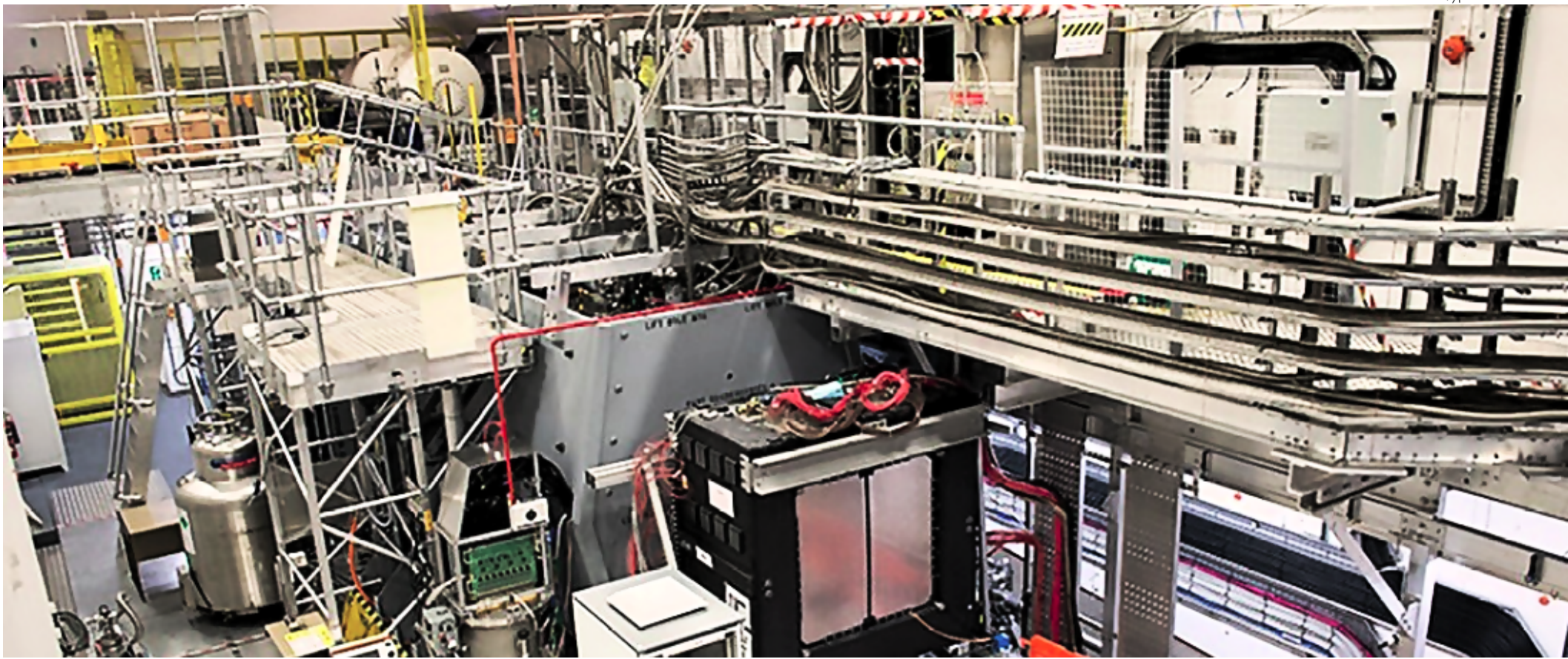
MICE in 10 Minutes

ILLINOIS INSTITUTE OF TECHNOLOGY

Tanaz Angelina Mohayai, for the MICE Collaboration

New Perspectives 2018, Fermilab, Batavia, IL



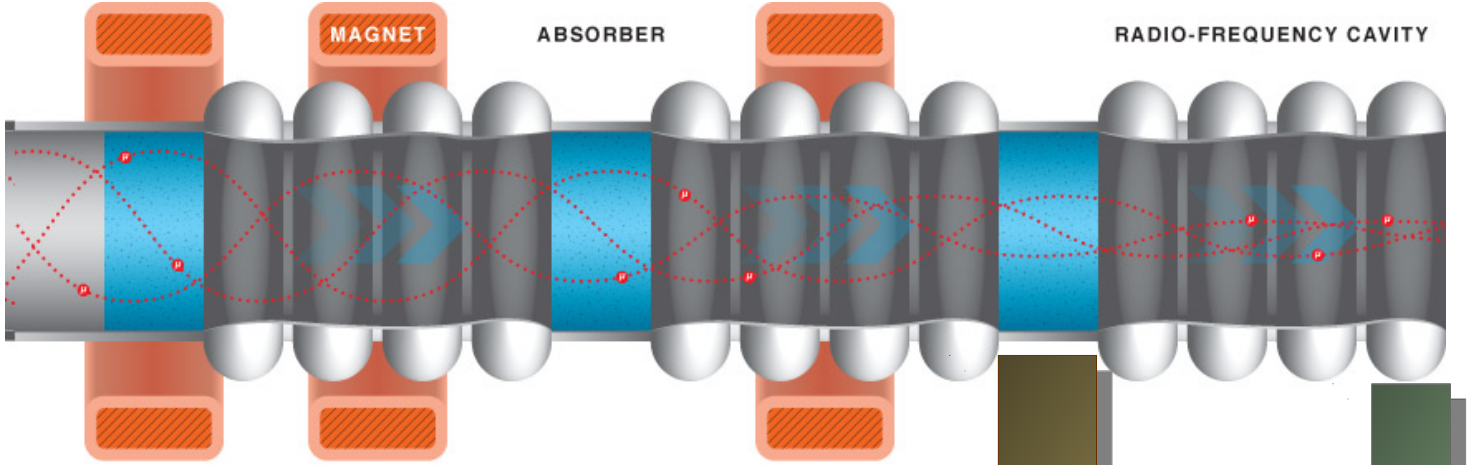
Overview

- Motivation
- Muon Ionization Cooling
- Muon Ionization Cooling Experiment (MICE)
- Demonstration of Ionization Cooling
- Conclusion and Future Prospects

Motivation

- **Muon Collider**:
  - ★ Much less energy loss from synchrotron radiation (m_μ/m_e~200); compact → cost-effective
  - ★ Clean multi-TeV collisions (e.g. $\mu^+ \mu^- \rightarrow H$)
- **Neutrino Factory** (shares same front-end with **Muon Collider**):
  - ★ Background-free, well-characterized, intense $\bar{\nu}_e/\nu_\mu$ from μ^- decay
  - ★ Best ν oscillation sensitivity
- Challenge: large phase-space volume of muon beam (μ from **proton source**)
- Solution: **rapid beam cooling** via ionization energy loss – Muon Ionization Cooling
- Test: **Muon Ionization Cooling Experiment** as first demonstrator of ionization cooling

