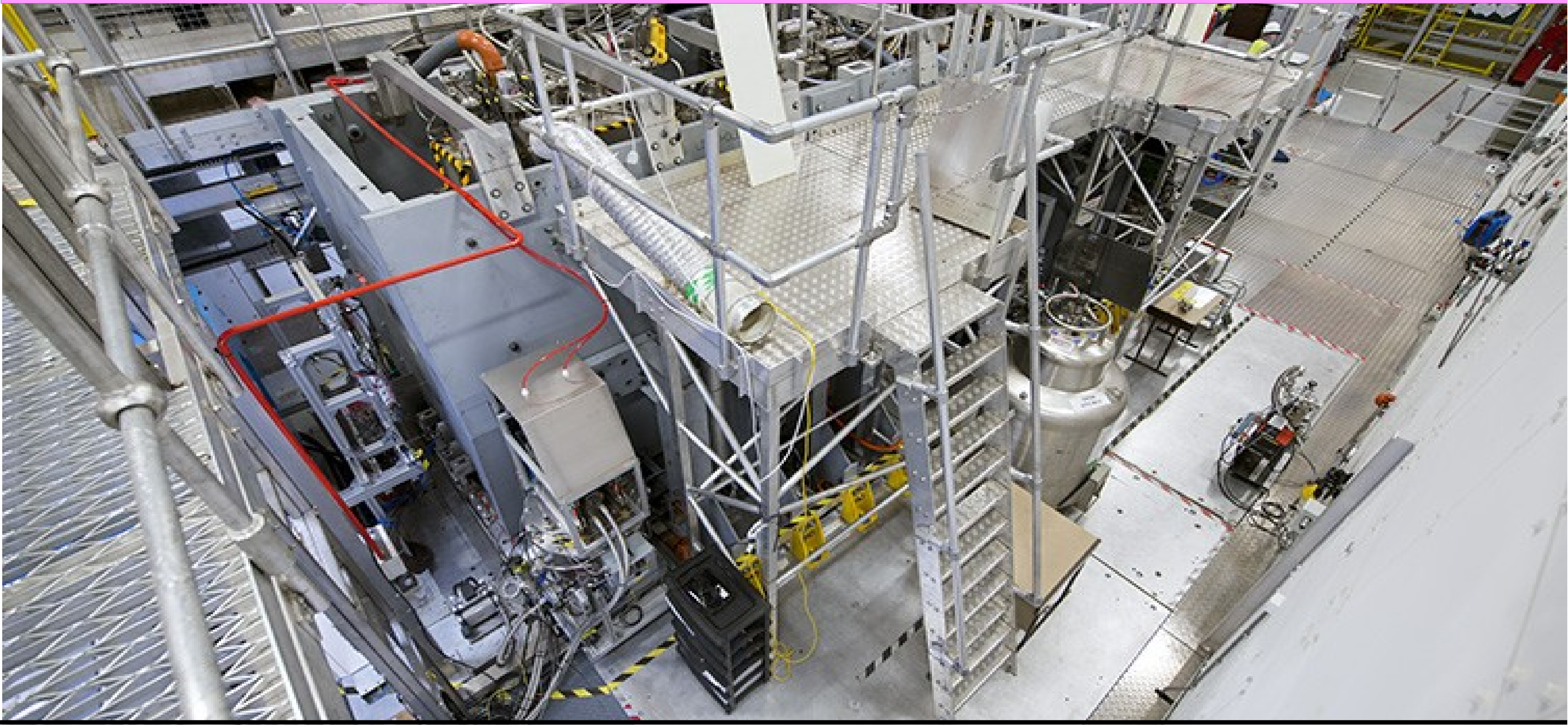
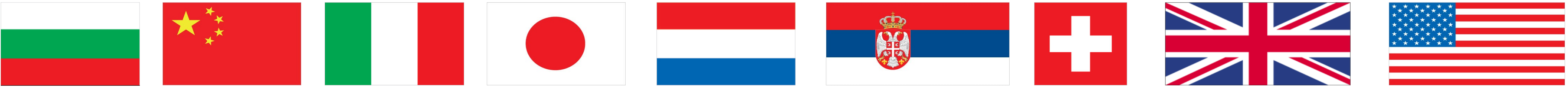
MICE

