Muon Ionization Cooling Experiment: Results & Prospects

Tom Lord, University of Warwick
On behalf of the MICE Collaboration
XIX International Workshop on Neutrino Telescopes

Muon beams for particle physics

- Muons, elementary leptons ~200 times heavier than electrons, make excellent collider candidates
  - Avoids large QCD background from hadron collisions
  - Collisions utilise full CM energy, unlike parton-parton collisions in hadron colliders
  - Synchrotron radiation is highly supressed due to mass
  - Also suppresses beamstrahlung, reduces beam degradation
  - Larger coupling to Higgs mechanism through larger m_μ
- Muon beams provide high quality neutrino source - nuSTORM and the Neutrino Factory
  - Well-defined spectrum and neutrino flux, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
  - Large ν_e event rate, orders of magnitude > T2K, Minerva
- Anomalous magnetic moment (g-2), Lepton Flavour Violation searches, test of SM

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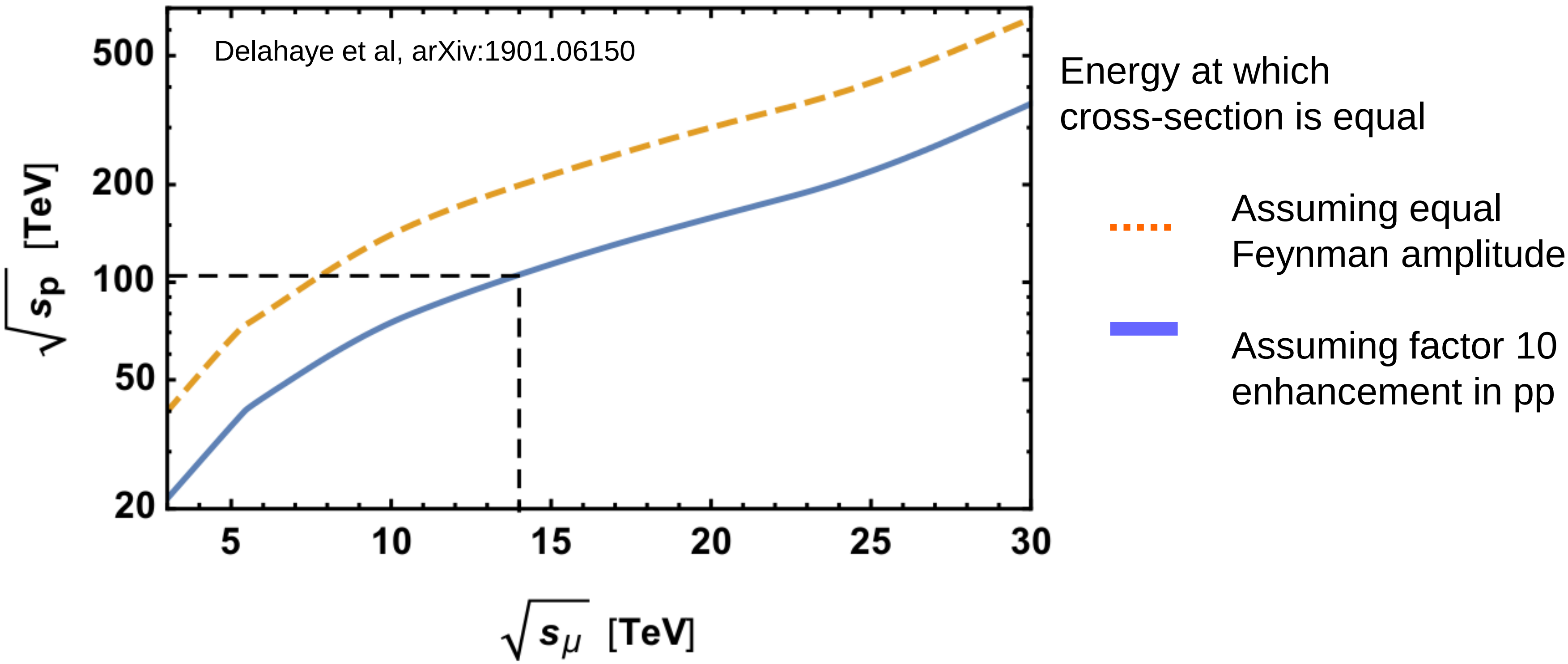
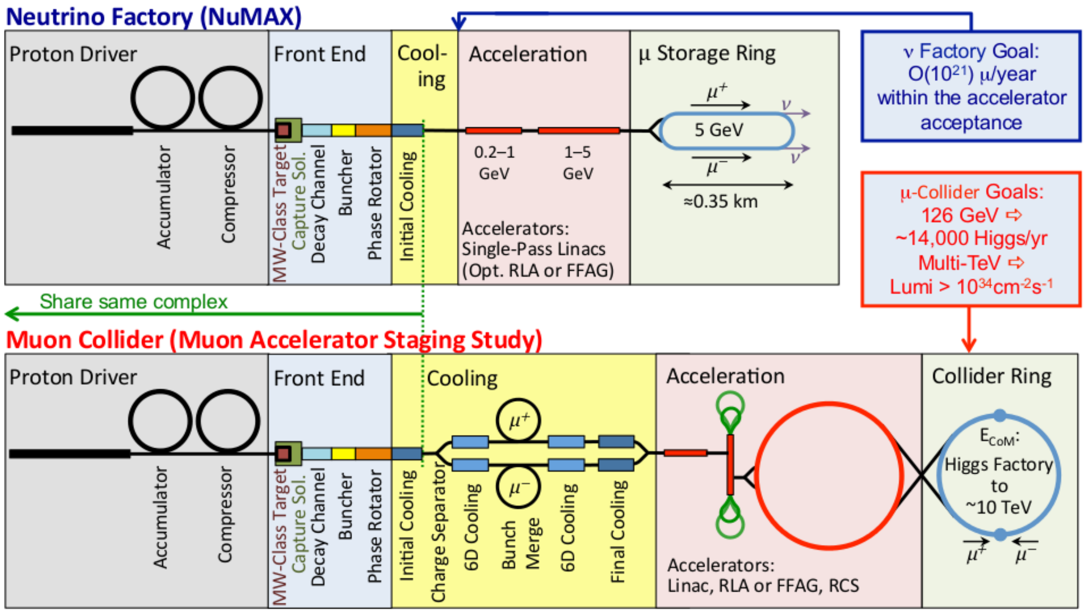
Muon Collider Physics Reach



- 14 TeV Muon Collider (LHC CM energy) comparable to 100 TeV proton-proton collider like FCC-HH

Muon Collider and Neutrino Factory



- Both facilities utilise:
  - High power protons
  - Target → pions
  - Capture → muons
  - Cooling
  - Rapid acceleration
  - Storage ring

- Muon beams are unstable (muon lifetime only ~2.2 μs at rest)
- Tertiary beam production ($p \rightarrow \pi \rightarrow \mu$) → large beam emittance

- Rapid cooling required → ionization cooling only technique fast enough!

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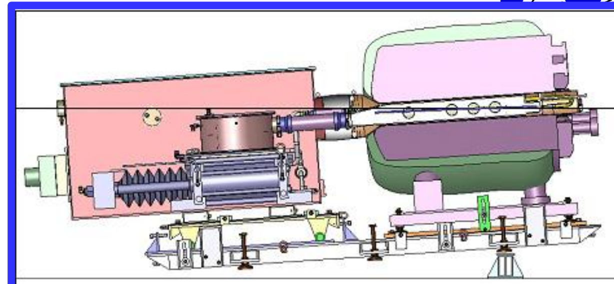
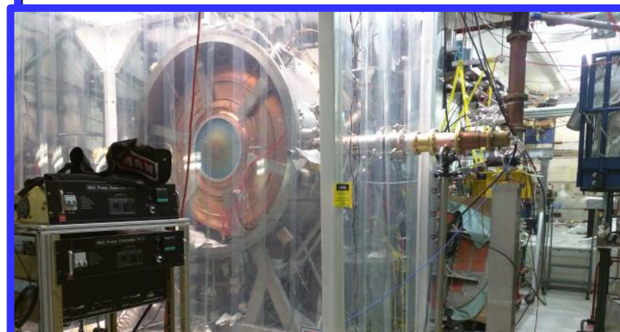
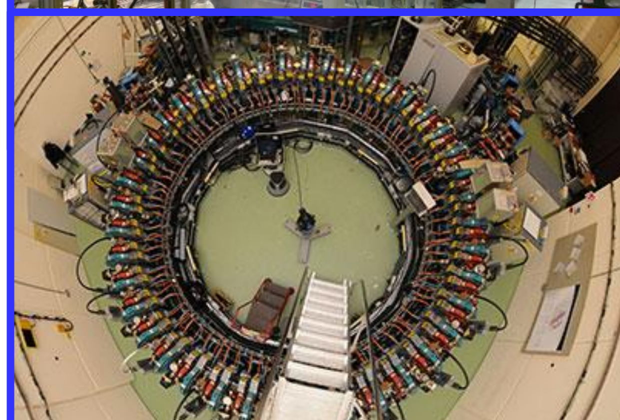
R&D Programme