Muon Ionization Cooling Principle

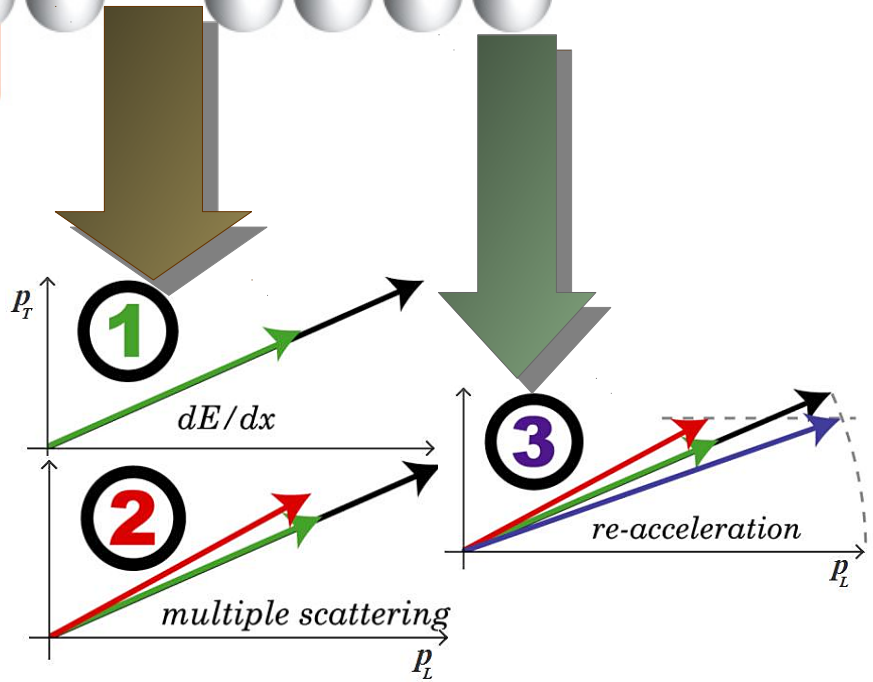


Cooling by ionization energy loss

$$\frac{d\varepsilon_T}{dx} \approx -\frac{\varepsilon_T}{\beta^2 E_\mu}\left\langle\frac{dE}{dx}\right\rangle + \frac{\beta_T (13.6\mathrm{MeV}/c)^2}{2\beta^3 E_\mu m_\mu X_0}$$

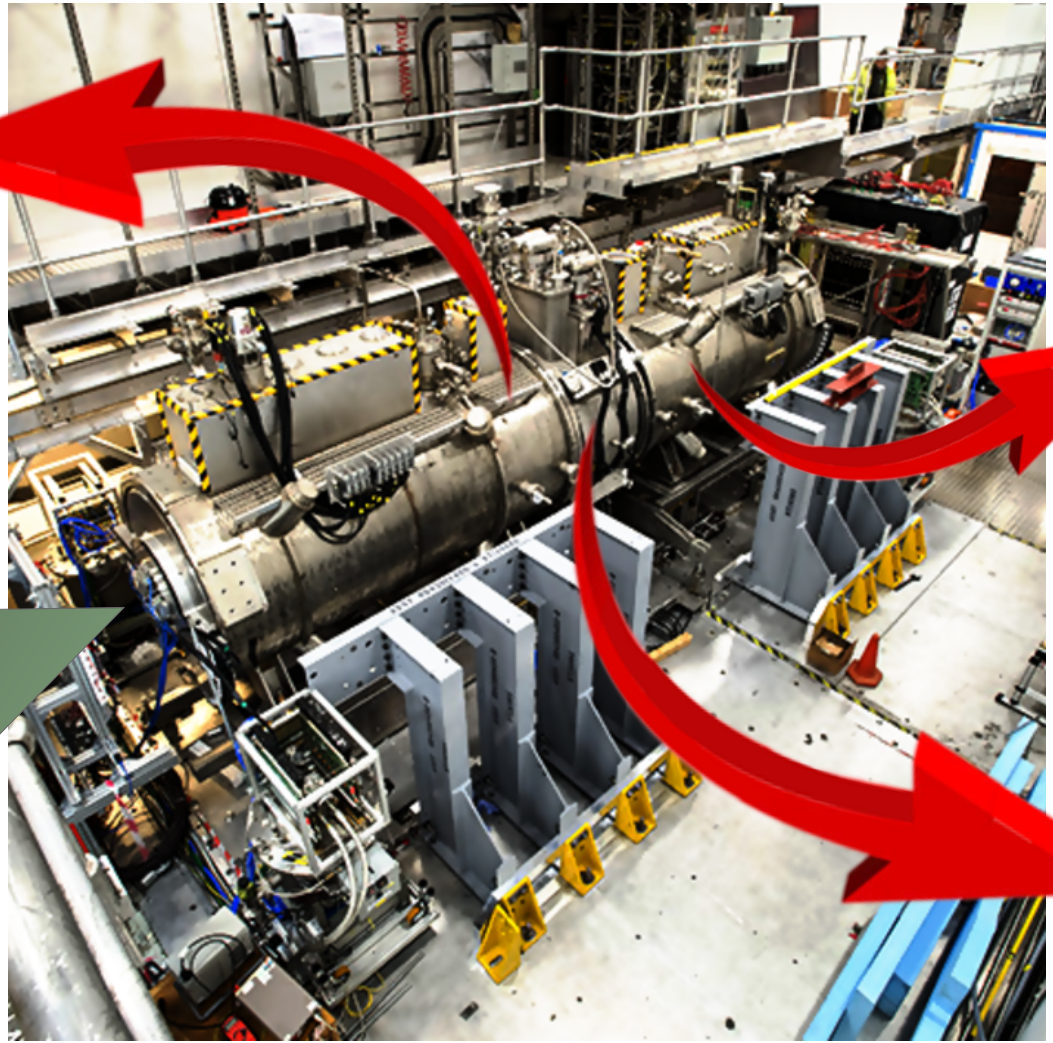
Minimize heating by multiple (Coulomb) scattering: ↓ β_T (strong focusing), ↑ $dE/dx \cdot X_0$ (low-Z material)

Minimize $\varepsilon_{equilibrium}$ (minimum achievable ε from the balance of cooling and heating terms)



Muon Ionization Cooling Experiment (MICE)

Measure muon position and momentum in Spectrometer Solenoid using scintillating fiber tracker, upstream of absorber