Muon Ionization Cooling Experiment

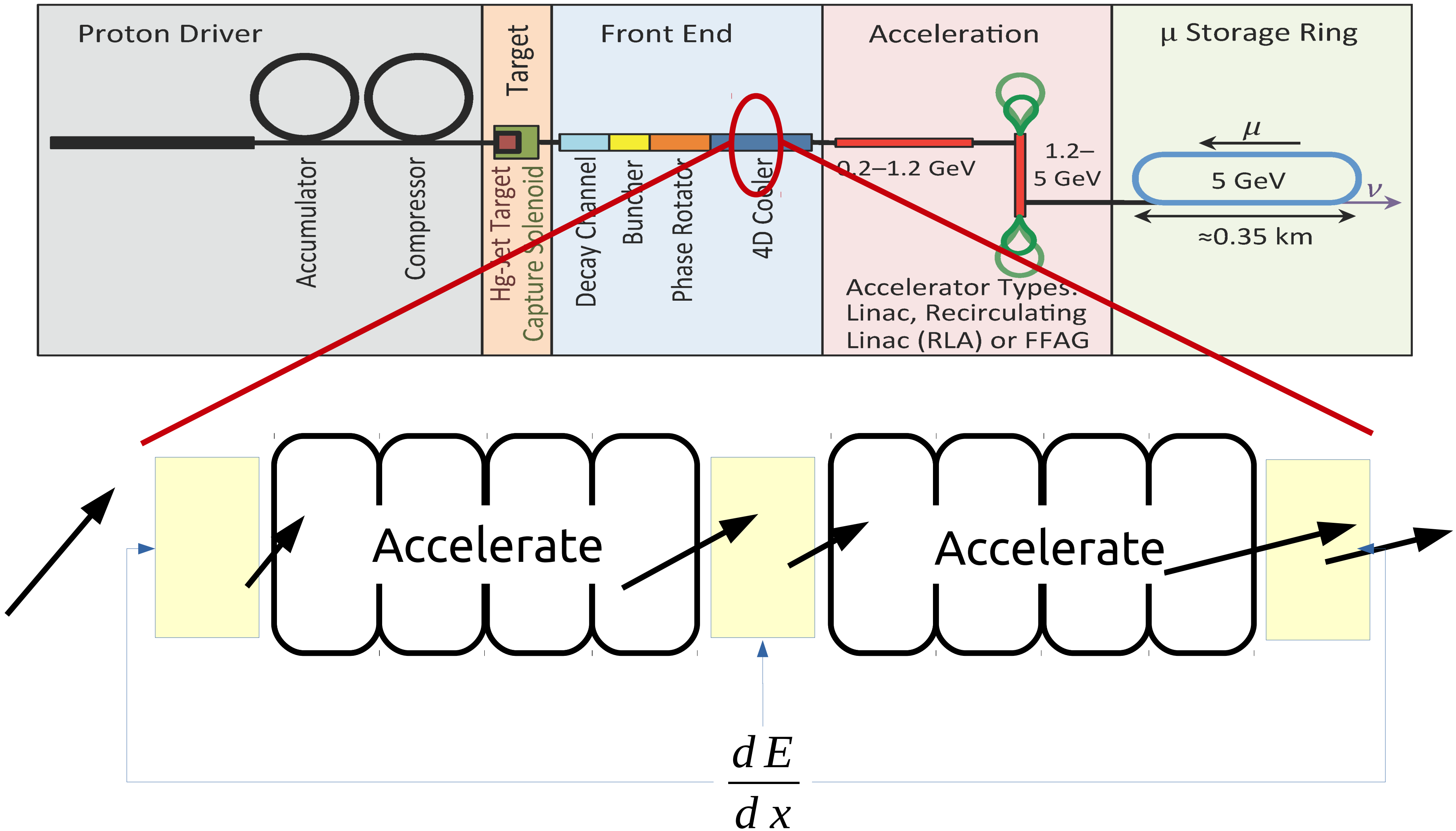




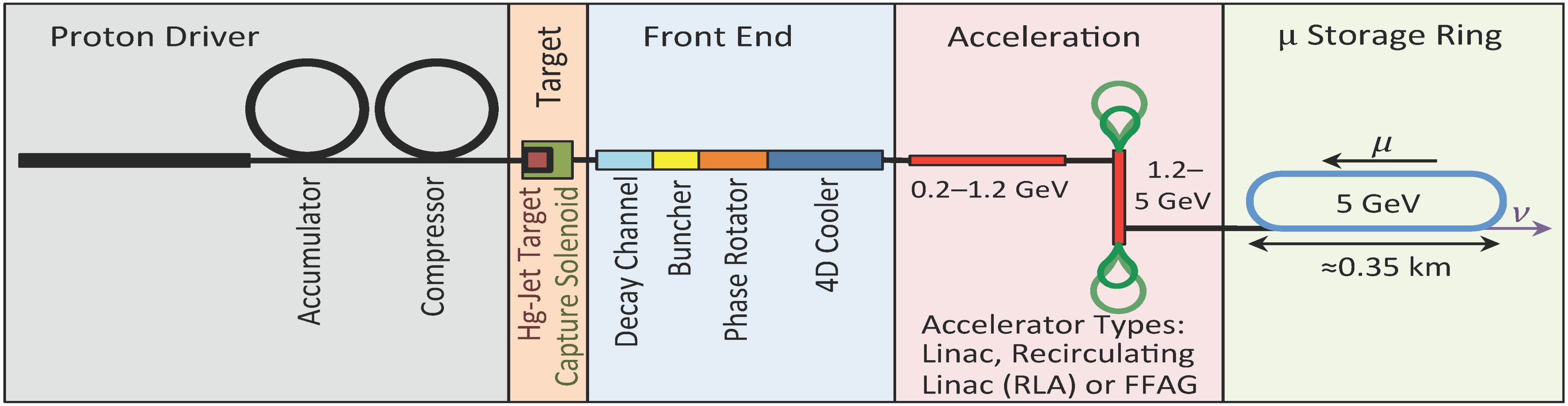
Warwick Steven Boyd ICHEP 2016

- Muon ionization cooling
- MICE and the MICE Muon Beam
- MICE - Step IV
- Demonstration of Ionization Cooling
- Summary

Muon ionization cooling



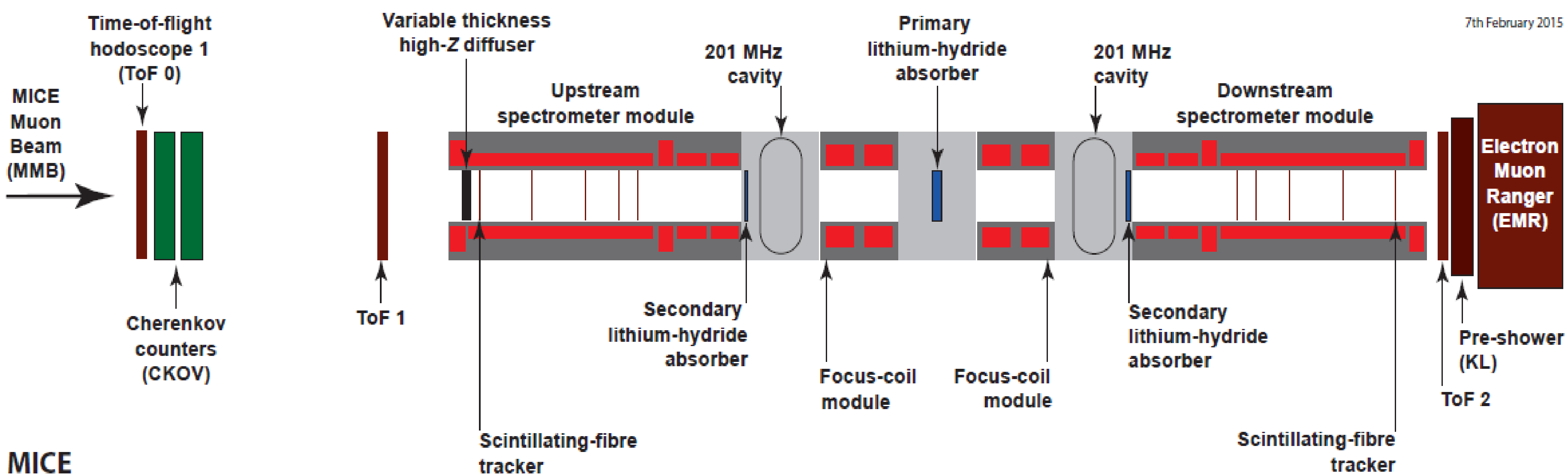
Muon ionization cooling



- Ionization cooling enables the operation of neutrino factories for precision oscillation physics and new-physics searches and multi-TeV muon colliders
- Experimental verification of muon ionization cooling technique is important in understanding the engineering and operation of these facilities.

MICE : Muon Ionization Cooling Experiment

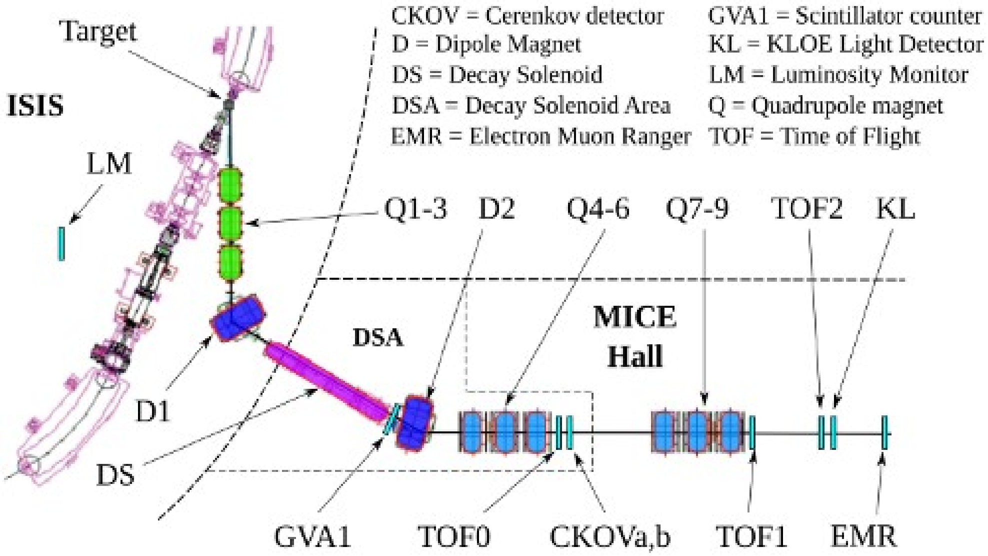
- MICE goal is to verify emittance reduction from ionization cooling



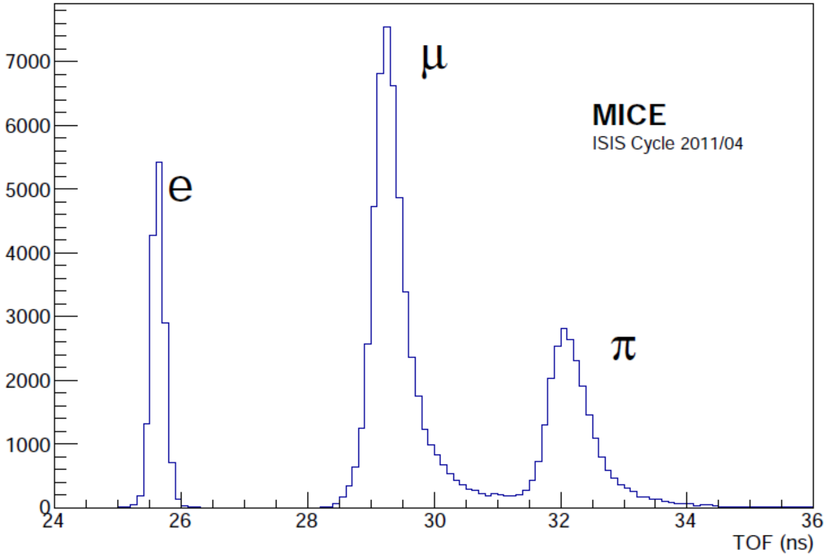
- Study properties of single muons from ISIS beam at STFC Rutherford-Appleton Laboratory, UK in the cooling channel

