First Demonstration of Ionization Cooling in MICE

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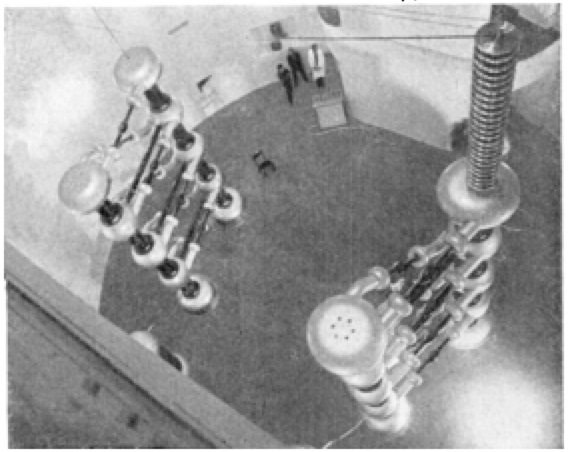
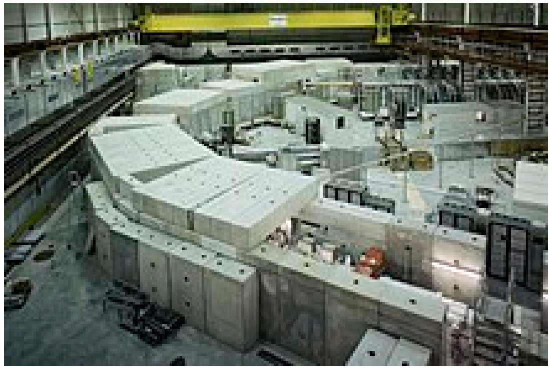
On behalf of the MICE Collaboration
ICHEP18, Seoul

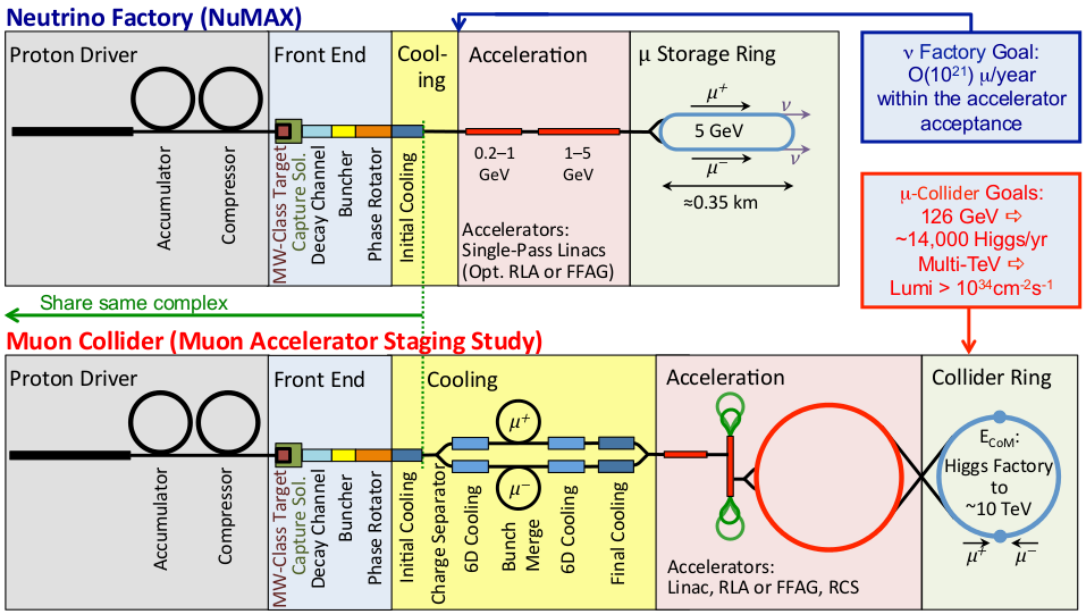
Probing the Nature of Matter with Muons

- First accelerators built in 1920s/30s
  - Accelerating protons, ions and electrons
- Antiproton acceleration in 1980s
  - Made possible by stochastic cooling
- Muon acceleration?
- Muon collider → excellent Higgs probe
  - Suppress synchrotron radiation
  - Strong coupling to Higgs
  - Potential for very high energy leptons
- Neutrino factory → Well-characterised neutrino source
  - Tunable energy
- Challenges
  - Muons produced as tertiary particle
  - Relatively short lifetime





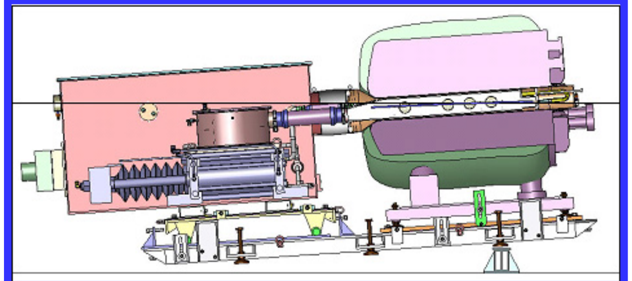
Muon Collider and Neutrino Factory

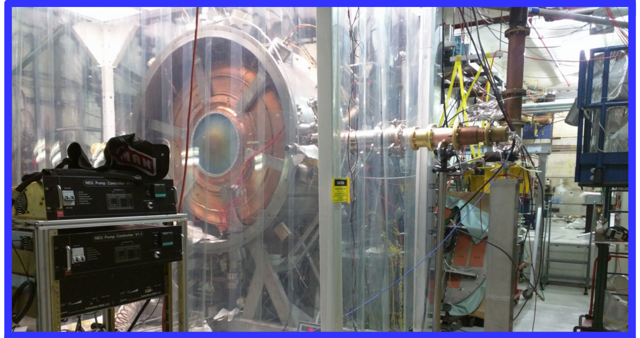


- Facility
  - High power protons
  - Target → pions
  - Capture → muons
  - Cooling
  - Rapid acceleration
  - Storage ring
- Rapid cooling → ionization cooling