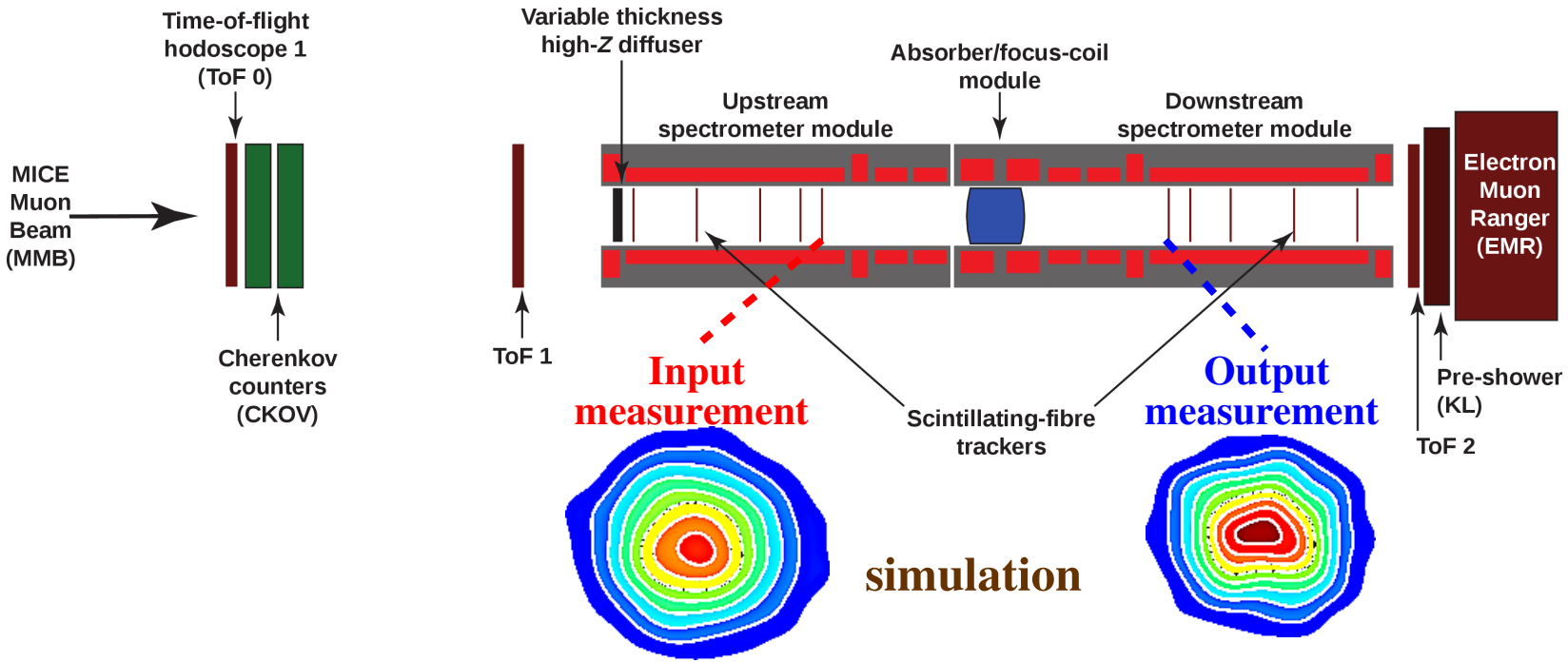
Measure muon position and momentum again downstream and compare with upstream

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

Beam Direction

Situated at RAL

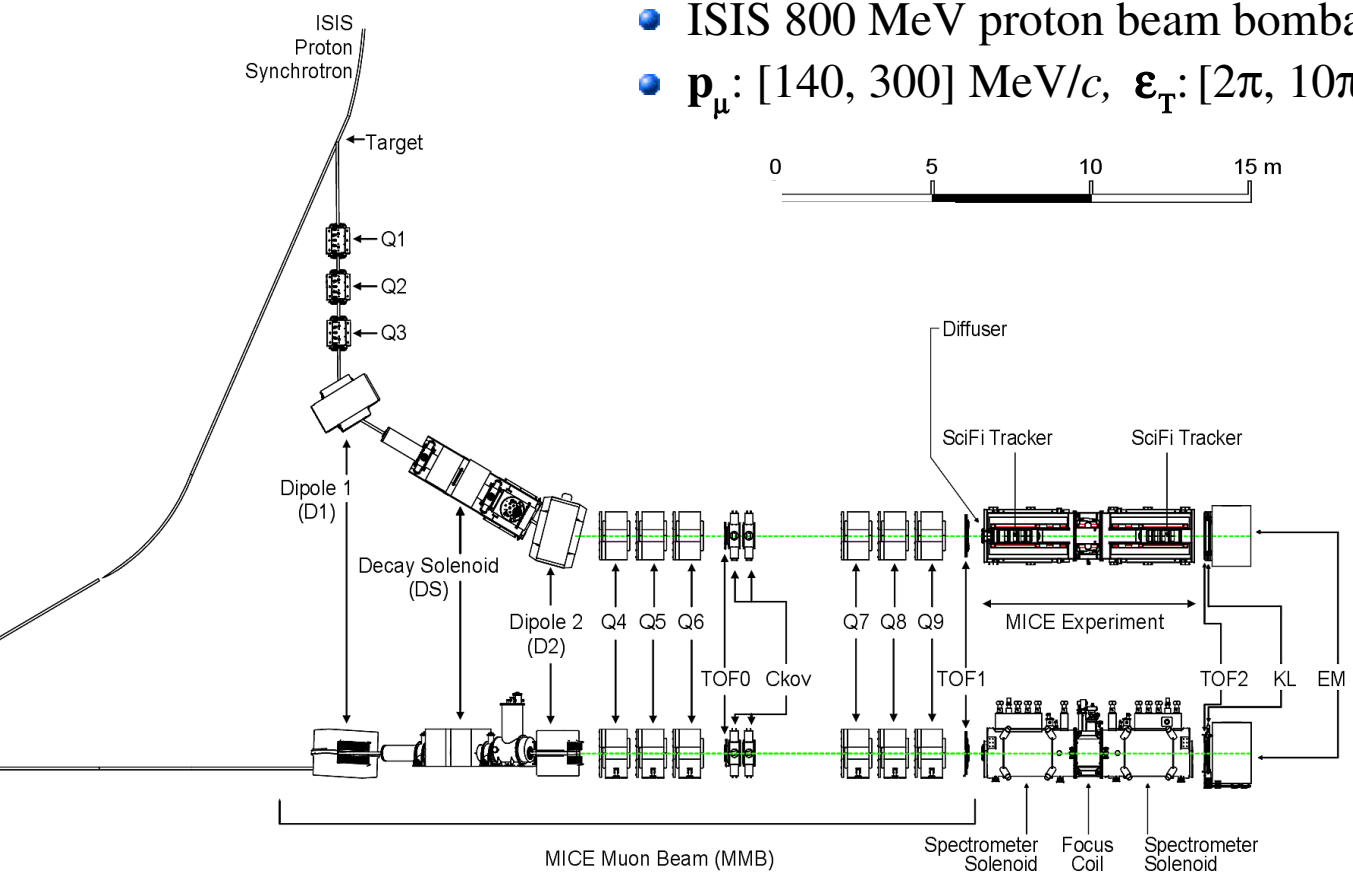
Cooling Measurement with MICE – Concept

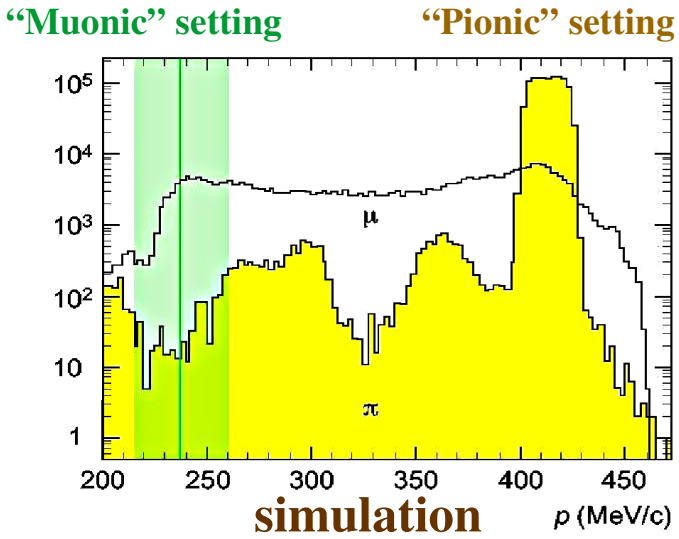


- Test cooling performance in different absorber (liquid hydrogen, LH2 and lithium hydride, LiH) and optics configurations
- Requires emittance measurement precision of 0.1% → achievable with use of **particle detectors**
- Muons measured **one by one**:
  - ★ Changes in muon beam **density**, **volume**, **emittance**, **amplitude** before (input) and after (output) the absorber