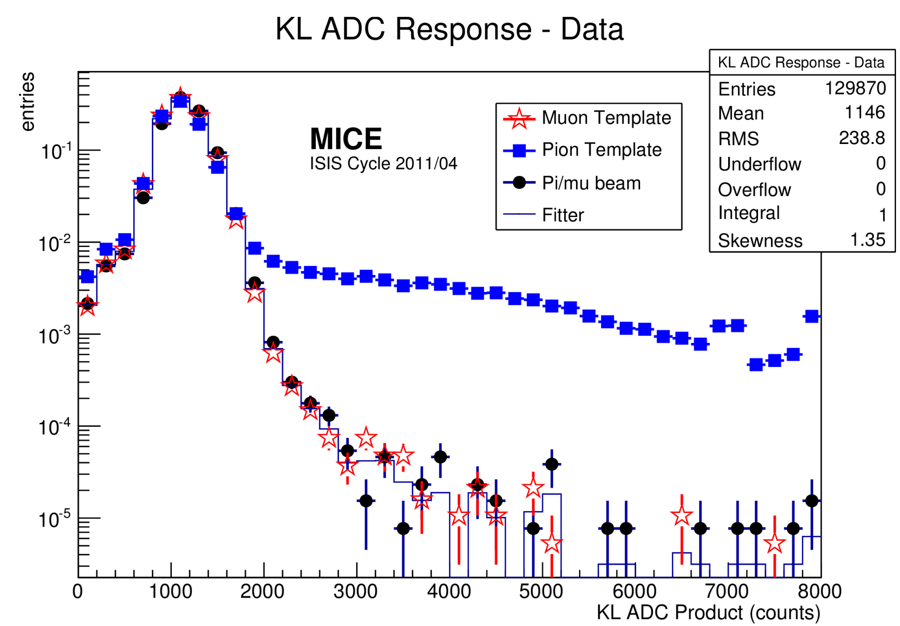
- Construct a beam from ensembles of single muons

MICE Muon Beam

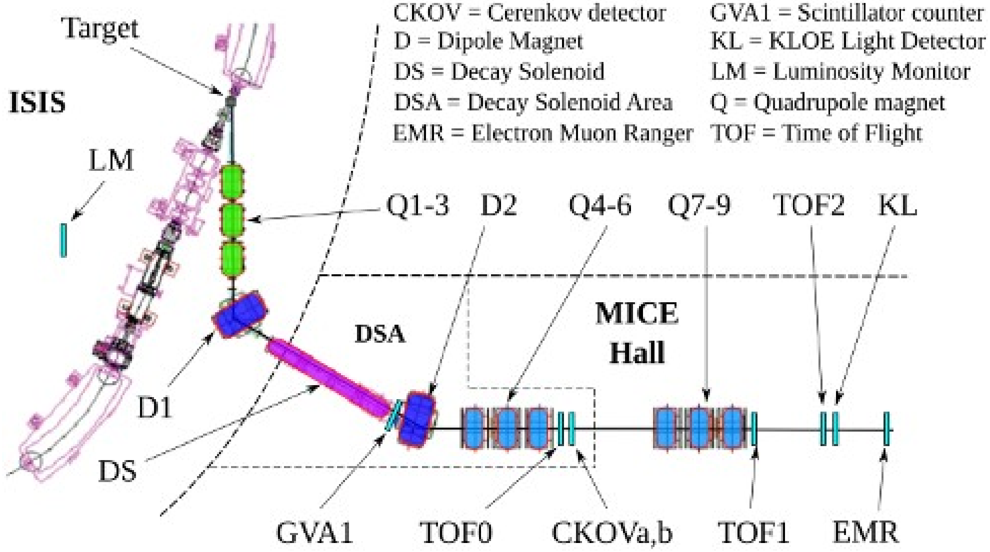


- ISIS 800 MeV/c proton beam colliding with a titanium target dipped into the beam
- $p_\mu \in [\,140, 300\,]$ MeV/c
- $\varepsilon_n \in [\,2\pi\,, 10\pi\,]$ mm rad
- π contamination < 1.4 %
- electron tag efficiency > 98.6%





MICE Muon Beam



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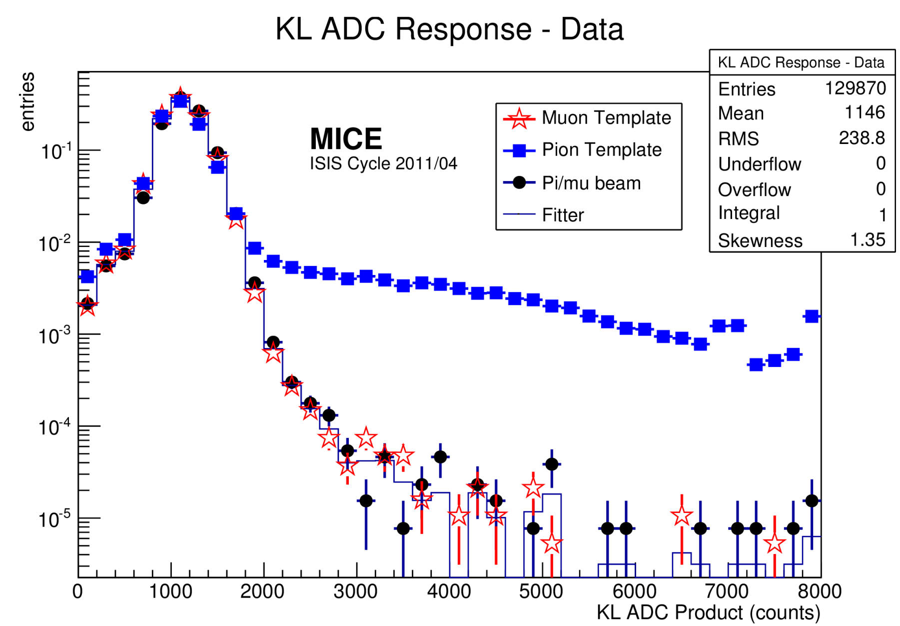
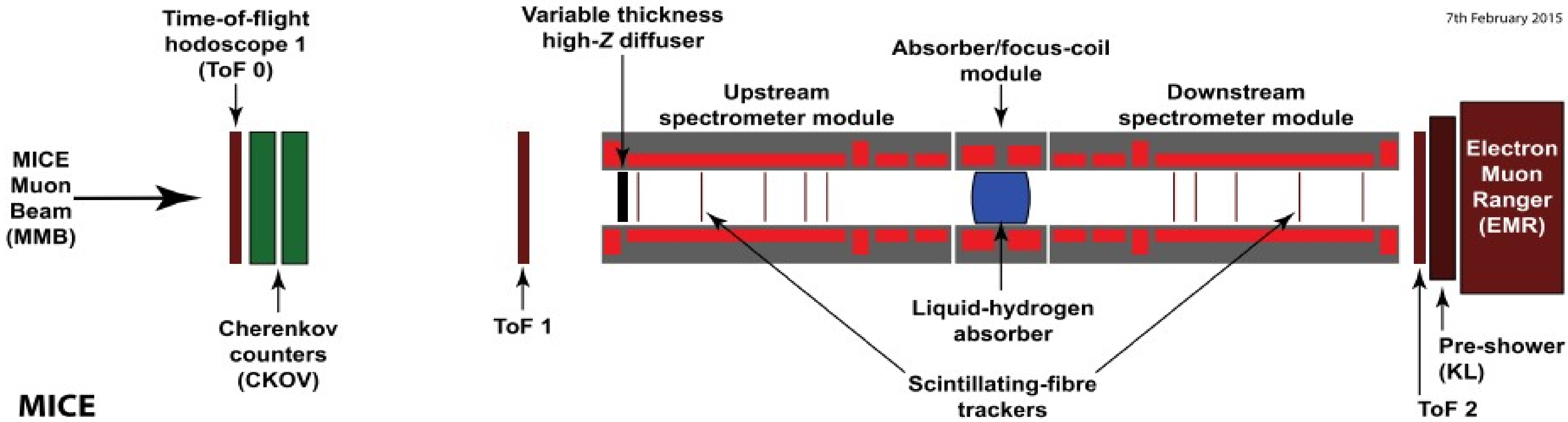
Pion Contamination in the MICE Muon Beam, JINST 11 P03001, 2016