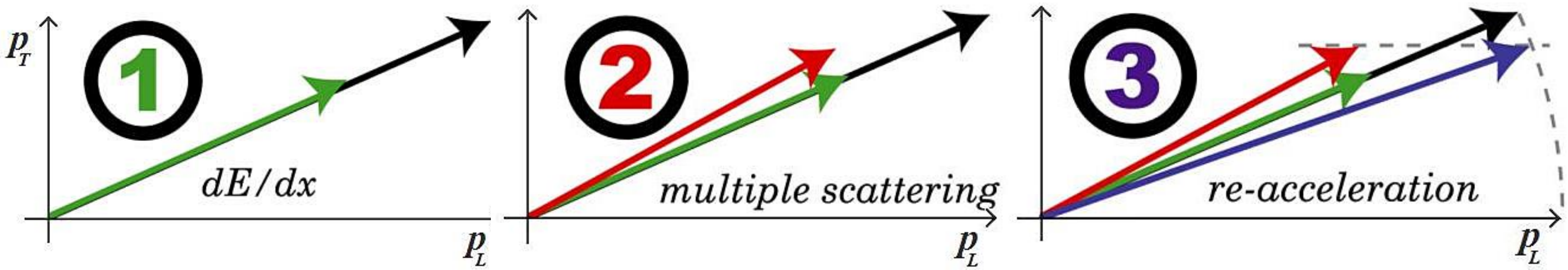
- MERIT
  - Demonstrated principle of liquid Mercury jet target
- MuCool Test Area
  - Demonstrated operation of RF cavities in strong B-fields
- EMMA
  - Showed rapid acceleration in non-scaling FFA
- MICE
  - Demonstrate ionization cooling principle
  - Increase inherent beam brightness → number of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







Ionization Cooling Principle



- Energy loss in absorbers reduces both p_L and p_T
- Multiple scattering heats beam
- RF cavities restore along p_L only
- Net reduction of p_T, beam emittance (cooling)
  - strong focussing and low-Z absorber material mitigate scattering effect
  - High RF gradient required
- Cooling Equation: $$\frac{d\epsilon_\perp}{ds} \sim -\frac{1}{\beta^2}\left|\frac{dE_\mu}{dz}\right|\frac{\epsilon_\perp}{E_\mu} + \frac{\beta_\perp (13.6\ MeV)^2}{2\beta^3 E_\mu m_\mu c^2\ X_0}$$

$\frac{d\epsilon_\perp}{ds}$ is rate of change of transverse 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; X_0 is the radiation length of the absorber material.

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Muon Ionization Cooling Experiment

- Over 100 collaborators, 10 countries, 30 institutions
- Operated at Rutherford Appleton Laboratory between 2008 and 2017

MICE aimed to:

- 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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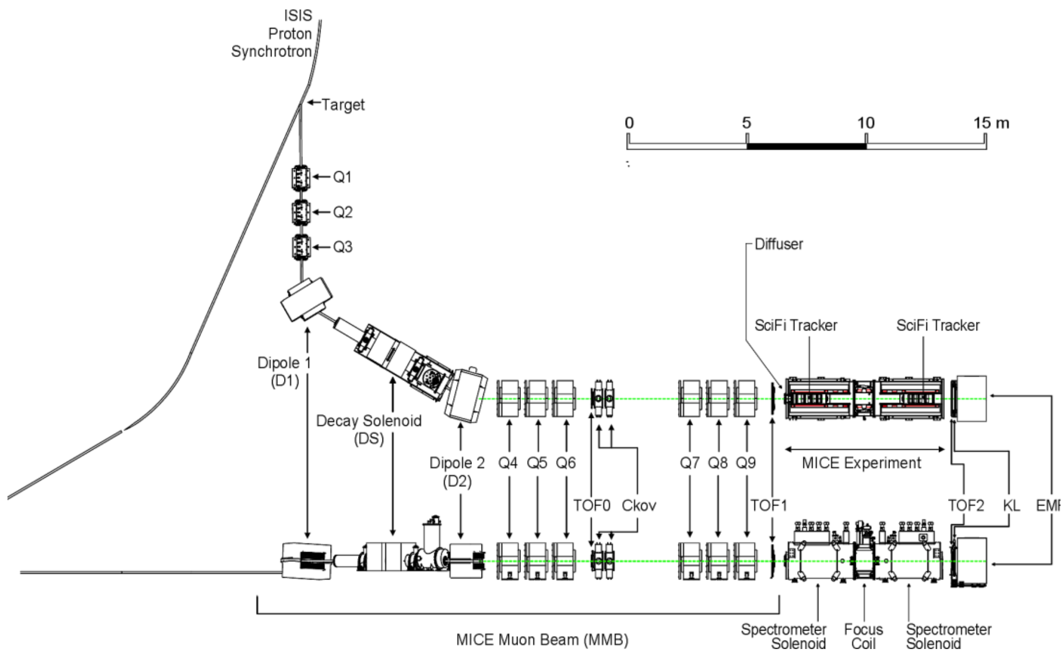
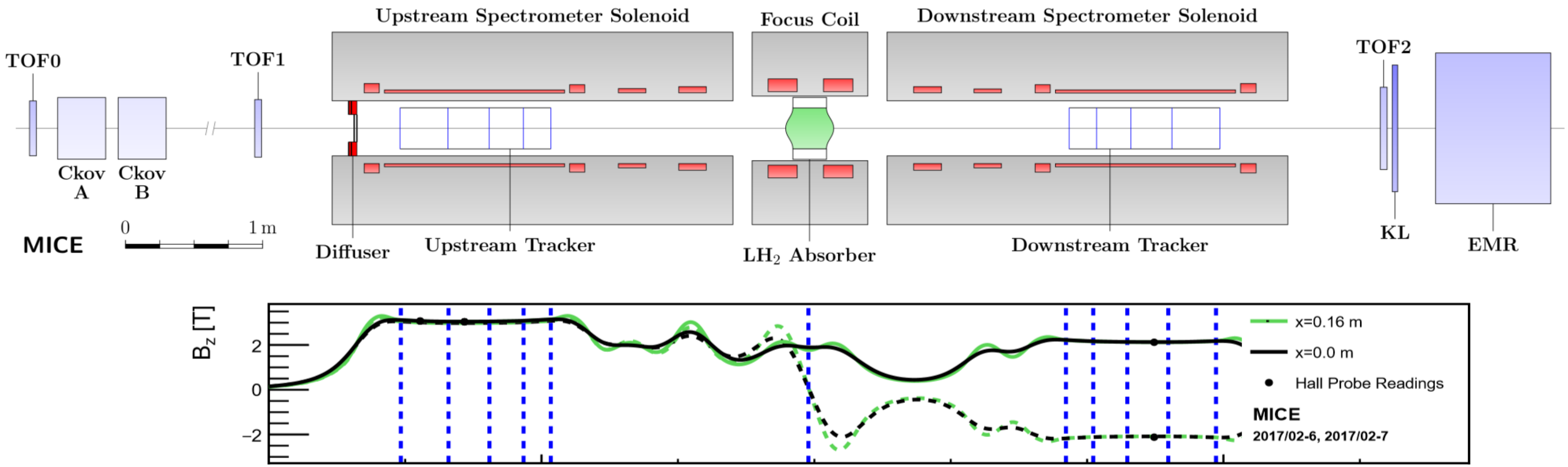
MICE Muon Beam line



