The MICE Muon Ionisation Cooling Experiment:
Progress and First Results

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IOP PAB
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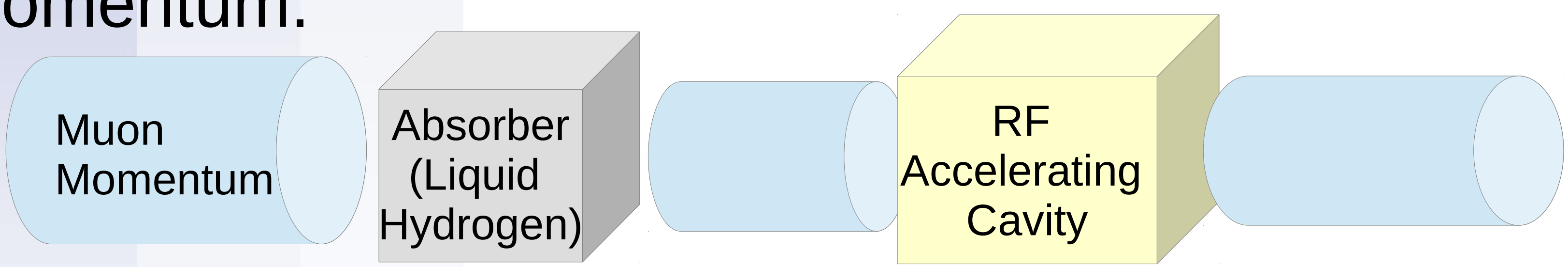
Imperial College London

What is Muon Ionisation Cooling?

- A muon beam loses both transverse (p_T) and longitudinal (p_L) momentum by ionisation when passed through an ‘absorber'.
- The lost longitudinal momentum is then restored by RF cavities.
- The result is a beam of muons with reduced transverse momentum.



- **MICE physics program**
  - Demonstrate the feasibility of ionisation cooling
  - Study and validate the cooling equation
  - Study energy loss and scattering of muons (material physics)

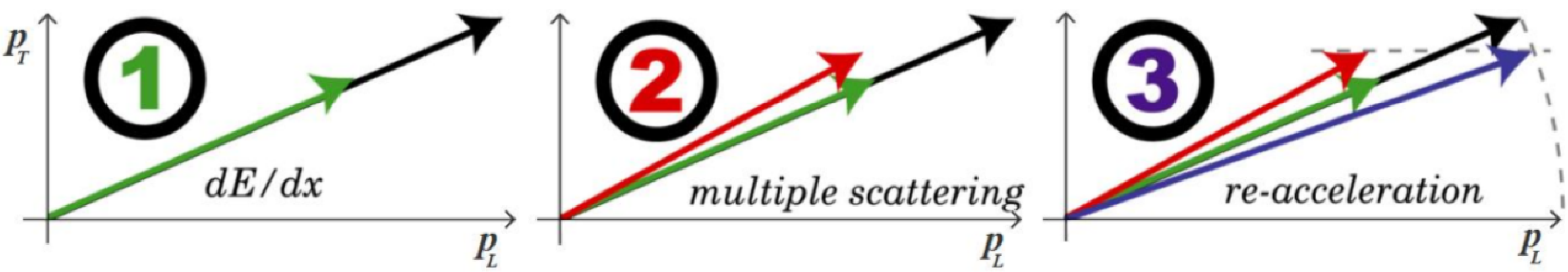
What is Muon Ionisation Cooling?

Muon cooling can be characterised by the rate of change of the normalised emittance (phase space occupied by the beam), approximated by:

$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}$$

$d\epsilon_n/ds$ is the rate of change of normalised-emittance within the absorber; β*c, E_μ and m_μ the muon velocity, energy, and mass, respectively; $\beta_\perp$ is the lattice betatron function at the absorber; L_R is the radiation length of the absorber material.

- Energy loss, dE_μ/ds, reduces both p_L and p_T
- Scattering heats the beam as $1/L_R$, must minimize $1/L_R$
- RF cavities restore p_L only
- The absorber must be placed at a focus for best cooling performance

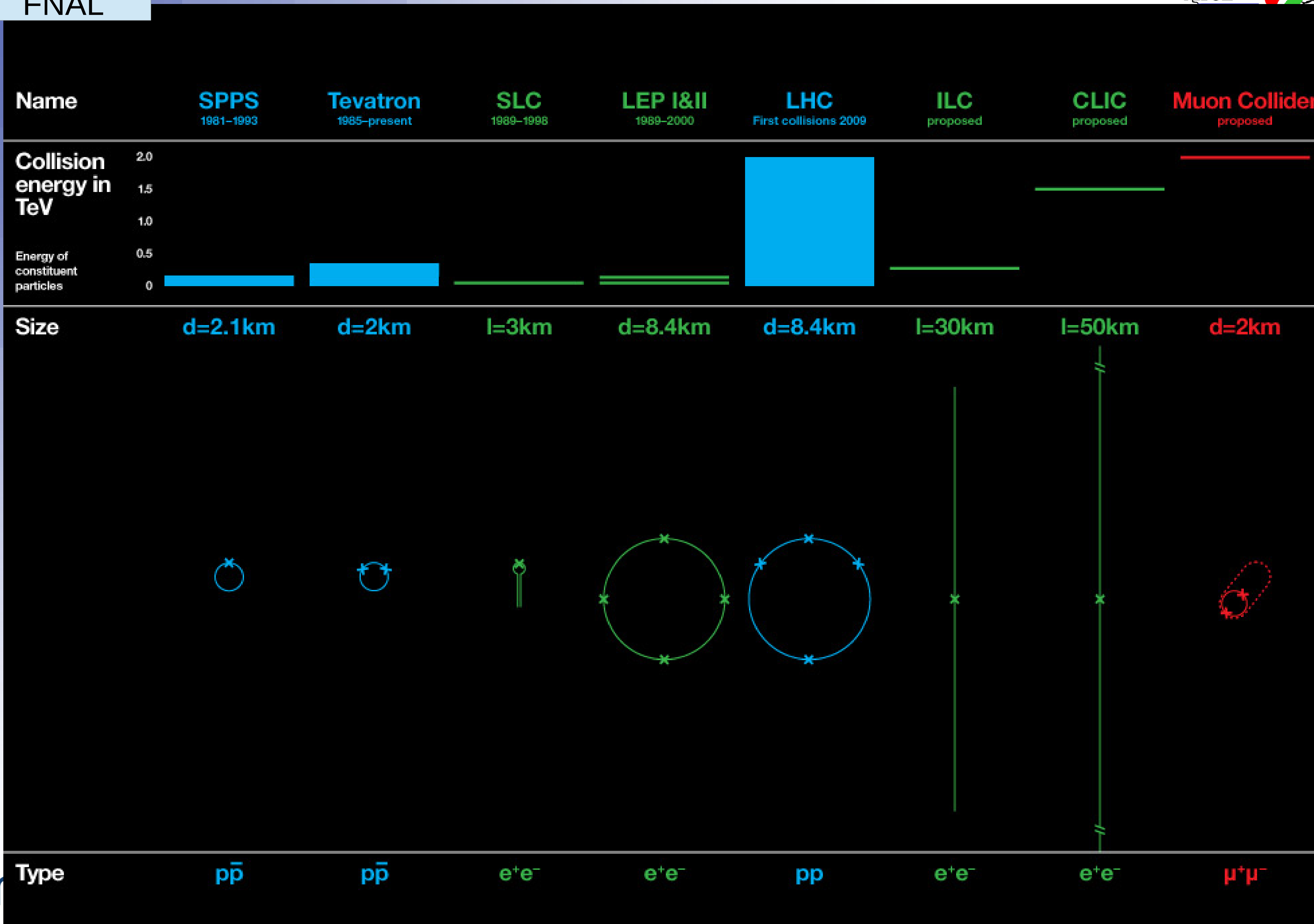


Motivation

- Muon colliders and neutrino factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies and precision measurements of parameters of the Higgs boson and the neutrino mixing matrix.
- Muons are produced with large emittance as they are tertiary particles ($p \rightarrow \pi \rightarrow \mu$).
- Performance and cost depends on how well a beam of muons can be “cooled”.
- Ionisation cooling is the only viable technique to reduce the emittance of a muon beam within their lifetime (~ 2.2 μs).
- Cooled muons are essential to achieve the luminosity required.
- MICE is currently the only experiment studying ionisation cooling of muons.
- Recent progress in muon cooling design studies and prototype tests nourishes the hope that such facilities can be begin to be built during the next 20 years.

Borrowed from FNAL

Size Comparison of Colliders



MICE: Muon Ionisation Cooling Experiment

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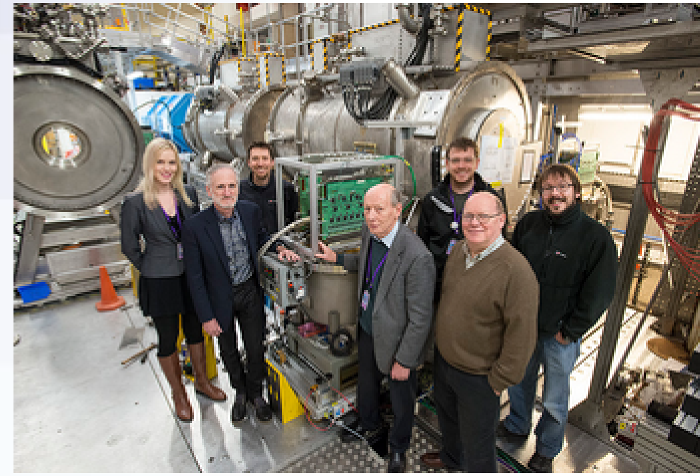
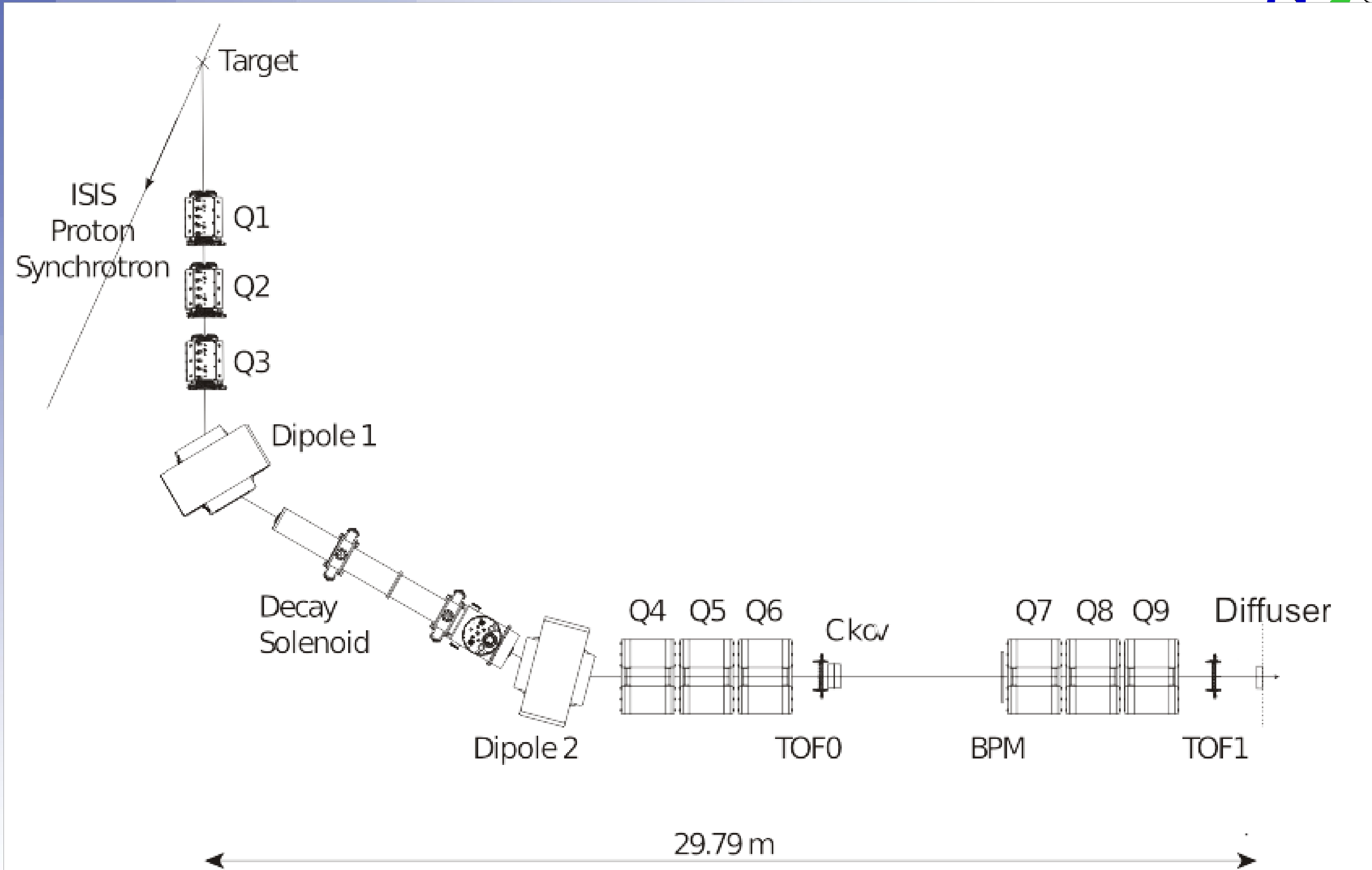
MICE: Collaboration

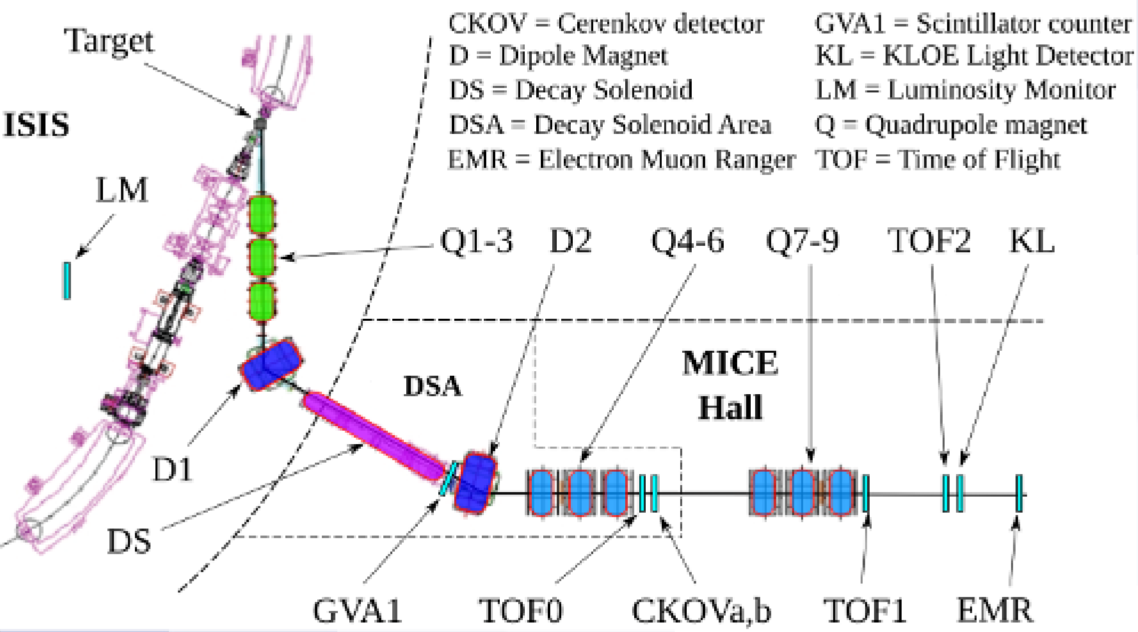


Over 100 collaborators from >10 countries and ~30 institutes.