EMR Performance in the MICE Muon Beam, JINST 10 P12012, 2015

Characterisation of the muon beams for MICE, EJP C73, 10, 2013



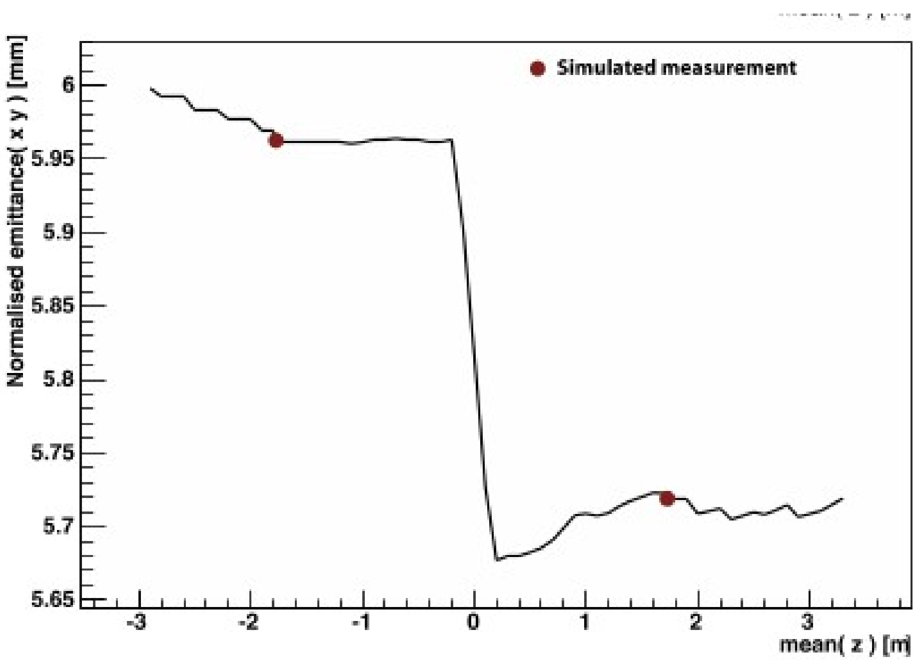
MICE – Step IV



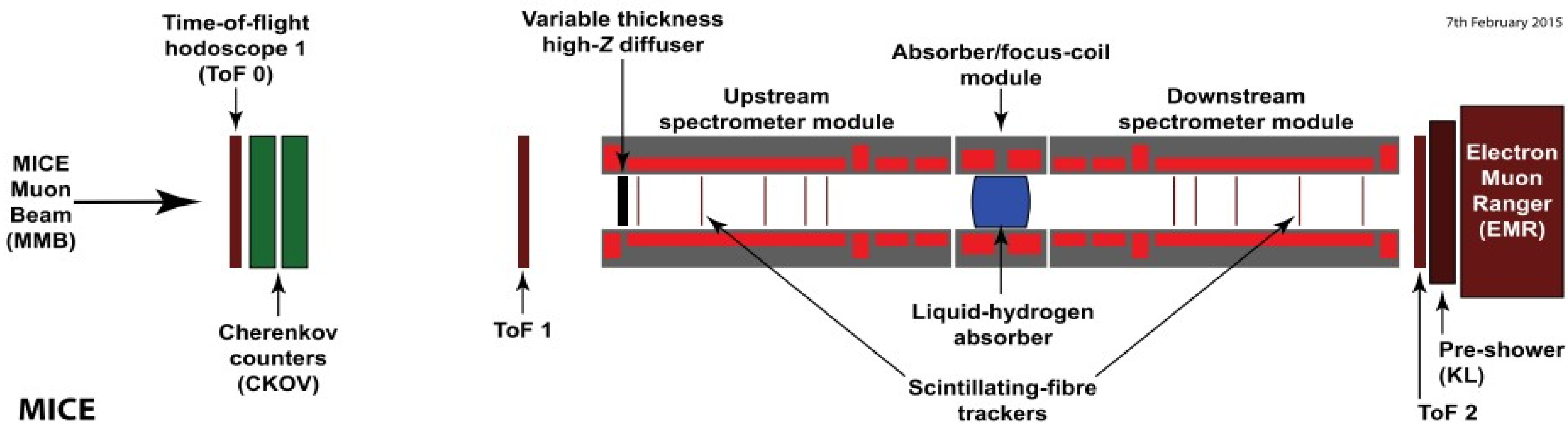
Heating (Multiple scattering)

$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

Cooling

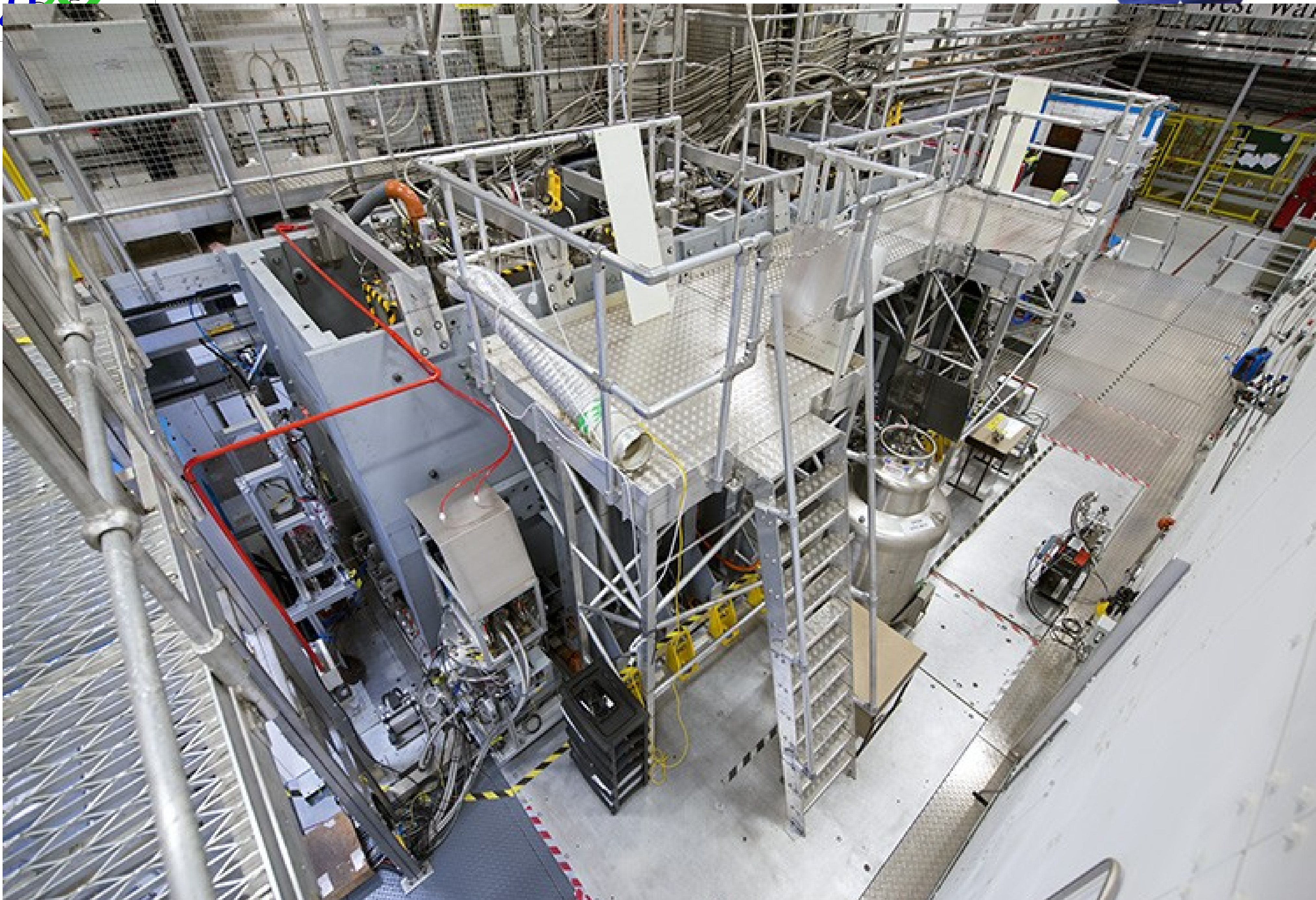


MICE – Step IV - Status



- Particle ID detectors are on-line and operating stably
- Solenoids, containing trackers, have been installed
- Focus coil is operating well
- Channel is being commissioned and characterised. All magnets operated together last week.