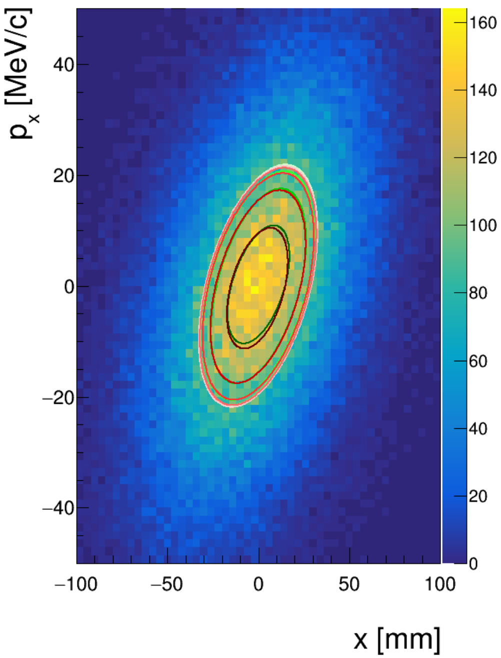
R&D Programme

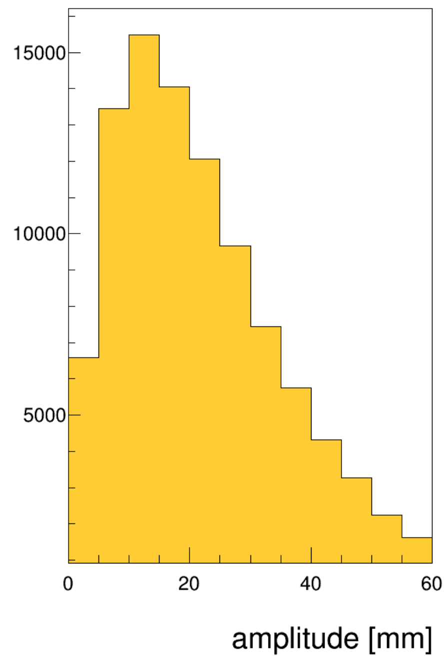
- MERIT
  - Demonstrated principle of liquid Mercury jet target
- MuCool Test Area
  - Demonstrated operation of RF cavities in strong B-fields
- EMMA
  - Showed rapid acceleration in non-scaling FFA
- MICE
  - Demonstrate ionization cooling principle
  - Increase inherent beam brightness → number of particles in the beam core
  - “Amplitude”





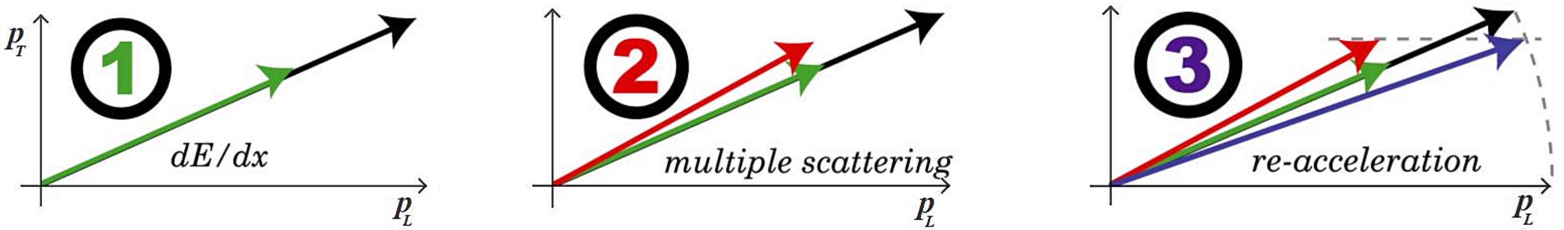
Amplitude





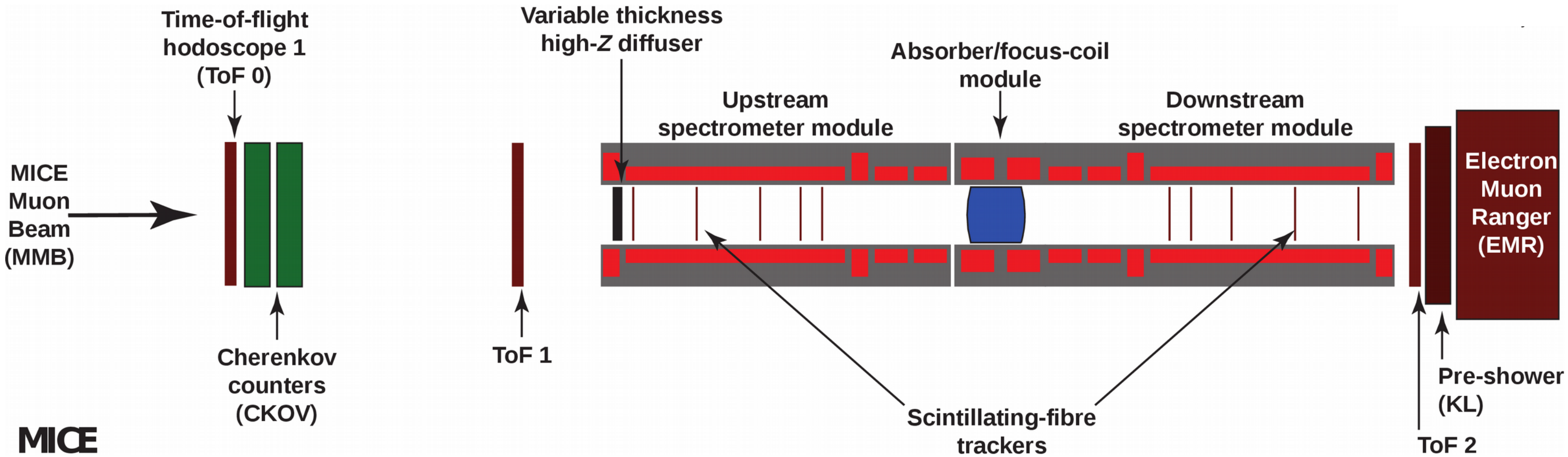
- Phase space (x, p_x, y, p_y)
- Normalise phase space to RMS beam ellipse
  - Clean up tails
- Amplitude is distance of muon from beam core
  - Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread
  - Reduces amplitude
- Mean amplitude ~ "RMS emittance"