MICE Beamline



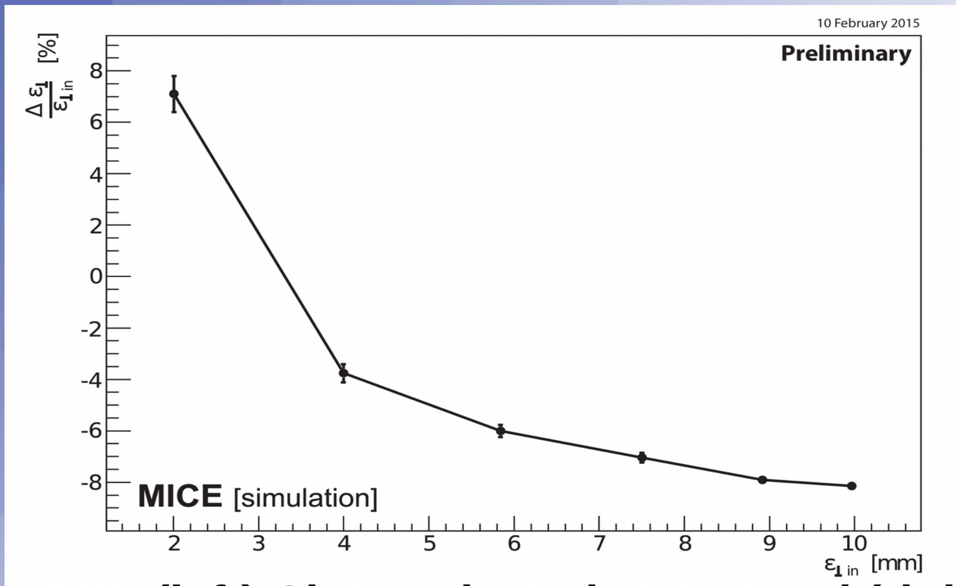
The Bean

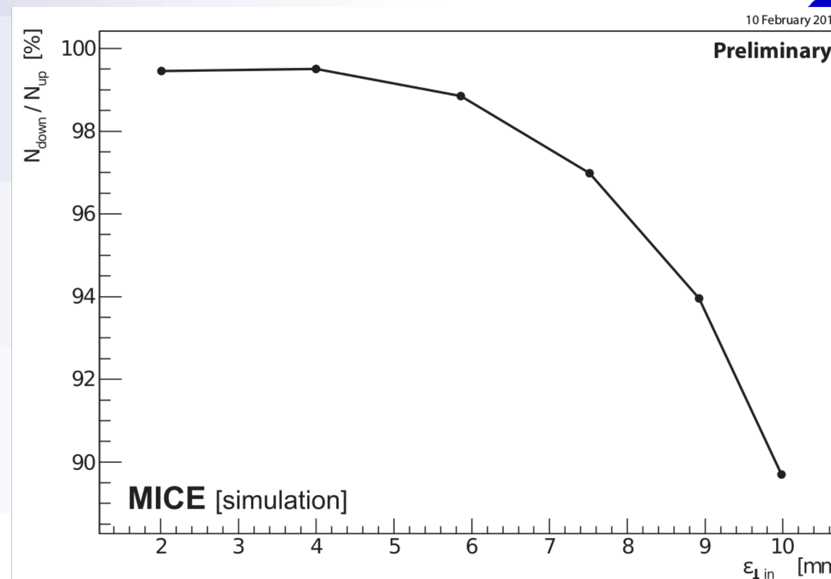


- ISIS 800 MeV proton beam
  - delivering 4 μC of protons
  - in two 100 ns long pulses
  - with mean current of 200 μA.
- Titanium target is dipped into ISIS beam every 1.28 s.

- Pions (π^+) produced in target decay to muons of lower momentum.
- Beam can be prepared as a π beam or μ beam with momenta between 140-450 MeV/c.
- Max particle rate:
  - μ^+ ~120 μ/dip
  - μ^- ~20 μ/dip
- Final μ beam: 1ms wide spill in two 100 ns long bursts every 324 ns.

MICE: The trade off

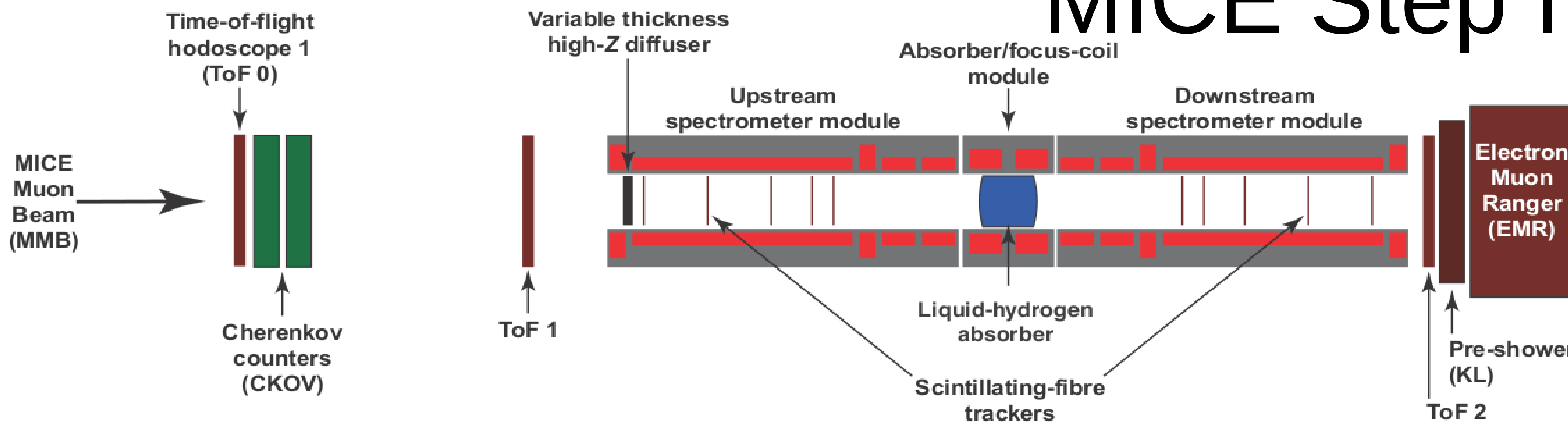




(left) Change in emittance, and (right) beam transmission (both in percent), vs. input emittance.

- The effect of heating & cooling terms is an equilibrium emittance, $\varepsilon_{n,eq} \propto \frac{\beta_\perp}{\beta X_0} \left\langle \frac{dE_\mu}{ds} \right\rangle$ below which the beam cannot be cooled.
- However, as input emittance increases, beam scraping results in increased loss.
- MICE will study scraping in order to obtain a complete experimental characterisation of the cooling process.
- (Since a typical cooling channel will employ dozens to hundreds of cooling lattice cells, the precision with which even the tails of distributions can be predicted will have important consequences for the performance of the channel.)

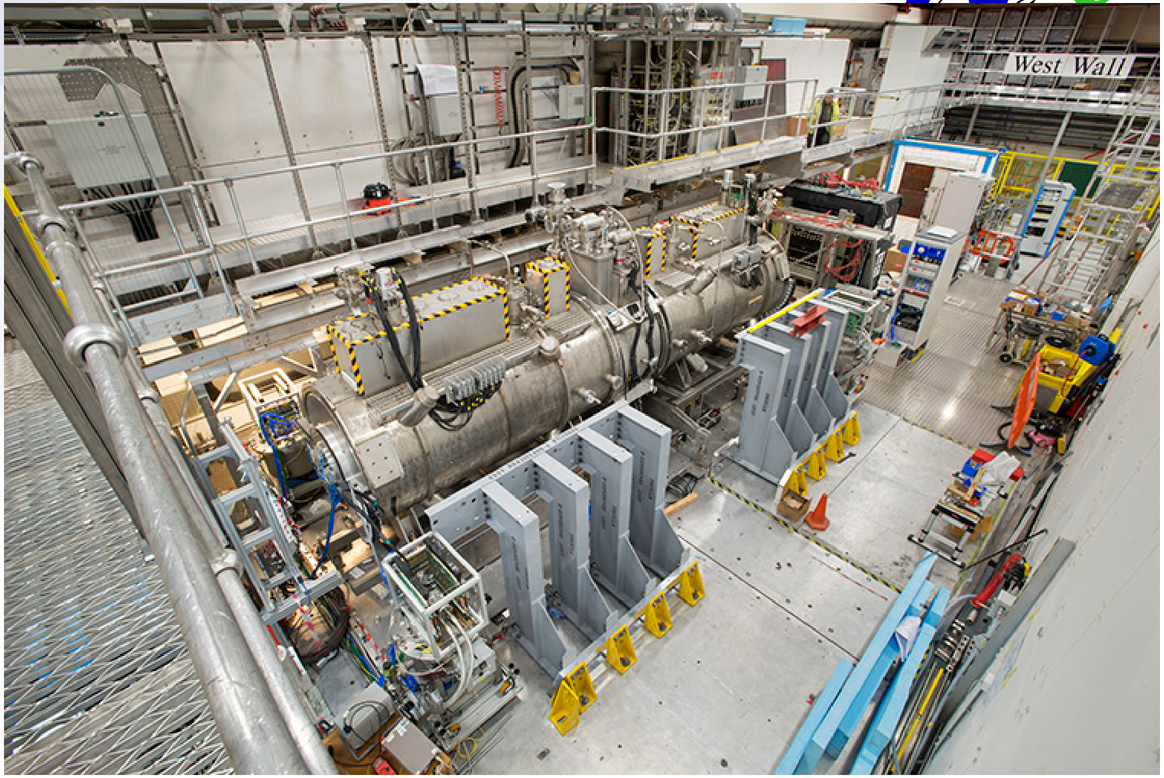
MICE Step IV



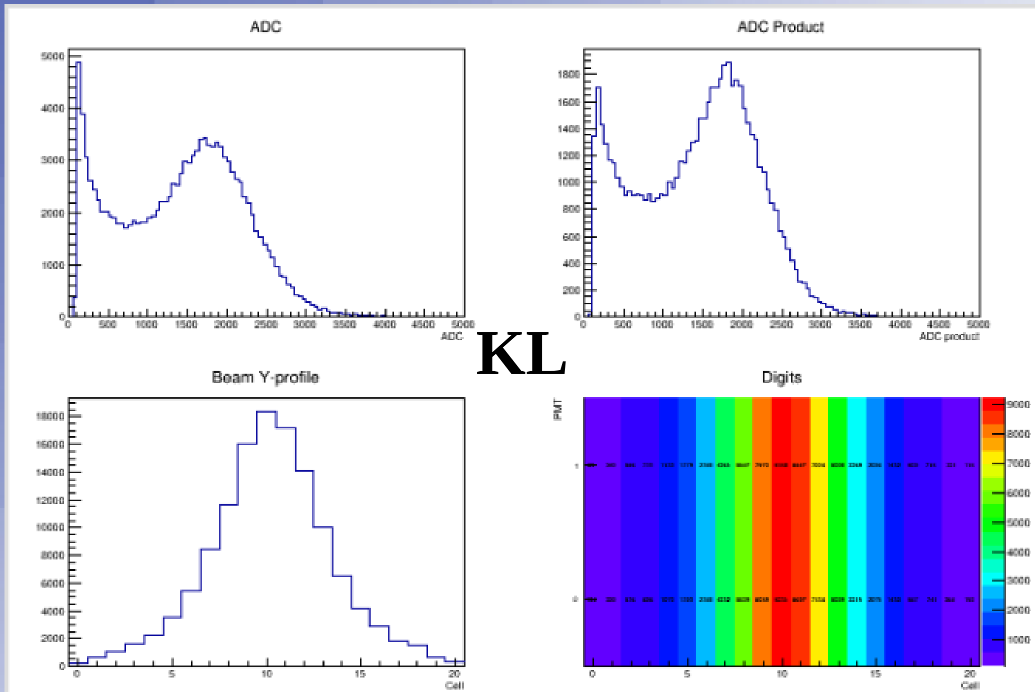
- Includes the two solenoidal spectrometers (5 coils each), an absorber focus coil (AFC 2 coils) and an absorber (liquid-hydrogen, lithium-hydride etc);
- Detectors: Time Of Flight, 2 cherenkov counters, a downstream calorimeter and 2 scintillating fibre trackers. All detectors have been installed.
- Normalised beam emittance change is measured before and after the absorber by the Trackers.
- Emittance change is studied using a range of beam momenta and under a variety of focusing conditions.
- Step IV will lack the RF re-acceleration required for “sustainable” cooling (lost energy is not restored hence cooling cannot be iterated).
- **Data taking has progress has been excellent, routine data taking!!!**

