Characterisation of Cooling in the Muon Ionisation Cooling Experiment

Chris Rogers*, ISIS Neutron and Muon Source,
On behalf of the **MICE Collaboration**
*chris.rogers@stfc.ac.uk

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Muons in particle physics

- Growing interest surrounding potential for a muon collider
  - Muon fundamental particle → full energy available for collision
    - Not composite like a proton
  - High mass suppresses synchrotron radiation
  - R&D recommended as high priority in European Strategy Update
    - New collaboration studying a collider at CERN
    - “Dream machine”
  - Highlighted as high priority by Snowmass Energy Frontier
- Muon beams can help at the neutrino frontier
  - Extremely pure, well characterised neutrino source
  - Measurement of neutrino cross-sections to support DUNE, T2K
  - Direct production of neutrino beam for neutrino oscillations
  - Neutrino beams from muons → unique access to BSM physics
- Strong European support
  - CERN and many European labs (INFN, STFC, CEA, KIT, …)
  - EU grant approved

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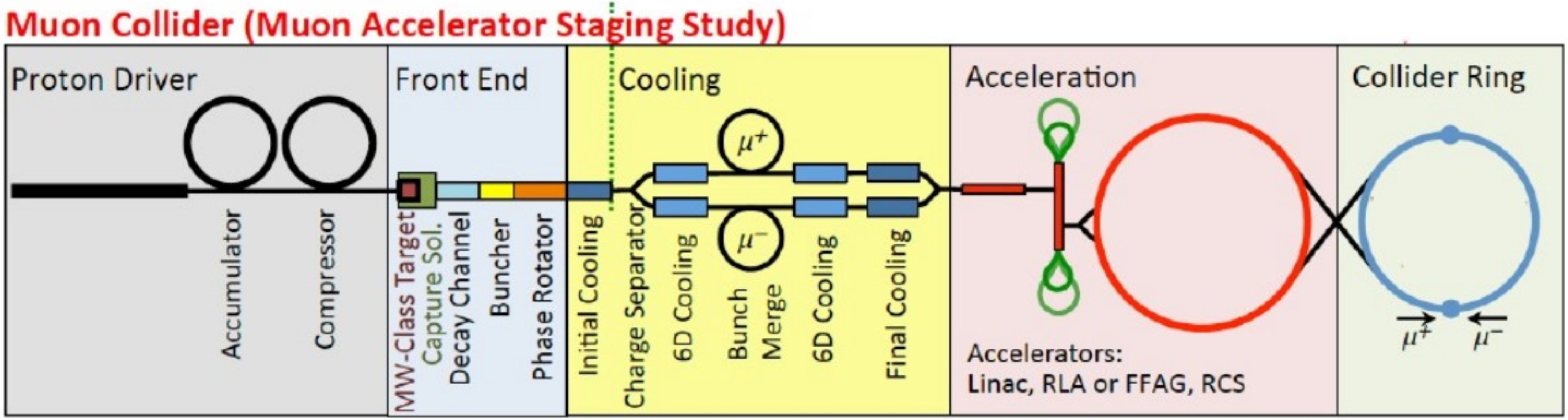
Muons at the energy frontier

EF Resources and Timelines

- **Five year period starting in 2025**
  - Prioritize *HL-LHC physics program,* including auxiliary experiments
  - Establish a targeted *e+e- Higgs Factory detector R&D* for US participation in a global collider
  - Develop an *initial design for a first stage TeV-scale Muon Coll.* in the US (pre-CDR)
  - Support critical *detector R&D towards EF multi-TeV colliders*
- **Five year period starting in 2030**
  - Continue strong support for *HL-LHC program*
  - Support *construction of an e+e- Higgs Factory*
  - Demonstrate principal risk mitigation and deliver *CDR for a first-stage TeV-scale Muon Coll.*
- **After 2035**
  - Evaluate continuing *HL-LHC physics program* to the conclusion of archival measurements
  - Begin and support the *physics program of the Higgs Factories*
  - Demonstrate readiness to construct and deliver *TDR for a first-stage TeV-scale Muon Coll.*
  - Ramp up funding support for *detector R&D for EF multi-TeV colliders*
- **EF recognizes the need for strong support to the Accelerator Frontier for the above requests.**

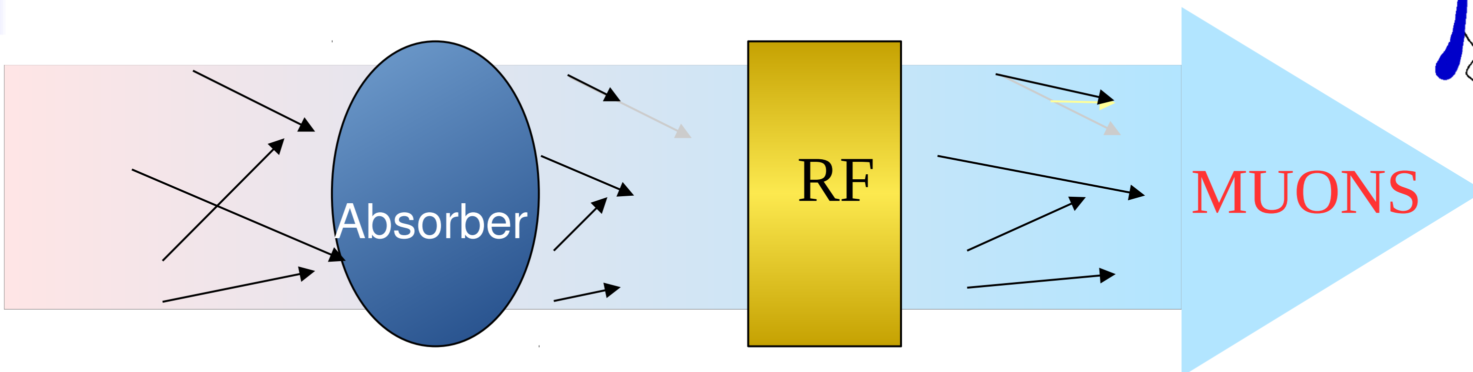
Alessandro Tricoli, Snowmass22 Energy Frontier report summary

Muons at the energy frontier



- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Critical Issues:
  - **High initial beam emittance**
  - Short muon lifetime
  - Neutrino radiation
  - Detector Beam induced Background

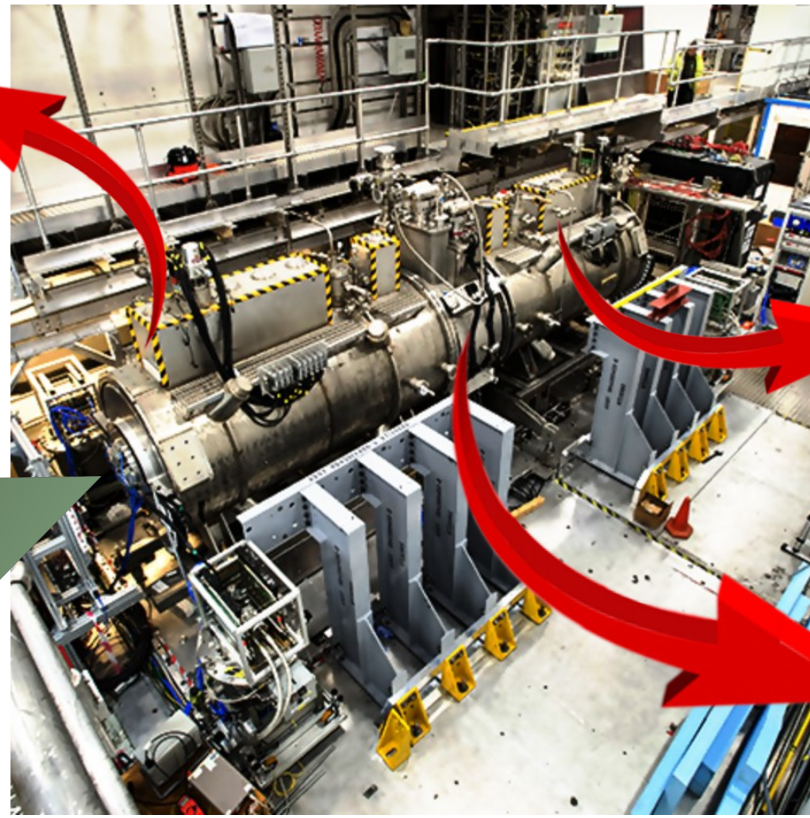
Ionisation Cooling



- 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 parallel
- Multiple Coulomb scattering from nuclei ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS cancels the cooling
- Verified by the Muon Ionisation Cooling Experiment (MICE)