- Incoming beam studies : 200 MeV/c with upstream solenoid on
- Multiple scattering studies : straight track with He and LiH absorbers



Measurement Program

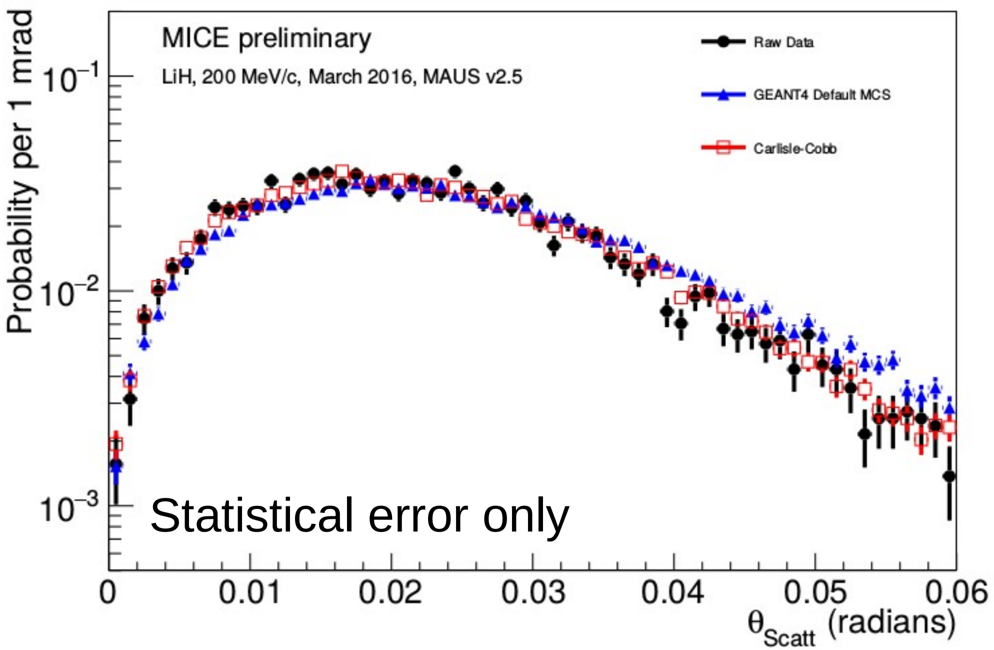
	Step IV	Demo
Study of properties that determine cooling performance		
Material properties of LH_2 and LiH	**Yes**	**No**
Observation of $\epsilon_{\perp}^{n}$ reduction	**Yes**	Yes
Demonstration of sustainable ionization cooling		
Observation of $\epsilon_{\perp}$ reduction with re-acceleration		**Yes**
Observation of $\epsilon_{\perp}$ reduction with $\epsilon_{\|\|}$ "management"		**Yes**
Observation of $\epsilon_{\perp}$ reduction with $\epsilon_{\|\|} \oplus \mathcal{L}$ "management"		**Yes**†

† Requires systematic study of "flip" optics.

Multiple Scattering Studies

MS theories do not agree with measurements of muon scattering on low Z materials (MuScat; NIM B, 251 (2006) 41-55)

Material	Momentum (MeV/c)
Empty	172, 200, 240
He	240
LiH	172, 200, 240



Straight track data with empty absorber

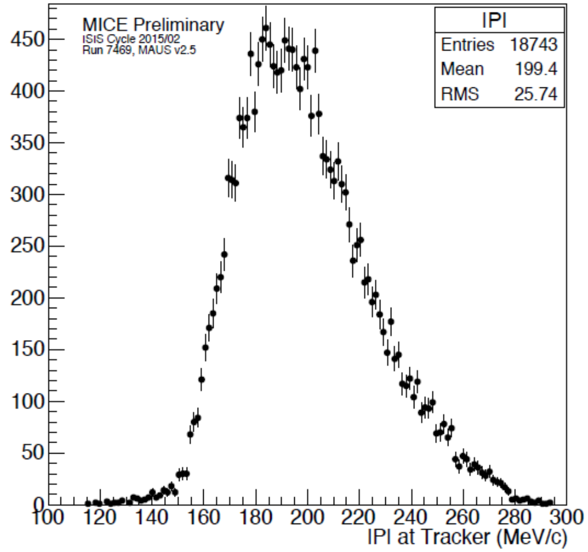
I. Convolve with MS models and compare with material data

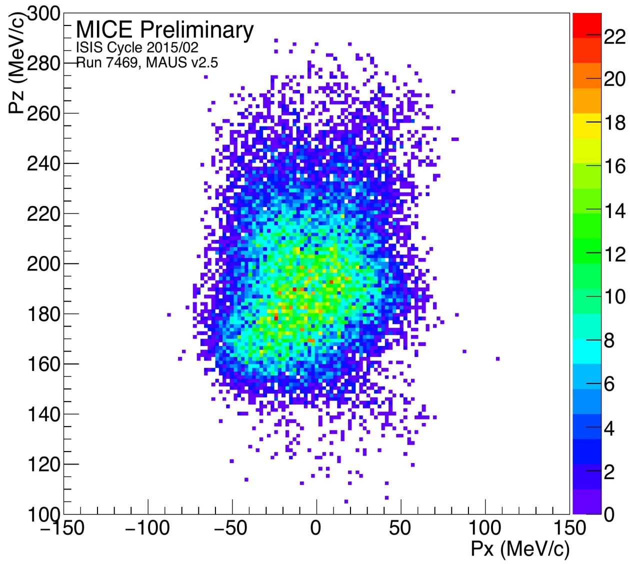
II. Unfold effect of absorber scattering