MICE Muon Beam

- ISIS 800 MeV proton beam bombarding MICE pulsed titanium target
- $\mathbf{p}_{\mu}$: [140, 300] MeV/*c*, $\boldsymbol{\varepsilon}_{T}$: [2π, 10π] mm rad

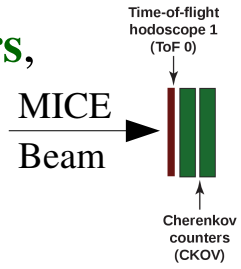


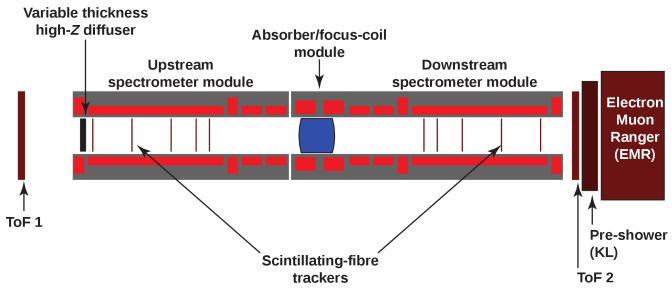


- **The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment**, JINST 7, P05009 (2012)
- **Characterisation of the muon beams for the Muon Ionisation Cooling Experiment**, EPJ C 73, 10 (2013)

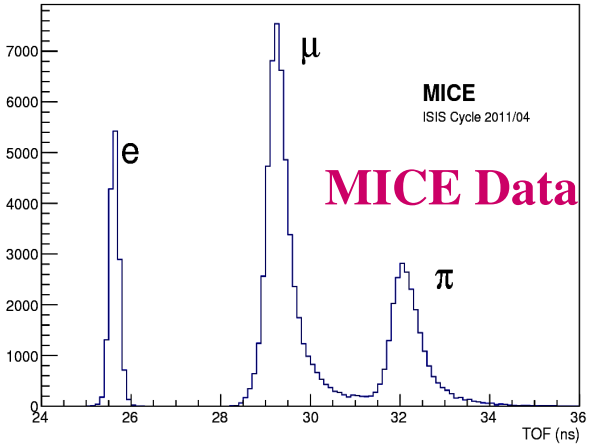
MICE Detectors

- PID detectors – **time of flight**, **Cherenkov counters**, **calorimetry** – μ beam has small e, π contents:
  - ★ π content with KL and TOF < 1.4%
  - ★ e tag efficiency with EMR > 98.6%

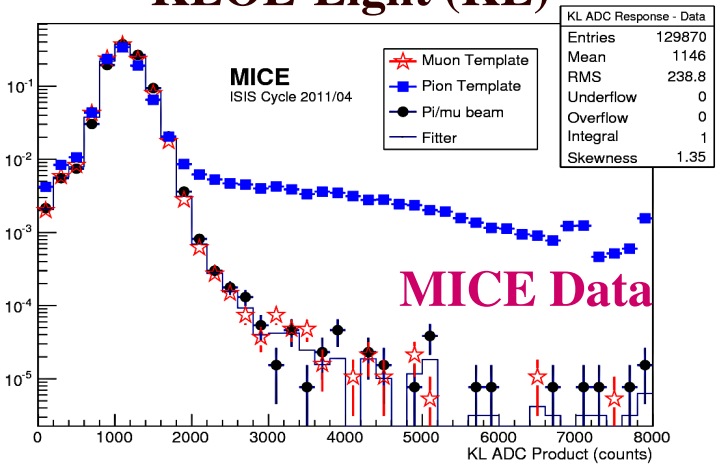




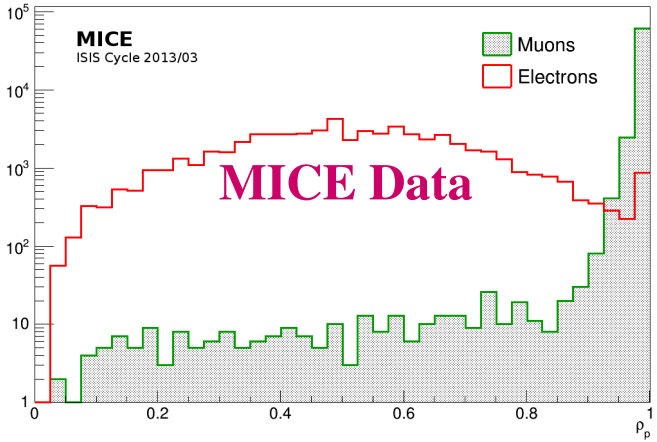
Time of Flight (TOF)



KLOE-Light (KL)



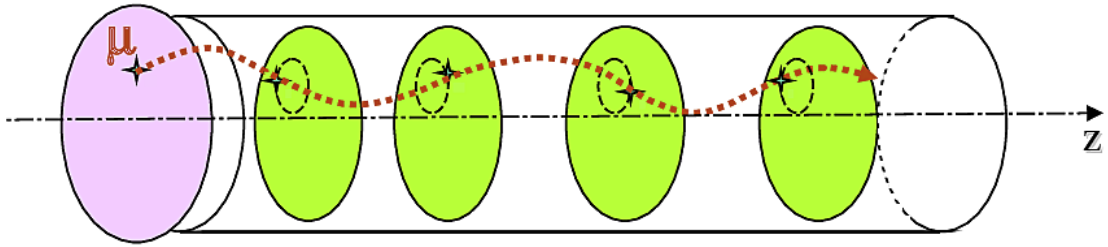
Electron-Muon Ranger (EMR)

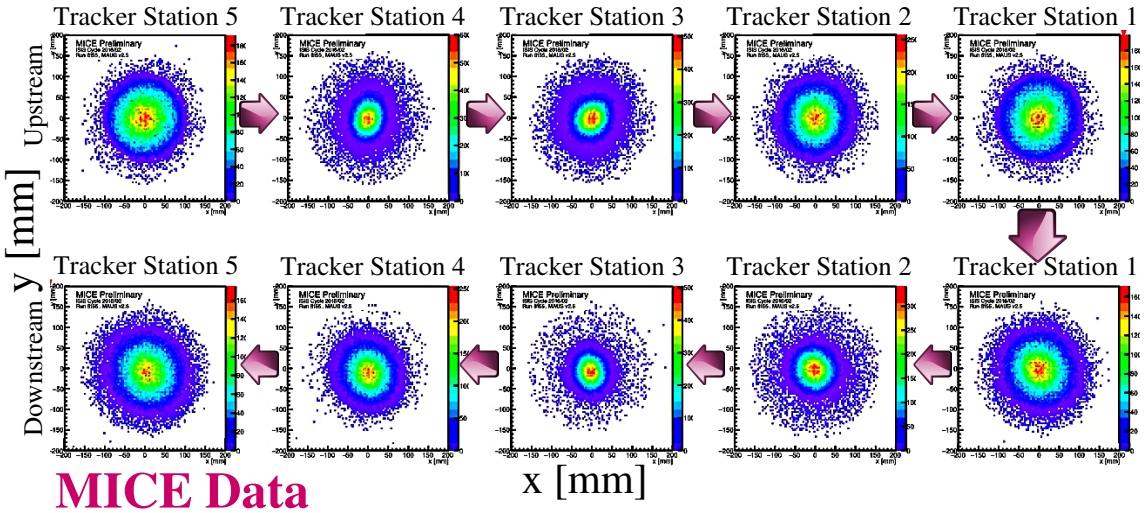


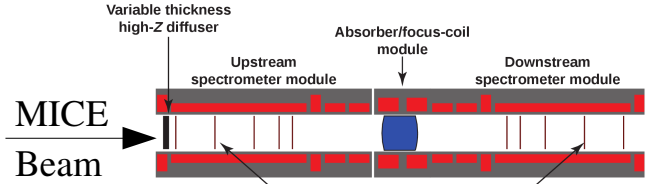
- **Pion Contamination in the MICE Muon Beam**, JINST 11 P03001 (2016)
- **Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam**, JINST 10 P12012 (2015)