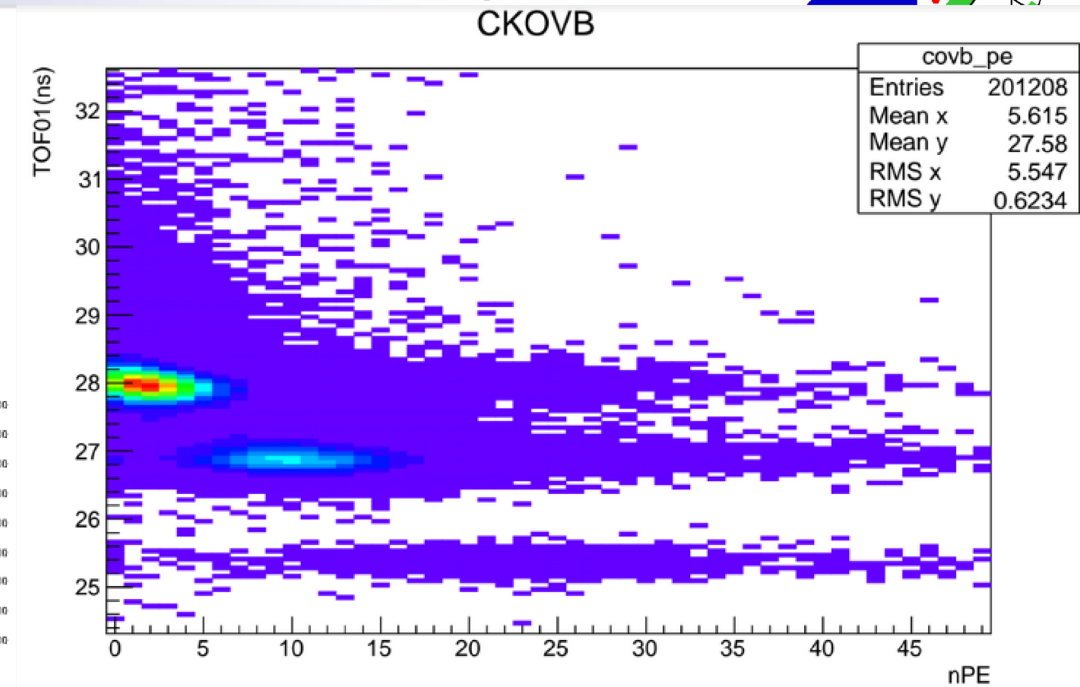
The Detectors

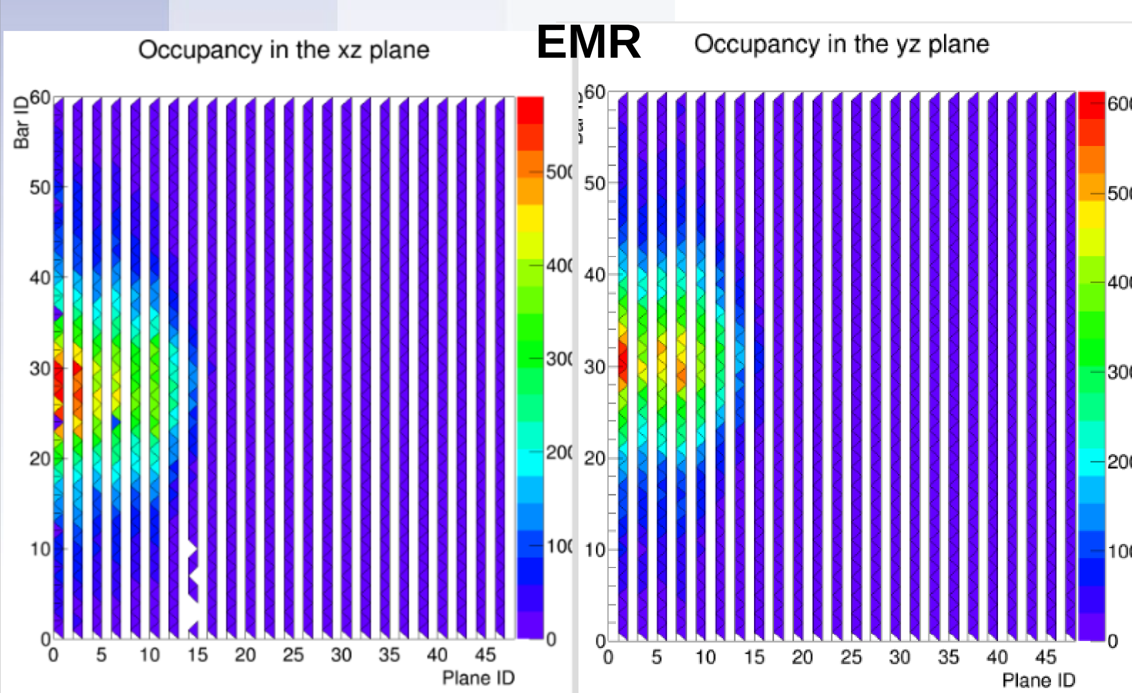
- Time Of Flight: TOF0-2
- Electron Muon Ranger: EMR
- KLOE-Light: KL
- Cerenkov: CkoVa CkoVb
- Trackers
  - Two Tracker detectors upstream and downstream of cooling section, each immersed in a uniform magnetic field of 4 T.
  - Measure the normalised emittance with precision of 0.1% (beam emittance measured before and after cooling).

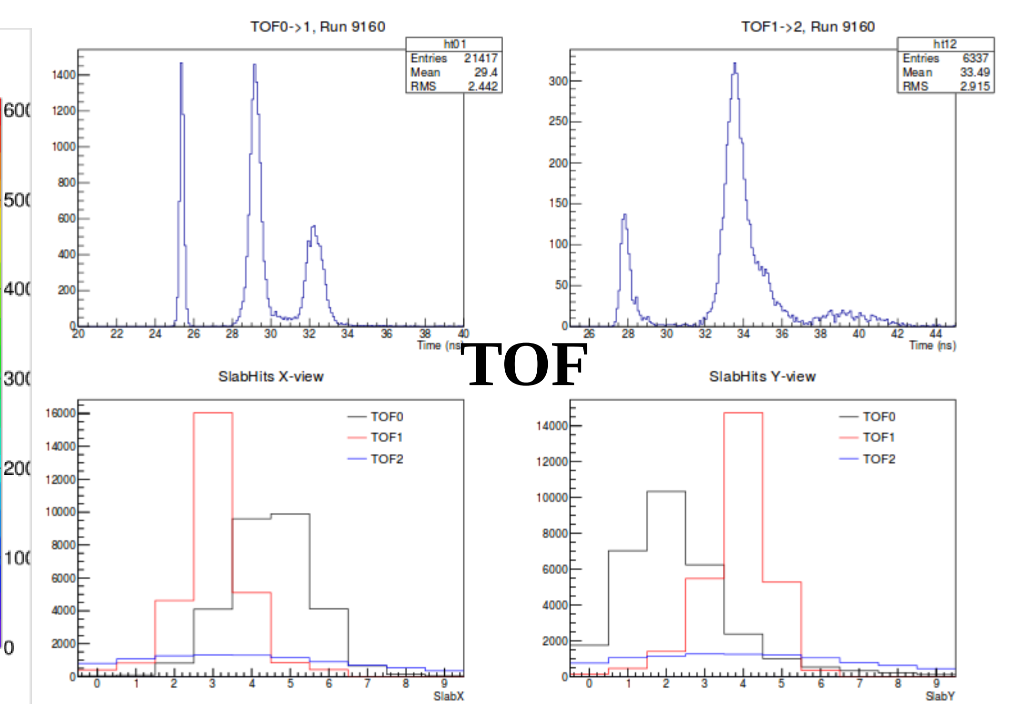


All Detectors Performing Well

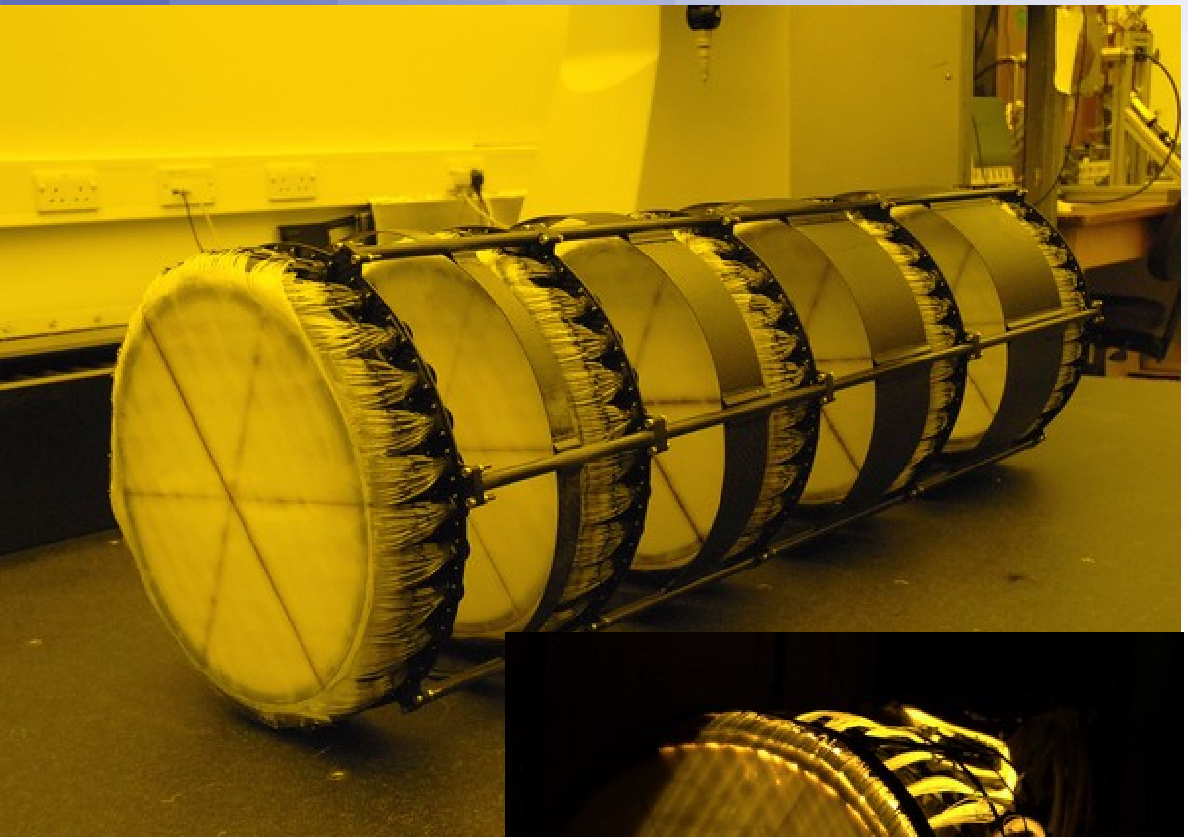


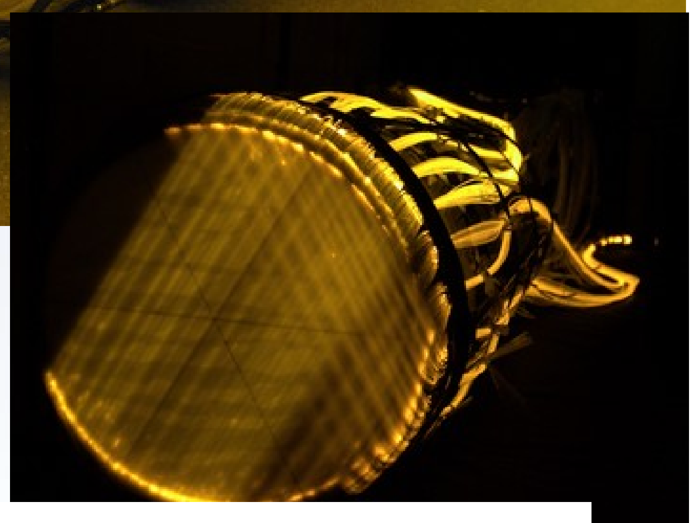




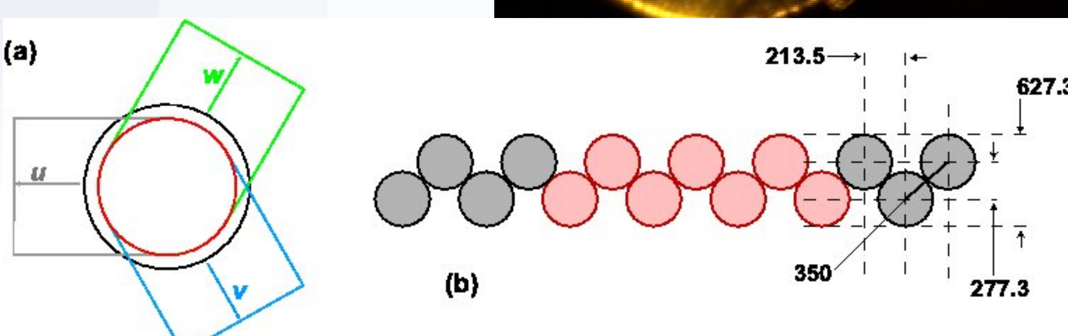


The Trackers





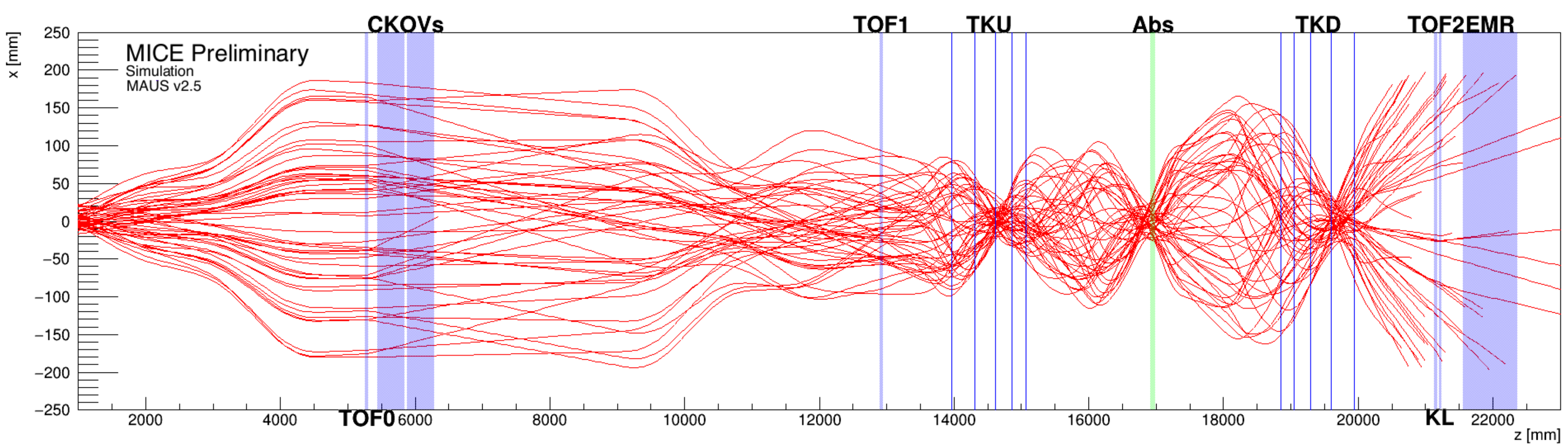
- Two scintillating fibre trackers, one upstream, one downstream of the cooling channel.
- Each within a spectrometer solenoid producing a 4 T field.
- Each tracker is 110 cm in length and 30 cm in diameter.
- 5 stations
  - varying separations 20-35 cm (to determine the muon p_T).
- 3 planes of fibres per station each at 120°.
- LED calibration system.
- Hall probes.
- Position resolution 470 μm.



Single Particle Experiment

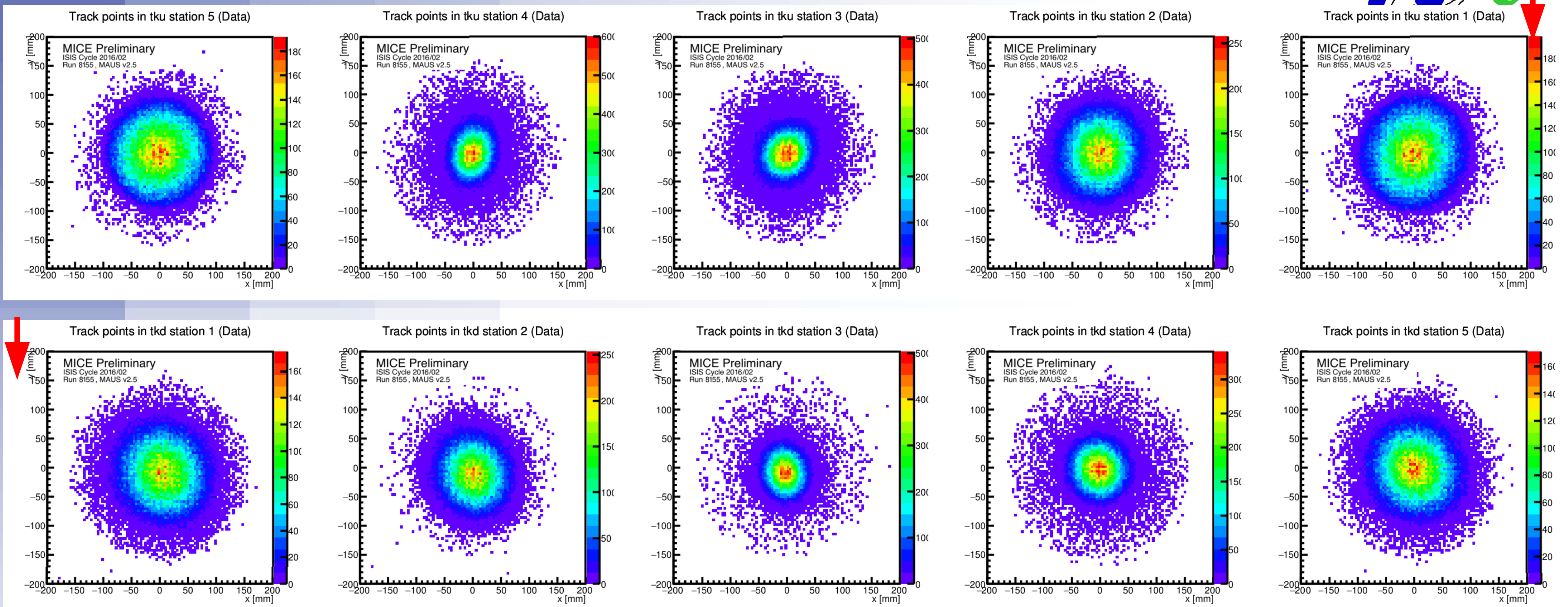
MICE is a single-particle experiment, i.e.