- 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)

Cooling Channel Lattice



- Spectrometer solenoids upstream and downstream provide uniform 2-4 T field for SciFi trackers / detector systems
- Focus coil module provides tight focussing on absorber
- Can flip field polarity across absorber, prevents canonical angular momentum buildup

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

LiH

Wedge

LH_2 vessel

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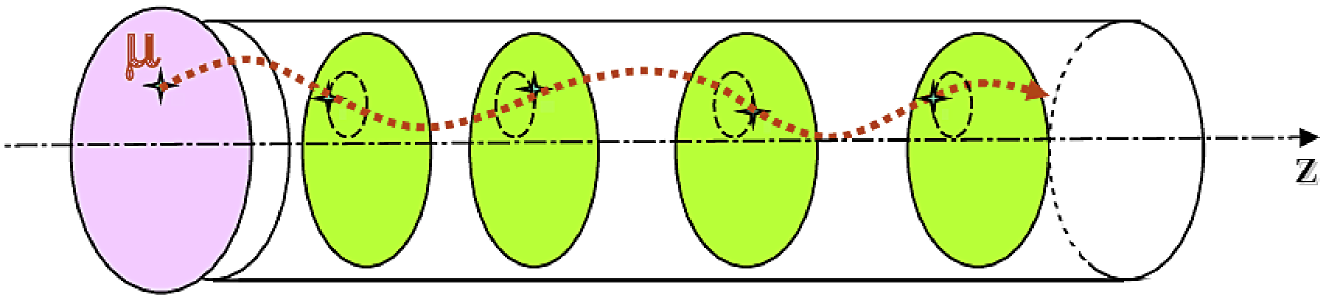
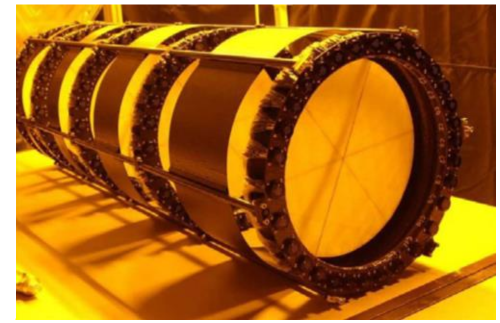
Scintillating Fibre trackers





- 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

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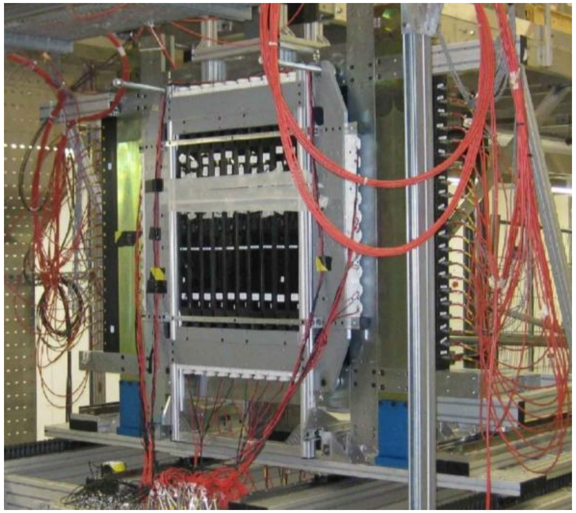
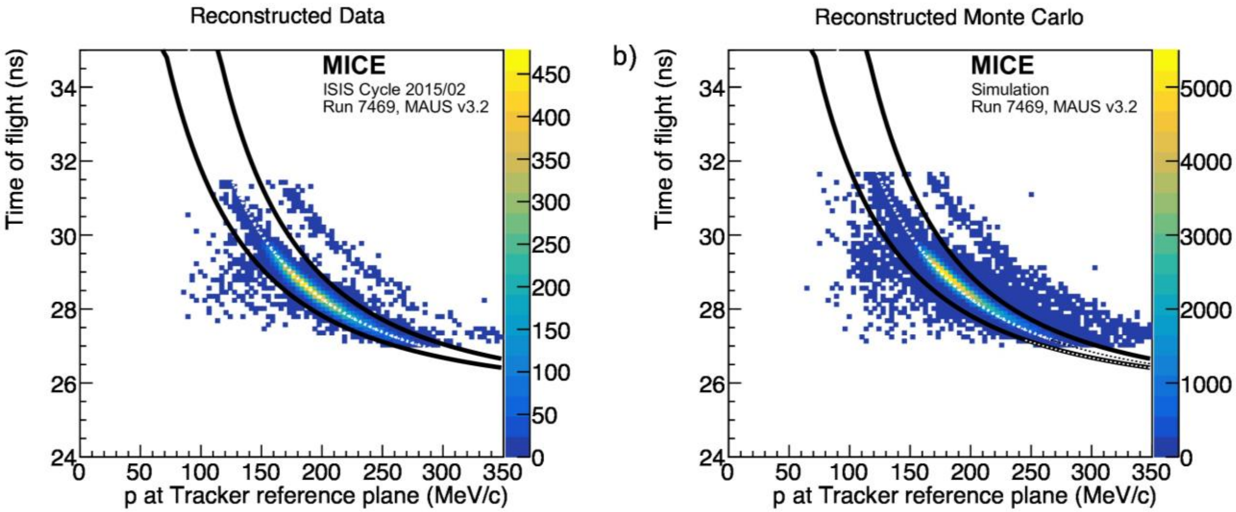
Time-of-Flight, Ckov and Calorimetry

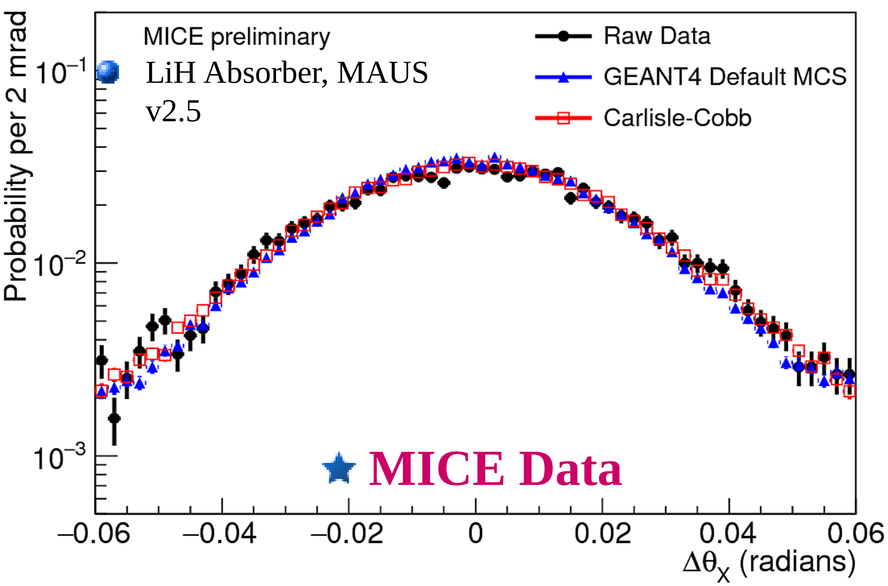
- High precision Time-of-Flight detectors
  - Comparison of time-of-Flight with momentum enables rejection of impurities
- Threshold Cherenkov detectors provide rejection of impurities near the relativistic limit
- KLOE Light and Electron Muon Ranger provide calorimetry and rejection of decay electrons in downstream region