Experimental set up

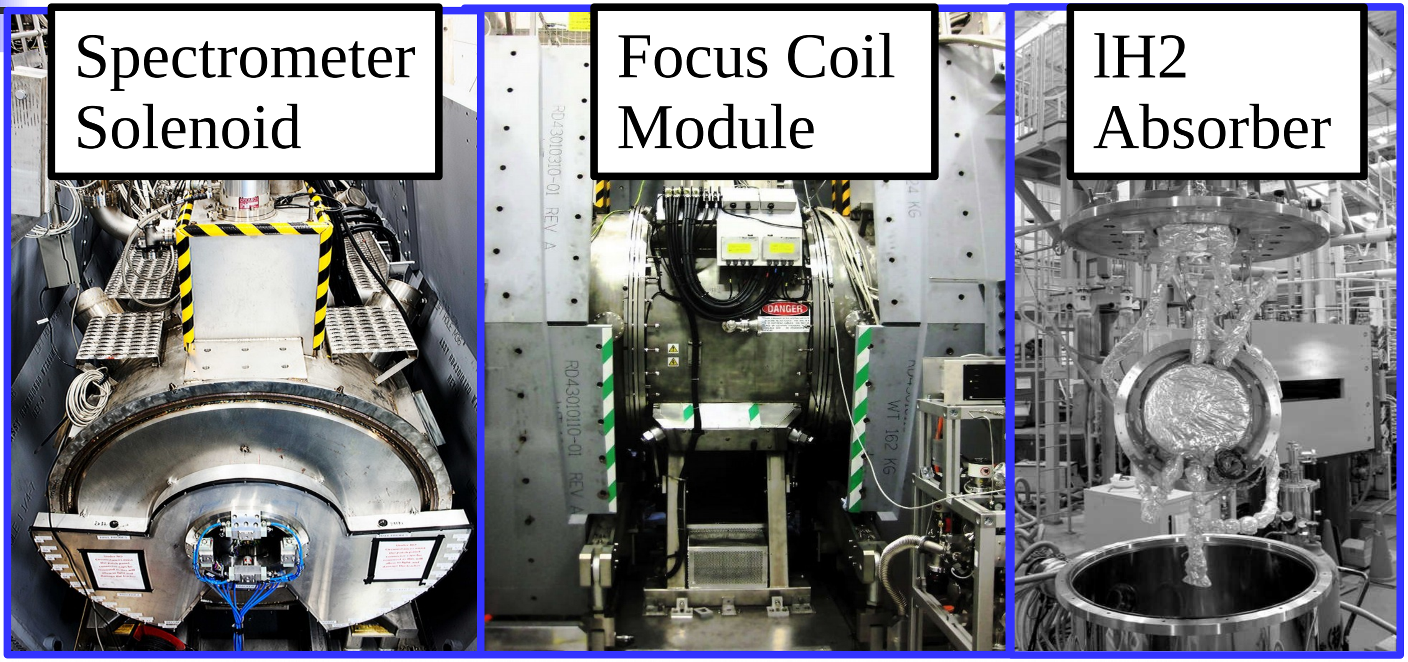
Measure muon position and momentum upstream

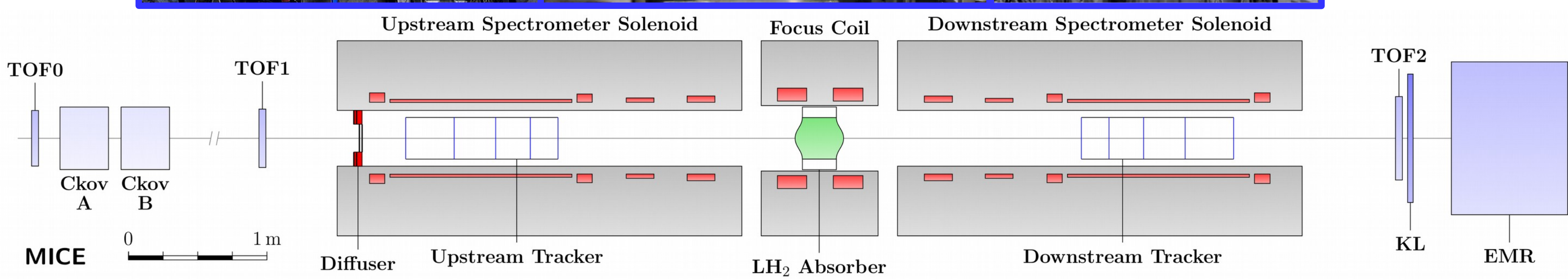


Measure muon position and momentum downstream

Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

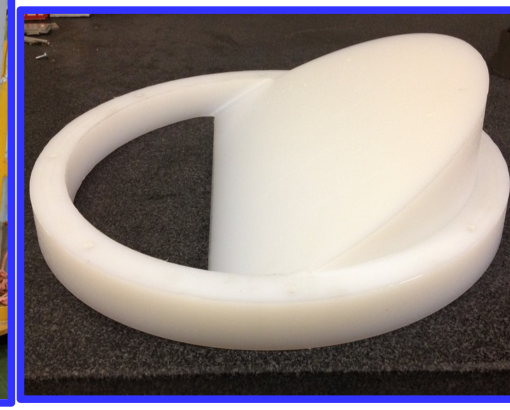
Cooling apparatus





- Spectrometer solenoids upstream and downstream
- Focus coil module provides tight focus on absorber
- Choice of liquid hydrogen or solid absorbers

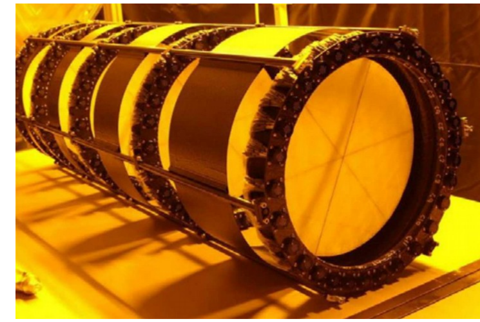
Absorber

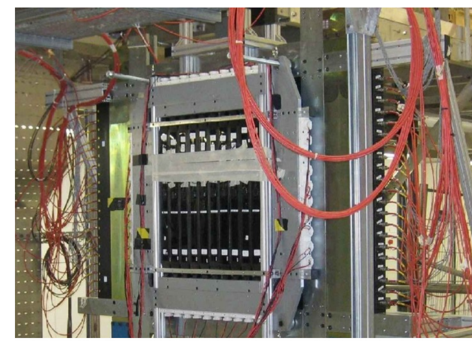


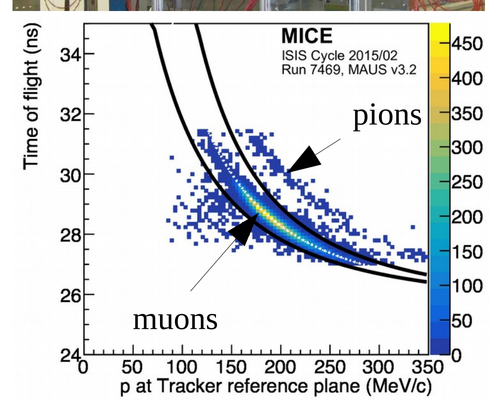
- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45° polythene wedge for longitudinal emittance studies

Instrumentation

- Scintillating Fibre Trackers
  - Individual muons follow helical path in spectrometer solenoids
  - Position of particles measured by 5 stations of scintillating fibres
  - Yields positions and momenta of particles
  - Measure “amplitudes” of individual muons
    - Distance from beam centre in phase space
- Time-of-flight measurement enables rejection of pion and electron beam impurities
  - Supported by threshold Ckov counters and calorimeters