With spectrometers

- Energy loss measurements
- Precise input momentum

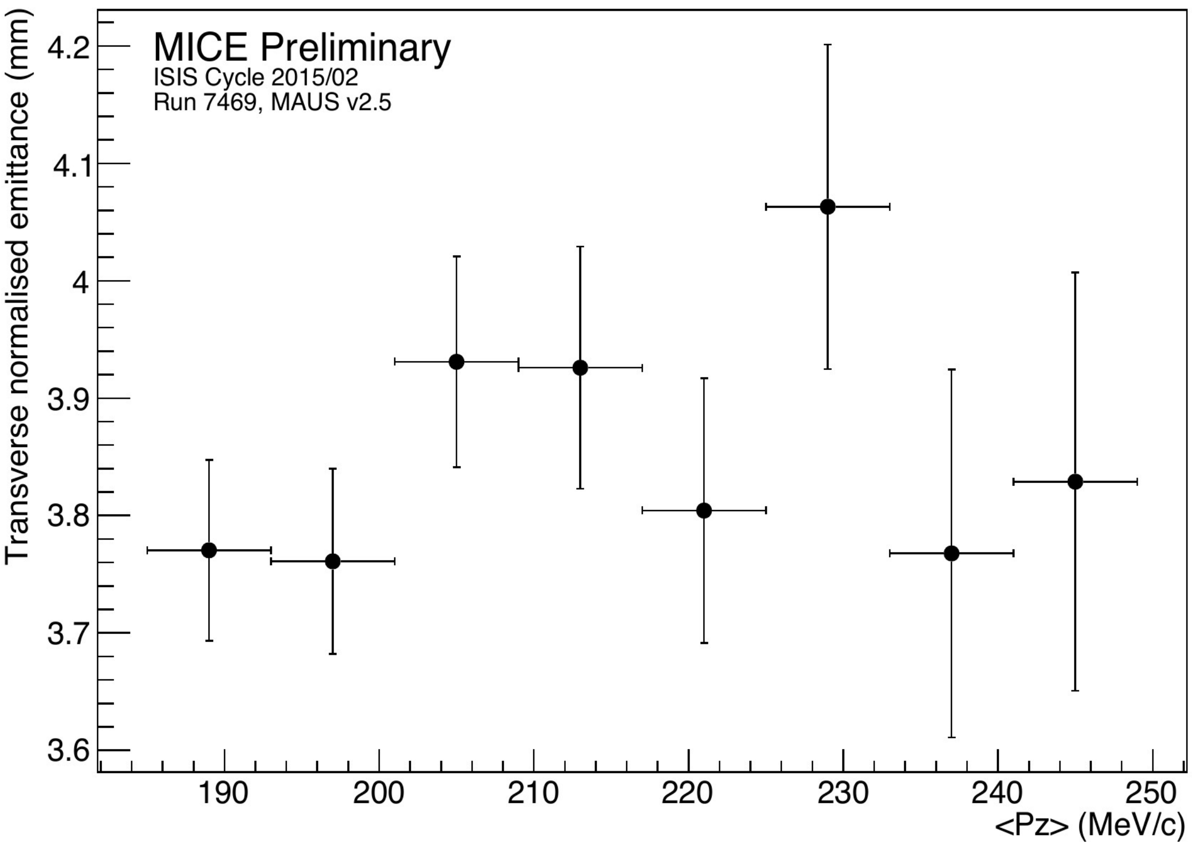
Input Beam Studies





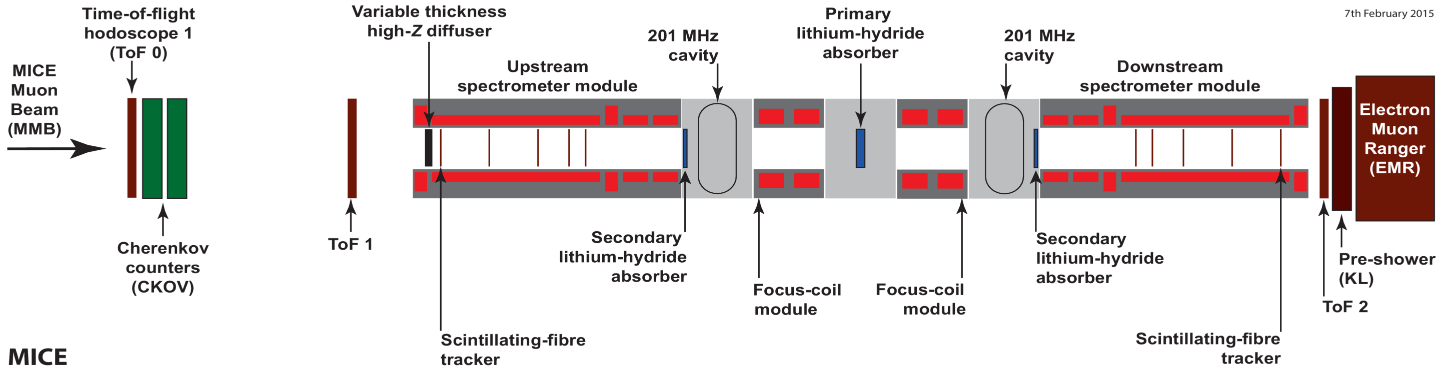
200 MeV/c muon beam

Upstream spectrometer operational

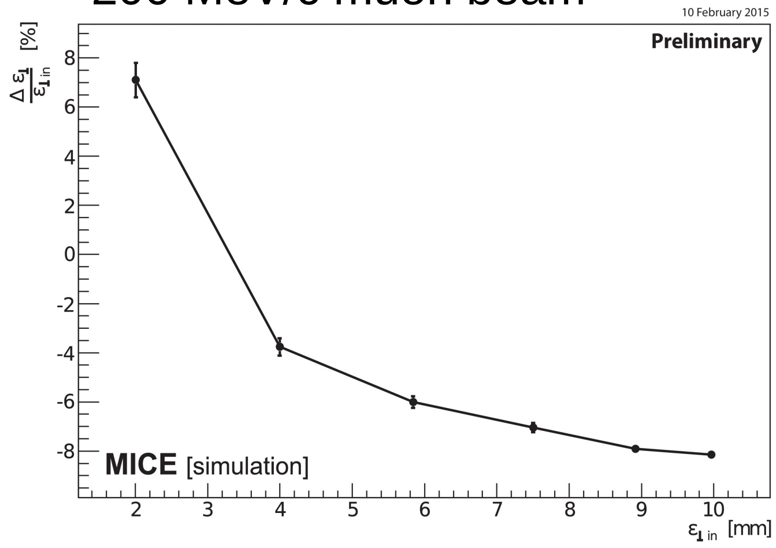


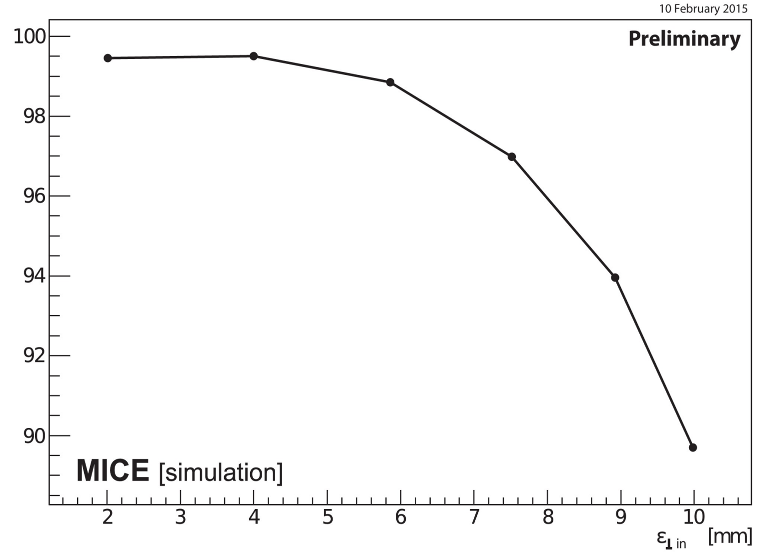
See poster "Emittance Measurement in the MICE Ionization Cooling Experiment" by V. Blackmore

Demonstration of Ionization Cooling



200 MeV/c muon beam





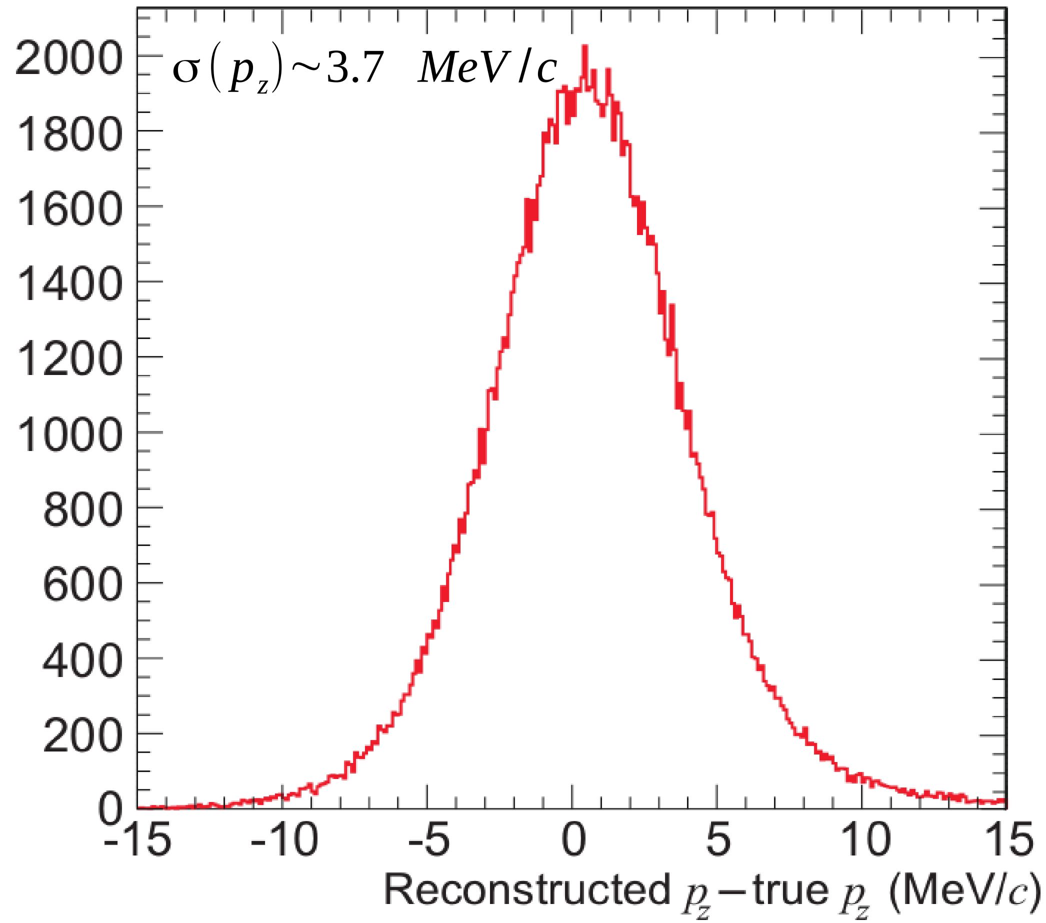
See poster "MICE Demonstration of Ionization Cooling" by T. Mohayai

Summary

- All components required for Step IV are now online
- Commissioning of the full channel is under way
- Data taking to date has :
  - Validated functioning of muon beam and detectors
  - Validated particle reconstruction and analysis codes
  - Delivered a preliminary multiple scattering study
  - Characterised the input muon beam characteristics
- Run plan for Step IV to August 2017 is well-defined
- Plans for the demonstration of ionisation cooling phase are being defined now
- MICE physics program is under way.