Muon Ionization Cooling Principle



- Muons lose longitudinal and transverse momentum through ionization energy loss in an absorber
  - Non-conservative system
  - Normalised amplitude decrease
- Muons regain only longitudinal momentum in RF cavities
  - Overall, transverse momentum and amplitude is reduced
- Multiple scattering degrades the cooling effect
  - Mitigate by tight focussing
  - Mitigate by choice of low-Z absorber material
- Challenge to maintain tight focussing and high acceptance

Muon Ionization Cooling Experiment



- Demonstrate high acceptance, tight focussing solenoid lattice
- Demonstrate integration of liquid hydrogen and lithium hydride absorbers
- Validate details of material physics models
- Demonstrate ionization cooling principle and amplitude non-conservation

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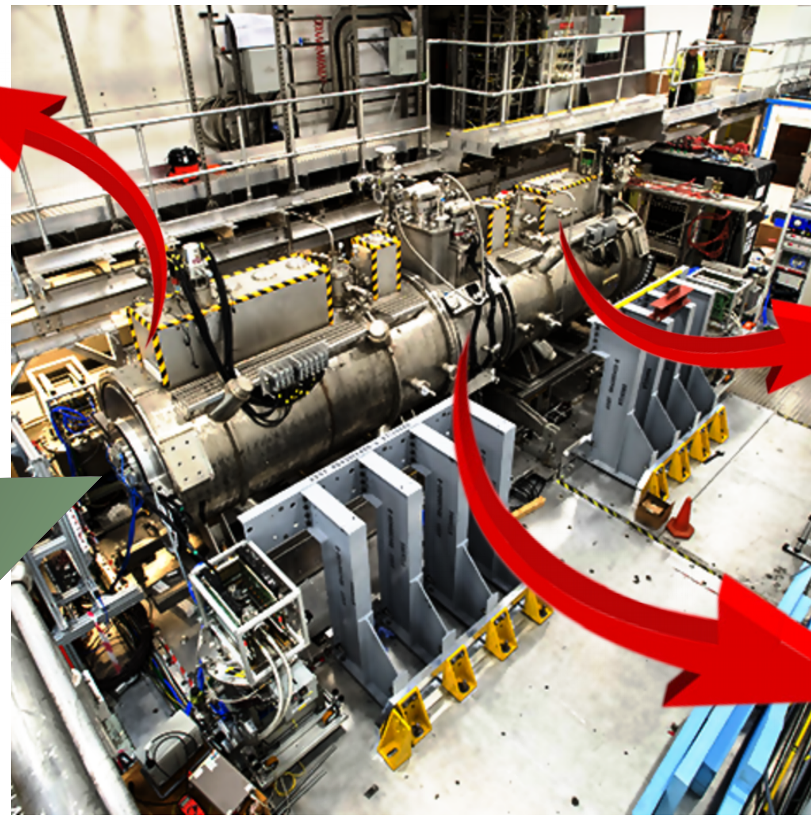
Muon Ionization Cooling Experiment

Measure muon position and momentum upstream

Beam



Measure muon position and momentum downstream

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

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Experimental Site

- Over 100 collaborators, 10 countries, 30 institutions
- Operated at Rutherford Appleton Laboratory between 2008 and 2017
- Dedicated transport line bringing pions/muons from ISIS synchrotron

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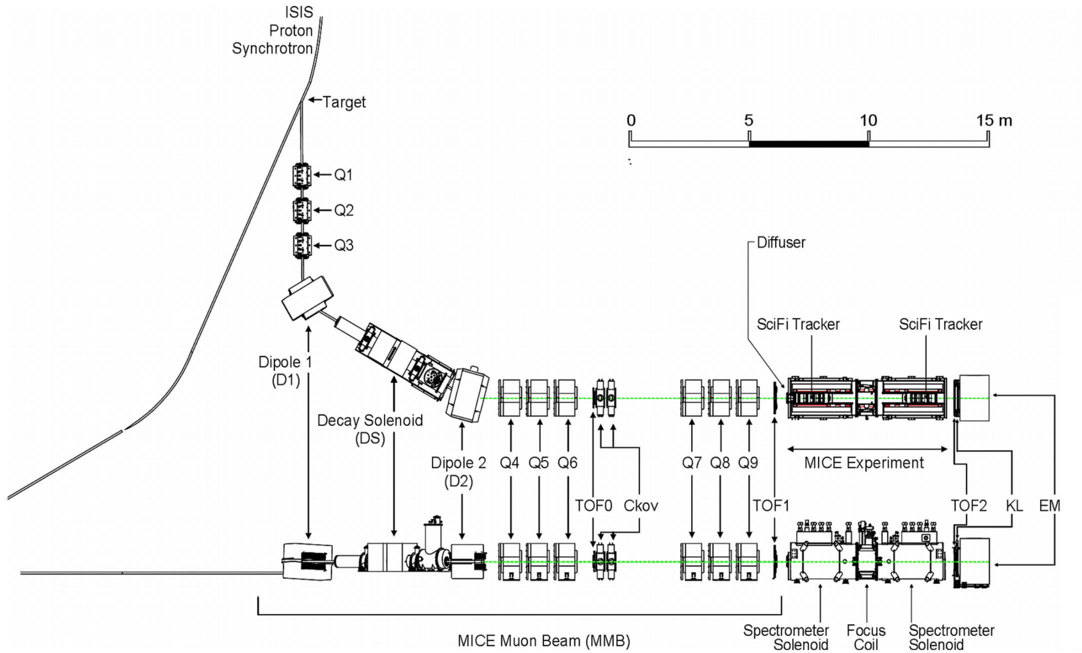
MICE Muon Beam line



- Muon momenta between 120 and 260 MeV/c
- Muon emittance between 2 mm and 10 mm
- Pion impurity suppressed at up to 99 % level

The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment, JINST 7, P05009 (2012)

