The MICE Muon Ionization Cooling Experiment

Melissa Uchida
Imperial College London

COOL 2017

Imperial College London

Outline

- How MICE works.
- Why its necessary.
- The collaboration.
- The beam.
- The hardware.
- The headlines!

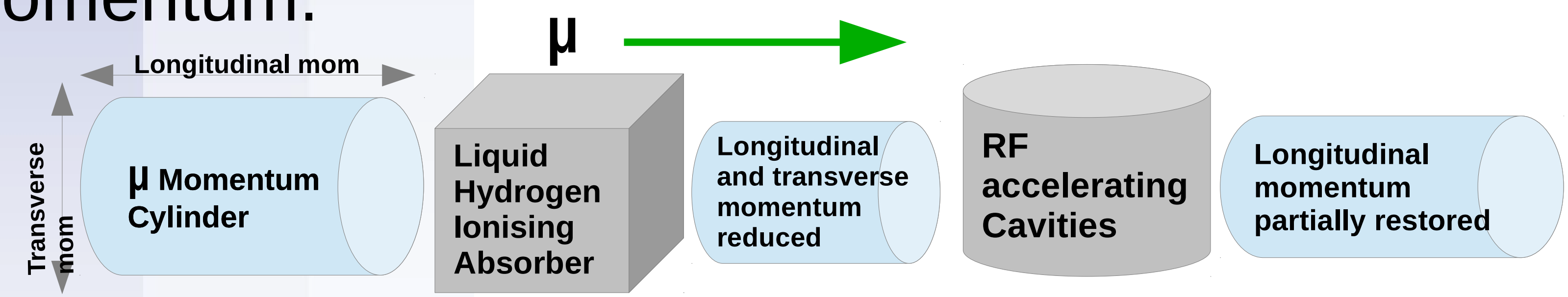
See the other three MICE talks today for more details.

Muon Ionization Cooling Experiment MICE

- ionization cooling is the process of reducing the beam emittance (phase space) through energy loss in ionization as particles cross absorber material combined with restoration of the longitudinal momentum of the beam through re-acceleration.
- Necessary for a Muon Collider or neutrino factory.
- Short lifetime of muon means that
  - traditional beam cooling techniques which reduce emittance cannot be used.
  - ionization cooling is the only practical solution to preparing high intensity muon beams for use in these facilities.

What is Muon Ionization Cooling?

- A muon beam loses both transverse and longitudinal momentum by ionization when passed through an `absorber'
- The lost longitudinal momentum is then fully/partially restored by RF cavities.
- The result is a beam of muons with reduced transverse momentum.



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

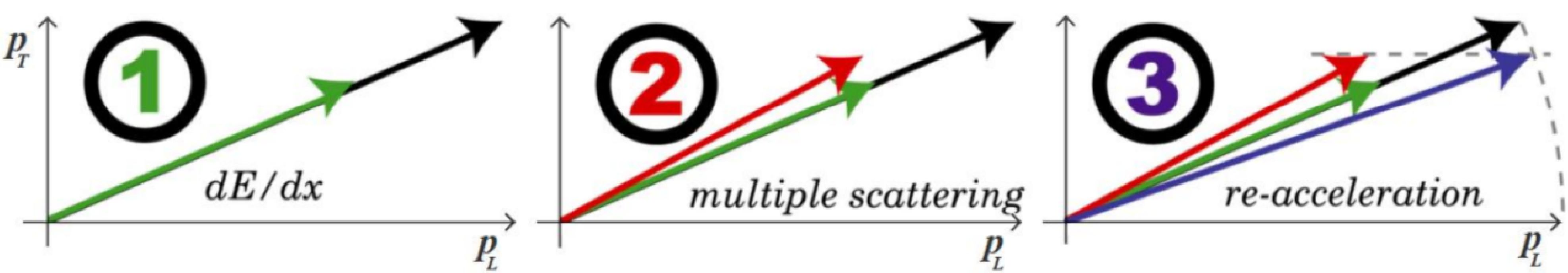
What is Muon Ionization Cooling?