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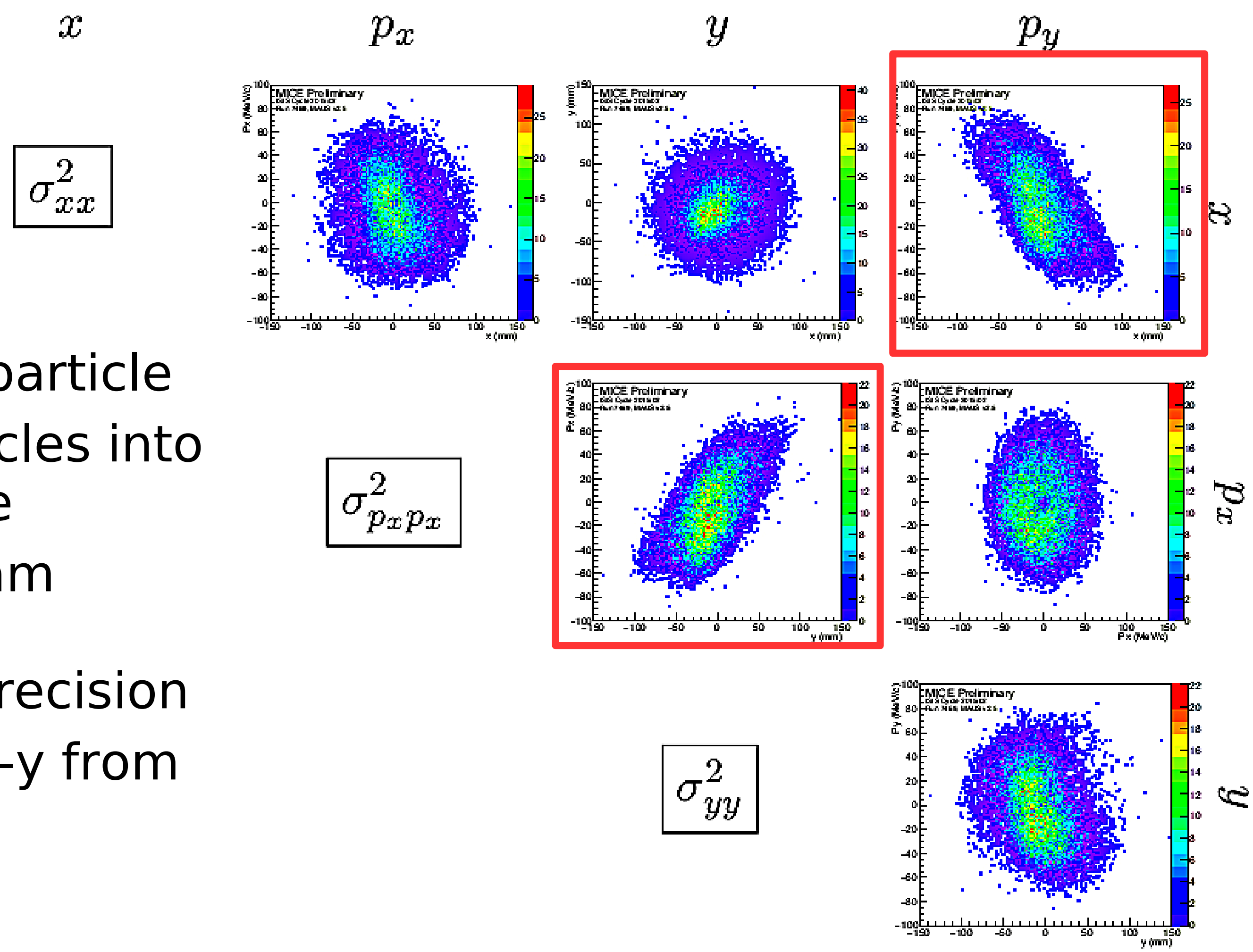
Phase space reconstruction



- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields

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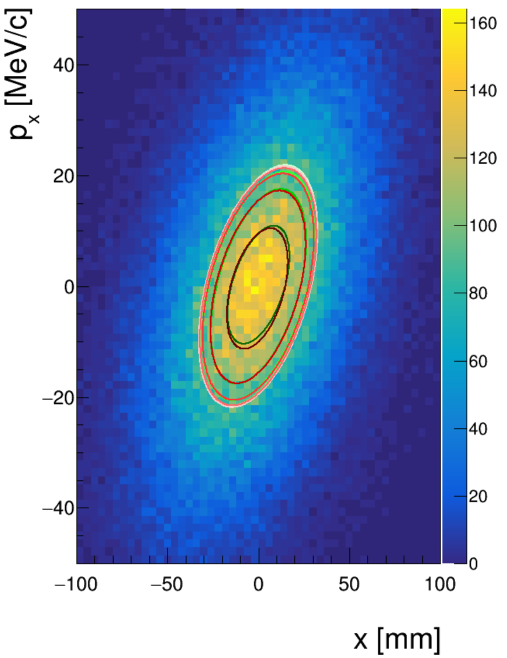
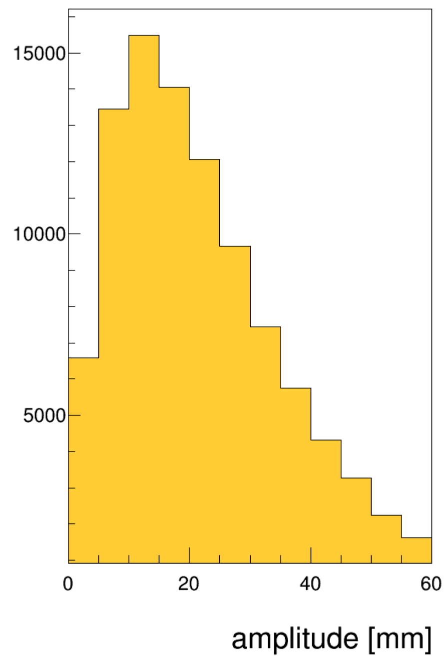
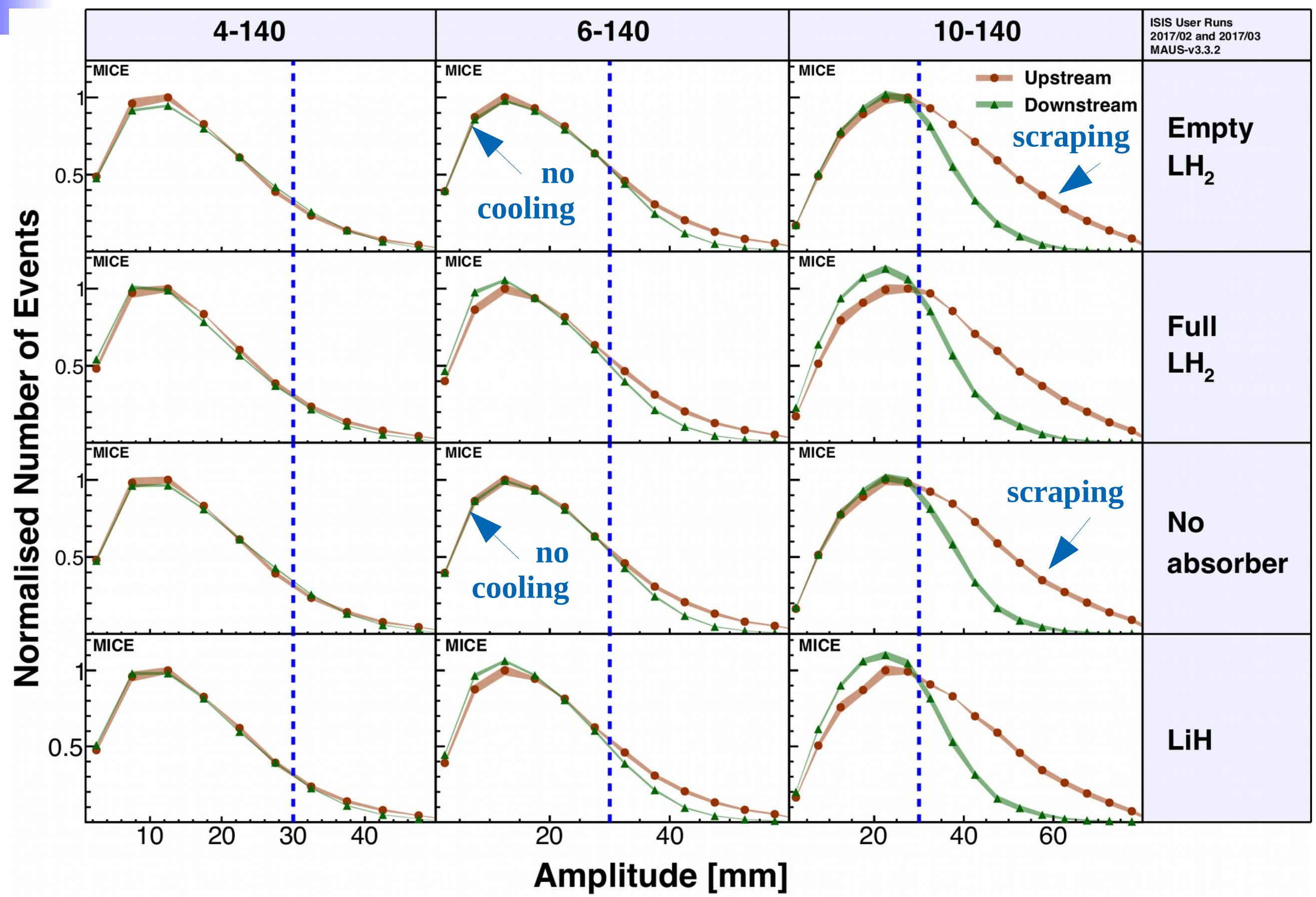
Amplitude reconstruction

