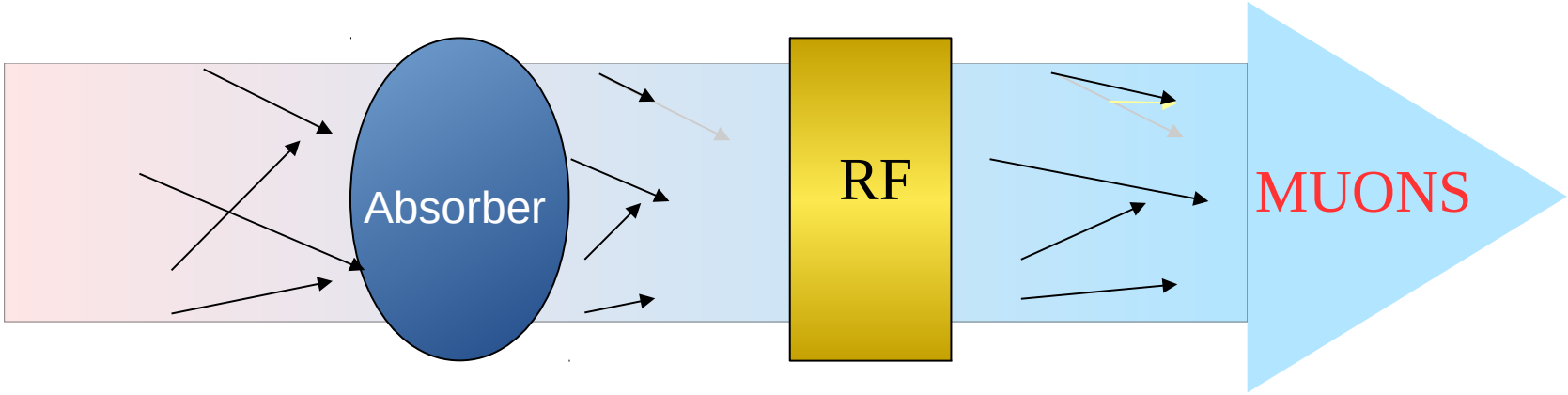




Low energy vFFA PoP
Arxiv 2011.10783 (accepted in PRAB)