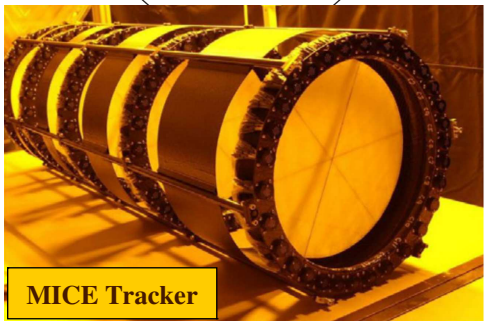
MICE Trackers

- **Helical tracks** formed in spectrometer solenoids:
  - ★ **Phase-space coordinates** of each muon reconstructed in **trackers**

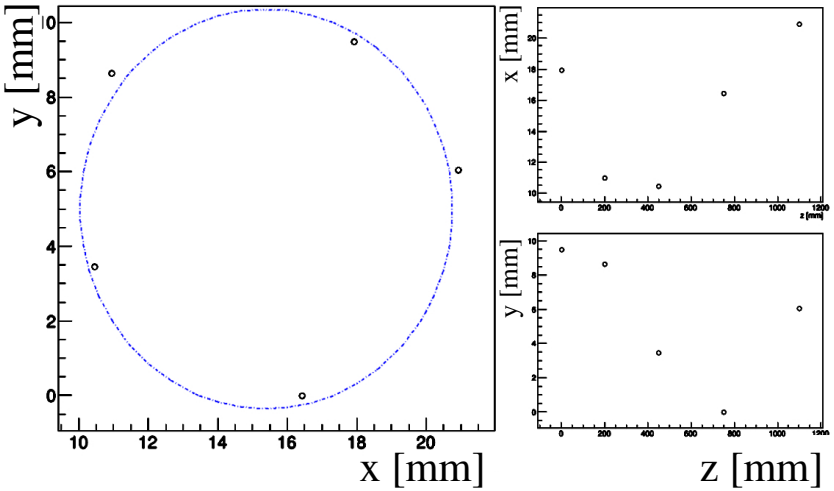






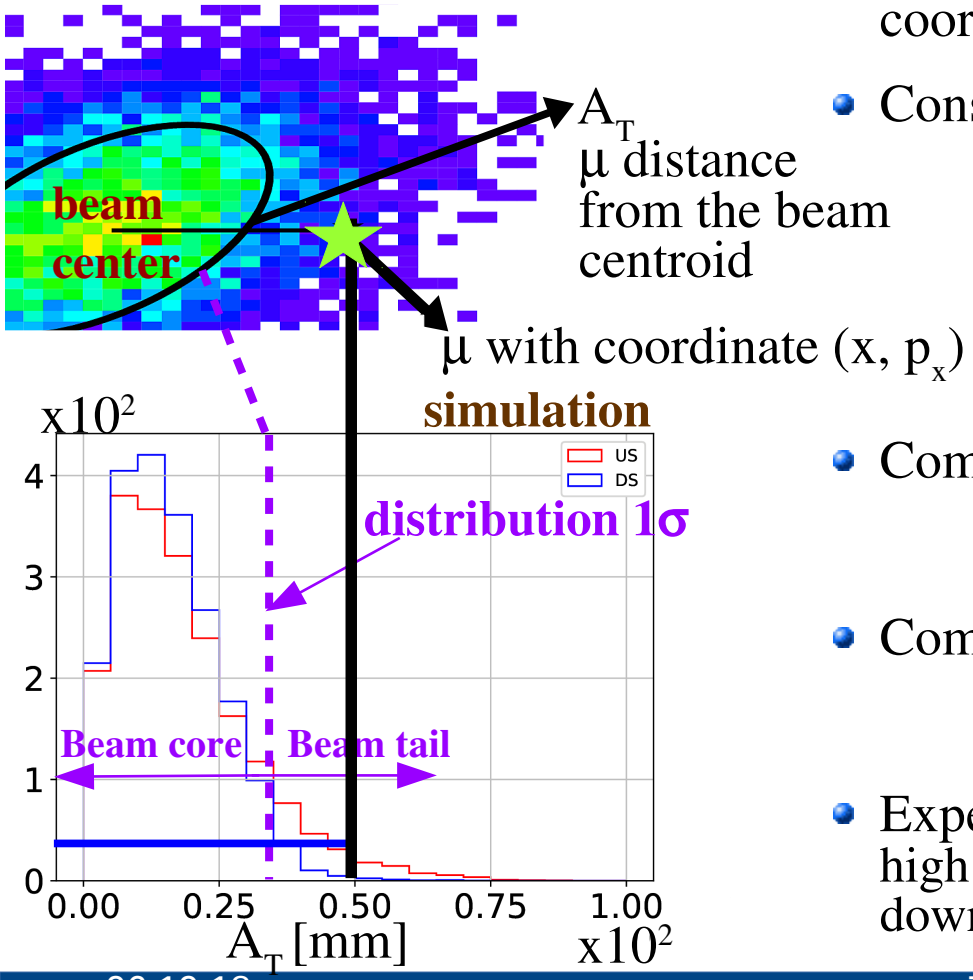


MICE Data



Single-particle Amplitude

Amplitude, 1D and 2D Illustrations



- Get **tracker-**reconstructed position and momentum coordinates
- Construct **covariance matrix**

$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{p_x x} & \sigma_{yx} & \sigma_{p_y x} \\ \sigma_{x p_x} & \sigma_{p_x p_x} & \sigma_{y p_x} & \sigma_{p_y p_x} \\ \sigma_{xy} & \sigma_{p_x y} & \sigma_{yy} & \sigma_{p_y y} \\ \sigma_{x p_y} & \sigma_{p_x p_y} & \sigma_{y p_y} & \sigma_{p_y p_y} \end{pmatrix}$$

where $\sigma_{x p_x} = \langle x p_x \rangle - \langle x \rangle \langle p_x \rangle$