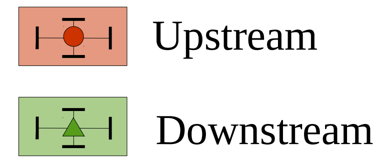


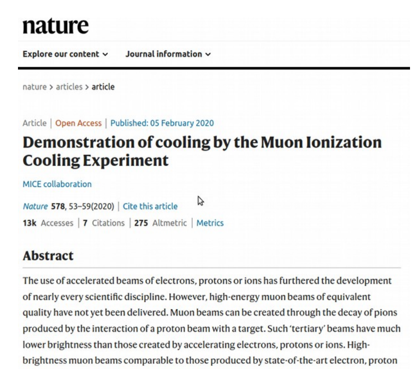


- Phase space (x, p_x, y, p_y)
- Normalise phase space to RMS beam ellipse
  - Clean up tails
- Amplitude is distance of muon from beam core
  - Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread
  - Reduces amplitude
- Mean amplitude ~ "RMS emittance"

Change in Amplitude Across Absorber



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Demonstration of cooling by the Muon Ionization Cooling Experiment
MICE collaboration
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Abstract

The use of accelerated beams of electrons, protons or ions has furthered the development of nearly every scientific discipline. However, high-energy muon beams of equivalent quality have not yet been delivered. Muon beams can be created through the decay of pions produced by the interaction of a proton beam with a target. Such 'tertiary' beams have much lower brightness than those created by accelerating electrons, protons or ions. High-brightness muon beams comparable to those produced by state-of-the-art electron, proton

- No absorber → slight decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

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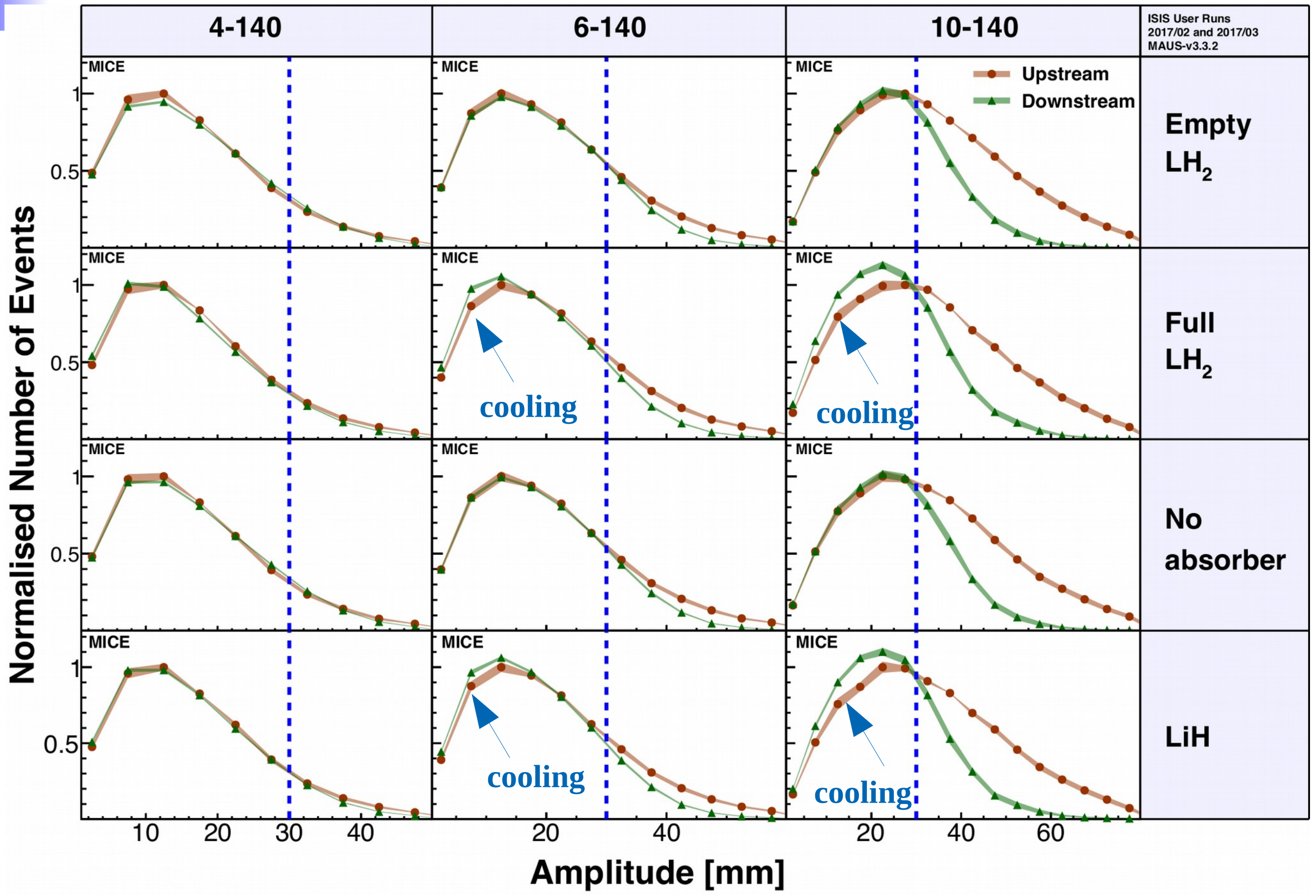
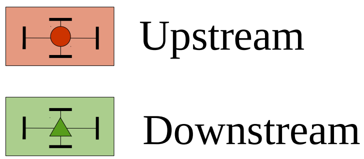
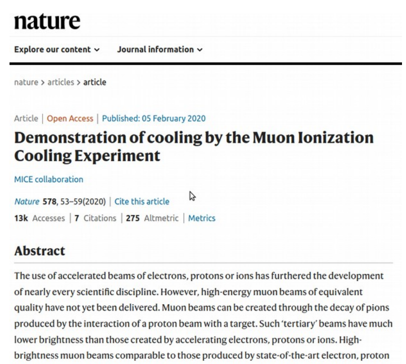
Change in Amplitude Across Absorber