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

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

$d\epsilon_n/ds$ is the rate of change of normalised-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; 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 L_R
- RF cavities restore p_L only
- The absorber must be placed at a focus for best cooling performance

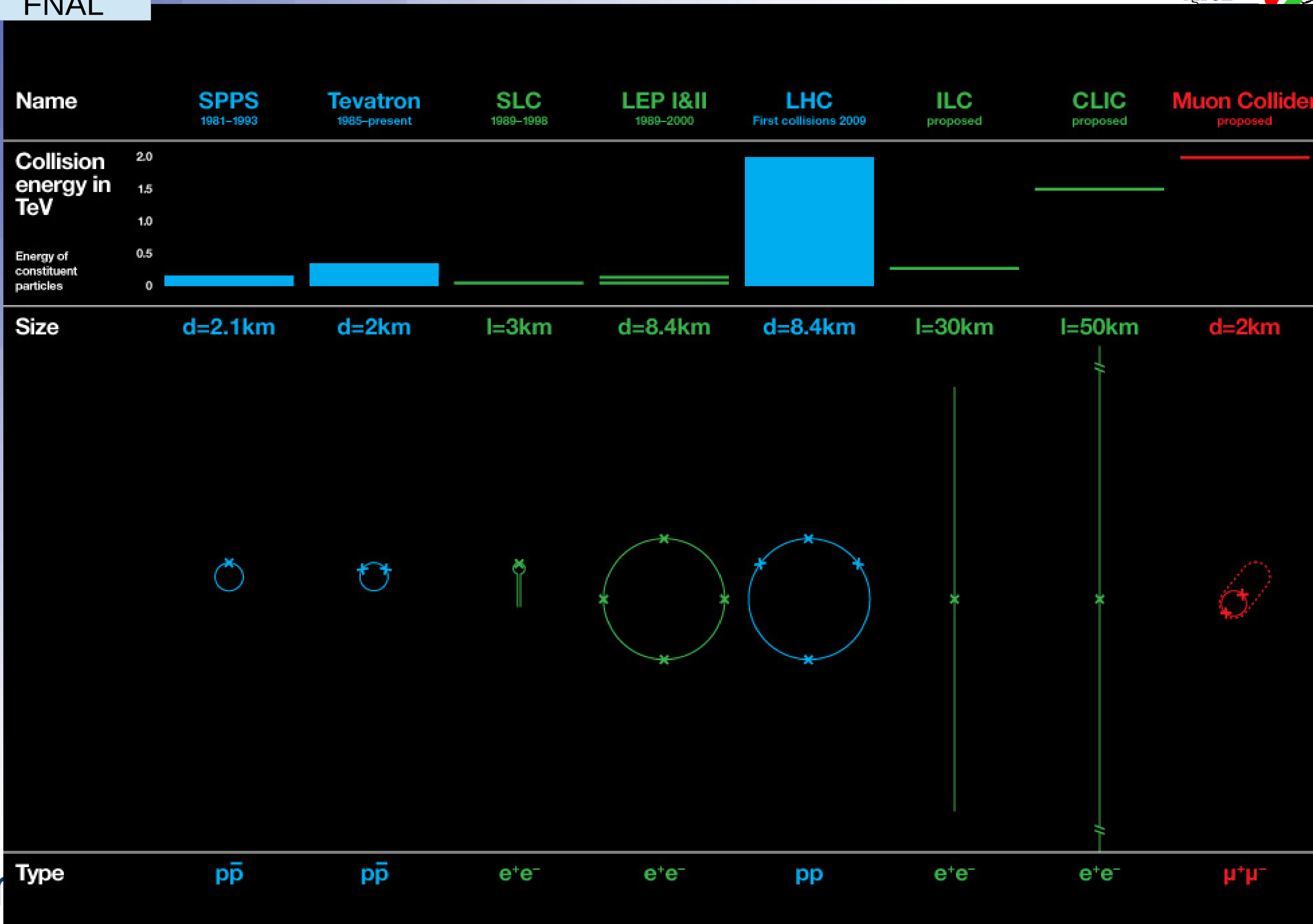


Motivation

- 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.
- Performance and cost depends on how well a beam of muons can be "cooled".
- Ionization 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 by a Muon Collider and will significantly improve physics potentials of future facilities such as a Neutrino Factory.
- MICE is currently the only experiment studying ionization cooling of muons.
- Recent progress in muon cooling design studies nourishes the hope that the building of such facilities can be begin within the next 20 years.