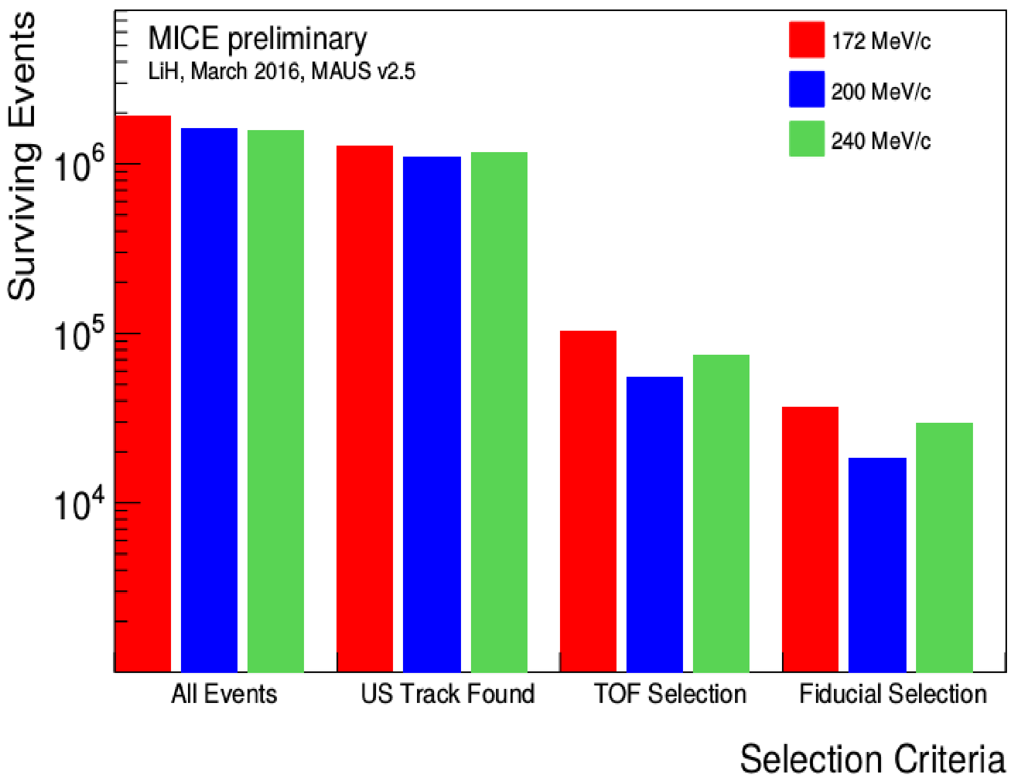
Backups

Tracker resolution



"Characterisation of the muon beams for the Muon Ionization Cooling Experiment", EJP C, Vol 73, Number 10

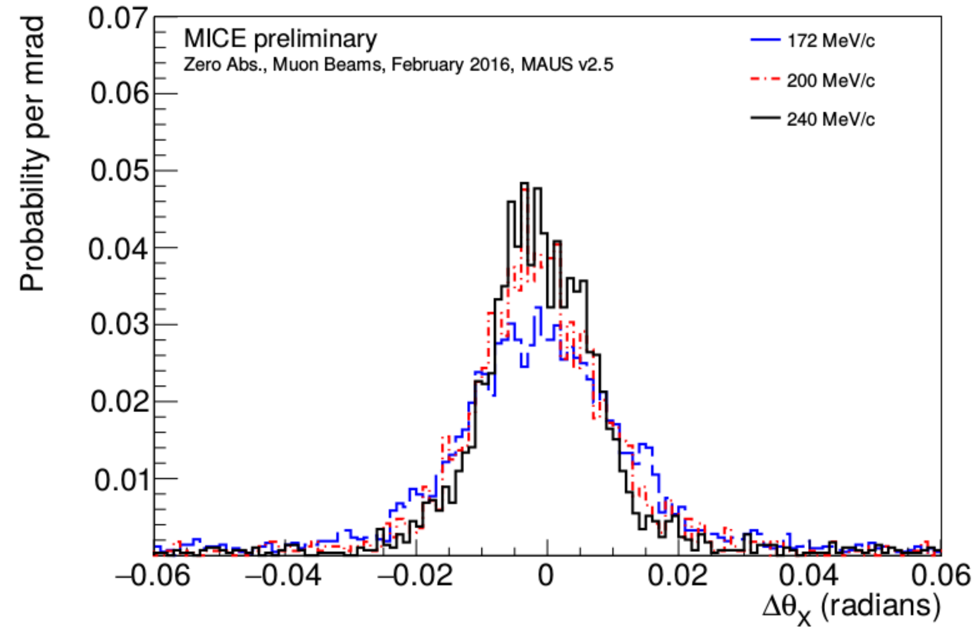
MS – Particle Selection

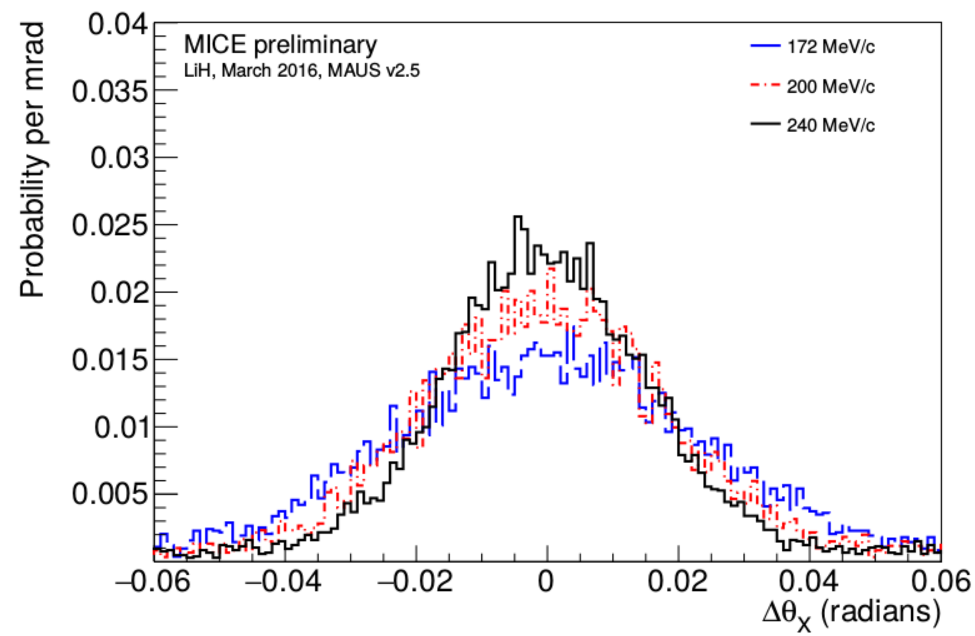


- TOF (PID) selection is vital for beam momentum and position selection
- Requires an US track. If a DS track is not extant, statistics and set to overflow values
- Require projection of US track to appear within central 150 mm radius of DS station 1