- There is no “beam” as such, instead, particles go down the beam line one by one
- At each DAQ cycle, a single particle track is recorded
- Particle tracks are bunched at the analysis level from which the emittance is computed.
- First direct measurement of emittance of muon beams by a scintillating fibre-tracker



Nearest to absorber

Tracker Reconstruction



Space point distributions in both trackers.

The stations are ordered such that station 1 in both trackers is closest to the absorber.

The red arrows denote the stations nearest to the absorber.

Emittance Calculation

The 4D normalised RMS transverse emittance is defined as

$$\epsilon_n = \frac{1}{m_\mu}\sqrt[4]{\det\Sigma}$$

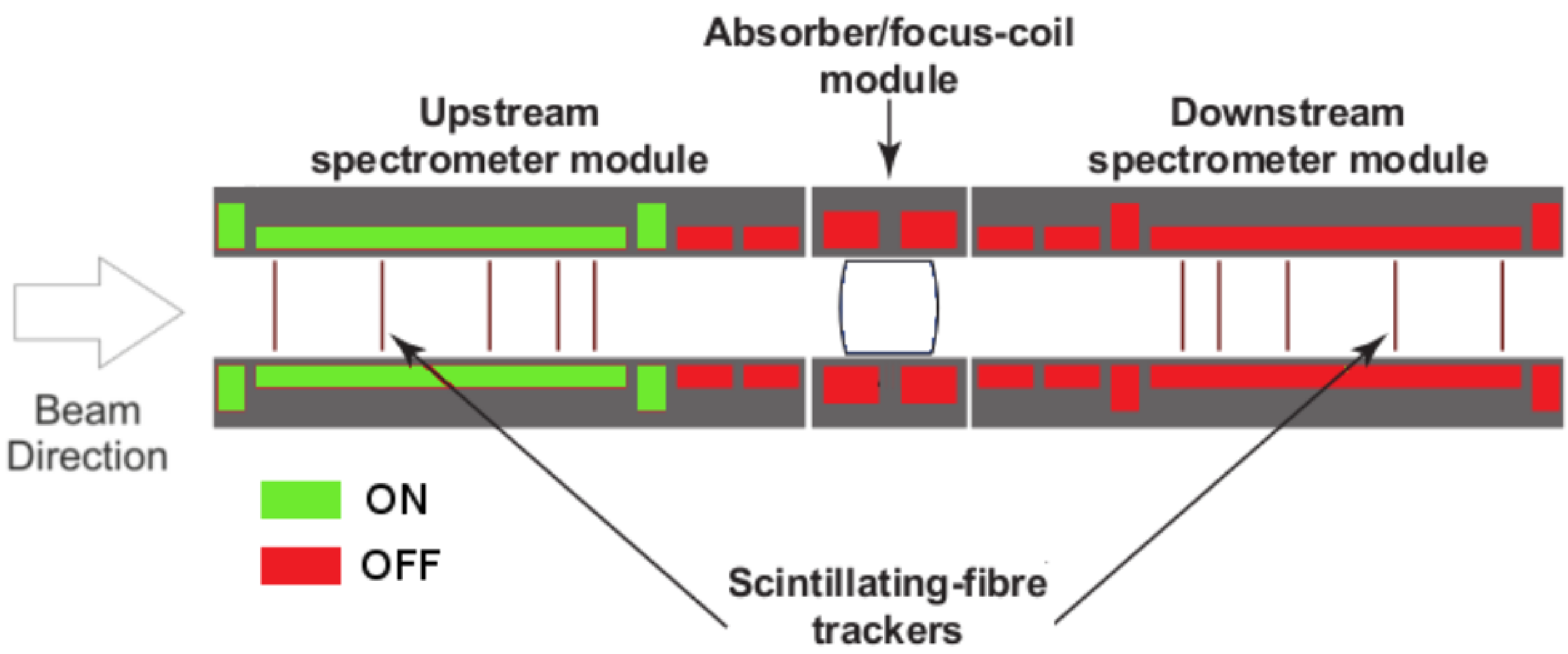
where m_μ the muon mass and Σ the covariance matrix:

$$\Sigma = \begin{pmatrix} \sigma^2_{xx} & \sigma^2_{xp_x} & \sigma^2_{xy} & \sigma^2_{xp_y} \\ \sigma^2_{p_x x} & \sigma^2_{p_x p_x} & \sigma^2_{p_x y} & \sigma^2_{p_x p_y} \\ \sigma^2_{yx} & \sigma^2_{yp_x} & \sigma^2_{yy} & \sigma^2_{yp_y} \\ \sigma^2_{p_y x} & \sigma^2_{p_y p_x} & \sigma^2_{p_y y} & \sigma^2_{p_y p_y} \end{pmatrix}$$

and $\sigma^2_{\alpha\beta} = \langle\alpha\beta\rangle - \langle\alpha\rangle\langle\beta\rangle$ the covariance of α and β.

Emittance Measurement First Results

- Data taken in October 2015
  - upstream spectrometer powered for the first time at its designed current.
  - 200 MeV/c positive muon input beam
  - 70 minutes of data taking
  - 19076 good muon tracks acquired
- This run was used to characterise the MICE muon beam and validate the tracker reconstruction.



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Emittance Measurement
Beam Selection

- Reject time-of-flights below threshold (e^+)
- Keep only particles that hit every TOF and tracker stations
- Remove particles that scraped the apparatus (magnet bore, diffuser)

Cut Description	Failed	Passed
Good PMT position at TOF0	14793	38659
Good PMT position at TOF1	6644	46808
Good TOF position reconstruction	15996	37456
Hit all Tracker stations	11603	41849
$26.47 \leq t_{01} \leq 40$ ns	15996	37456
Hit all detectors	20903	32549
One, and only one, spacepoint at TOF0	15463	37989
One, and only one, spacepoint at TOF1	6886	46566
One, and only one, track in the Tracker	14749	38703
Track P-value ≥ 0.01	1144	52308
$5 \leq P_{loss} \leq 43$ MeV/c	25998	27454
All criteria	30835	22617

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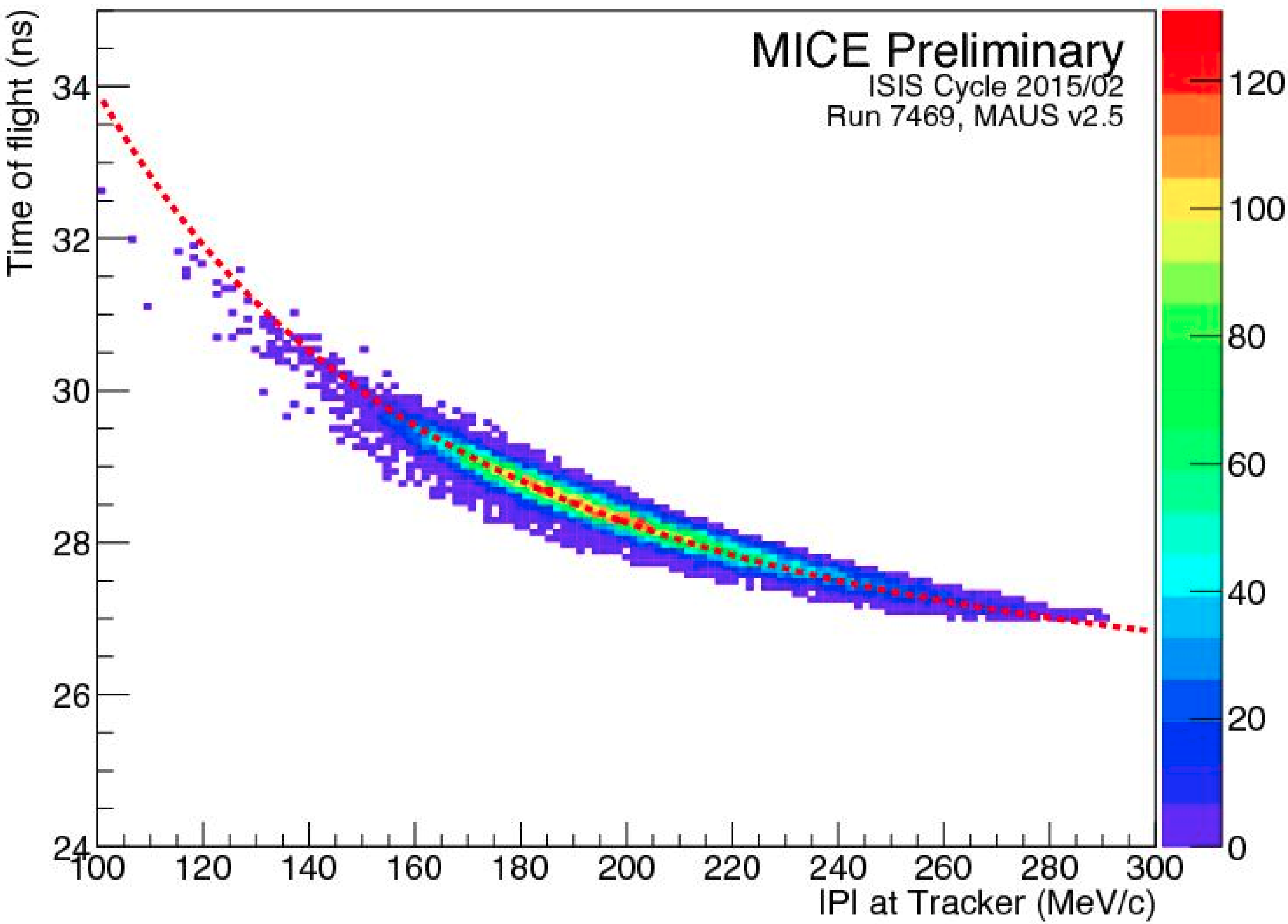
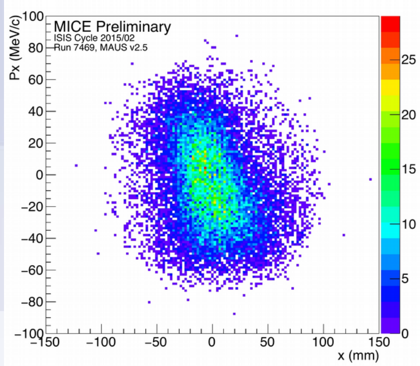
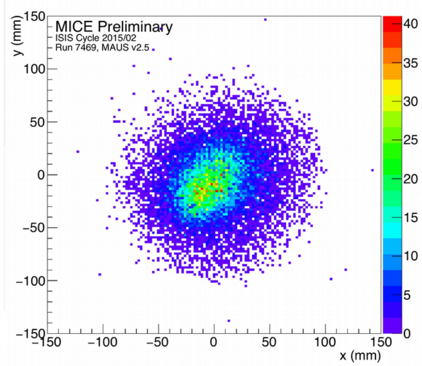
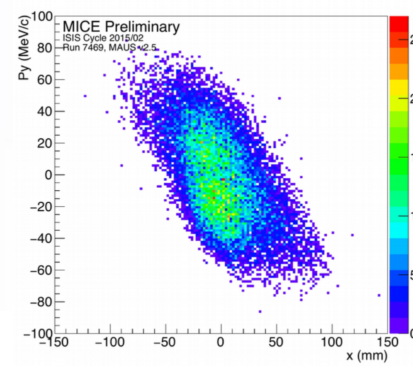
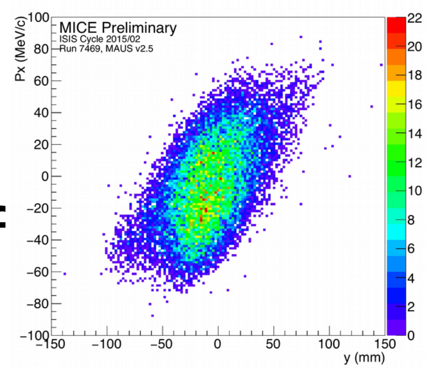
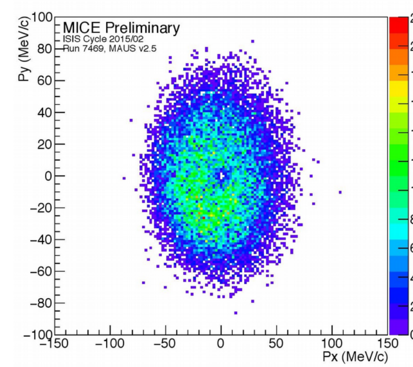
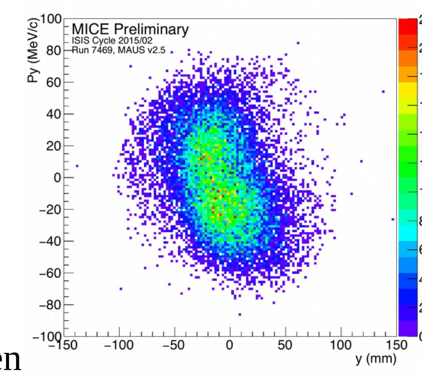
Emittance: Beam Selection



Total muon momentum and time-of-flight between TOF0 and TOF1.