Characterisation of the muon beams for the Muon Ionisation Cooling Experiment, EPJ C 73, 10 (2013)

Pion contamination in the MICE muon beam, JINST 11 (2016)

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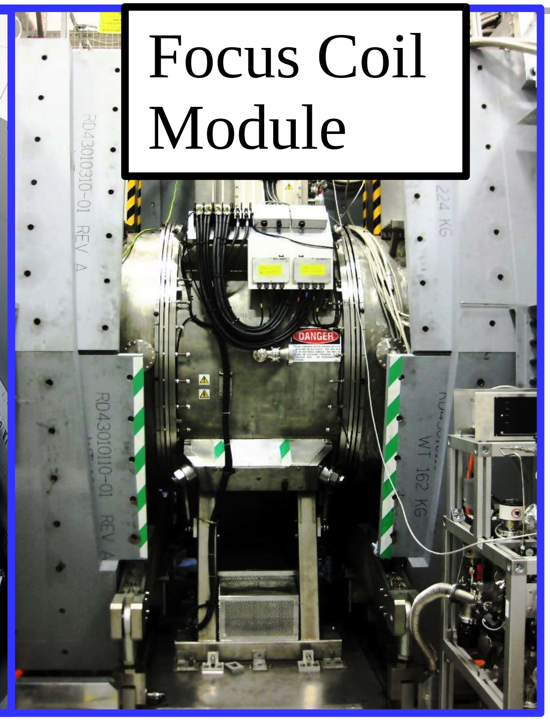
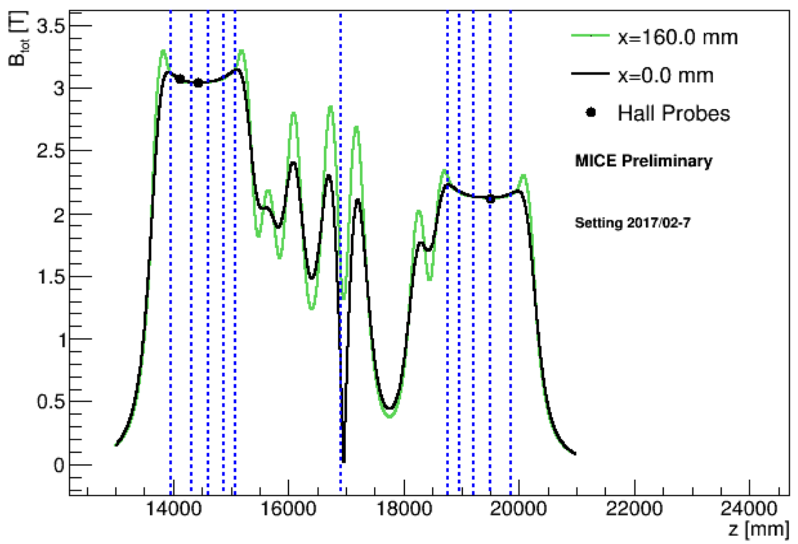
Magnets

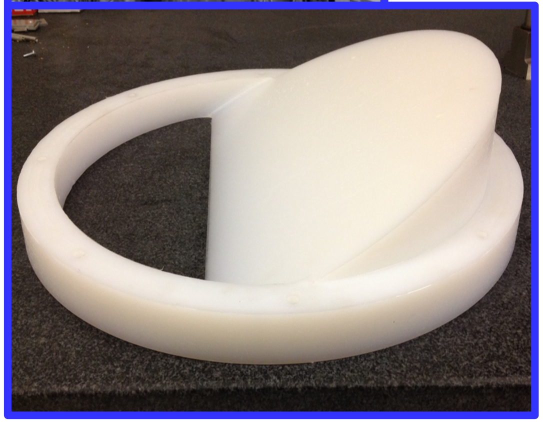




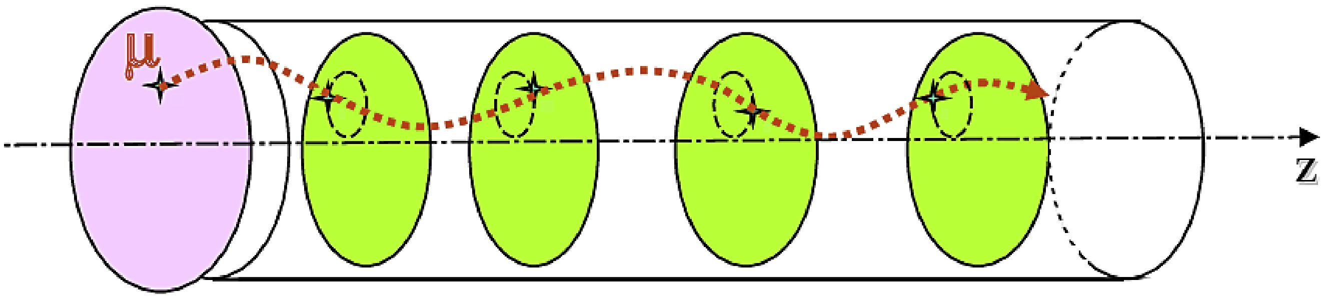
- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Match coils enable choice of beam focus
- Focus coil module provides final focus on absorber
  - Dual coil assembly - possible to flip polarity

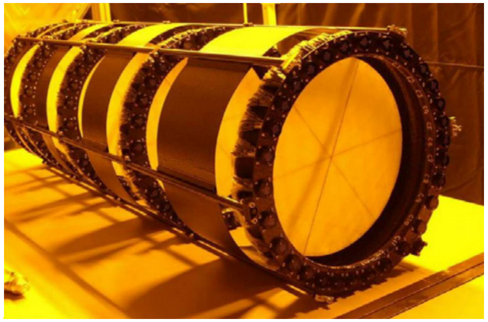
Absorbers

- 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 absorber for longitudinal emittance studies