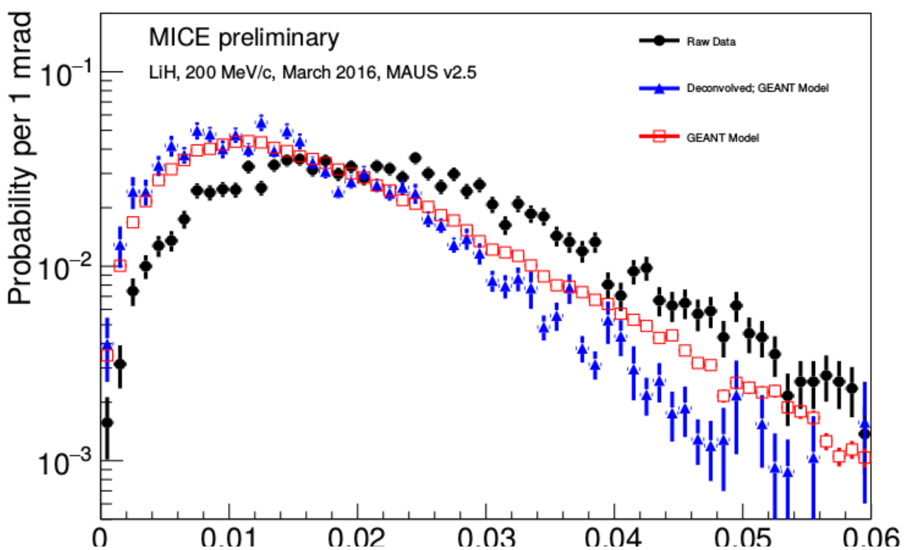
Angle Distributions

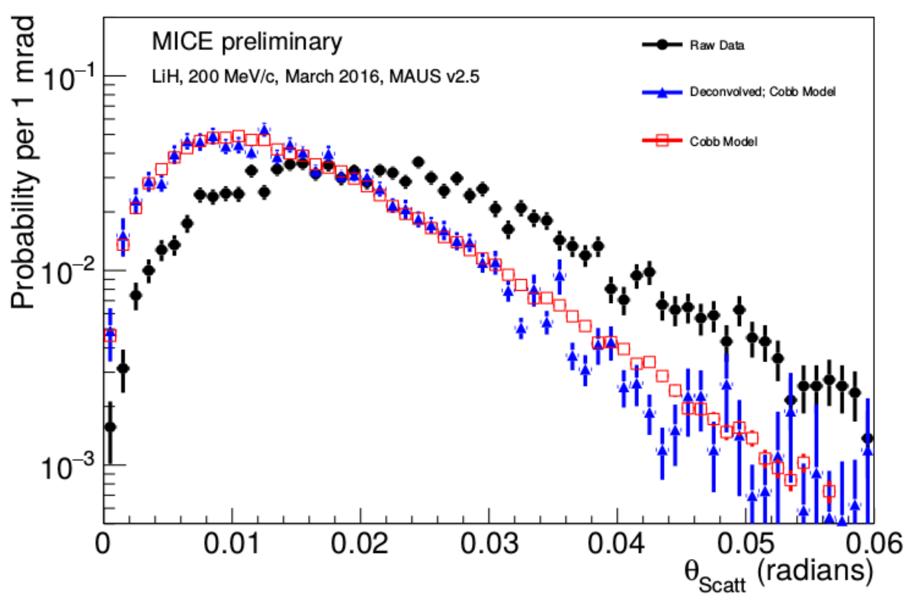
- Particles follow straight paths through spectrometers.
- Scatter off of materials along its path.
  - Need to identify scattering from absorber material only.
- Use TOFs to measure momentum.
  - Consider scattering as a function of momentum.
- Define scattering angles for trajectories
  - $\Delta\theta_x = \text{atan}(\frac{dy}{dz})_{US} - \text{atan}(\frac{dy}{dz})_{DS}$
  - $\Delta\theta_y = \text{atan}(\frac{dx}{dz})_{US} - \text{atan}(\frac{dx}{dz})_{DS}$
  - $\theta_{scatt} = \text{acos}\left(\frac{\mathbf{p}_u \cdot \mathbf{p}_d}{|\mathbf{p}_u| p_d|}\right)$





Deconvolution





- Measurement of the scattering in the absorber
- Unfold underlying scattering from absorber model from measured scattering
- Uses iterative Bayes deconvolution (other unfolding methods being investigated)

ELMS

Wentzel-Moliere form including effect of scattering from atomic electrons and of nuclear screening by atomic electrons

$$\frac{d\langle\theta^2\rangle}{dx} = 4\pi N \frac{Z^2}{A} r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \left\{ \ln\left[\left(\frac{\theta_2}{\theta_1}\right)^2 + 1\right] - 1 + \frac{1}{Z}\left(\ln\left[\left(\frac{\theta_{2e}}{\theta_{1e}}\right)^2 + 1\right] - 1\right)\right\} \qquad \theta_{1e} = \theta_1 \qquad \theta_{2e} \sim \frac{m_e}{m_\mu}$$

ELMS : uses photoabsorption coefficients to describe atomic structure

Only for LH_2

W. Allison, Calculations of energy loss and multiple scattering (ELMS) in molecular hydrogen, J. Phys.G 29:1701-1703, 2003.

Cobb-Carlisle : uses a Monte Carlo method to extend Wentzel-Moliere to other materials.

Building a covariance matrix

Each particle that passes the selection criterion

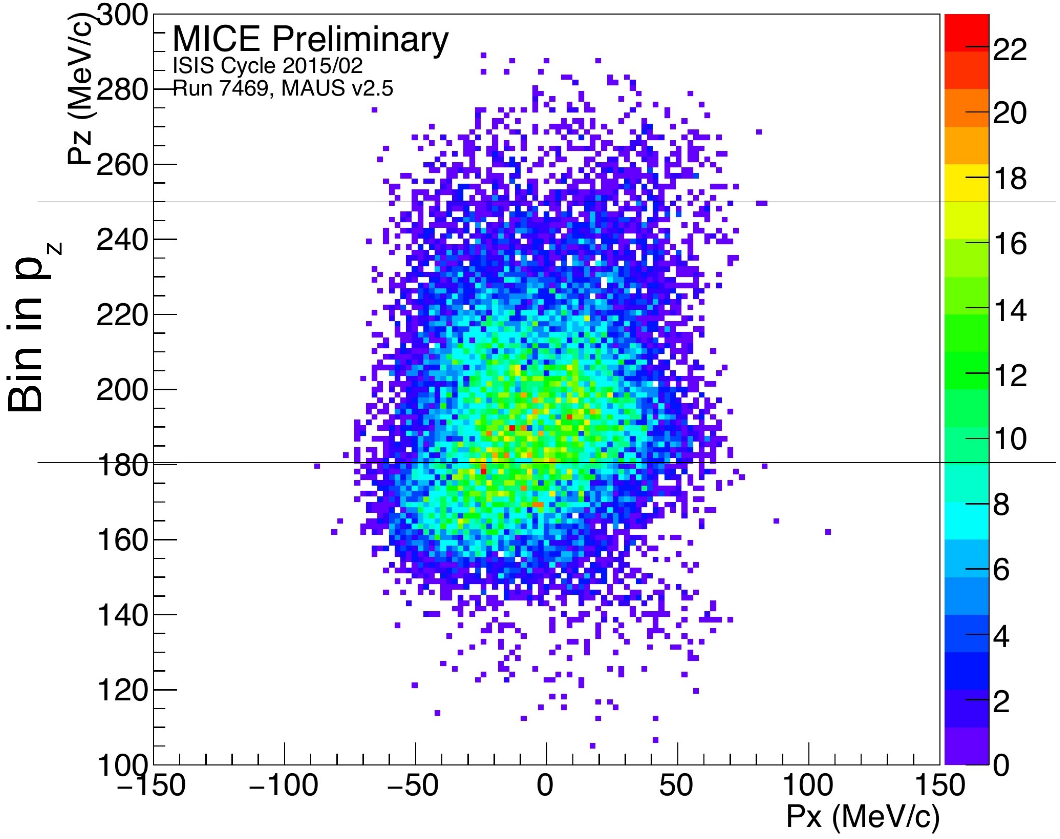
Generates a (x,p_x,y,p_y) tuple

Over ensemble of muons, calculate

$$\Sigma_{4D} = \begin{pmatrix} \sigma_{xx} & \sigma_{x p_x} & \sigma_{xy} & \sigma_{x p_y} \\ \sigma_{x p_x} & \sigma_{p_x p_x} & \sigma_{y p_x} & \sigma_{p_x p_y} \\ \sigma_{xy} & \sigma_{y p_x} & \sigma_{yy} & \sigma_{y p_y} \\ \sigma_{x p_y} & \sigma_{p_x p_y} & \sigma_{y p_y} & \sigma_{p_y p_y} \end{pmatrix}$$

$$\sigma_{ab} = \langle ab \rangle - \langle a \rangle \langle b \rangle$$

$$\epsilon_N = \frac{1}{m_\mu} \left(det \left| \Sigma_{4D} \right| \right)^{1/4}$$



Beam dispersion