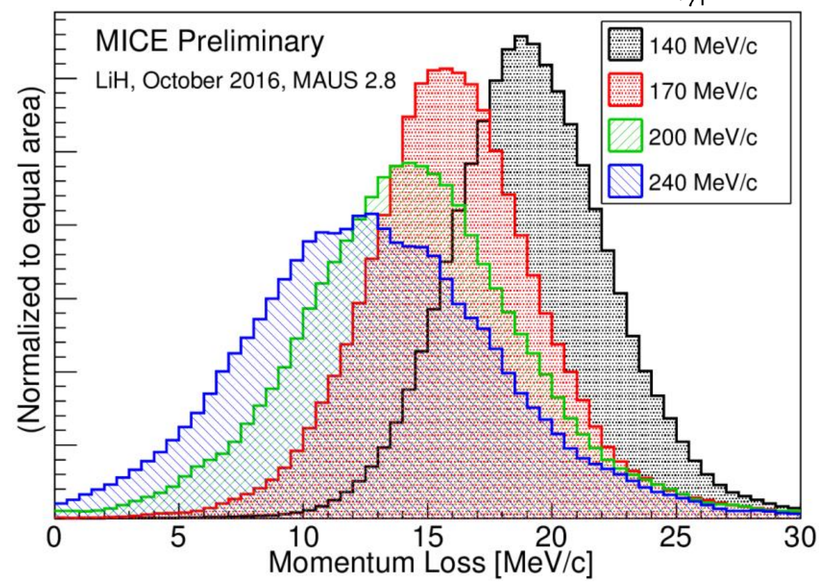


- **Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam**, JINST 10 P12012 (2015)
- **The design and commissioning of the MICE upstream time-of-flight system**, **NIM** A 615 (2010) 14-26



Material physics processes





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

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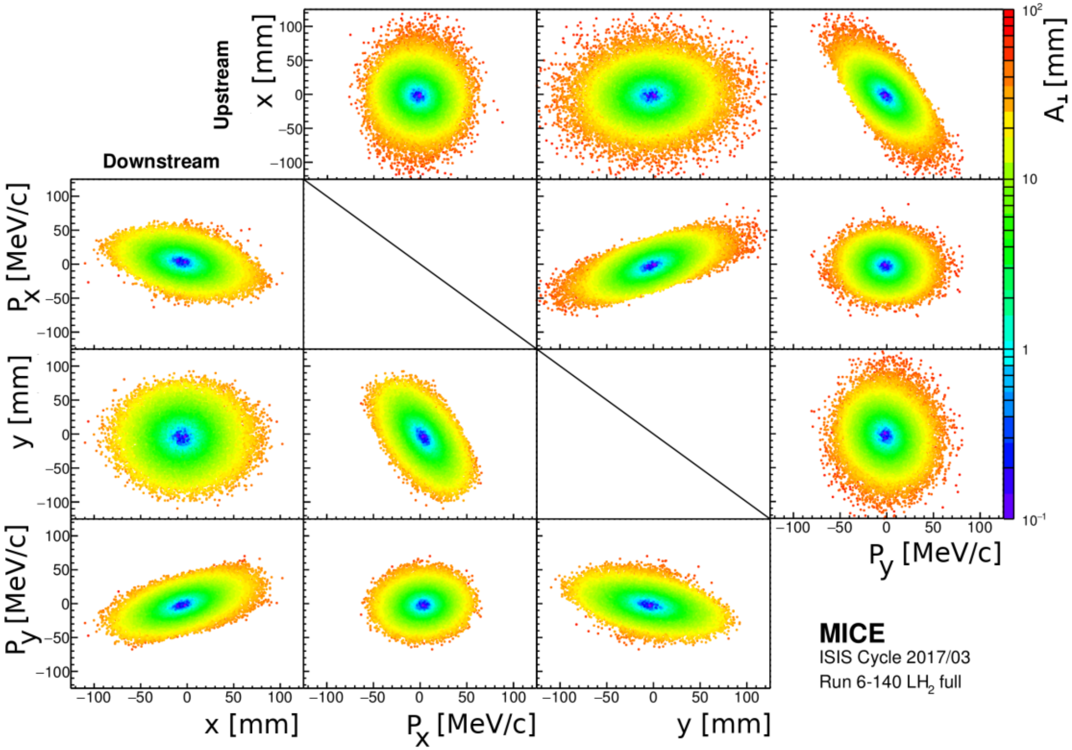
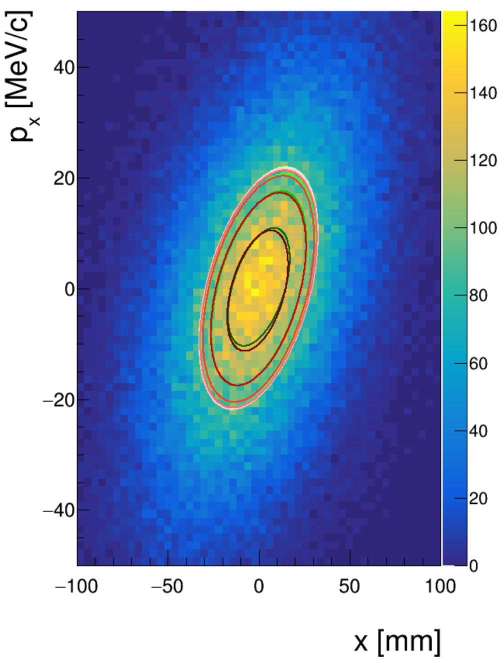
Measurement of Beam Properties

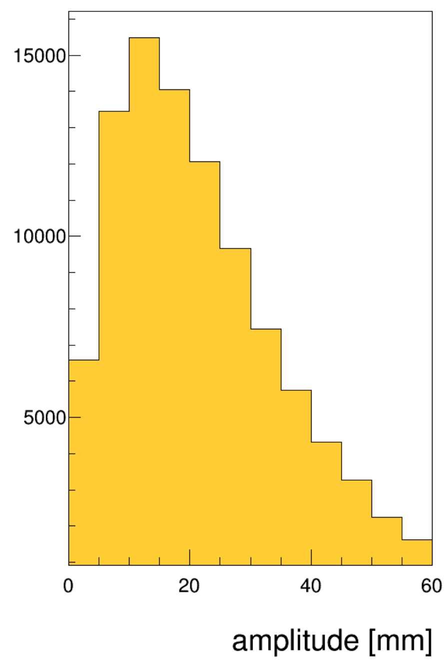
- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields



First particle-by-particle measurement of emittance in the Muon Ionization Cooling Experiment, *Eur. Phys. J.* C **79**, 257 (2019)