Scintillating Fibre trackers

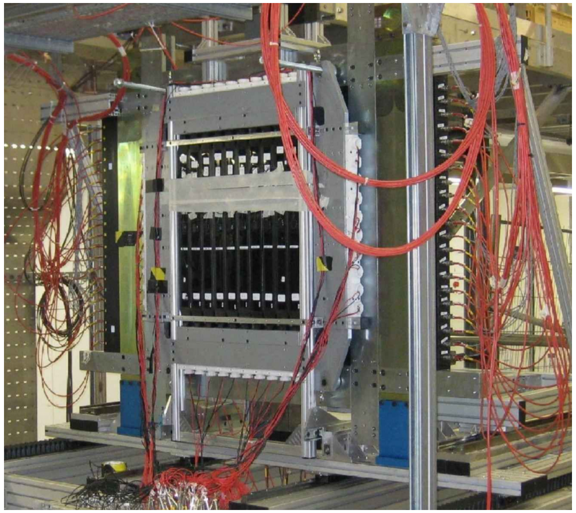


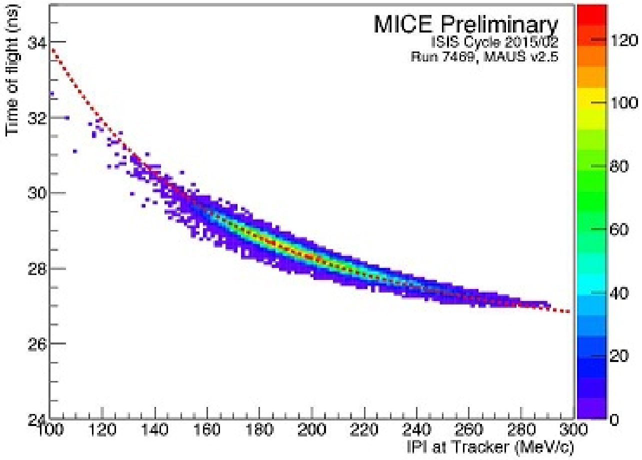


- Tracks form a helix in spectrometer solenoids
- Position of particles measured by 5 stations of scintillating fibres
- Reconstruct helix in two phases
  - Pattern recognition to reject noise
  - Kalman filter to get optimal trajectory
- Yields momentum and position of particles at reference plane
- **A scintillating fibre tracker for MICE**, NIM A 659, 2011
- **The reconstruction software for the MICE scintillating fibre trackers**, J.Inst.11, 2016

Time-of-Flight, Ckov and Calorimetry

- High precision Time-of-Flight detectors
  - Comparison of time-of-Flight with momentum enables rejection of impurities
- Threshold Cerenkov detectors provide rejection of impurities near the relativistic limit
- KLOE Light and Electron Muon Ranger provide calorimetry and rejection of decay electrons in downstream region
- **Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam**, JINST 10 P12012 (2015)





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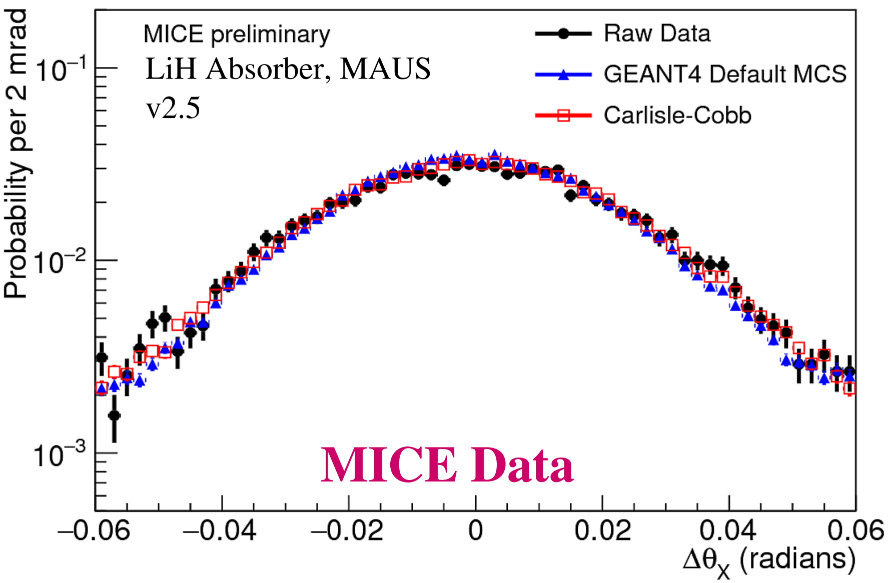
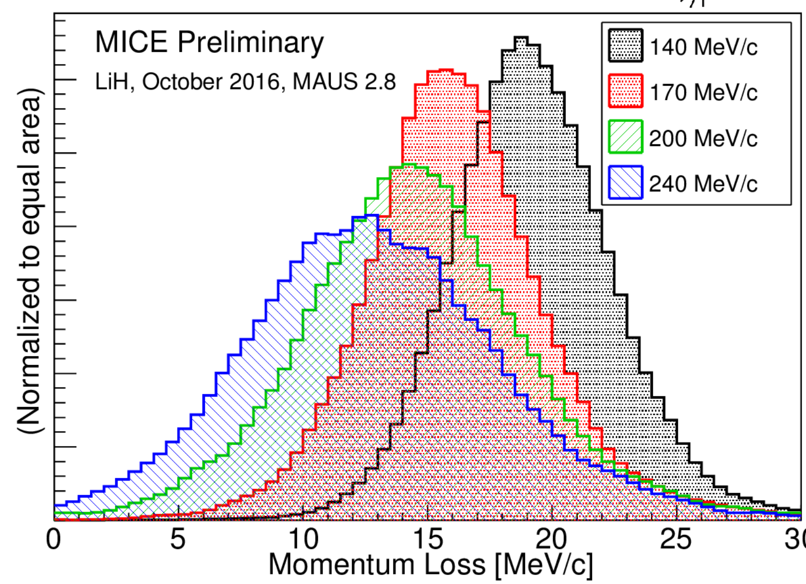
Material physics processes