- Compute transverse normalized RMS emittance

$$\varepsilon_T = \frac{|\Sigma|^{\frac{1}{4}}}{m_\mu}$$

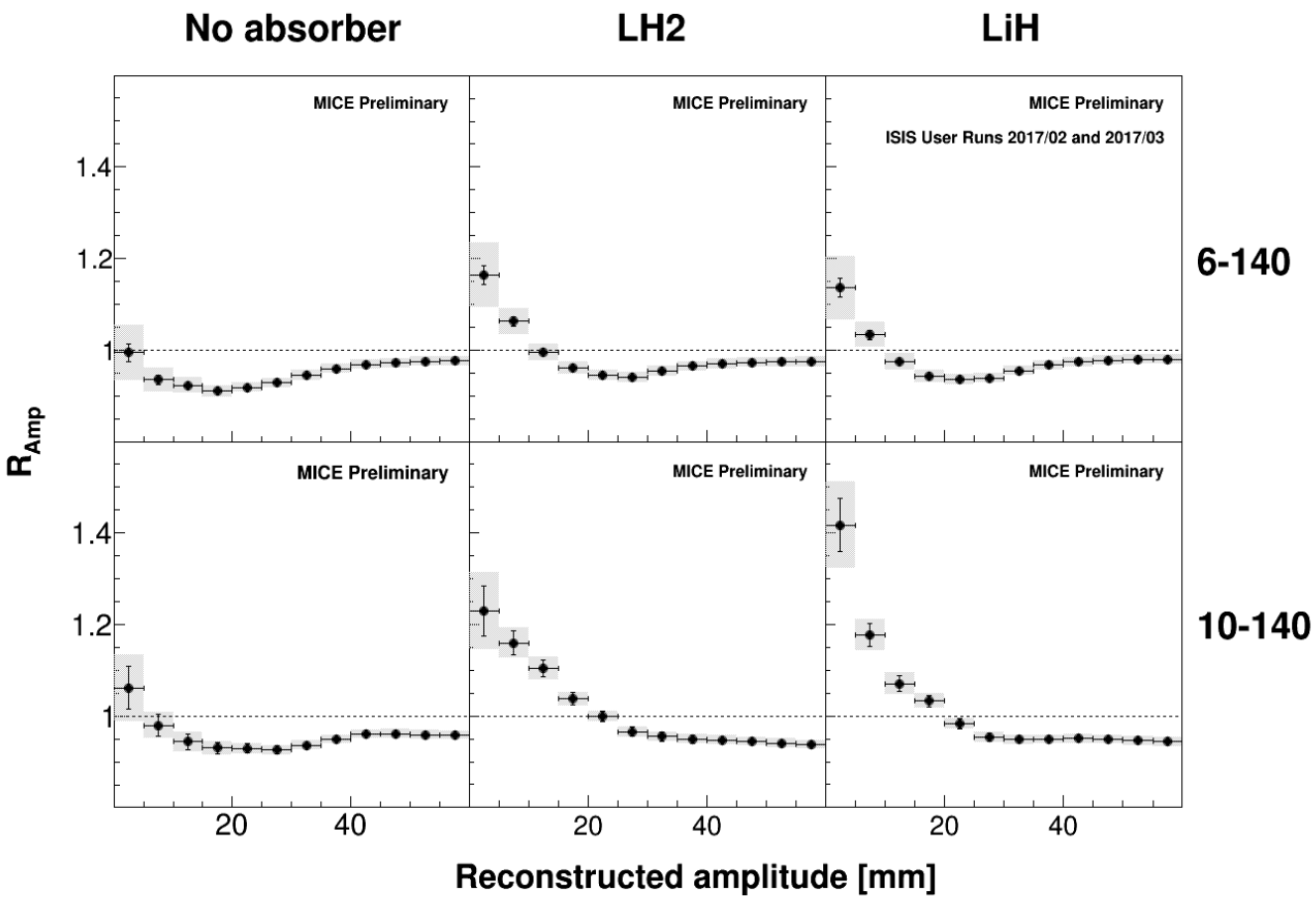
- Compute transverse amplitude,

$$A_T = \varepsilon_T \, u^T \, \Sigma^{-1} \, u$$

- Expected cooling trend: average migration of muons from high amplitude tail to low amplitude core → ratio of downstream to upstream > 1