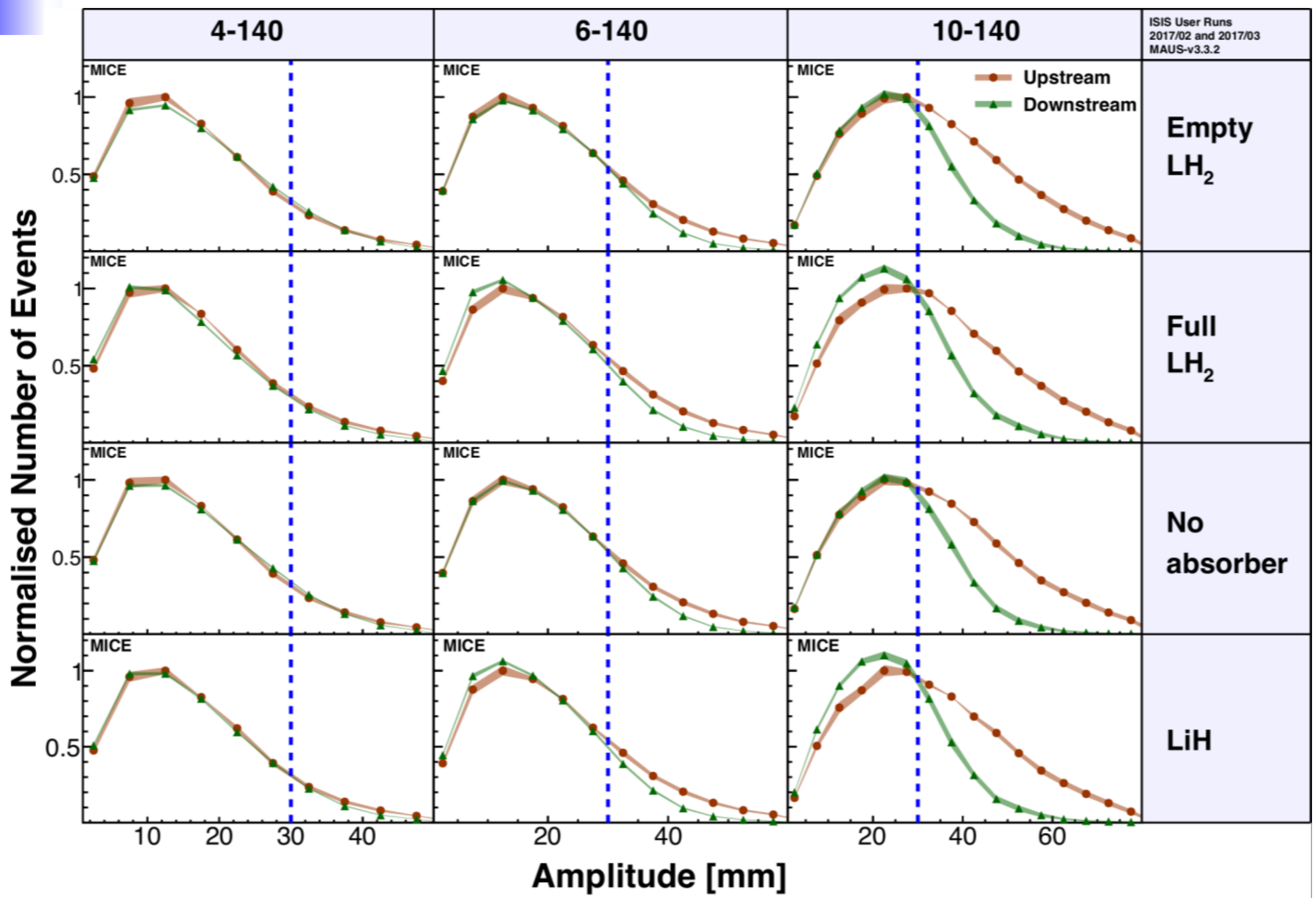
Amplitude

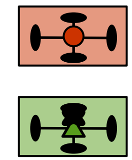




- Transverse amplitude is distance of muon at point $p = (x, p_x, y, p_y)$ from beam core in phase-space
  - Normalise phase space to RMS beam ellipse
- Related to transverse emittance by $A_\perp = \epsilon_\perp (p - \bar{p})^T \Sigma^{-1} (p - \bar{p})$, with Σ = 4D covariance matrix
- Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread, reducing amplitude
- Mean amplitude $\langle A_\perp \rangle \sim$ RMS emittance

Amplitude Change Across Absorber – 'Flip Mode'





Upstream

Downstream

140 MeV/c data

Nature volume 578, pages 53-59 (2020)

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

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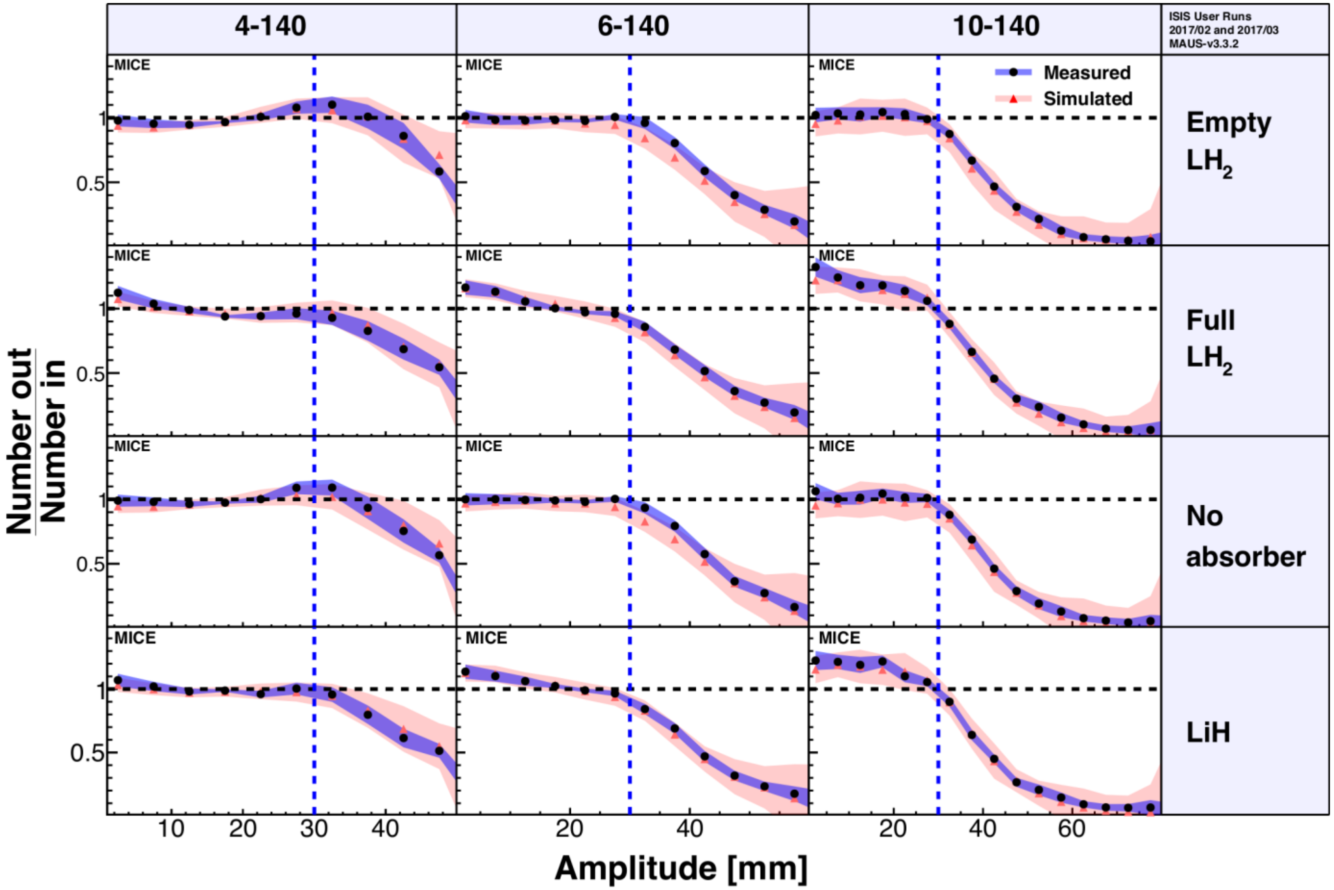
Ratio of core densities – ‘Flip Mode’



Nature volume 578, pages 53-59 (2020)

- Ratio of downstream over upstream CDFs
- Core density increase for LH_2 and LiH absorber → cooling
- More cooling at higher emittances