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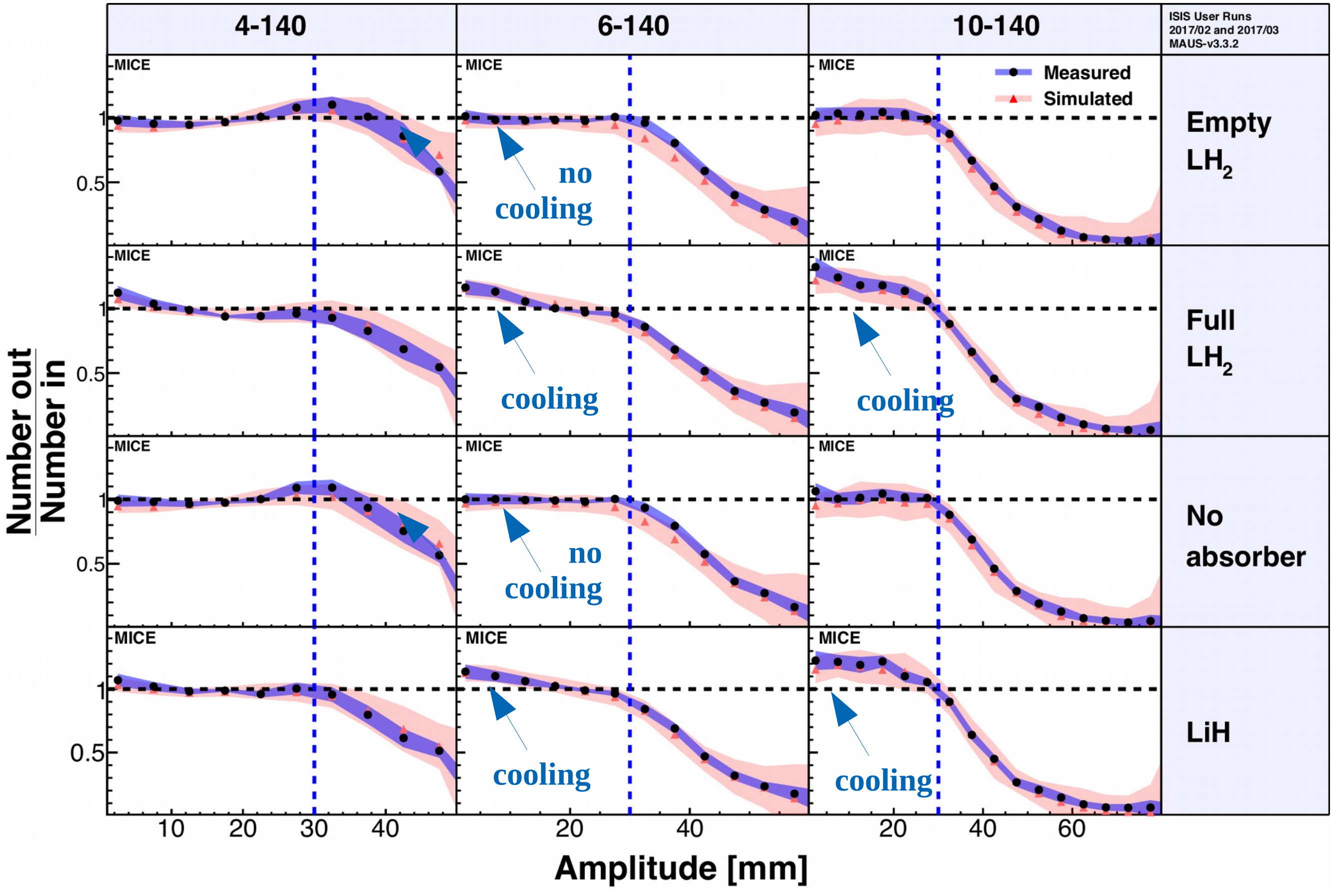
Ratio of core densities



- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances
- Consistent with simulation

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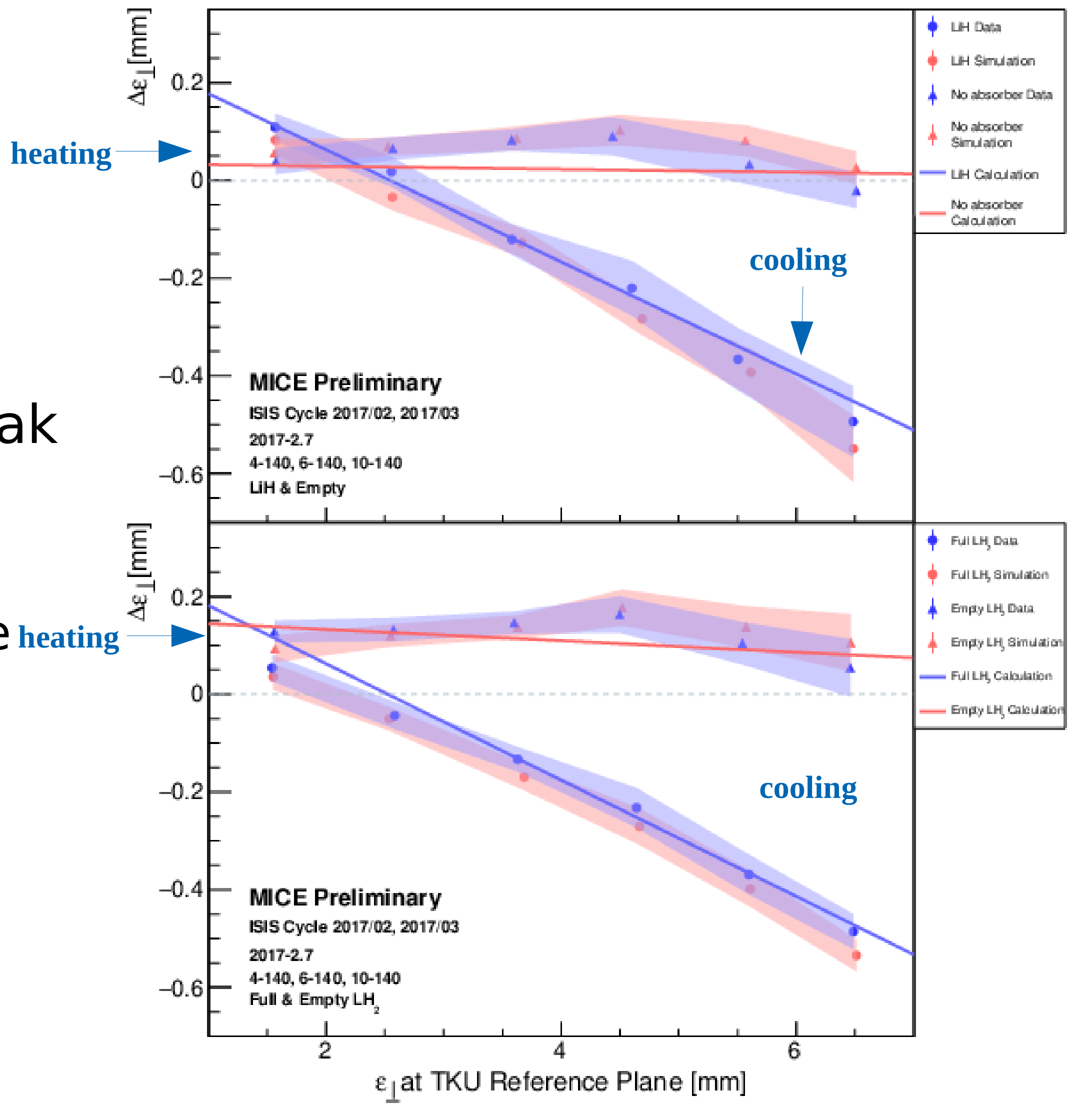
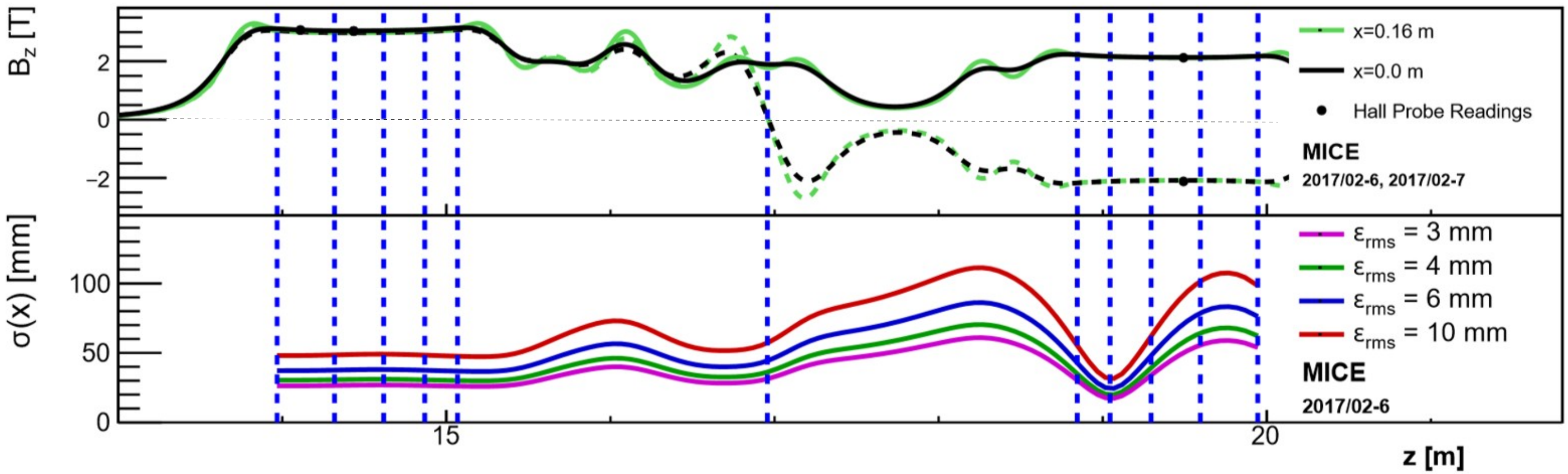
Transverse Emittance