Single-particle Amplitude Result

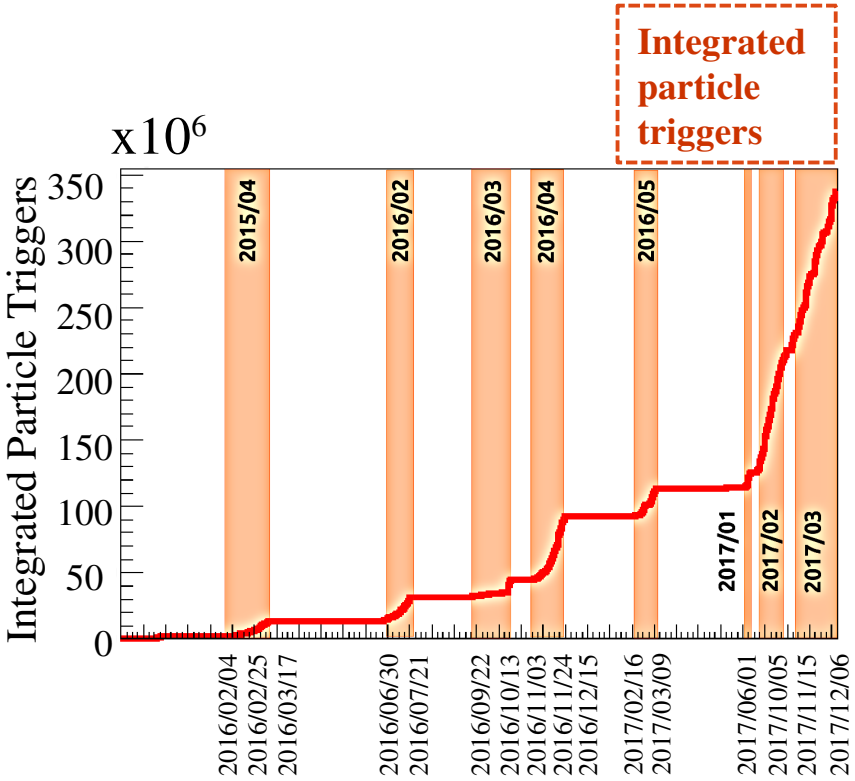
MICE Data



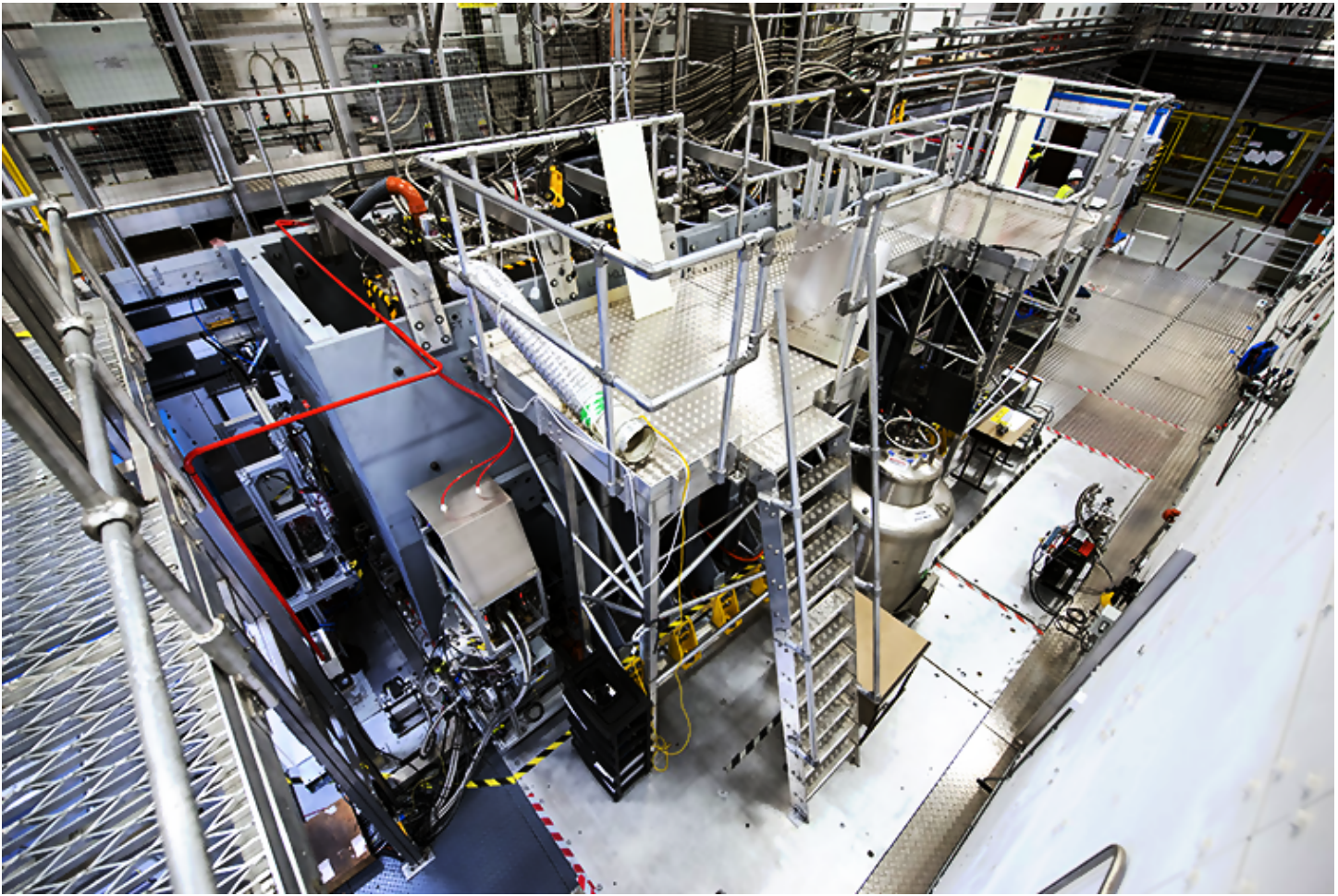
- **6-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 6 mm
- **10-140** – $P_{reference}$ of 140 MeV/*c* and ε_{input} of 10 mm
- R_{Amp}: ratio of downstream muon count to upstream
- **$R_{Amp} > 1 \rightarrow$ cooling:**
  - ★ Migration of high amplitude muons to low amplitude
- "No absorber" does not show cooling, agrees with Liouville's theorem

Conclusion and Future Prospects

- **MICE has measured muon ionization cooling!**
- Successfully **concluded all data taking** over a range of p_μ, ε_n, absorber material (LiH, LH_2, polyethylene), focusing conditions
- LiH and LH_2 data taken and analysis underway
- Preliminary measurements of emittance and amplitude complete
- Many papers published and more papers in preparation: ***http://mice.iit.edu/publications/***



Thank you for listening!

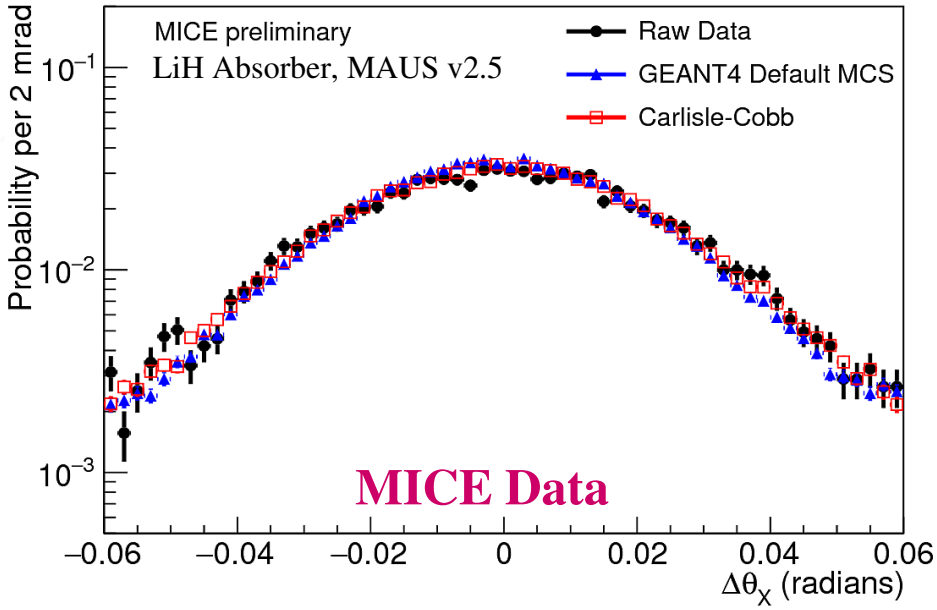


MICE has been made possible by grants from DOE, NSF (USA), the INFN (Italy), the STFC (UK), the European Community, the Japan Society for the Promotion of Science, and the Swiss National Science Foundation. We are grateful to the support given to us by the staff of the STFC Rutherford Appleton and Daresbury Laboratories. We acknowledge the use of Grid computing resources deployed and operated by GridPP in the UK, http://www.gridpp.ac.uk/.