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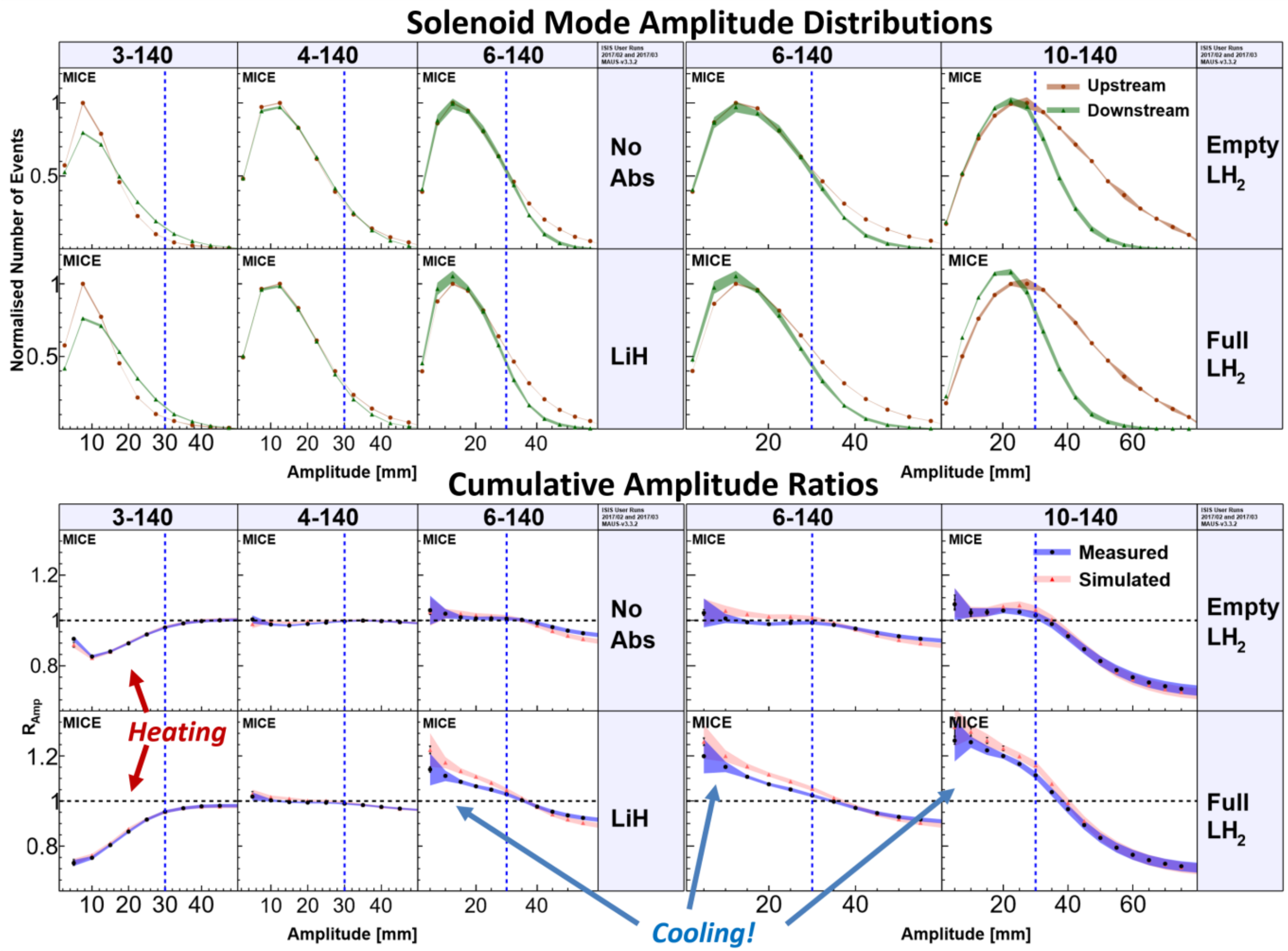
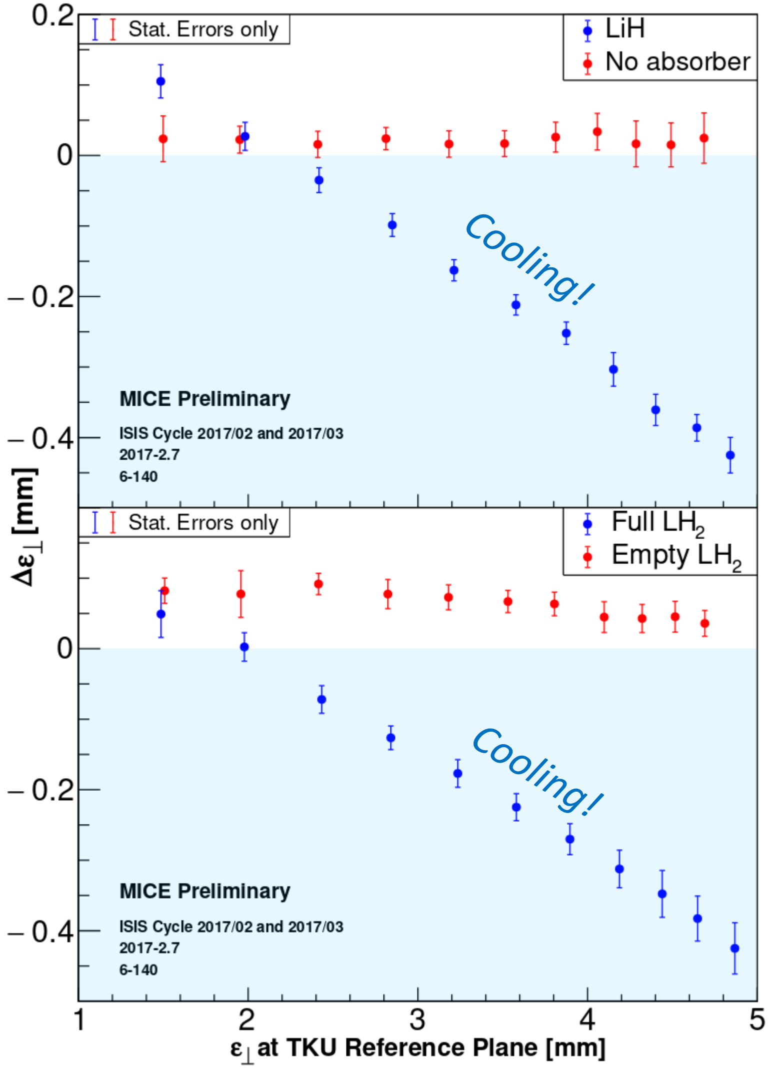
'Solenoid Mode' Amplitude Change

- 140 MeV/c data
- Core density increase for LH_2 & LiH absorbers
- More cooling at higher emittances
- Heating in 3mm beam



Emittance reduction in 'Flip Mode'



- Matched distribution selected in upstream sample using rejection sampling
- 4D Normalised emittance, defined as:

$$\epsilon_{\perp} = \frac{1}{m_{\mu}} \sqrt[4]{|\Sigma|}$$

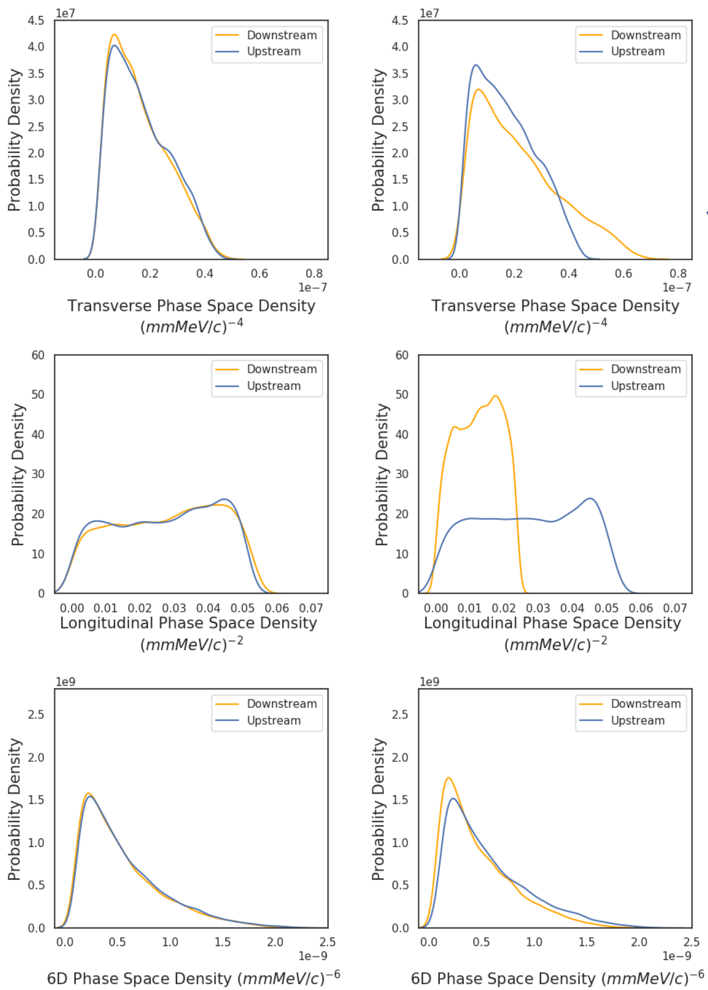
$$\Delta\epsilon_{\perp} = \epsilon_{downstream} - \epsilon_{upstream}$$

Σ = covariance matrix

- Slight heating in no absorber, empty LH_2 beams
- Clear emittance reduction in LiH, Full LH_2 beams - cooling

Wedge Absorber Simulation

No Absorber MC Truth Phase Space Densities | Wedge MC Truth Phase Space Densities



- Reverse emittance exchange with wedge absorber, essential for 6D cooling
  - Increase in transverse phase-space density
  - Decrease in longitudinal phase-space density
- Kernel Density Estimation (KDE) technique used to calculate phase-space density
- Data analysis in progress