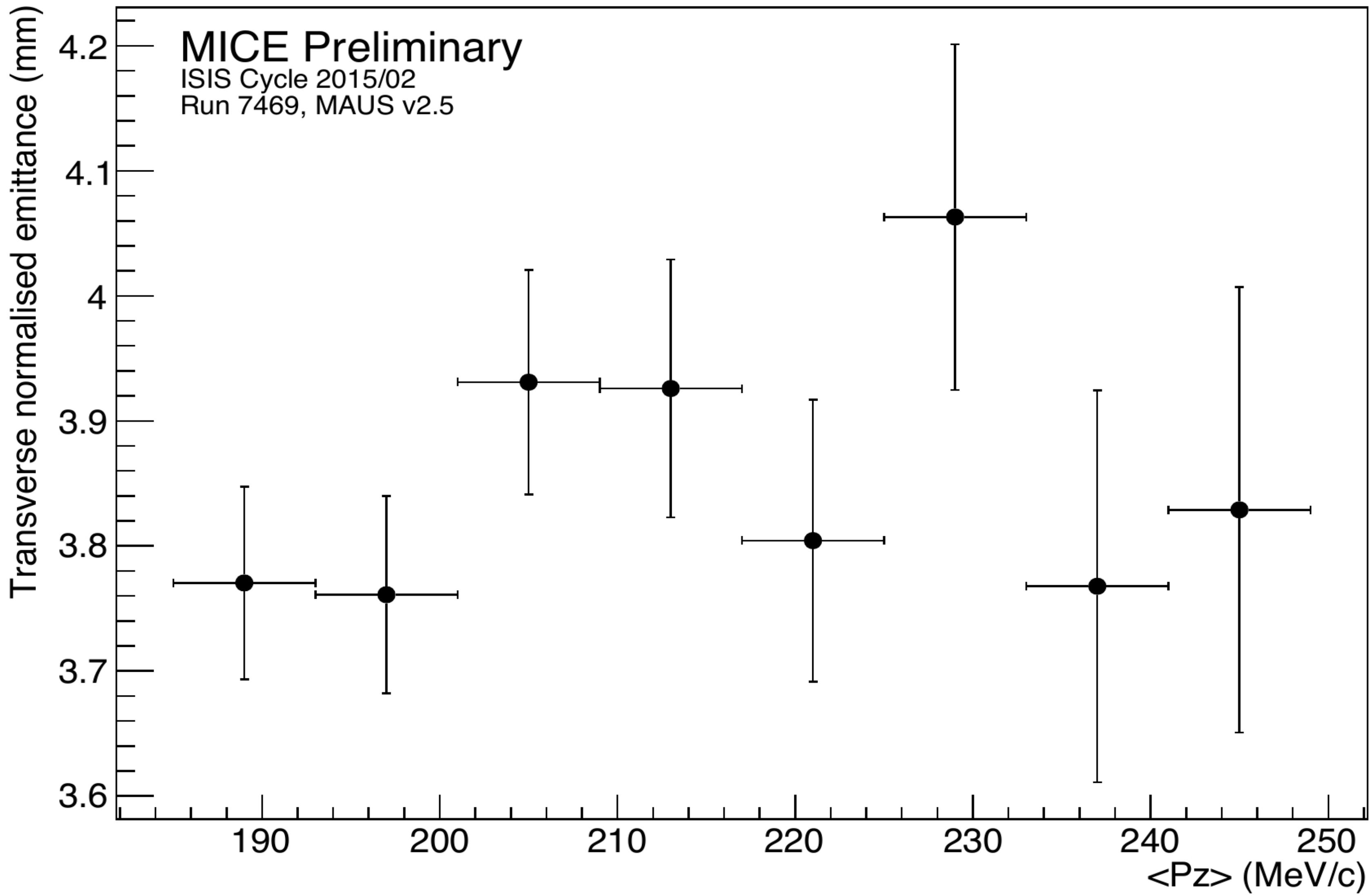
- The absence of other populations indicates selection of a pure muon sample.
- The (red) dotted line is the trajectory of a muon that loses the mean momentum (20 MeV/c) between TOF1 and the Tracker.

Emittance: Covariance Elements

x	p_x	y	p_y	
$\boxed{\sigma^2_{xx}}$				x
	$\boxed{\sigma^2_{p_xp_x}}$			p_x
		$\boxed{\sigma^2_{yy}}$		y

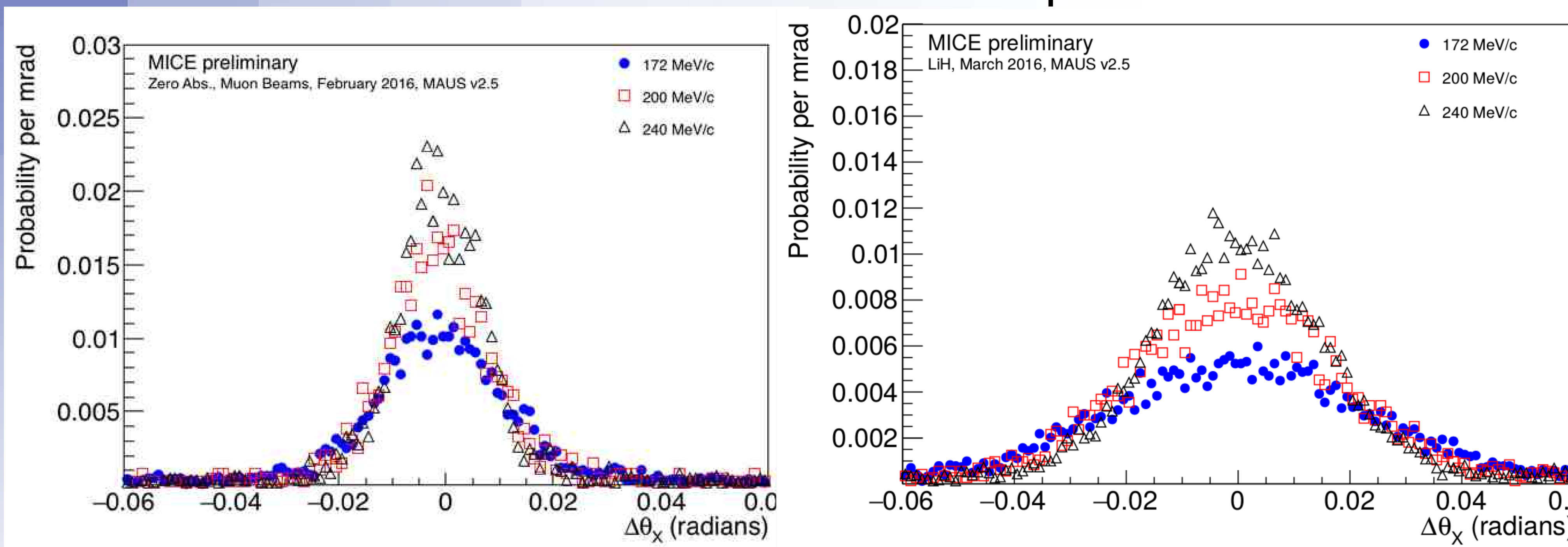
Visual representation of the off-diagonal elements of the covariance matrix used to calculate emittance

First Direct Measurement of Emittance



LiH Multiple Scattering Results

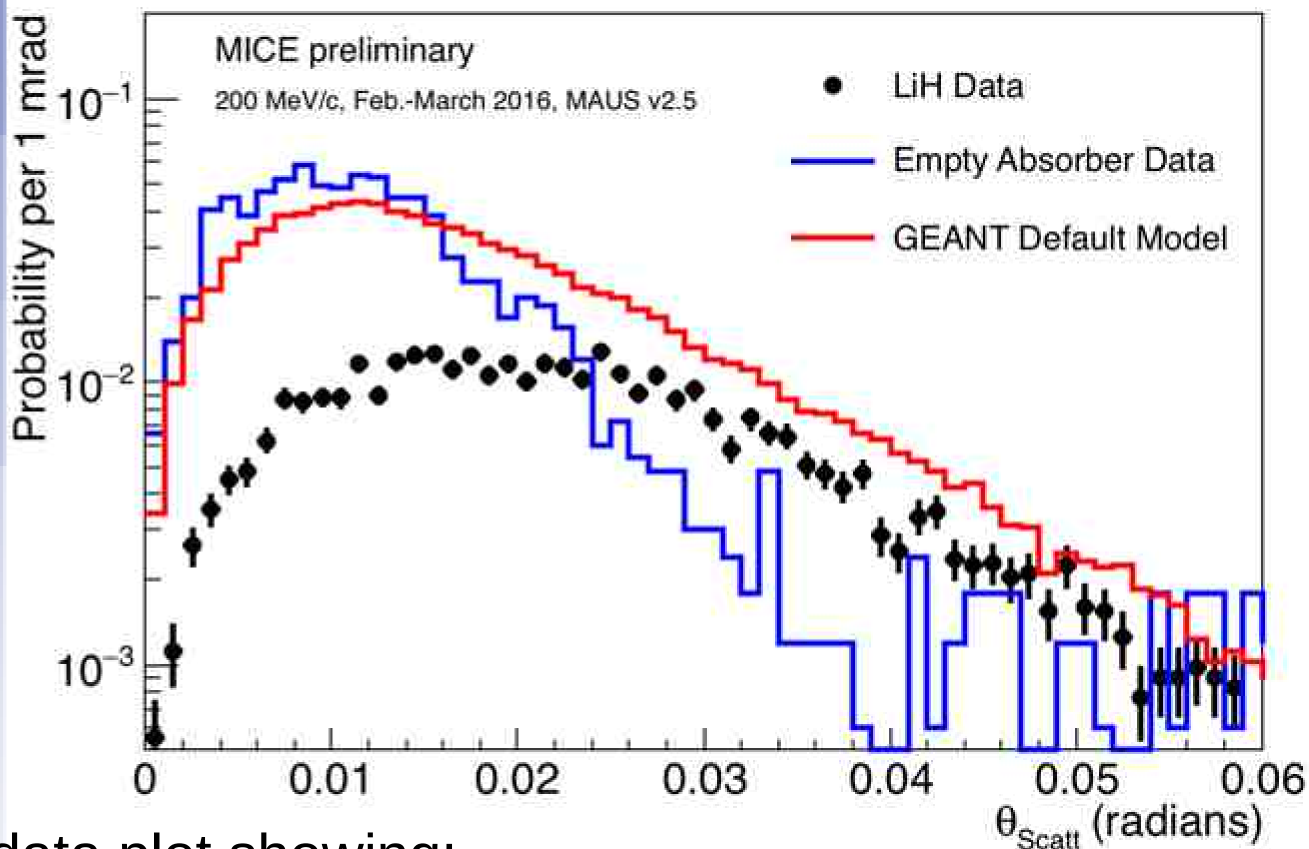
- MICE aims to measure emittance reduction and scattering in low-Z absorbers e.g. liquid hydrogen and lithium hydride.
- Multiple scattering is not well modelled for low-Z absorbers in standard simulations and hence must be improved.



Scattering distributions from data taken at three momenta with a null/empty absorber (left) and lithium hydride absorber (right).

Empty absorber data scatter: measurement resolution and scattering in windows, tracker planes, etc

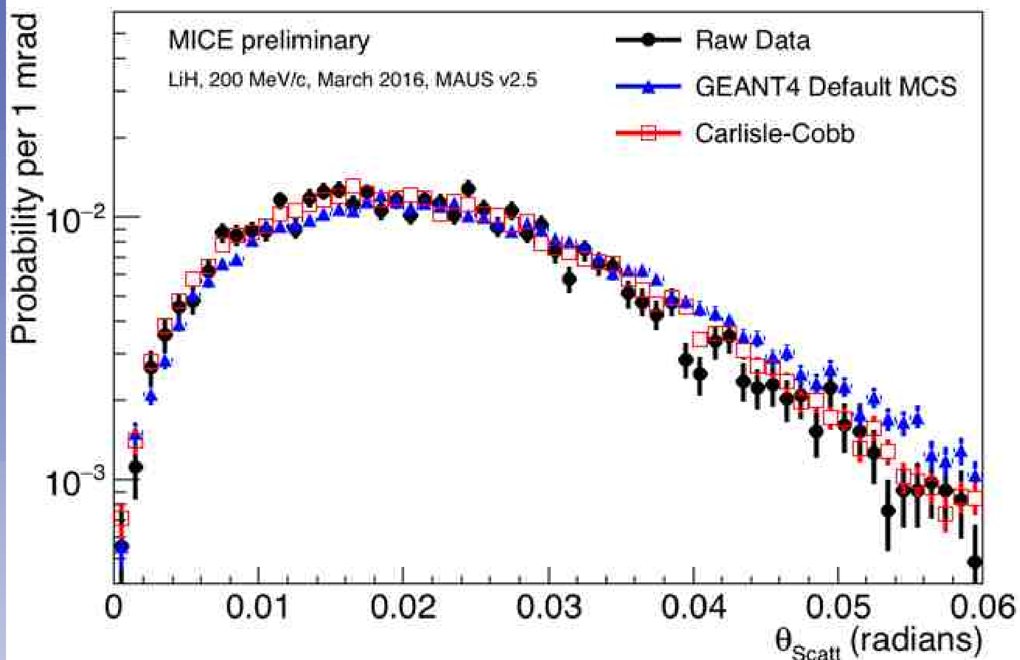
LiH Scattering Data vs Models



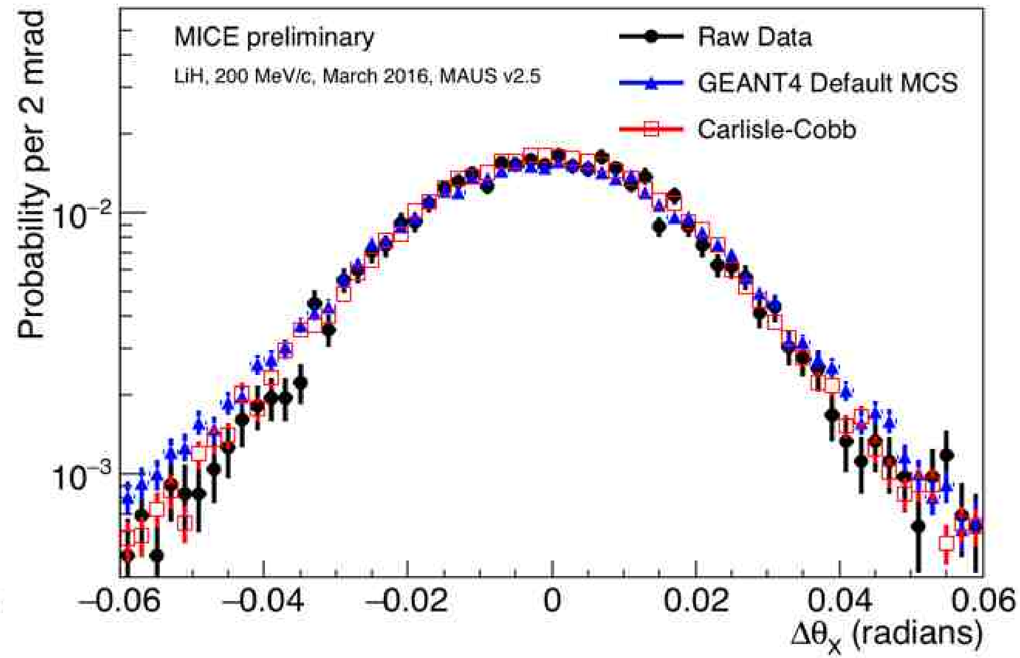
Scattering data plot showing:

- the GEANT model of scattering in lithium hydride (red),
- the data collected with the empty focus coil used in the convolution (blue) and
- the scattering data (black) collected with the lithium hydride absorber in the focus coil.

LiH Scattering Results



Scattering angle distribution



Scattering angle projected on yz plane

- The projection of the scattering angle distributions (left) and angle on the yz plane (right)
- from selected muon events from the 200 MeV/c muon beams
- from the March 2016 lithium hydride absorber data
- with the convolution between the zero absorber data and the GEANT4 prediction of scattering in lithium hydride and the convolution between the zero absorber data and the Cobb-Carlisle (a Monte Carlo implementation of the Wentzel scattering single-particle cross-section (as opposed to the Rutherford cross-section which is used in the original Moliere theory) prediction of scattering in lithium hydride.