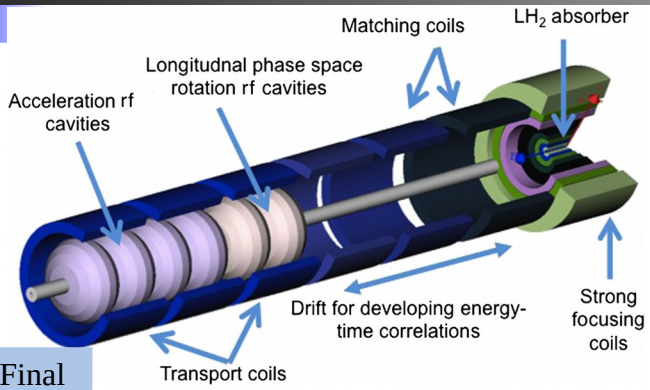


Ionisation Cooling

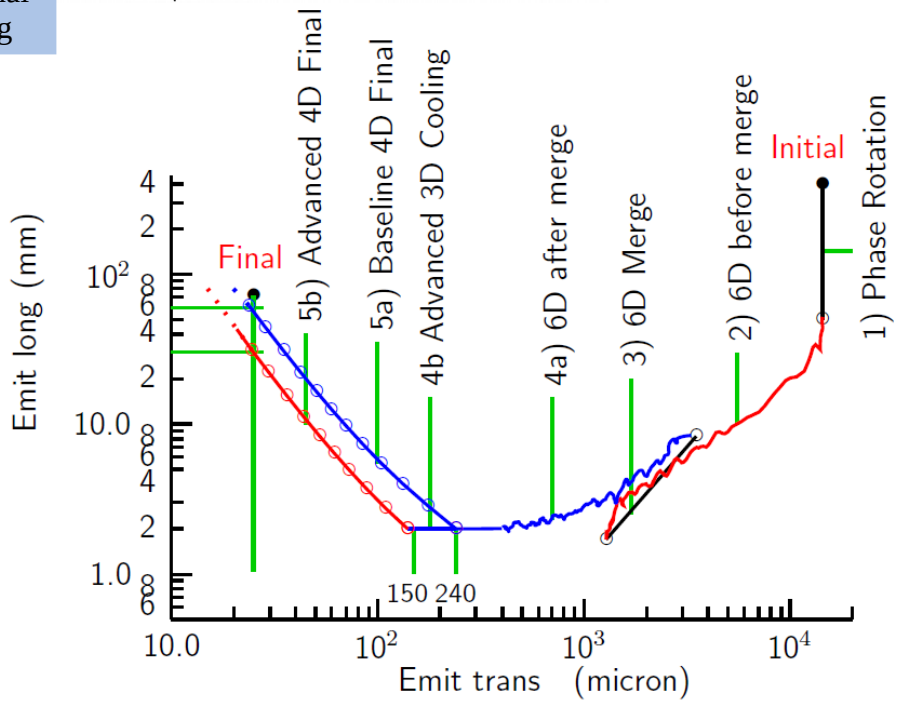


- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS completely cancels the cooling