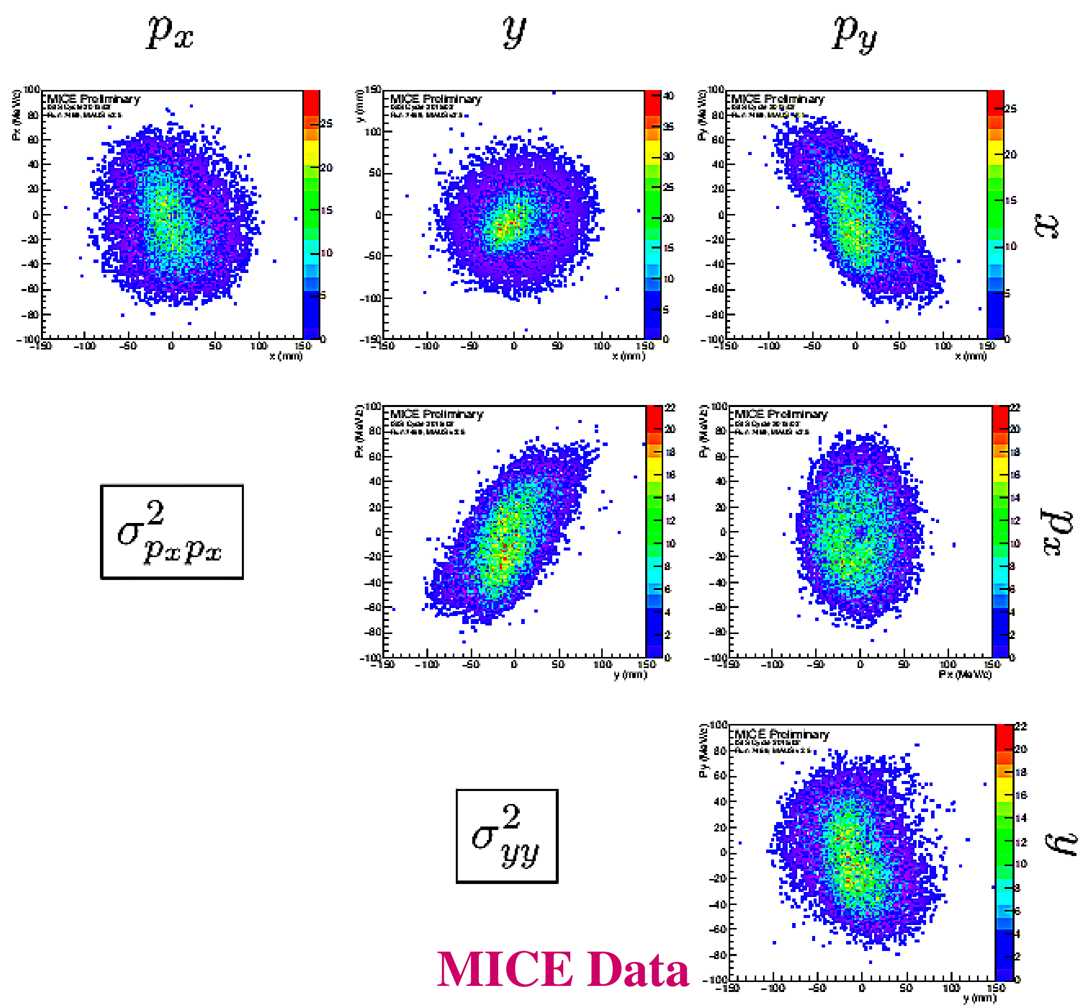
- Energy loss and multiple Coulomb scattering underlie ionization cooling emittance decrease
- Precision measurement of multiple coulomb scattering
  - See next talk
- Validation of energy loss model