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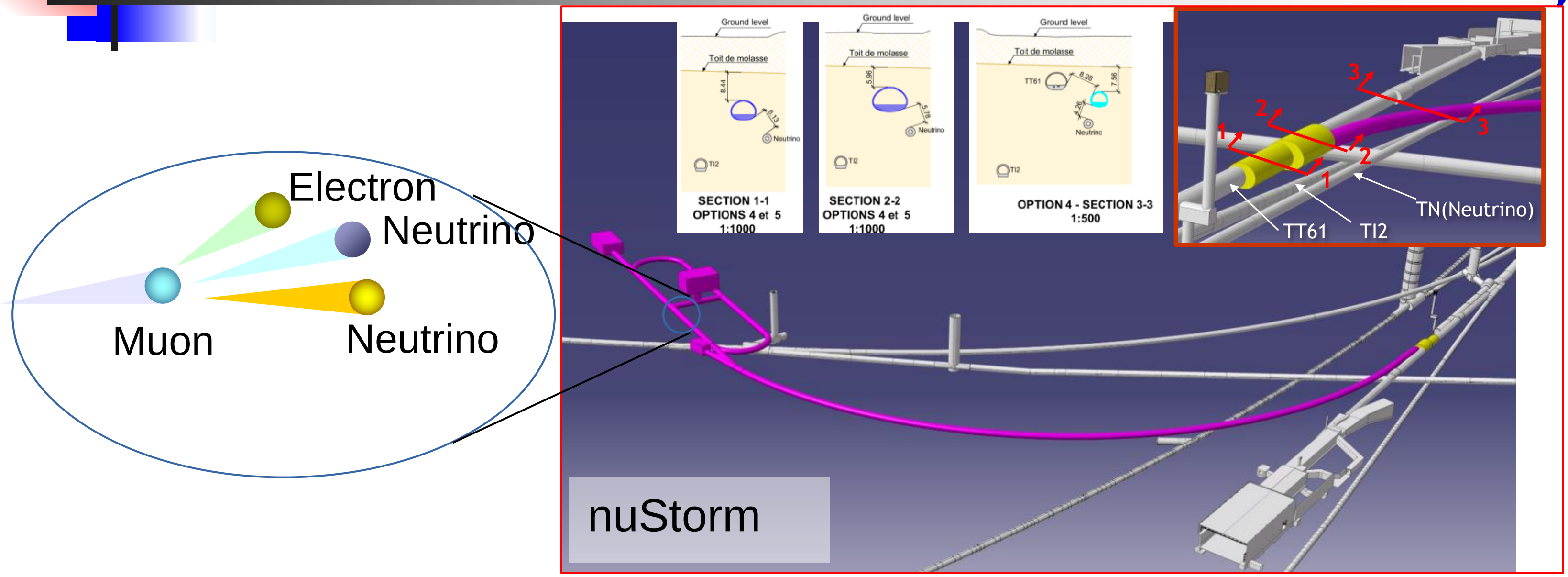
Neutrino Source (Proposed)



- Neutrinos from StORed Muons – “nuSTORM”
  - Precise measurement of ν interaction cross-sections
  - Precise probe of neutrino oscillations
  - Search for sterile neutrinos and other BSM physics
- Future neutrino experiments (DUNE, T2HK) high-statistics, likely systematics limited
- Neutrino-nucleus interaction cross-sections major contributor
- Percent-level cross-section measurements with nuSTORM → significant in reduction of systematics

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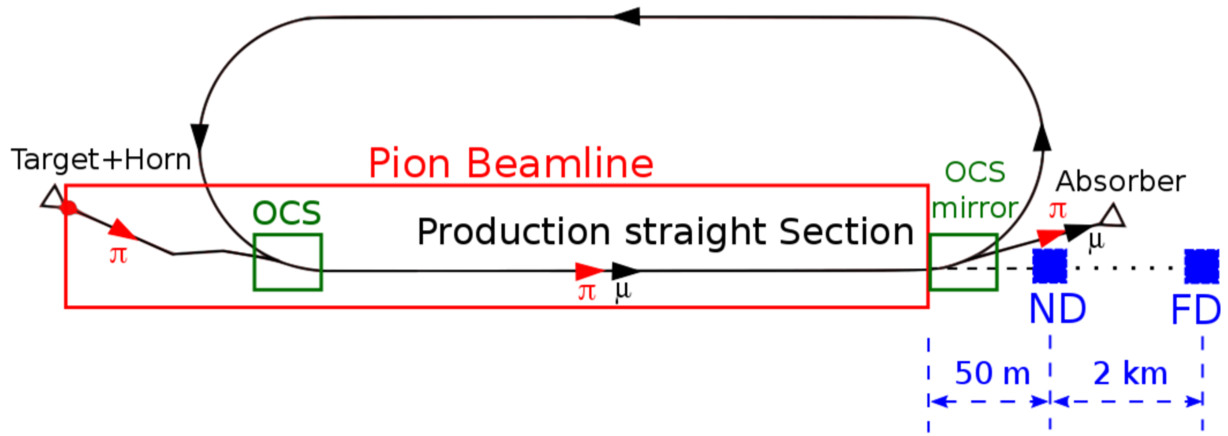
nuSTORM as a Demonstrator



D. Adey et al, **Overview of the Neutrinos from Stored Muons Facility - nuSTORM**, J. Inst. (2017)

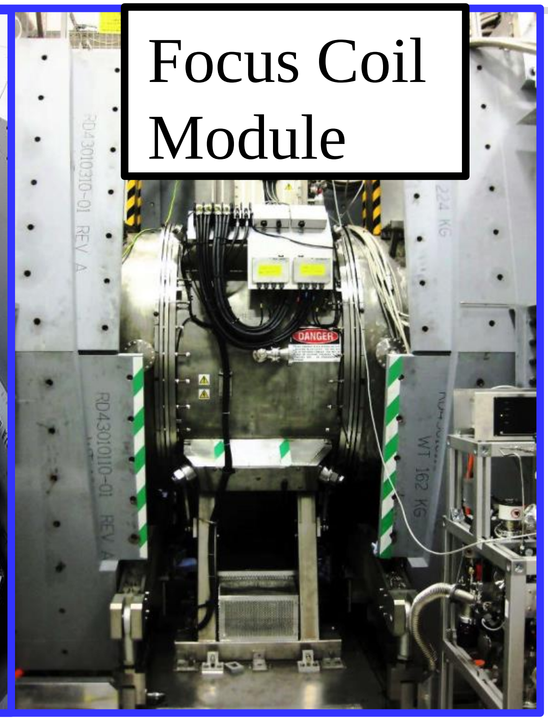
- Hurdles still to address in Muon Collider design
  - Solenoidal focusing target for both-sign muon capture
  - Radiation load, energy deposition on superconducting magnets
  - Collective effects: space charge, plasma loading of cavities
  - High field solenoids + low-freq RF cavities
- Longitudinal cooling not yet demonstrated
- Tighter focusing, lower emittance cooling than MICE
- Operational experience for Muon Collider

Summary

- 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 the first observation of ionization cooling
  - Nature volume 578, pages 53-59 (2020)
- Opens the door for high luminosity muon beam facilities as a probe of fundamental physics