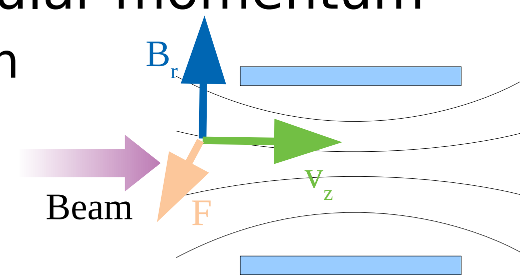
- Also measure change in RMS emittance
  - Mean of the amplitude distribution
- Look at different sub-samples of the muon ensemble
- In absence of absorber weak heating
- With absorber
  - Cooling for high emittance beams
  - Heating below equilibrium emittance
  - Consistent with theory
- Publication in progress



Field flips and solenoid mode



- Beams entering solenoids develop kinetic angular momentum
  - Radial field component → transverse momentum
  - Canonical angular momentum conserved
- Energy loss is non-conservative process
  - Kinetic angular momentum is lost
  - Canonical angular momentum builds up
  - Unless field is 0 → "flip" the field



$\underline{L}_{can} = \underline{r} \times (\underline{p}-q\underline{A})$

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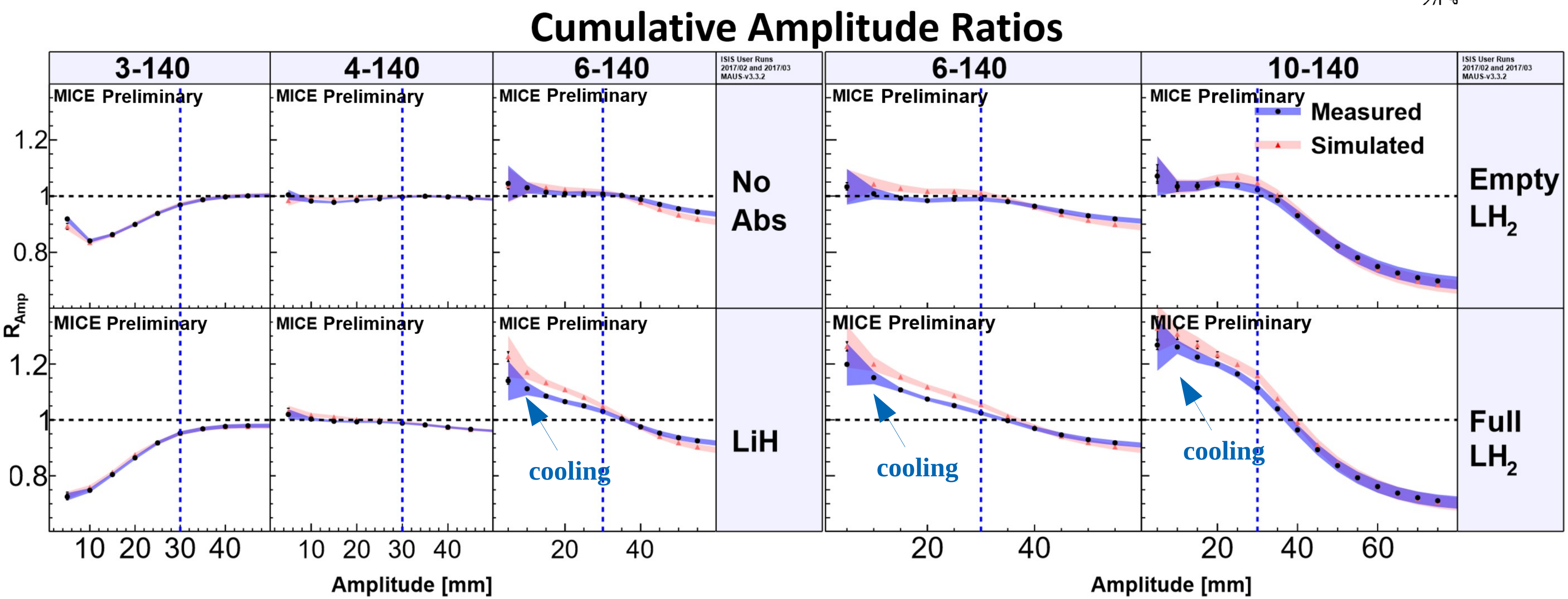
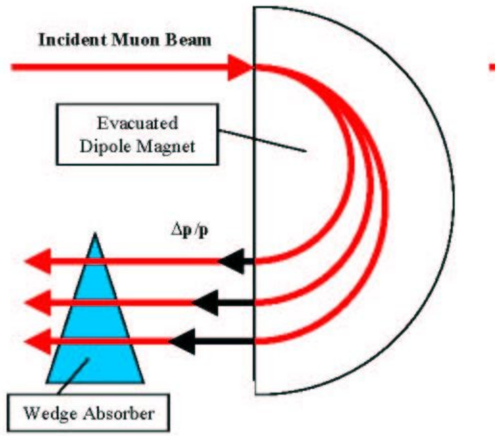
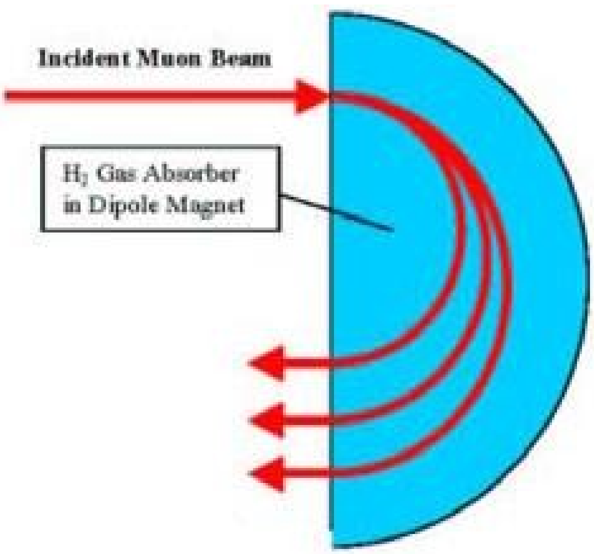
Solenoid Mode



- Non-zero field
  - easier magnets
  - angular momentum non-conservation
  - Considered for final cooling system
- Cooling performance in solenoid mode → similar to flip
  - Compatible with simulation

Beyond MICE - Emittance Exchange





- Introduce energy-position correlation using dipole
- Higher energy particles pass through more material
- Higher energy particles lose more momentum
- Results in "emittance exchange"
  - Emittance moves from longitudinal to transverse
- Results in reduction in longitudinal emittance and transverse emittance