Measurement of Beam Properties

- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision

x

σ^2_{xx}



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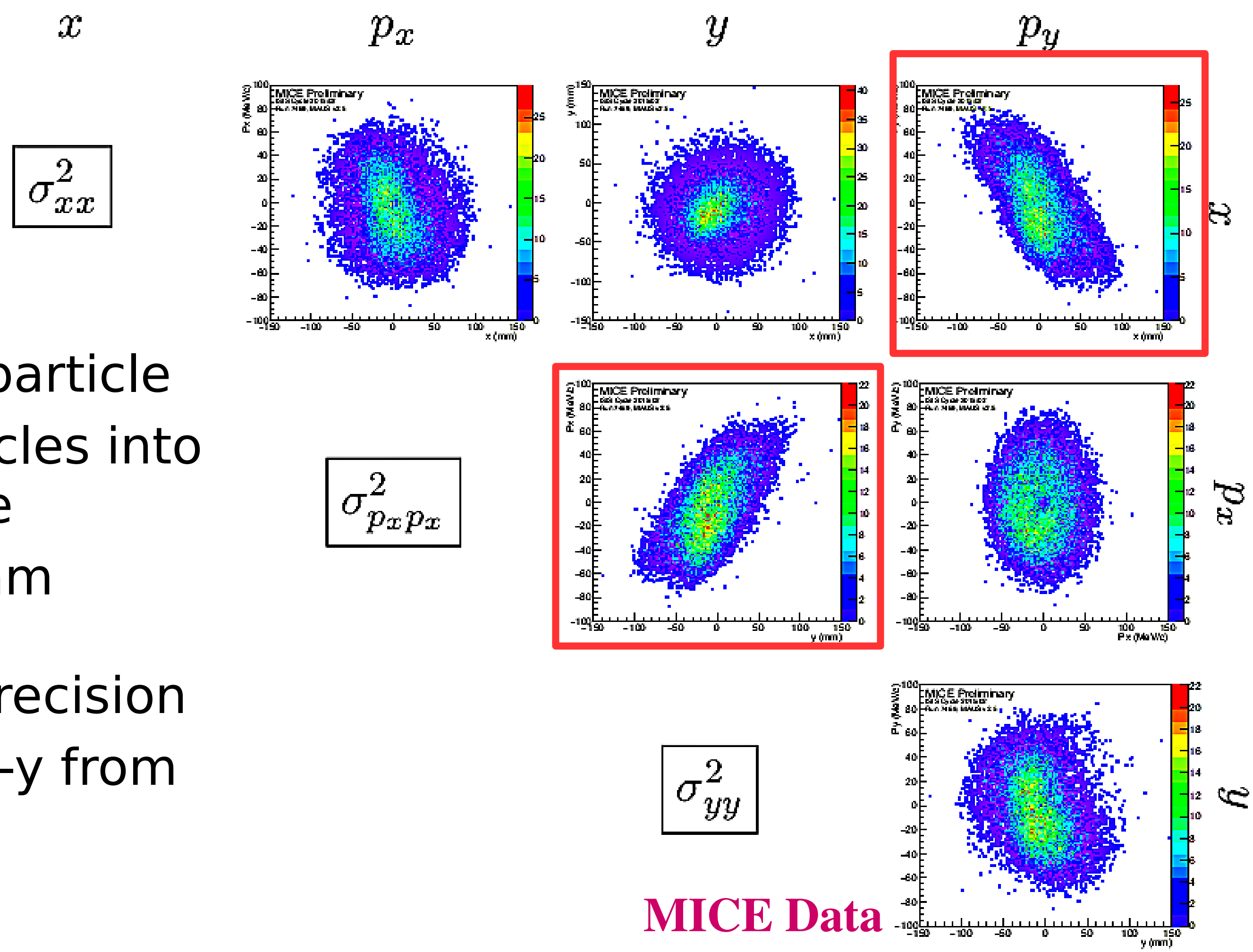
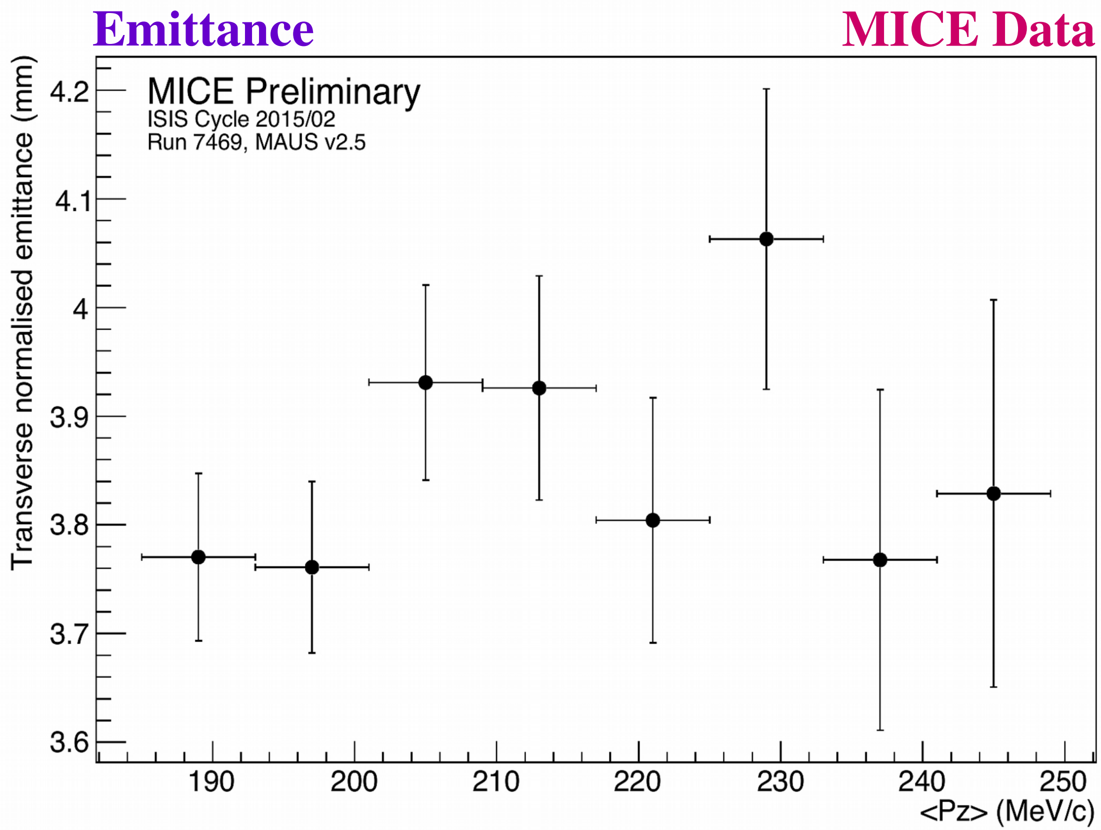
Measurement of Beam Properties