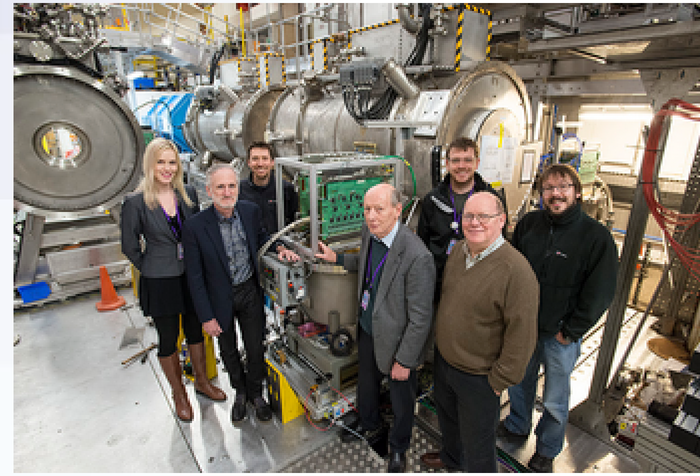
Borrowed from FNAL

Size Comparison of Colliders



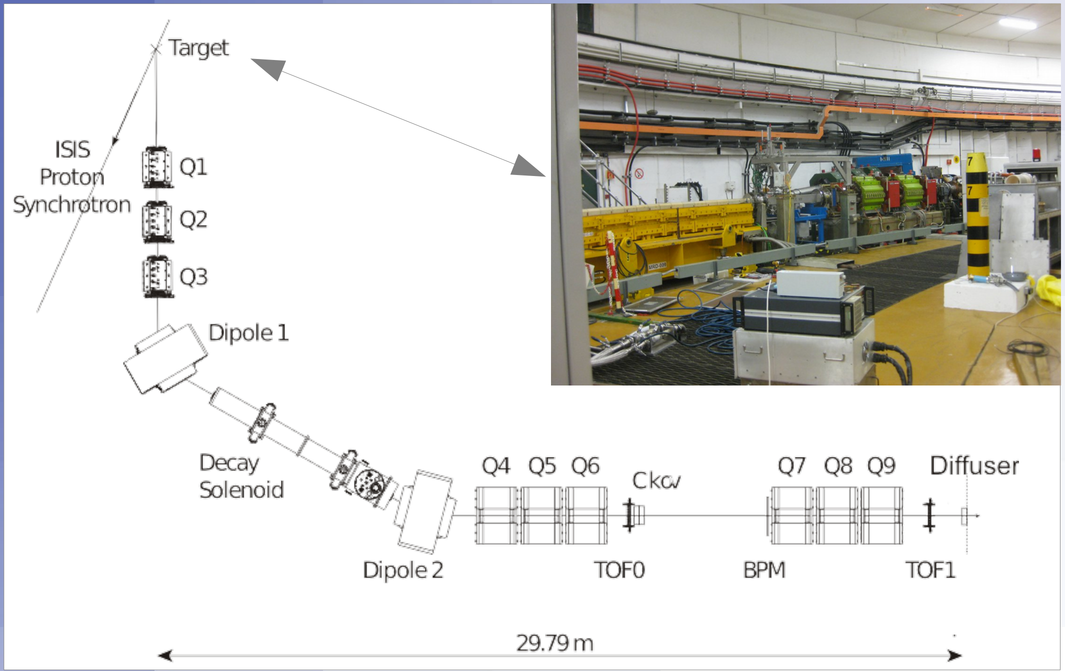
MICE: Muon Ionization Cooling Experiment