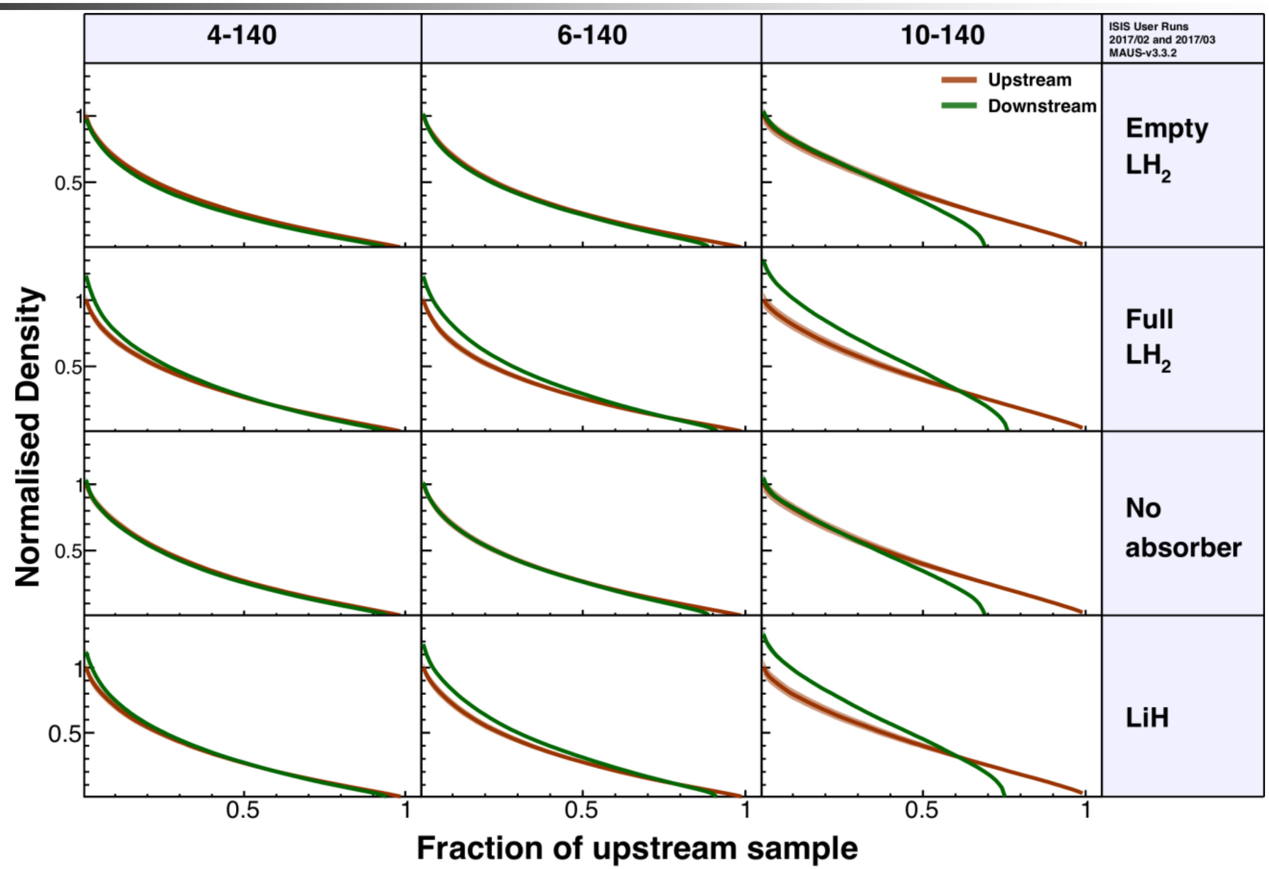
Backup

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

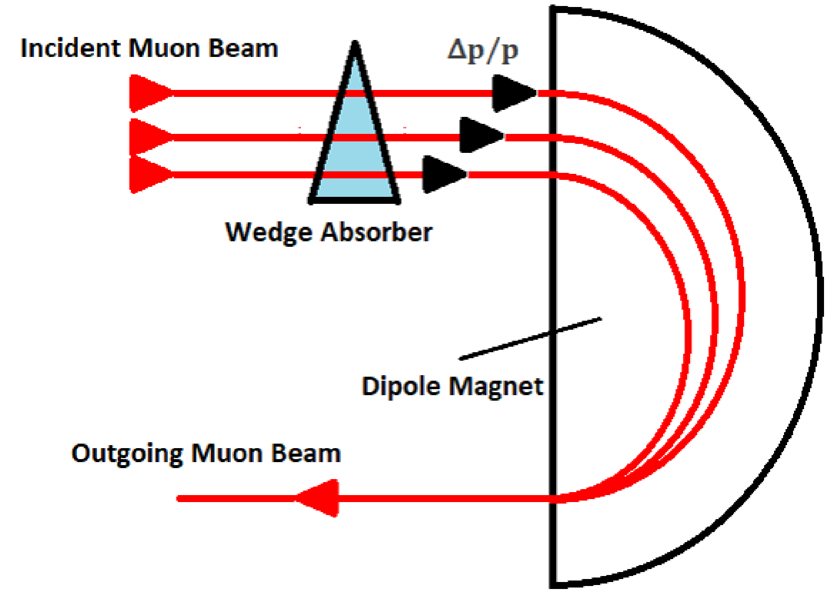
Beam densities



- Density normalised to upstream sample
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances

Reverse Emittance Exchange

- In full process, beam passes through a wedge absorber, followed by a dipole magnet
- Transverse phase-space density is increased at cost of decrease in longitudinal phase-space density
- In MICE, 45° polythene wedge absorber was placed between trackers to study exchange



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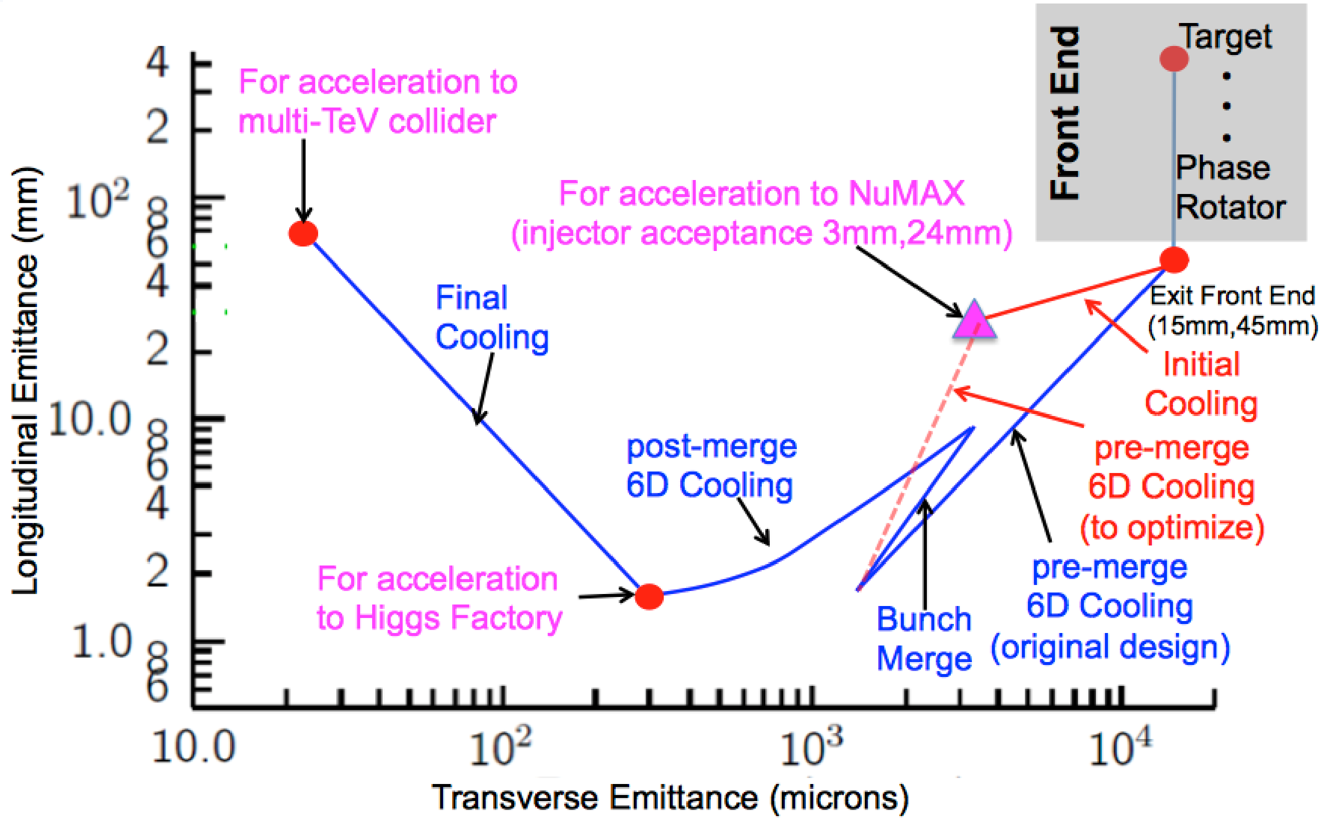
Emittance Evolution



- Emittance evolution for Neutrino Factory and Muon Collider facilities

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