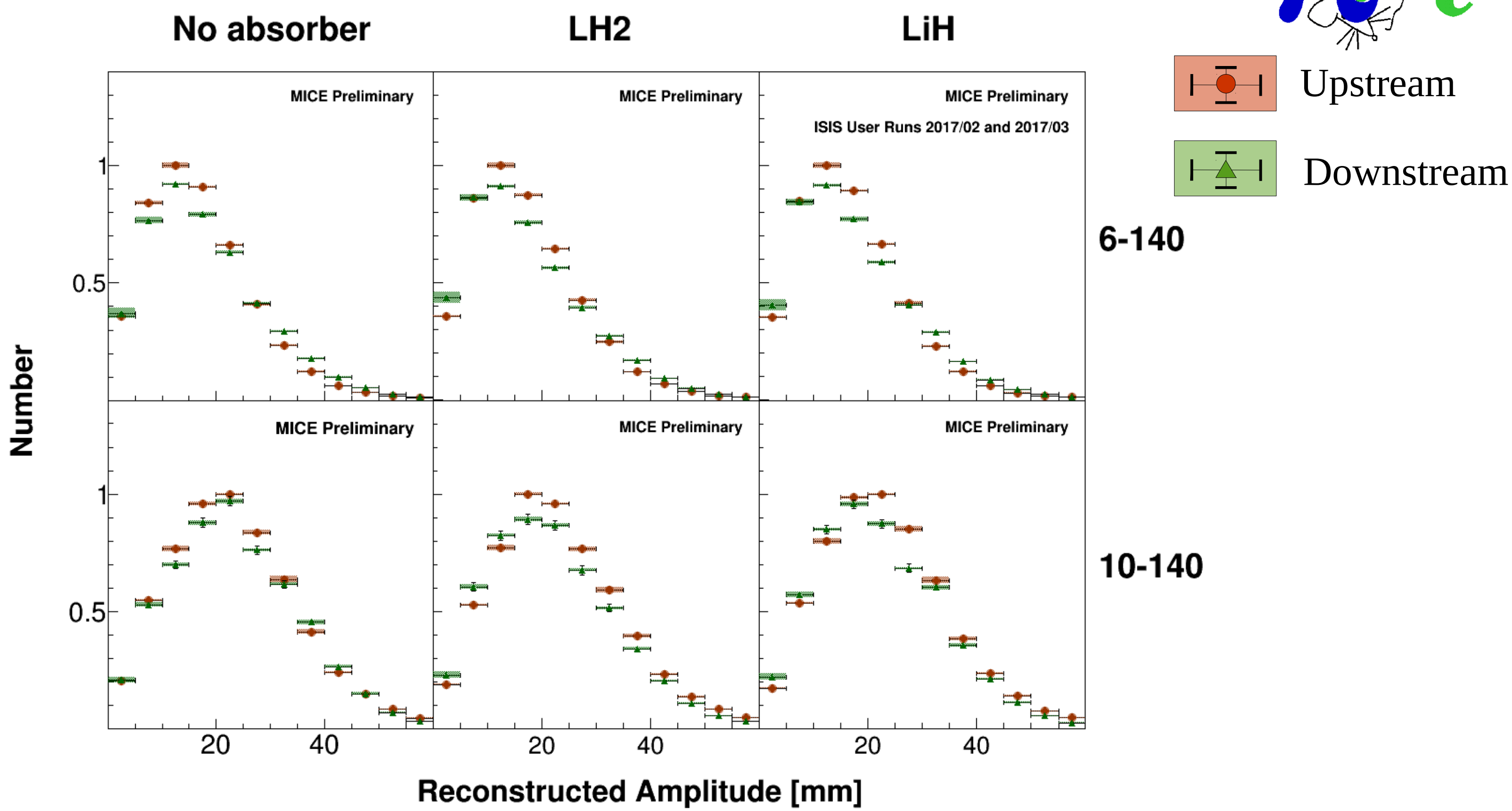
- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields

Measurement of Emittance



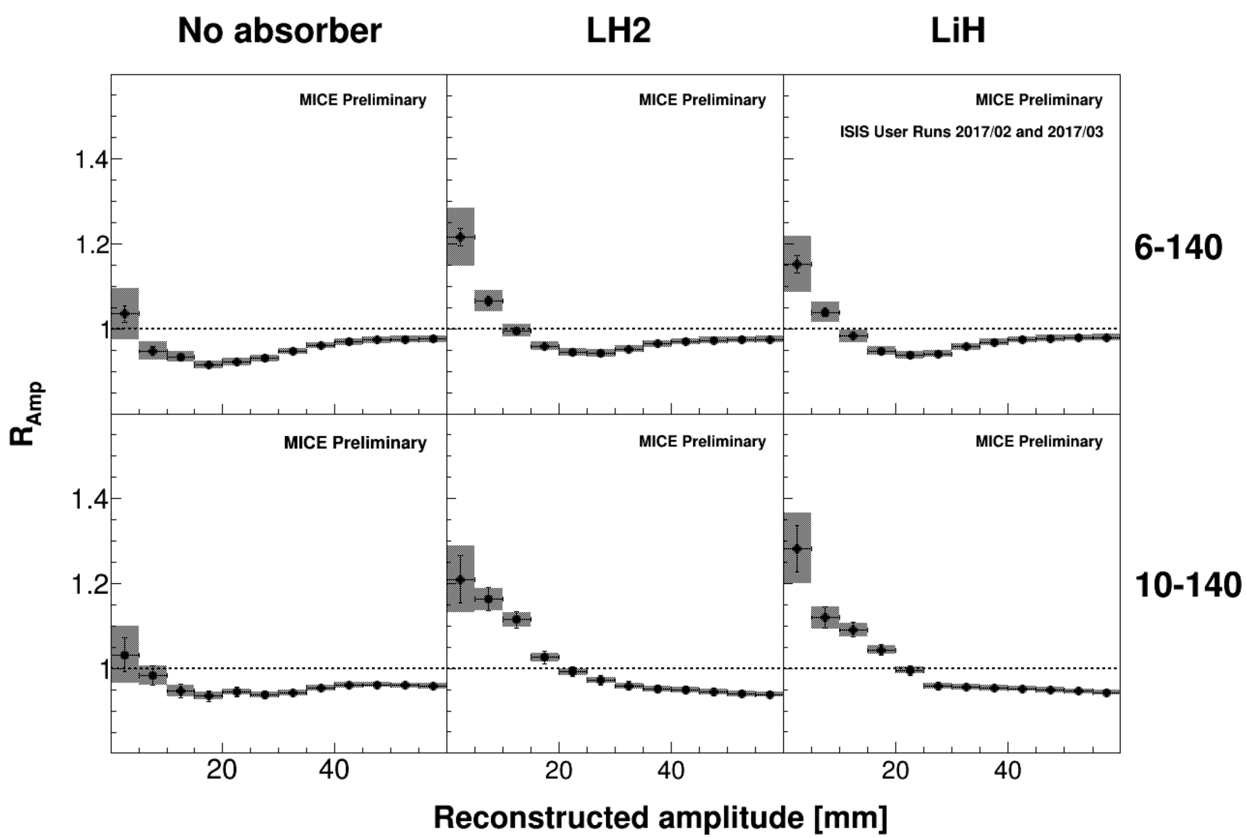
- Measure four dimensional beam emittance (mean amplitude)
  - Including e.g. x-y coupling terms
  - Slice in p_z to understand effect of dispersion

Change in Amplitude Across Absorber



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

Ratio of core densities



- R_{amp} is ratio of CDF
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances

Ratio of core densities

- Muon cooling is last “in-principle” challenge for neutrino factory or muon collider R&D
- MICE has measured the underlying physics processes that govern cooling
- MICE has made an unprecedented single particle measurement of particle trajectories in an accelerator lattice
- MICE has made first observation of ionization cooling
- Opens the door for high energy muon accelerators as a probe of fundamental physics