MICE: Collaboration



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

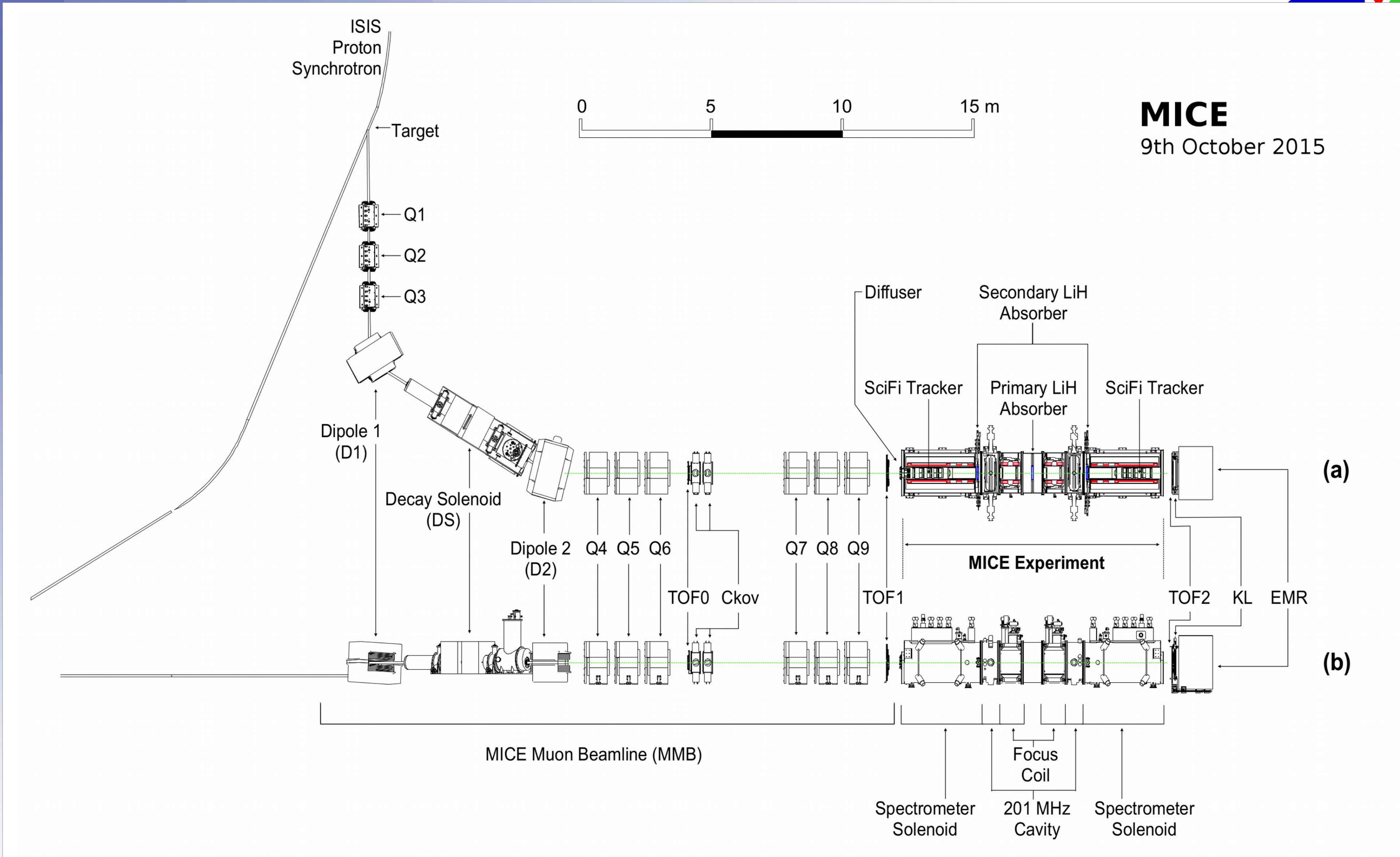
The Beam



- 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 beamline.

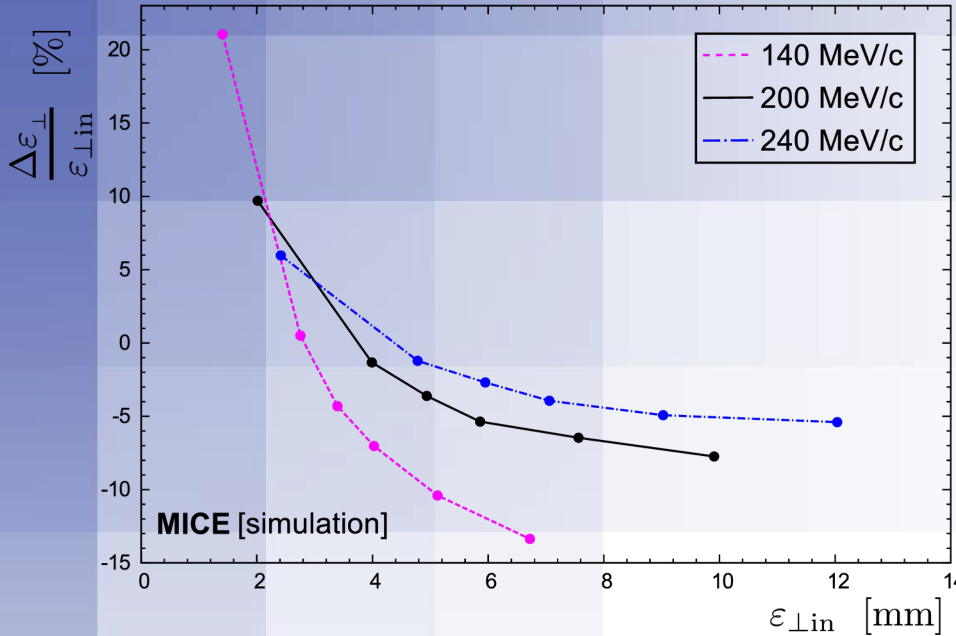
- Pions (π^+) produced in target decay to muons of lower momentum.
- Beam can be prepared as a π beam or μ beam with momenta between 140-450 MeV/c.
- Dip rate: 1 dip/1.28s
- Max Particle rate:
  - μ^+ ~120 μ/dip
  - μ^- ~20 μ/dip
- Final μ beam: 3ms wide spill in 2 100ns long bursts every 324 ns.