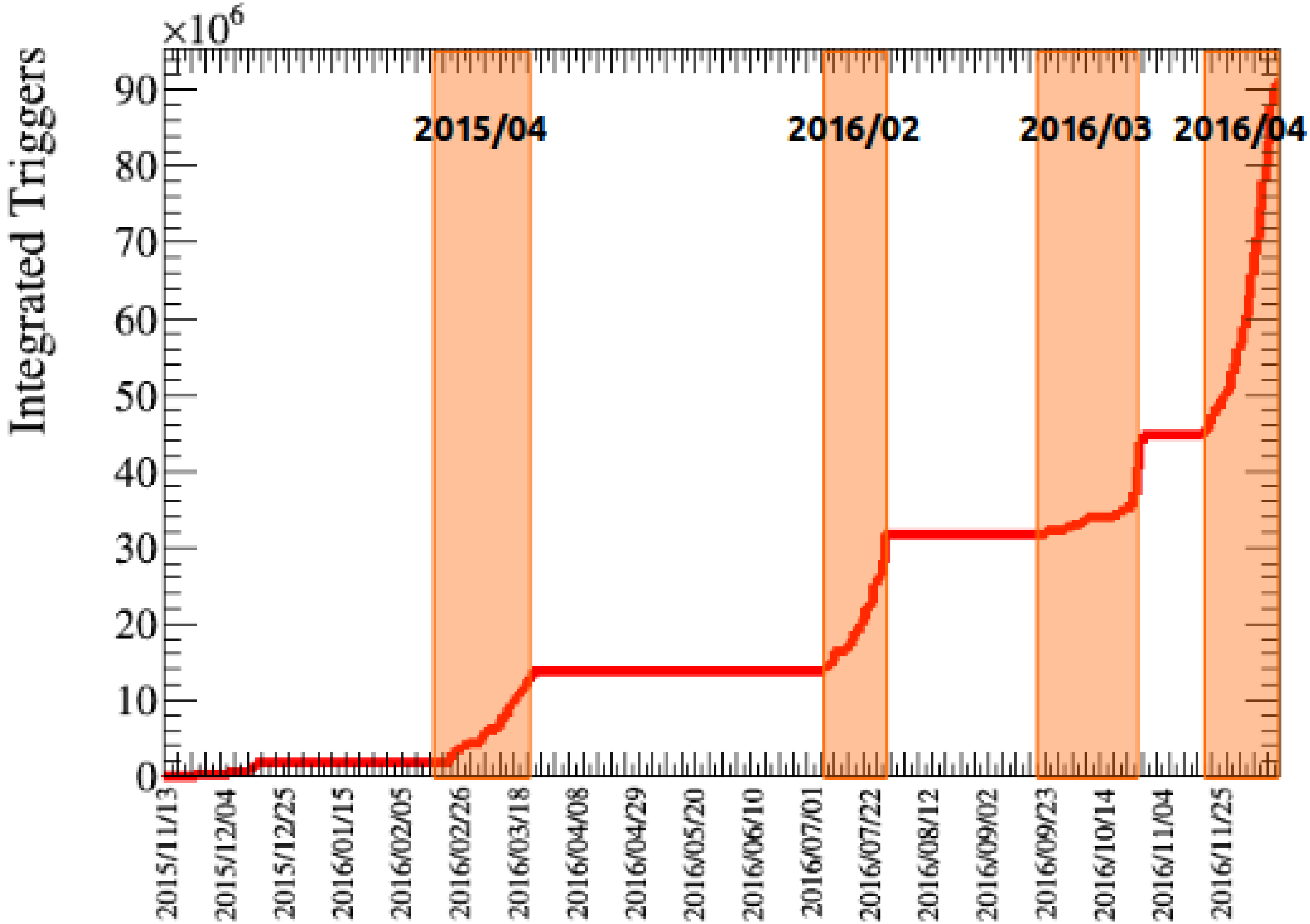
All Step IV Milestones Met So Far...

- Alignment data taken and analysis complete.
- Straight track data taking completed.
- Magnet training complete.
- Empty absorber data taken.
- Lithium Hydride data complete, with an without field
- Diffuser data taken and analysis in progress.
- First direct measurement of emittance in progress.
- Flip and Solenoid Mode data taken.
- NEXT → Liquid Hydrogen data, installation in progress.

A Year in Papers

Title	Status
The reconstruction software for the MICE scintillating fibre trackers	JINST 11 (2016) T12001
The design and construction of the Electron Muon Ranger	arXiv:1607.04955
The design and performance of an improved target for MICE	JINST 11 (2016) no.05, P05006
Pion Contamination in the MICE Muon Beam	JINST 11 (2016) no.03, P03001
Electron-Muon Ranger: performance in the MICE Muon Beam	JINST 10 (2015) no.12, P12012
The MICE Analysis and User Software Framework	Paper in preparation
First Measurement of Emittance in Step IV	Paper in preparation
Measurement of Scattering Distributions in MICE	Paper in preparation
Design and expected Performance of the MICE Demonstration of Ionization Cooling	Paper in preparation

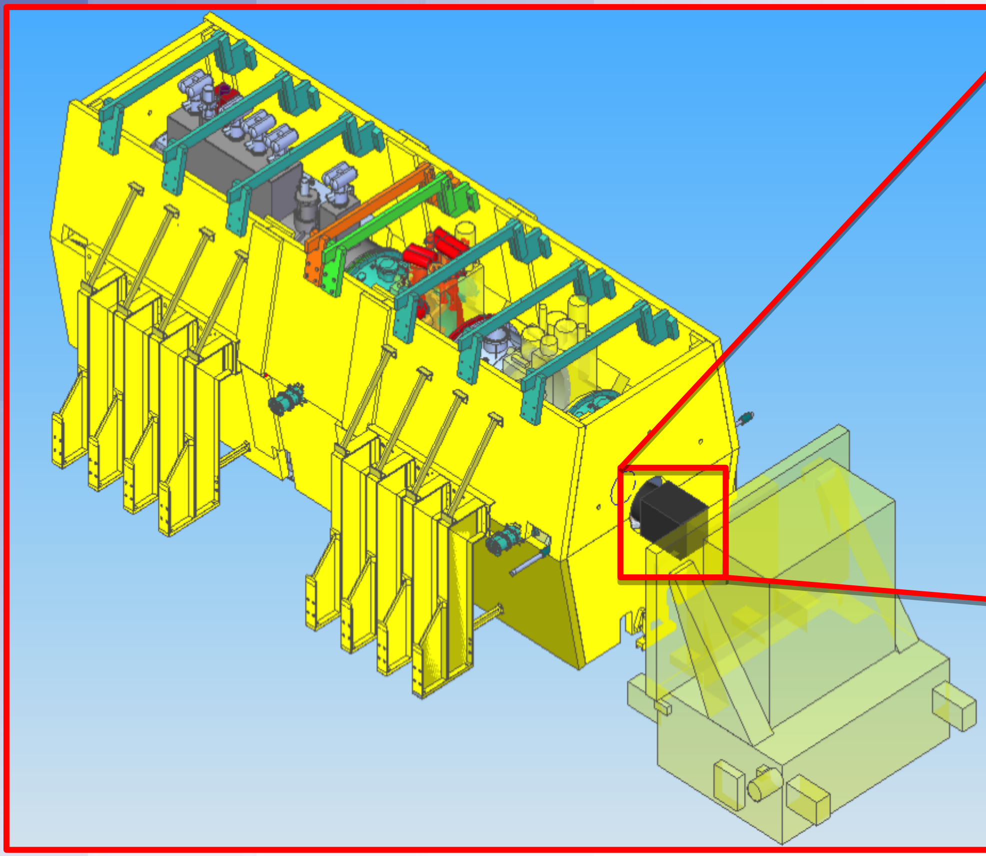
There is a lot more Data Being Analysed though...

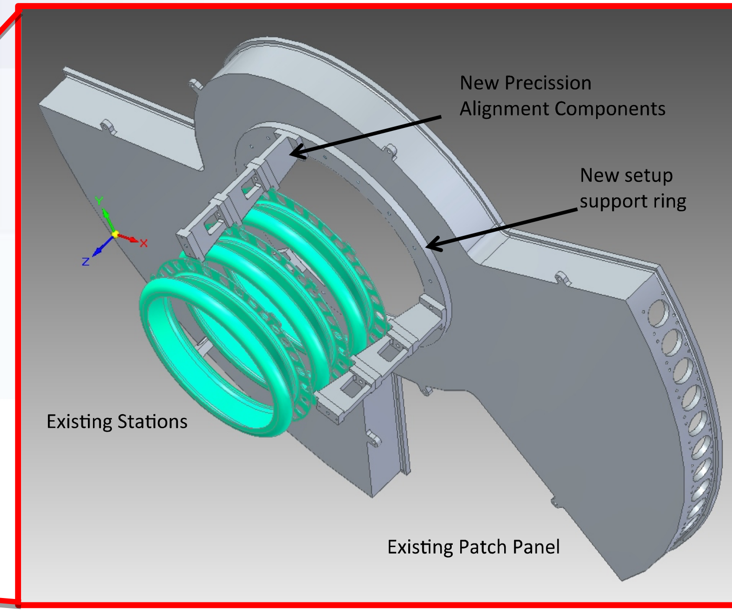


The integrated number of particle triggers collected by the MICE experiment in 2016. The shaded bands highlight the ISIS user cycles during which the ISIS machine was operational. MICE had collected just under 90×10^6 particle triggers in 2016.

The Future

MICE Step IV Extended



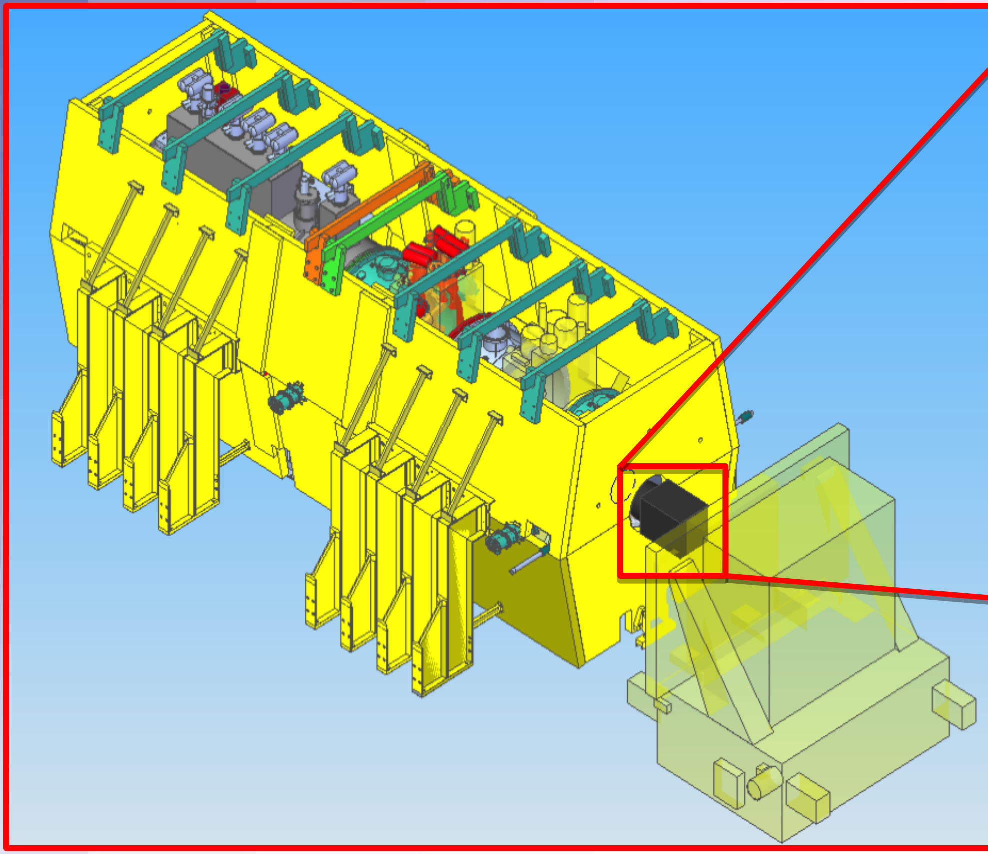


- RF cavity built and fully tested in Fermliab.
- RF to arrive at RAL within the next month.
- Tracker support vessel, first build stage complete.

- Including RF for beam acceleration.
- Fits in existing setup with new Tracker design.
- Feasibility study complete.
- The performance is very good.
- Minimal hardware works required and in hand.
- Program would complete by 2019.

The Future

MICE Step IV Extended



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The Future

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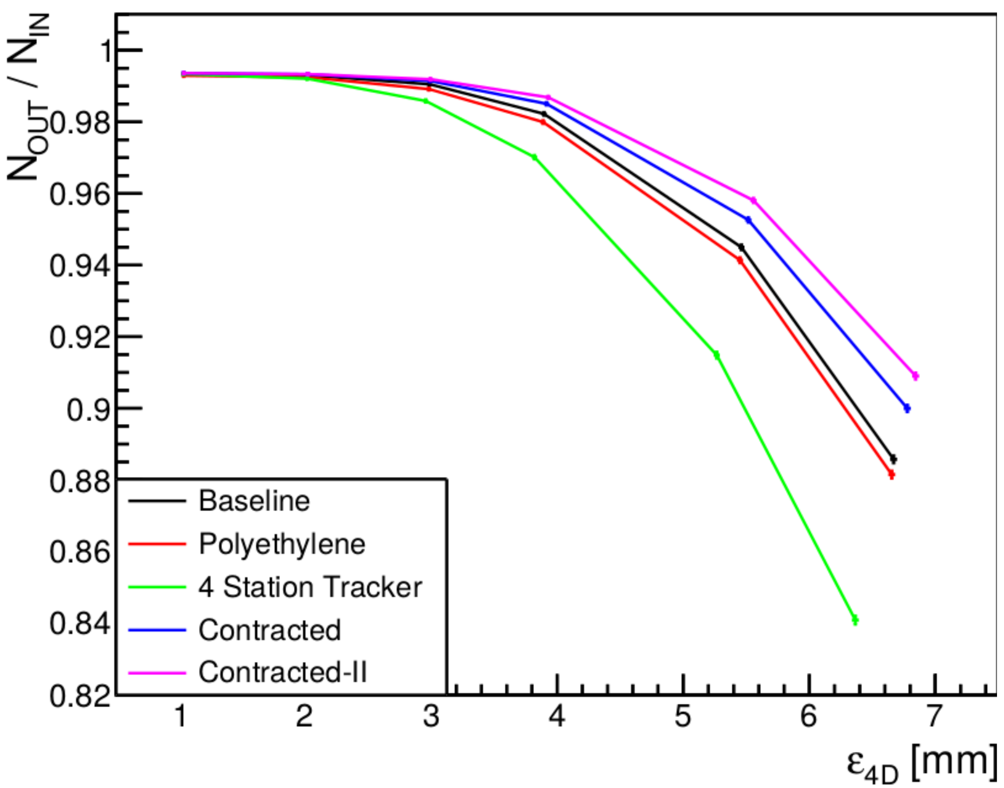