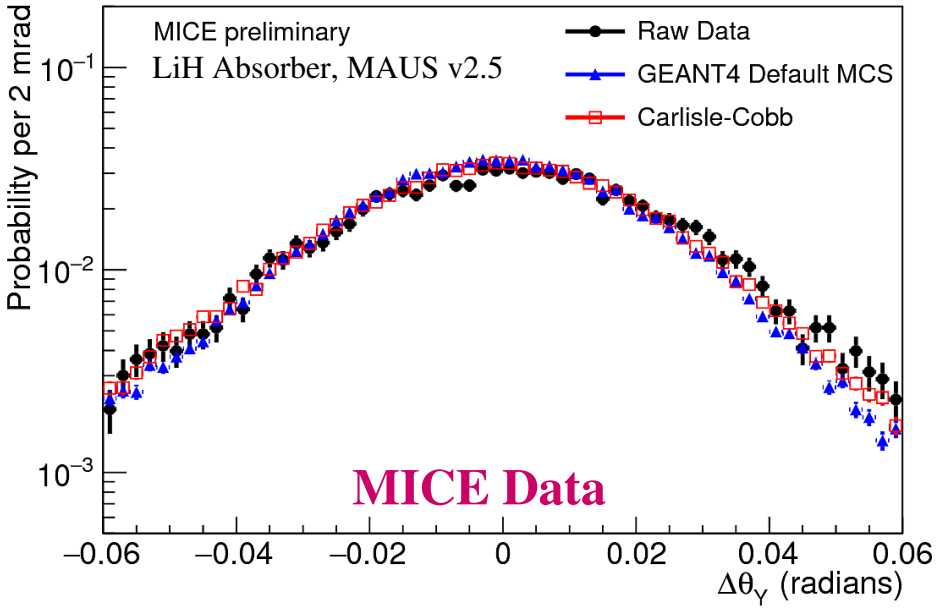
Additional Slides

Multiple Coulomb Scattering

YZ Projected Scattering Angle



XZ Projected Scattering Angle

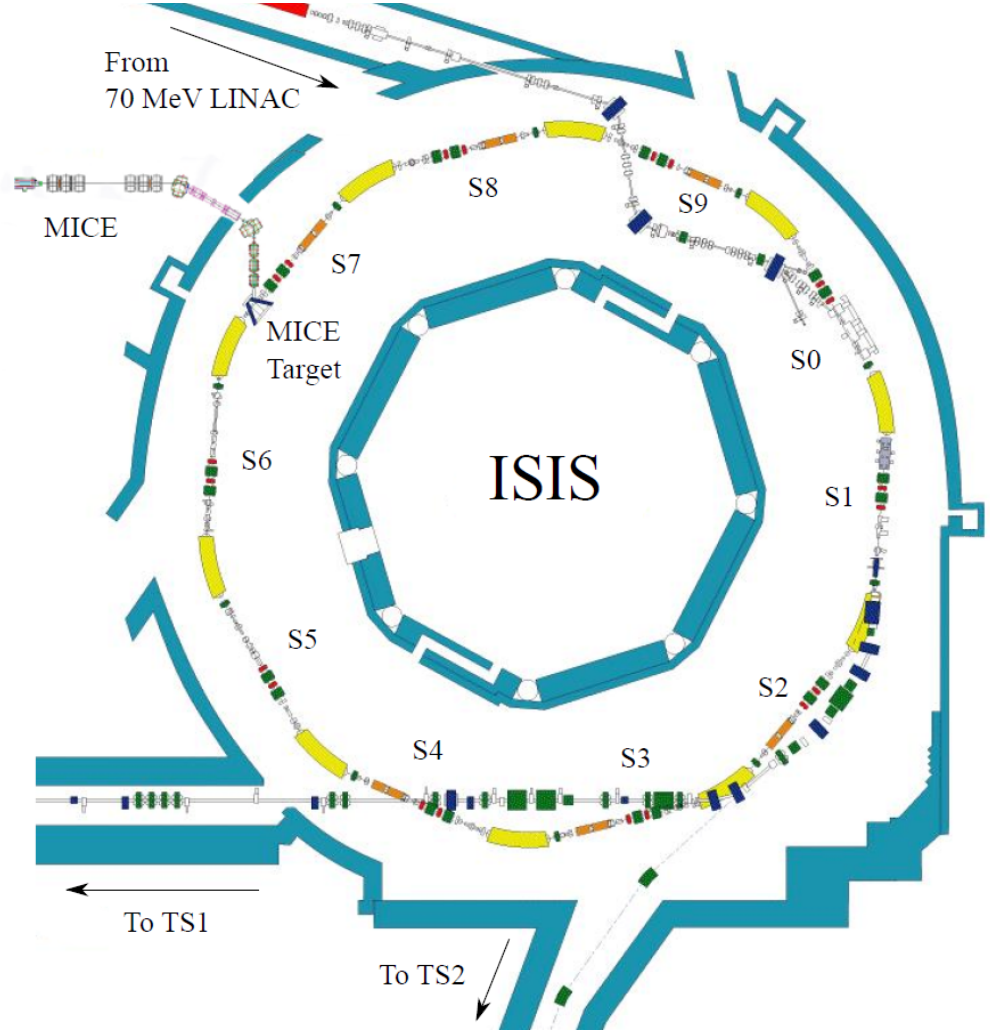


- Multiple scattering causes beam **heating**, needs to be well-understood in MICE
- Characterized as the **angle** between the initial and final momentum as projected onto **YZ and XZ**

MICE Muon Beam – Detail

- 800 MeV proton beam from ISIS proton synchrotron:
  - ★ 4 μC of protons in two 100 ns long pulses
  - ★ Beam current: 200 μA

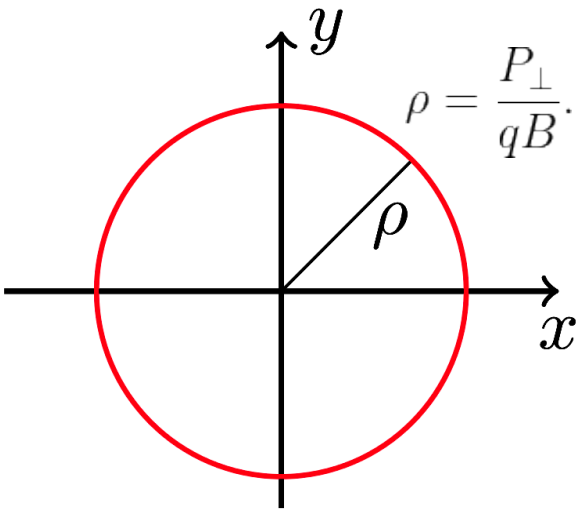
- MICE titanium target directly dipped into the ISIS proton beam:
- Dip rate: 1 dip/1.28s
- Max particle rate:
  - ★ 120 μ+/dip
  - ★ 20 μ–/dip
- Final μ beam: 1ms wide spill in two 100 ns long bursts every 324 ns.

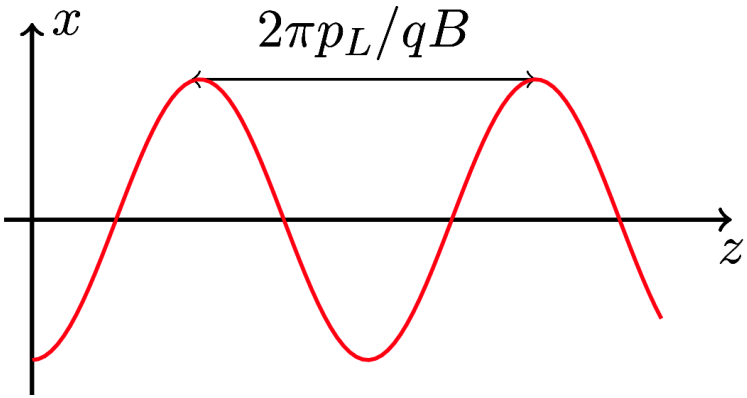


Tracker Reconstruction – Detail

- Scintillating fiber stations:
  - 5 stations per tracker
  - 3 planes per station (mutual orientation @ 120°)
  - 214 fibers per plane
- Measured tracker resolution: $\sigma_x = \sigma_y = 467\ \mu m$
- Immersed in solenoidal fields:
  - Helical tracks formed in solenoids
  - Circle fit in transverse direction → radius, ρ and P_T
  - Arc length gradient → p_L
  - Momentum resolution: σ_{pL} and σ_{pT} ~ 1.3 and 4 MeV/*c*

$$x = -\rho \cos\left(q_\mu B t / m_\mu\right)$$
$$y = \rho \sin\left(q_\mu B t / m_\mu\right)$$
$$z = p_L t / m_\mu$$





Equilibrium Emittance – Detail

$$\frac{d\varepsilon_T}{dx} \approx -\frac{\varepsilon_T}{\beta^2 E_\mu}\left\langle\frac{dE}{dx}\right\rangle + \frac{\beta_T(13.6\mathrm{MeV}/c)^2}{2\beta^3 E_\mu m_\mu X_0}$$

- Set **cooling rate** equal to **heating rate** to get **equilibrium emittance**:

$$\varepsilon \sim \frac{\beta_\perp\,(13.6\ \mathrm{MeV}/c)^2}{2\beta m_\mu X_0\left\langle\frac{dE}{dx}\right\rangle}$$

- Smaller equilibrium emittance (better cooling) obtained with minimized $\beta_\perp$ & maximized $X_0 dE/dx$

ε_T: transverse beam emittance

βc: velocity

E_μ: muon energy

dE/dx: ionization energy loss

β_T: transverse beta function

m_μ: muon mass

X_0: radiation length