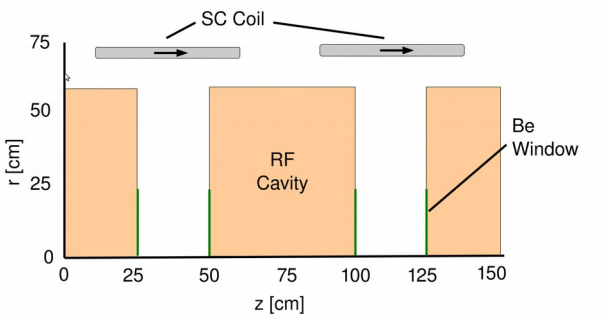
Muon Cooling



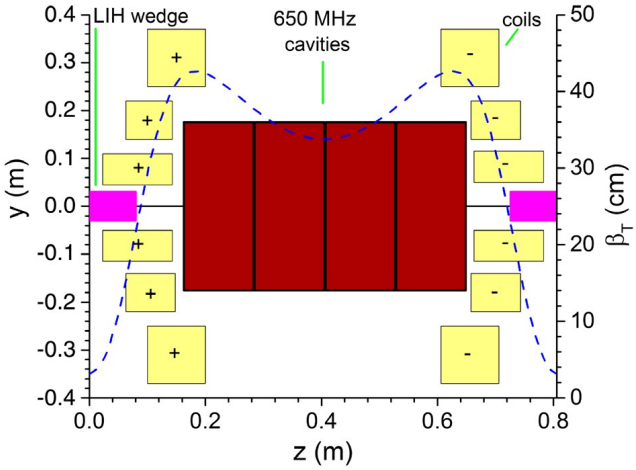
4D Final cooling



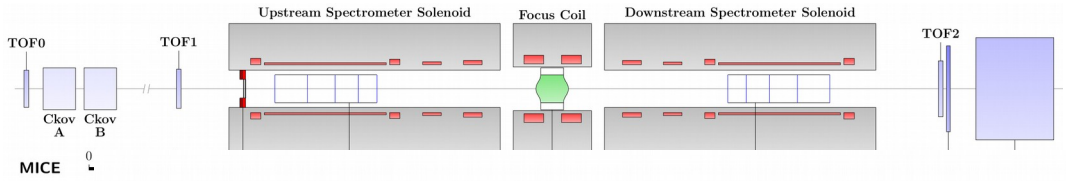
Phase rotation

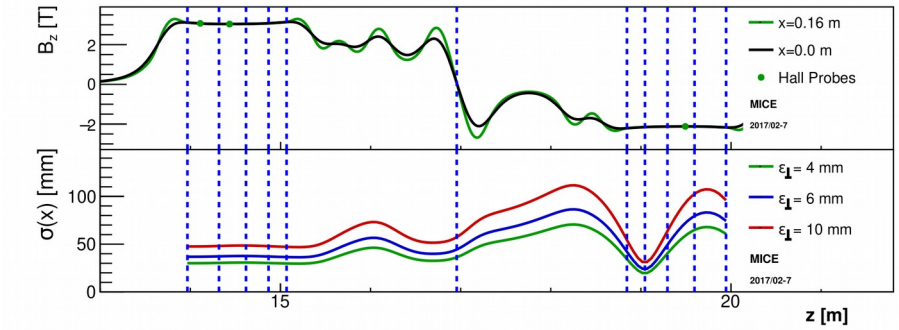


6D cooling

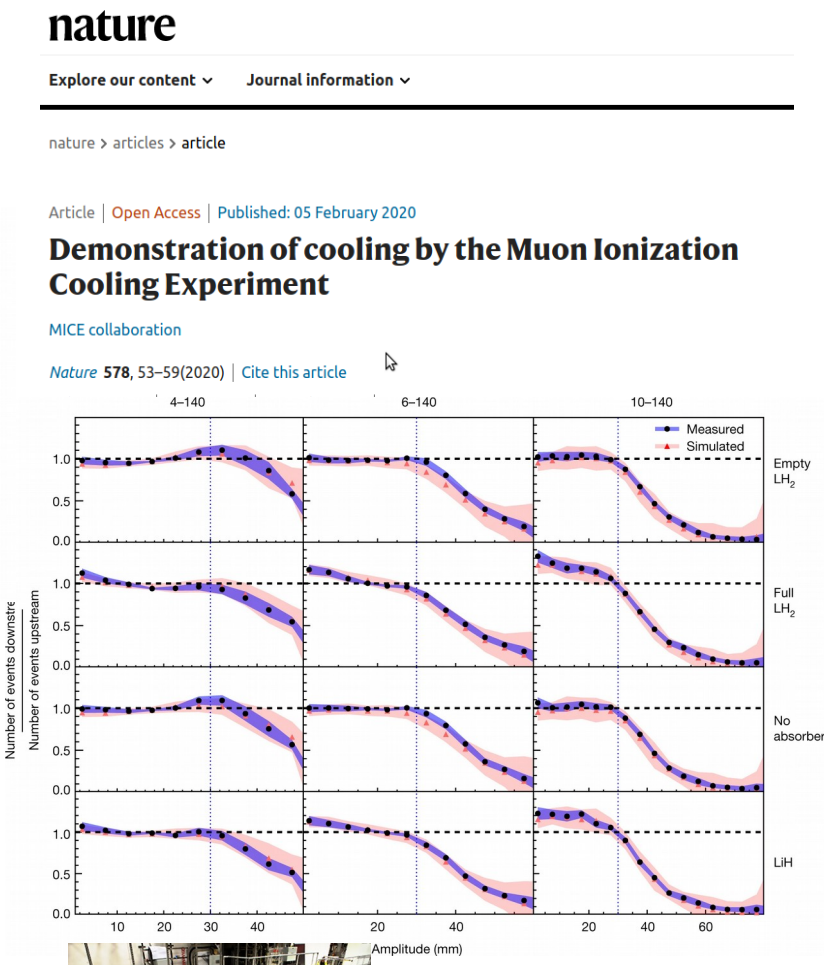


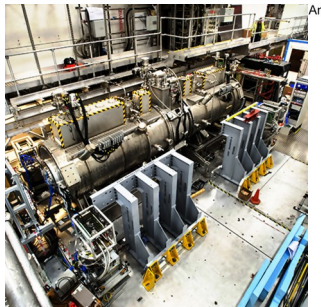
MICE



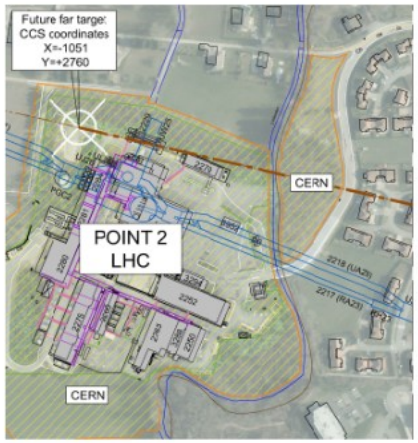


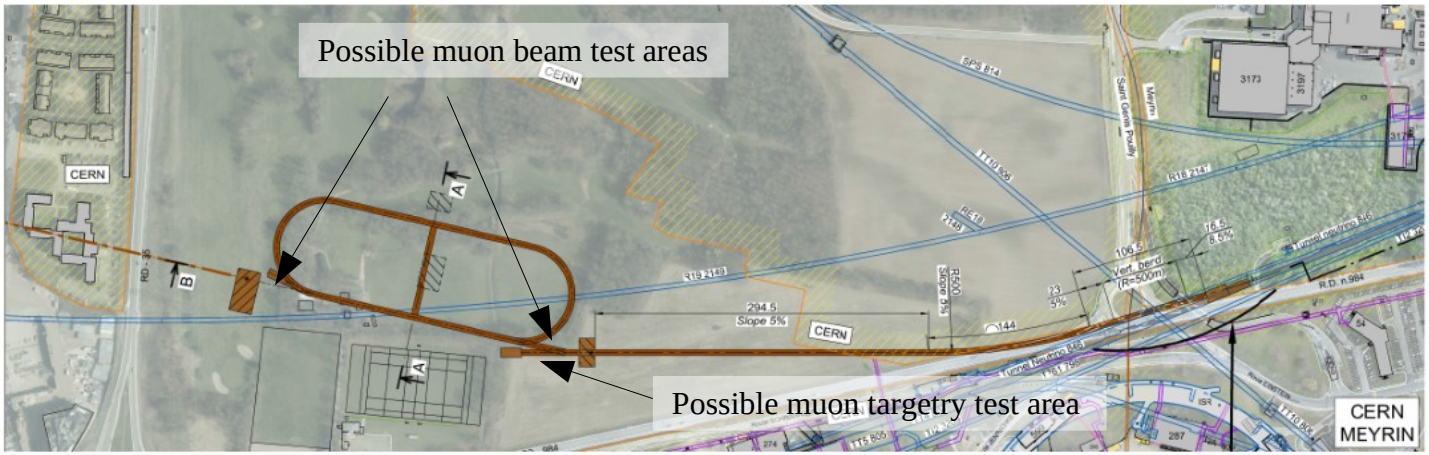
- Muon ionisation cooling has been demonstrated by MICE
  - Muons @ ~140 MeV/c
  - Talk earlier today
- But
  - Transverse cooling only
  - No re-acceleration
  - No intensity effects