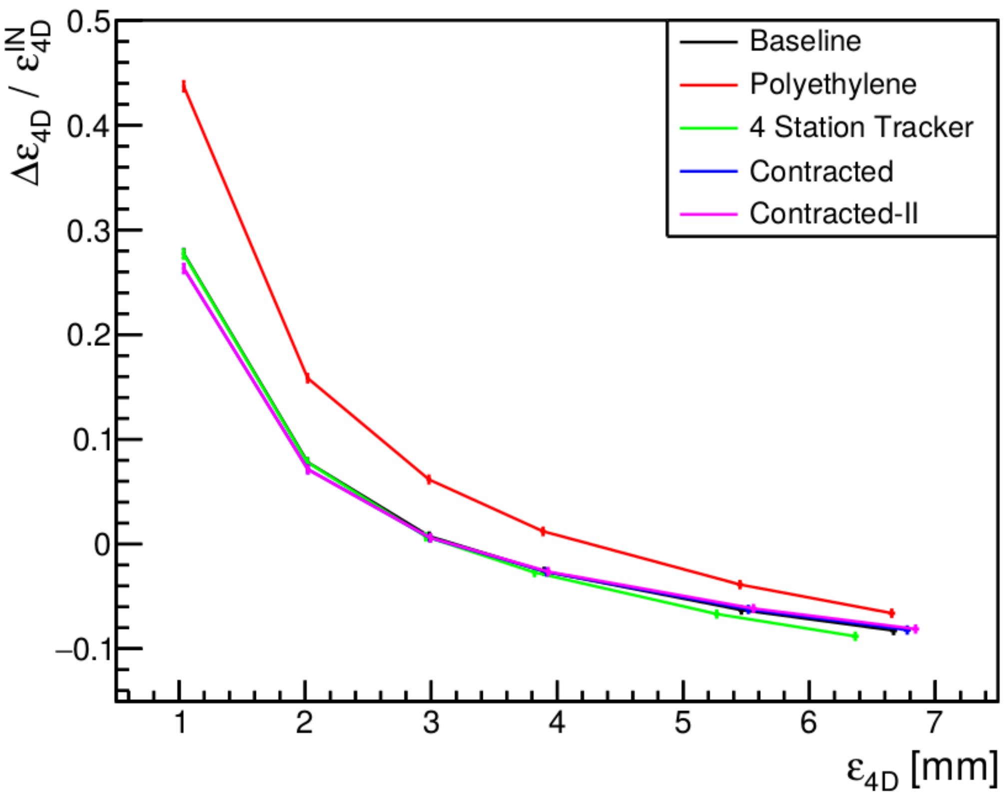

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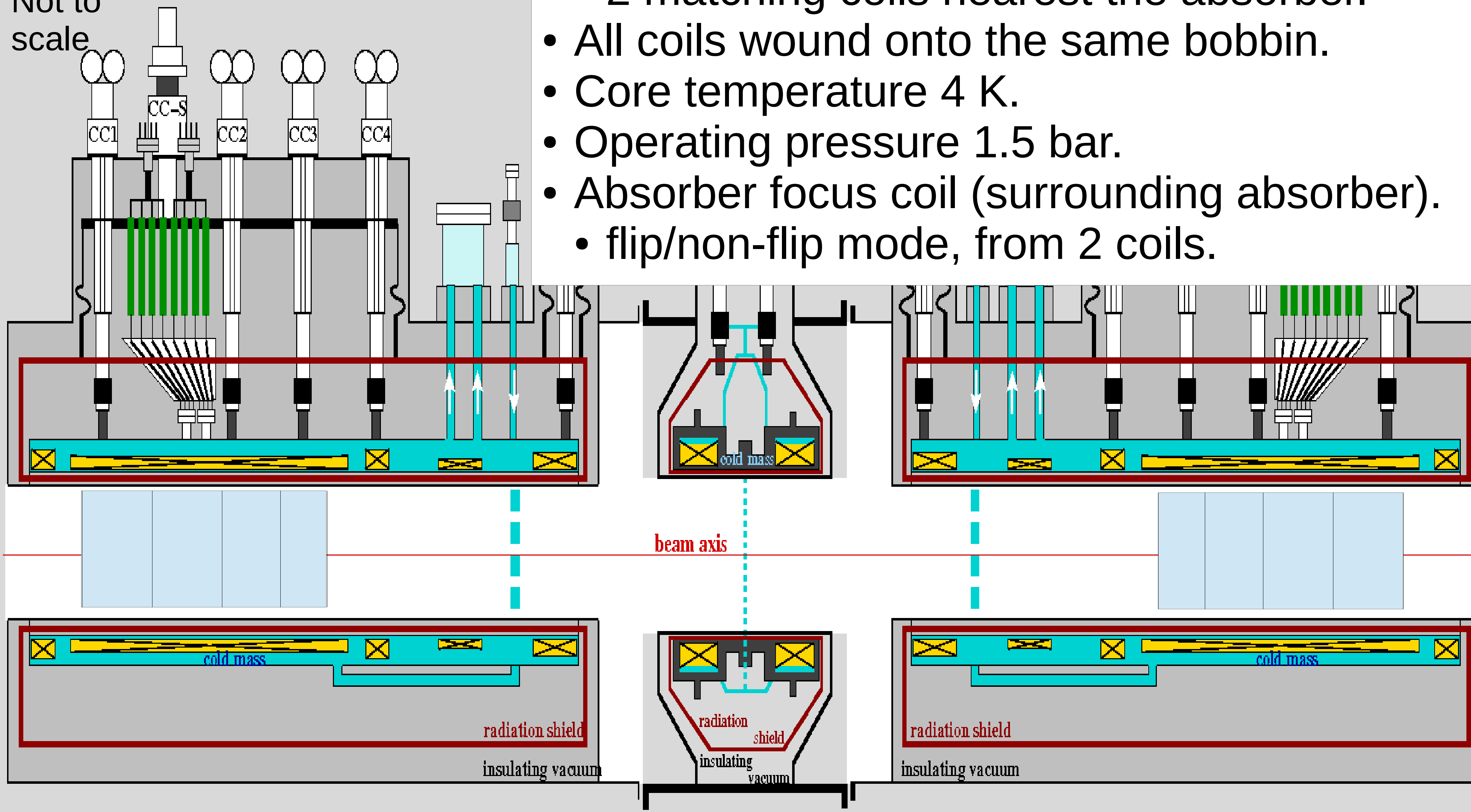
Conclusions

- MICE has been taking data since 2015.
- LiH scattering data taken and analysis nearly complete.
- Cooling channel magnets operated and data taken in flip and solenoid modes successfully.
- Diffuser data taken and analysis underway.
- Liquid Hydrogen installation in progress with data taking to being in June.
- The first direct measurement of emittance has been made in MICE.
  - The emittance was measured and chromatic effects were understood.
  - A technique paper is in preparation.
- First emittance change measurement to come in the near future.
  - MICE will observe transverse muon beam emittance reduction.
  - More to come!

The Magnets

- Two Spectrometer solenoids.
- Produce a 4 T magnetic field.
- 5 coils in each spectrometer solenoid:
  - Central coil which covers the Trackers.
  - 2 end coils either side of the central coil.
  - 2 matching coils nearest the absorber.
- All coils wound onto the same bobbin.
- Core temperature 4 K.
- Operating pressure 1.5 bar.
- Absorber focus coil (surrounding absorber).
  - flip/non-flip mode, from 2 coils.

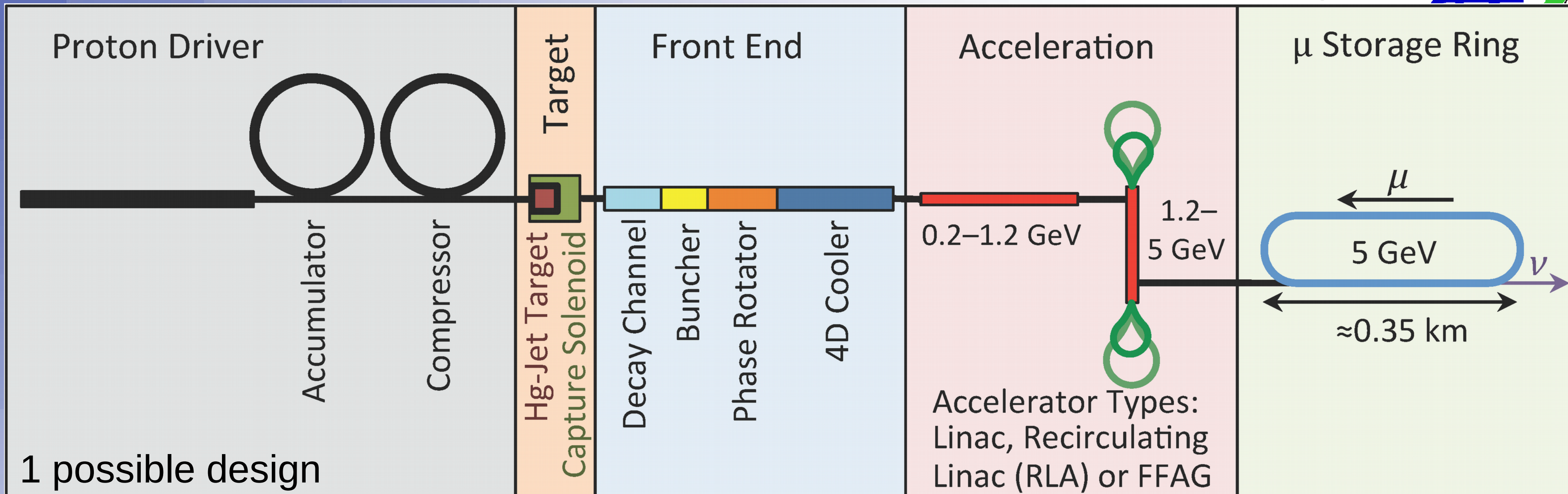
Not to scale



Motivation: Muon Colliders

- Muons have many important advantages over electrons for high-energy lepton colliders:
  - suppression of radiative processes as $m_\mu = 207 * m_e$
  - enables the use of storage rings and recirculating accelerators
  - "Beamstrahlung" effects, (radiation due to beam-beam interactions), much smaller in a muon collider than an e^+e^- machine
    - Circular e^+e^- colliders are energy limited and linear colliders are long and expensive.
  - The centre of mass energy of the collision can be precisely adjusted and the resonance structures and threshold effects studied in great detail in a muon collider.
  - Can sit on existing laboratory sites.

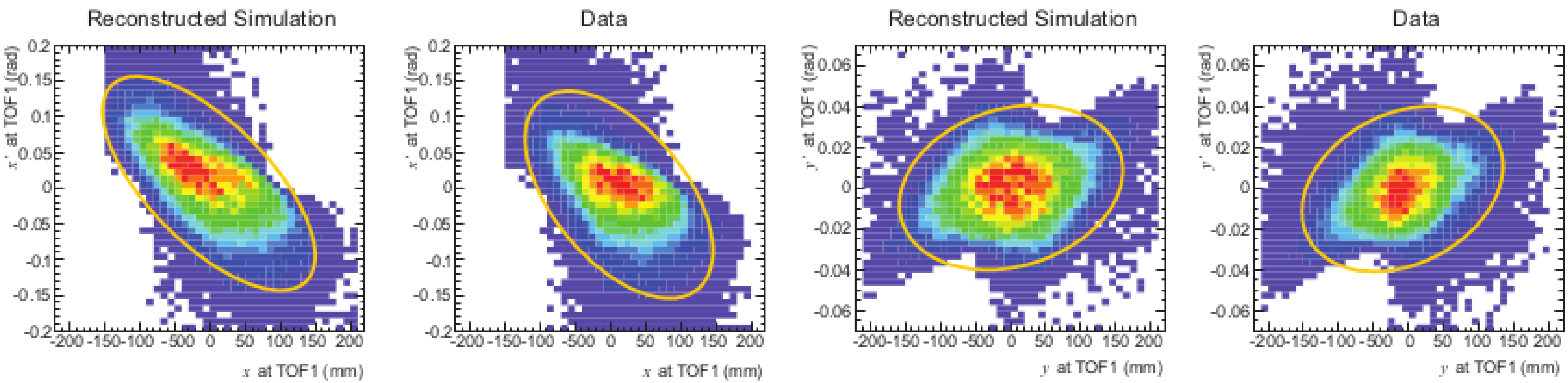
Motivation: Neutrino factory



- In order to measure δ_{CP} to 5σ we must understand the neutrino cross section to the 1% level.
- A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \rightarrow e^- \nu_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
- Provides collimated, high-energy neutrino beams with well-understood composition and properties.

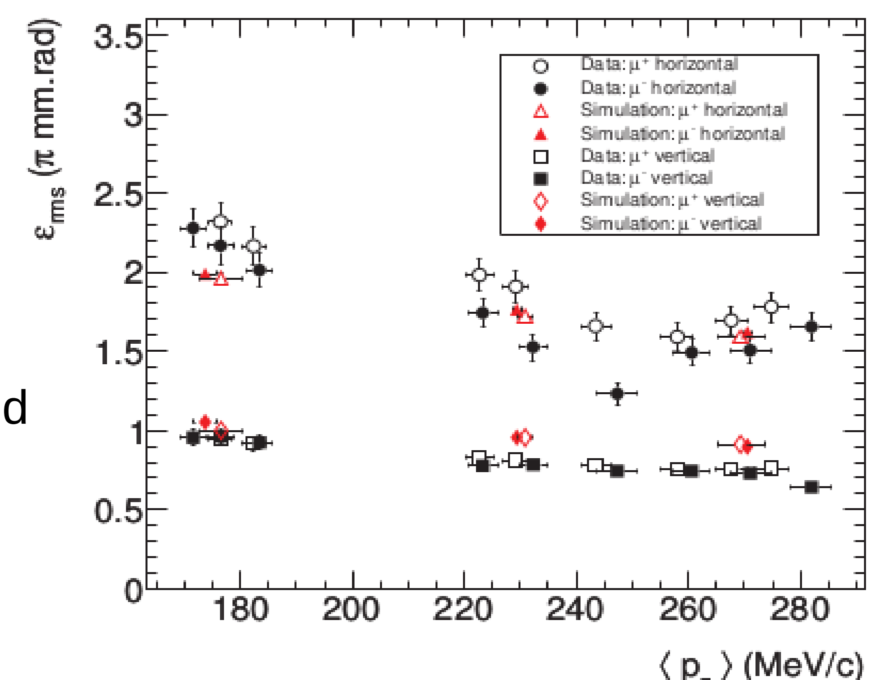
Step I

Reconstructed horizontal and vertical trace-space in simulation and data.



Horizontal and vertical RMS emittance in data and simulation.

A novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 π mm-rad, with central momenta from 170–280 MeV/c, and momentum spreads of about 25 MeV/c.