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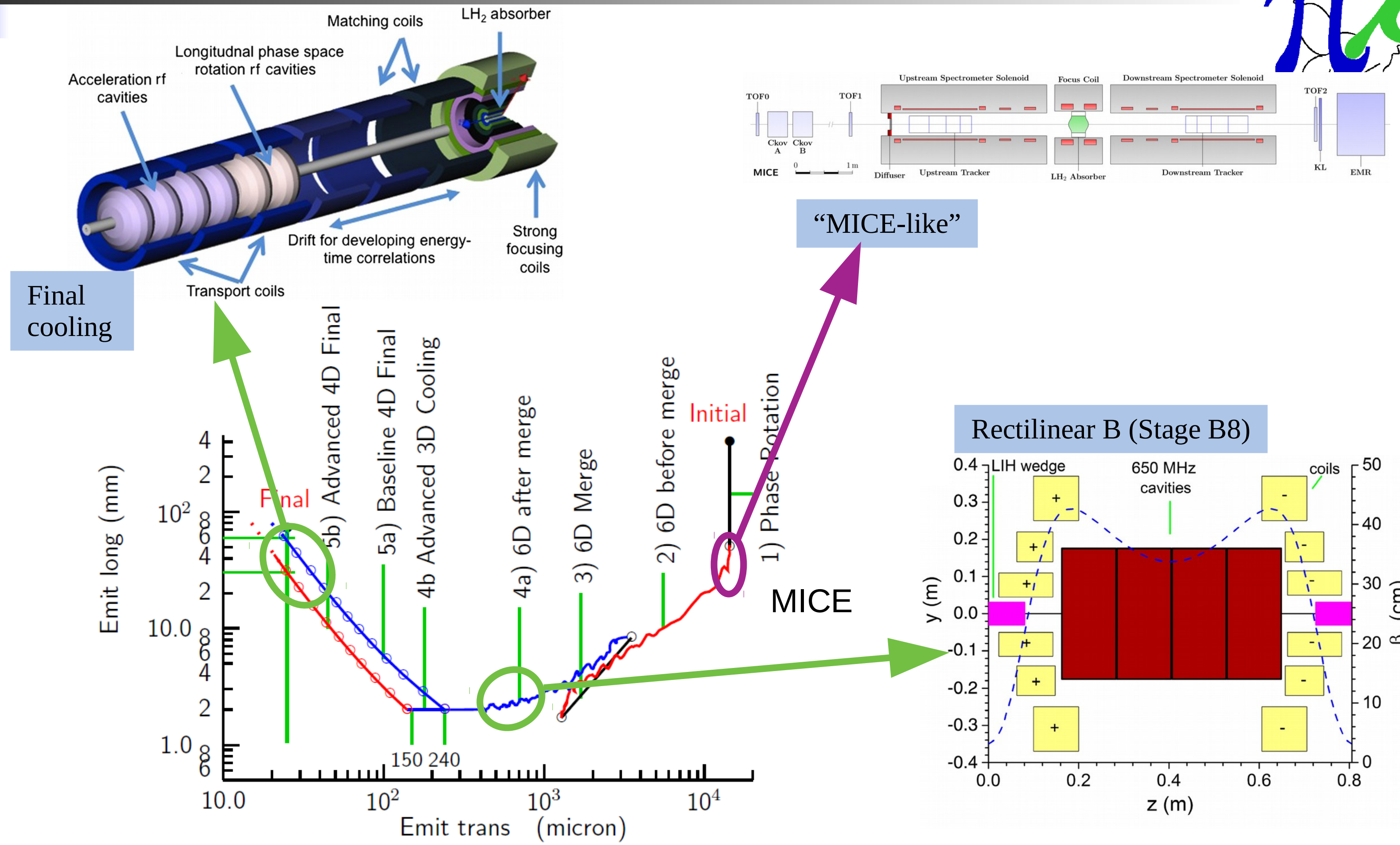
Future Experiment



- Significant interest in a follow-up experiment
  - Longitudinal and transverse emittance reduction
  - Explore lower emittances

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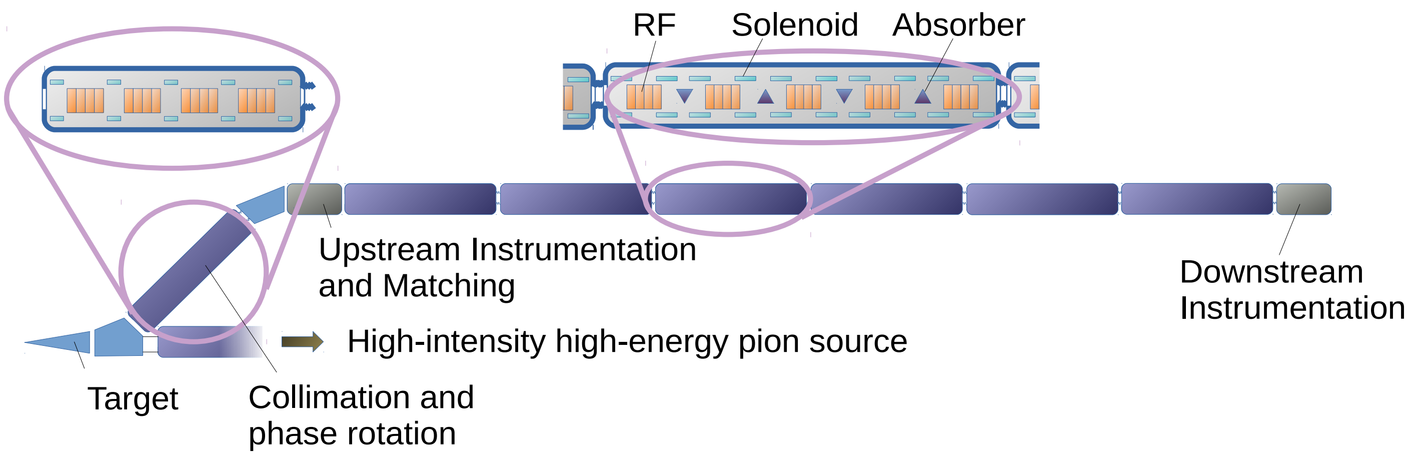
Demonstrator baseline



- IPAC paper on Demonstrator baseline
  - Nothing new, but reporting on previous work
  - Of course, optimisation is still in progress
  - Helpful to document a baseline I hope
- Optimisation
  - Looking at optical arrangement
  - Consideration of dynamic aperture
- **Talk Friday, 11:40 AM - 12:05 PM**

Muons at the neutrino frontier

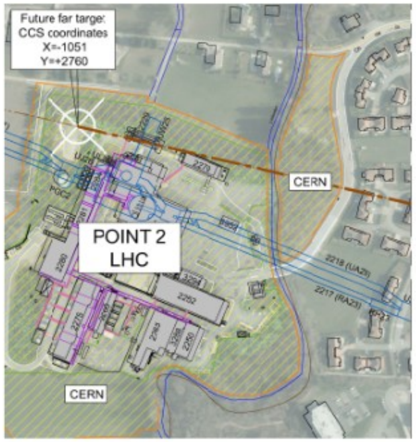
- Neutrino oscillation measurements limited by two main sources of uncertainty
  - Number and flavour of the neutrino beam
  - Neutrino interactions with matter → energy uncertainty