  - Larger emittance beams

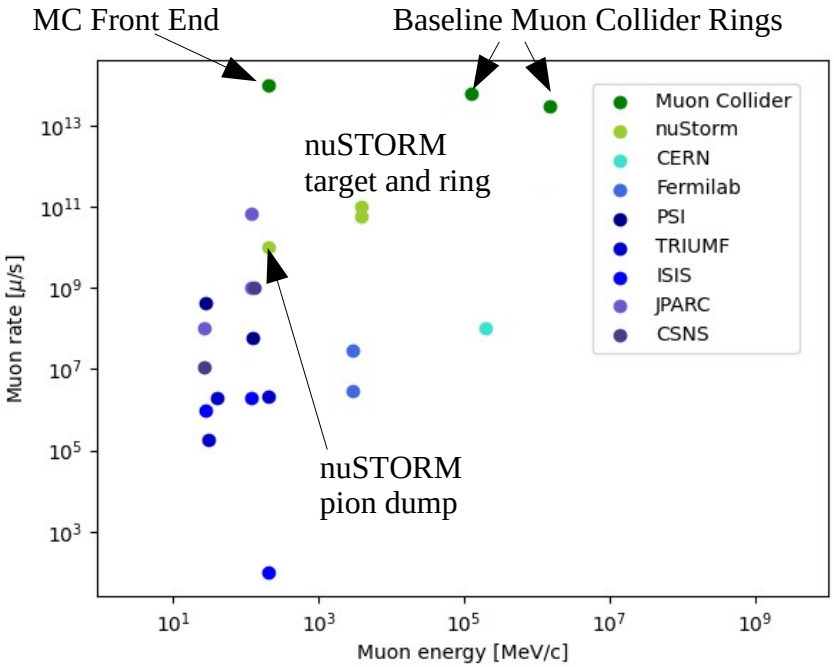




Survey of Muon Beamlines







- NuSTORM would make an excellent facility
  - One of the highest current high energy muon beams
- Target/irradiation test area
- Muon beam physics tests

Summary

- nuSTORM facility ideal facility for a number of aims
  - Measure neutrino scattering cross sections
  - Search for sterile neutrinos and other BSM physics
  - Provide a technology test-bed for the muon collider
- Unique facility to yield
  - High muon rate
  - Well-characterised beam
- Potential to be the highest current high energy muon beam