Ref. ArXiv:1306.1509

Step I

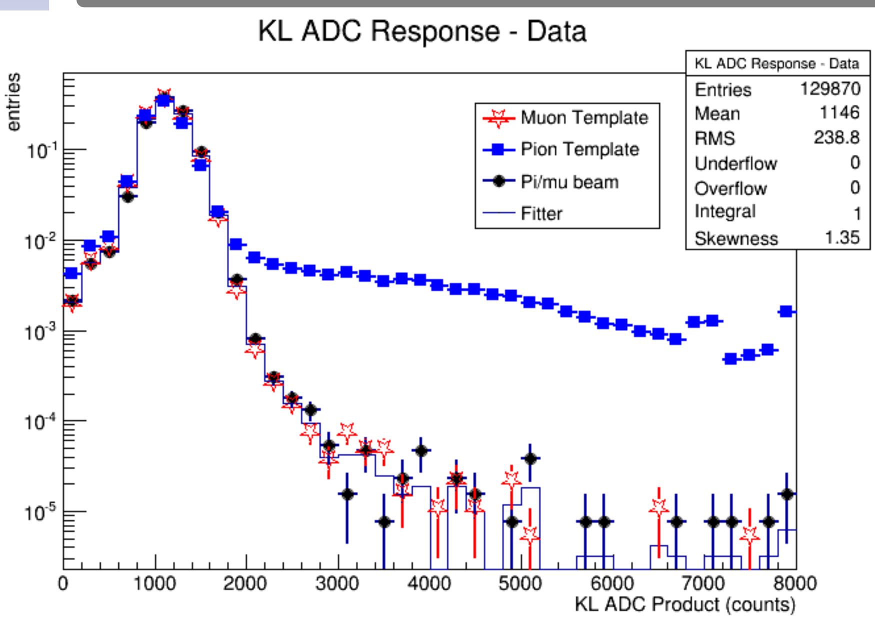
Muons per MICE target dip (spill) as a function of ISIS beam loss

μ⁻

ε_N (π mm · rad)	μ^- rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	4.1±0.2	6.3 ±0.2	4.9±0.2
6	4.1±0.4	4.8±0.2	4.5±0.2
10	4.6 ±0.2	5.4±0.2	4.4±0.1

μ⁺

ε_N (π mm · rad)	μ^+ rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	16.8±1.8	33.1±3.2	33.0±2.6
6	17.8 ±1.8	31.0±2.0	31.7±2.0
10	21.6±2.2	34.0±2.5	26.1±1.5

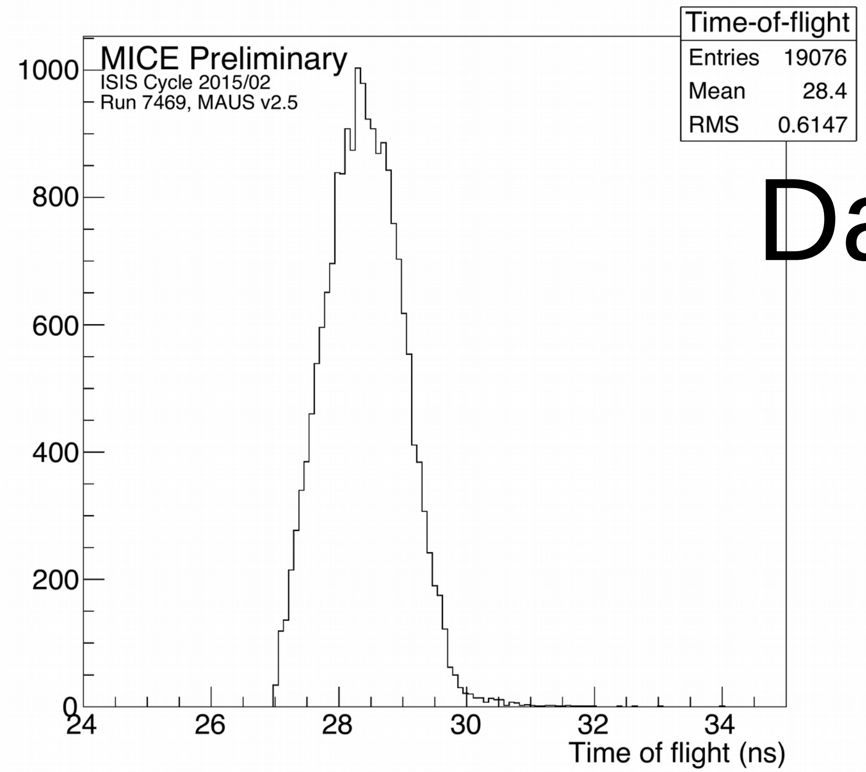


- Observed particle rates in TOF0 and TOF1 detectors were recorded and time-of-flight used to select good μ tracks.
- The rates are found to be linear with the ISIS beam loss/target depth.
- Errors mainly due to the time-of-flight cuts used to define a muon.
- Muons per spill is presently limited by the tolerance of the irradiation caused in ISIS by protons and secondary particles produced in the MICE target.
- Rates obtained are sufficient to collect the ~10^5 muons necessary to perform a relative measurement of cooling with a precision of 1%, in maximum one day.

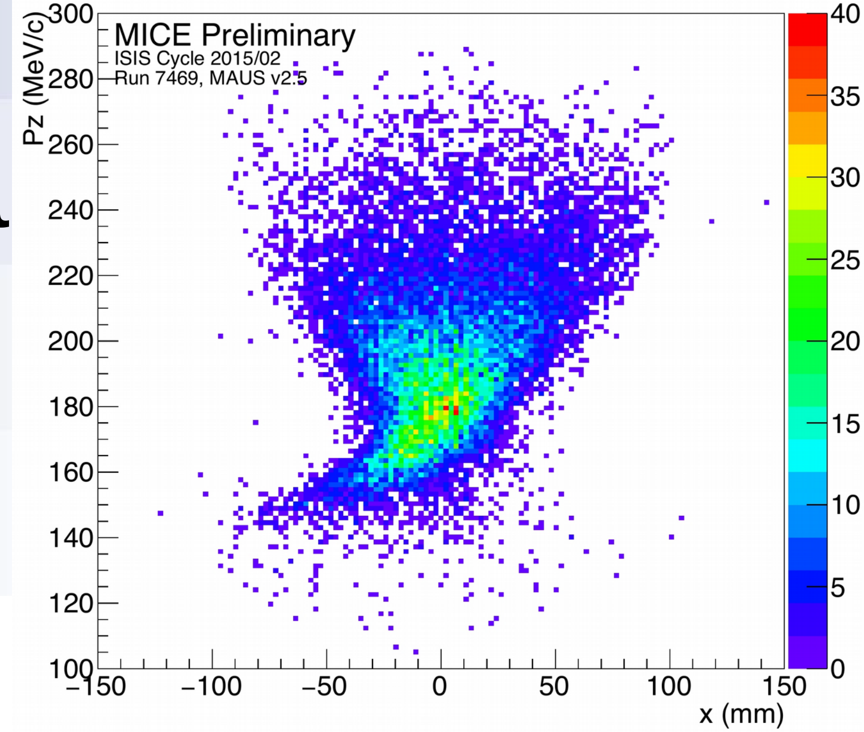
Ref. ArXiv:1203.4089

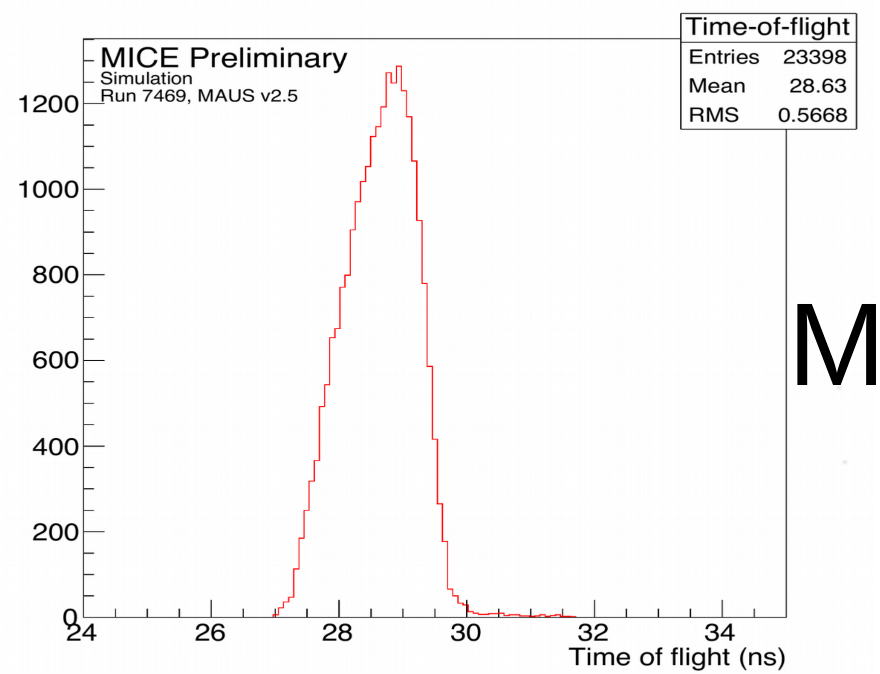
MICE Muon beam contamination

- Determination of MICE muon beam purity using the KL detector. A pion contamination in the muon beam at or below the 1% level (<5% for μ^+) is determined.

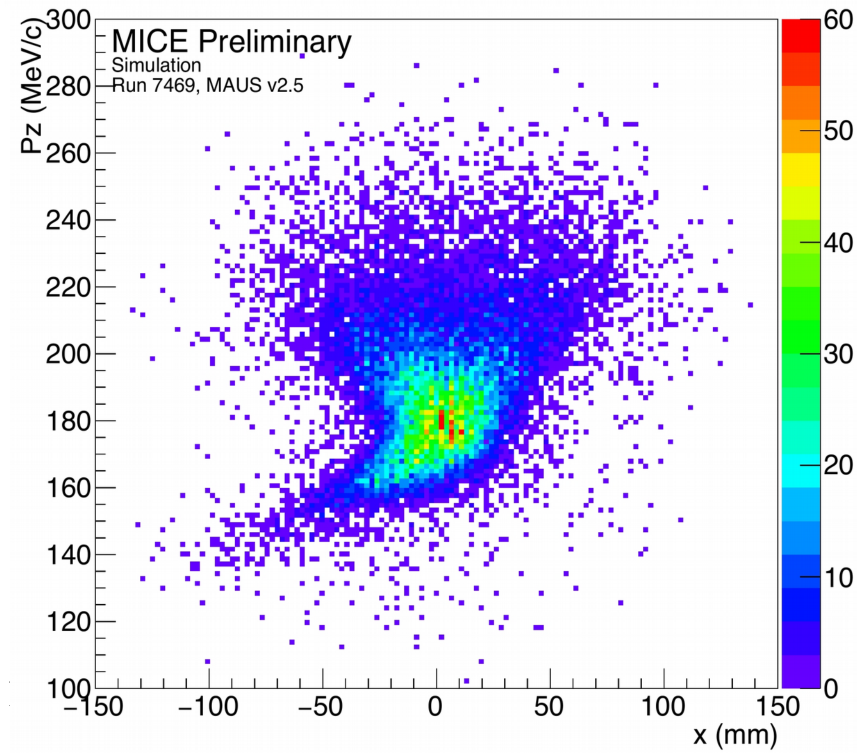

MICE Preliminary
ISIS Cycle 2015/02
Run 7469, MAUS v2.5
Time-of-flight
Entries 19076
Mean 28.4
RMS 0.6147
Time of flight (ns)

Data

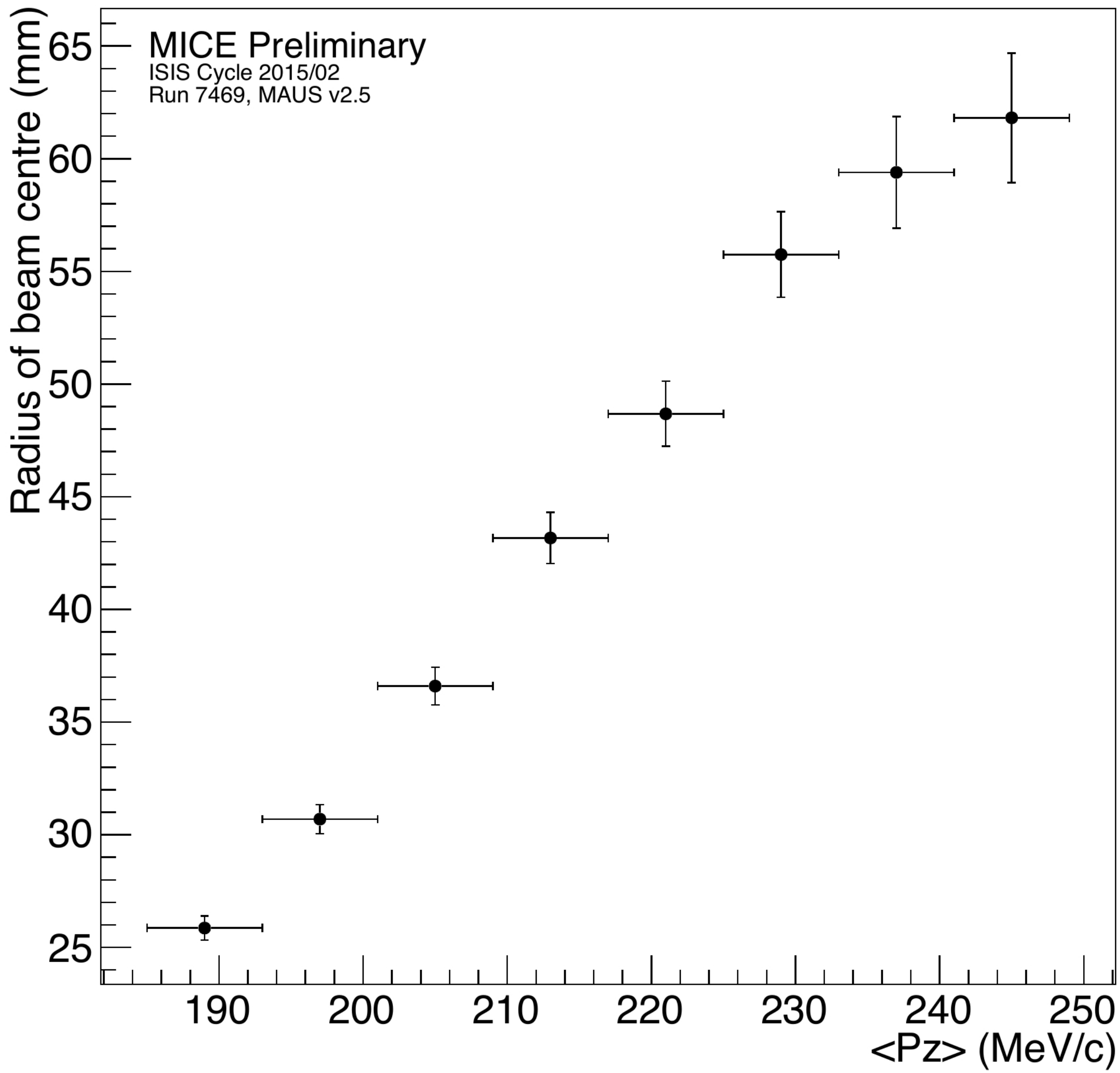

MICE Preliminary
ISIS Cycle 2015/02
Run 7469, MAUS v2.5
Pz (MeV/c)
x (mm)


MICE Preliminary
Simulation
Run 7469, MAUS v2.5
Time-of-flight
Entries 23398
Mean 28.63
RMS 0.5668
Time of flight (ns)

MC


MICE Preliminary
Simulation
Run 7469, MAUS v2.5
Pz (MeV/c)
x (mm)

Radial Position of Beam Centre against Pz in Data



Nearest to absorber

Tracker Reconstruction