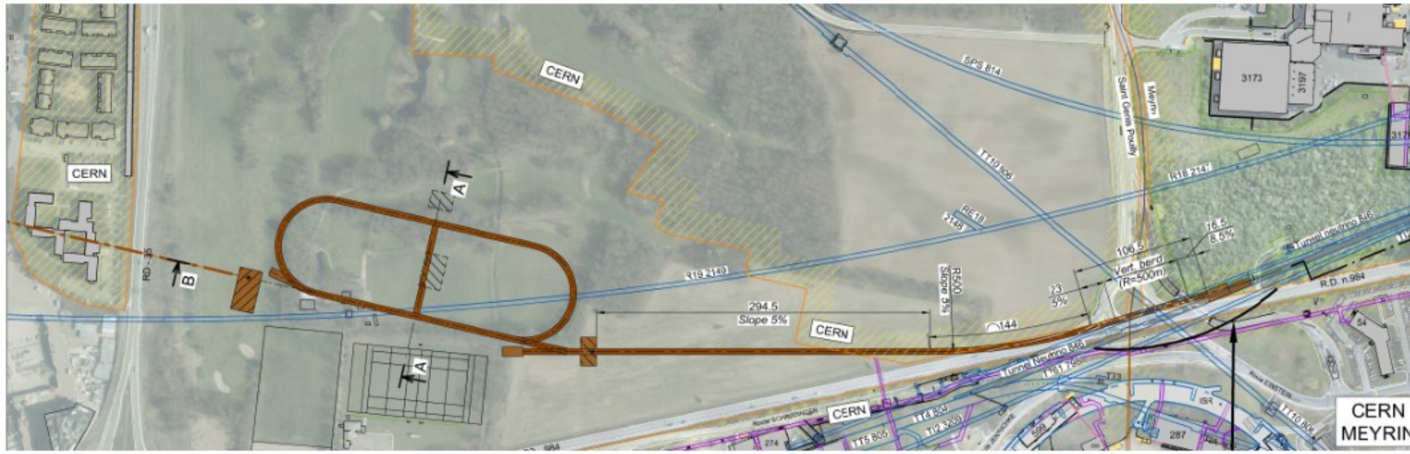
NF Exec summary:
Our current **modeling of neutrino-nucleus interactions is insufficient for the precision required** for the future oscillation program. Improving it will require cooperation among experimentalists making new measurements, nuclear and particle theorists developing new models, and computing professionals enabling the preservation and interoperability of the data, theory, and software tools.

(emphasis mine)

- Muon beams can help!

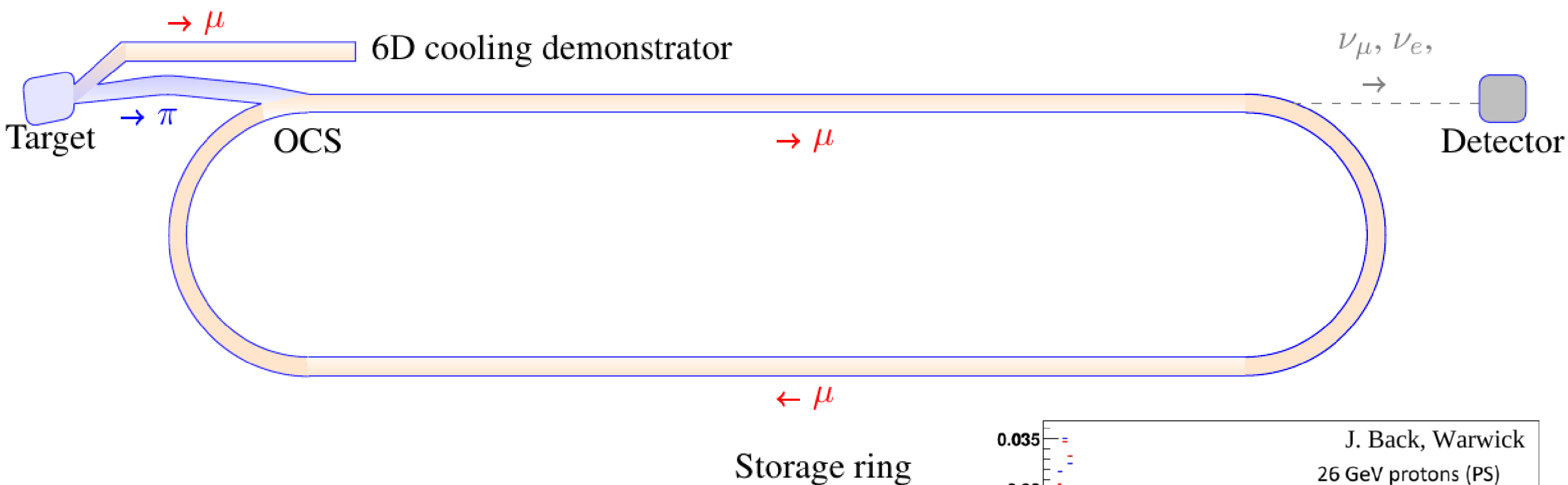
nuSTORM as a Muon Source

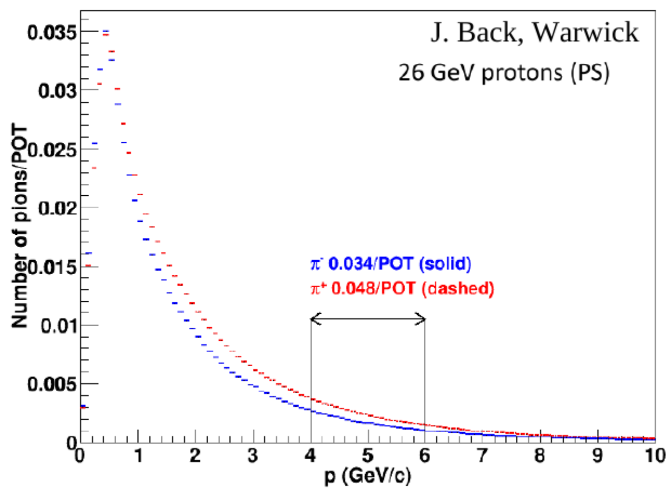




- High-brightness muon source needed for a future experiment
- nuSTORM would make an ideal candidate
  - Demonstrate capture and storage of high energy, high current muon beam
- Important physics goals
  - Neutrino scattering cross section measurements
  - Beyond Standard Model physics including sterile neutrinos
- **Two talks Friday, 4:10 PM - 4:40 PM**
  - **(instruments and machine parallel)**

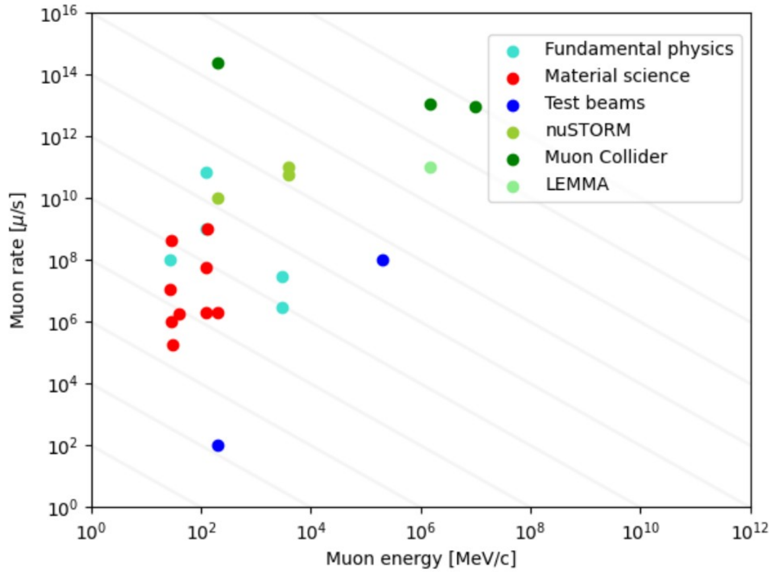
nuSTORM as a Muon Source





- nuSTORM and cooling demonstrator can share the same pion source
  - Opportunity to test muon collider target concepts

nuSTORM as a Muon Source



- Accelerator key systems/technology issues:
  - Possibility to test muon collider target concepts
  - 6D ionisation cooling Demonstrator
    - High-field solenoids, compact lattice
    - High-gradient RF in magnetic field
  - FFA storage ring can test concepts for rapid acceleration in MuC
  - Beam protection and pion beam handling
- In a facility that delivers neutrino physics

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Summary

- Muon collider high priority initiative in European Strategy and Snowmass
  - “Dream machine” for high-energy physics
- High-brightness muon source needed
  - Beam needs to be cooled using ionisation cooling
- MICE built to study muon cooling
  - Unprecedented single particle measurement of particle trajectories in an accelerator lattice
- MICE has made first observation of ionization cooling
- Growing excitement for a follow-up experiment
  - nuSTORM would make an excellent muon source
- More info:
  - http://mice.iit.edu
  - https://www.nustorm.org
  - https://muoncollider.web.cern.ch/

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