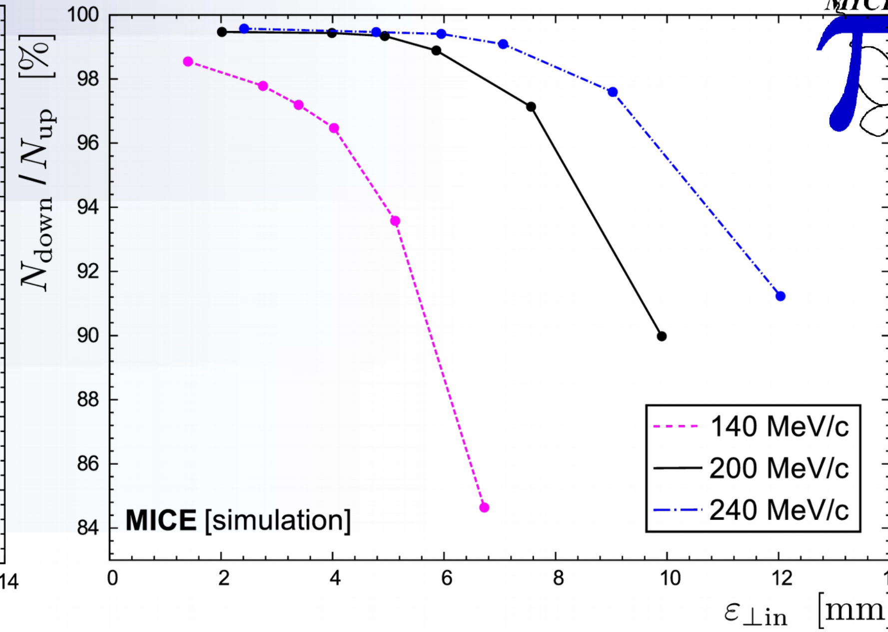
MICE Beamline



Decay Solenoid to enhance the initial pion to muon decay process, dipoles for momentum selection and quads for beam focusing.

MICE: The trade off

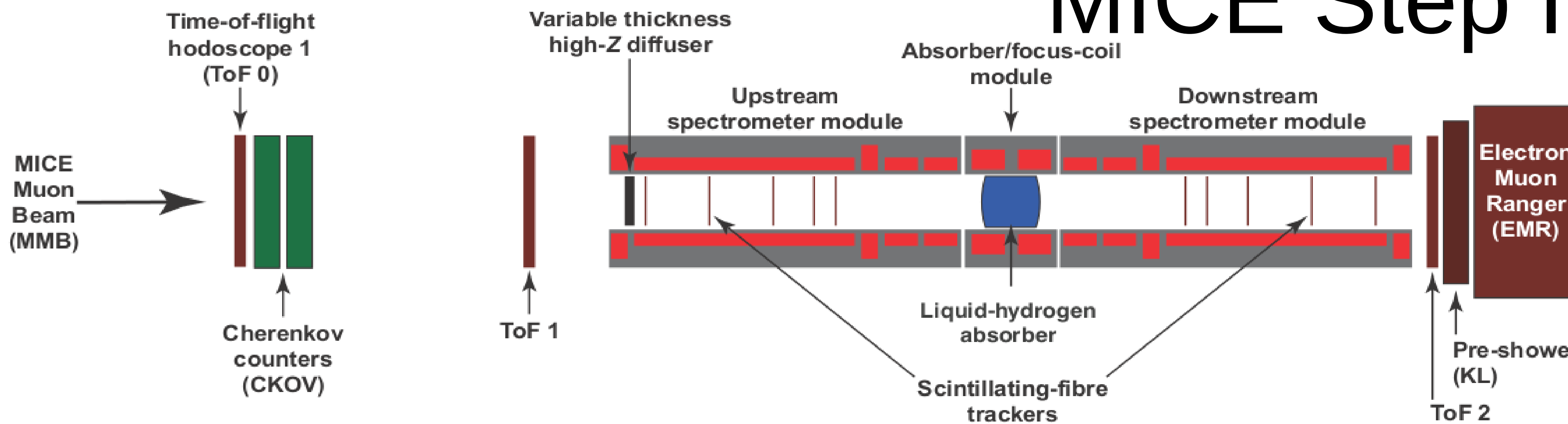




(left) Change in emittance, and (right) beam transmission (both in percent), vs. input emittance.

- The effect of the heating & cooling terms is an equilibrium emittance $\varepsilon_{n,eq} \propto \beta_\perp / \beta X_0 \langle dE_\mu /ds \rangle$ below which the beam cannot be cooled.
- However, as input emittance increases, beam scraping results in increased loss.
- MICE will study this 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

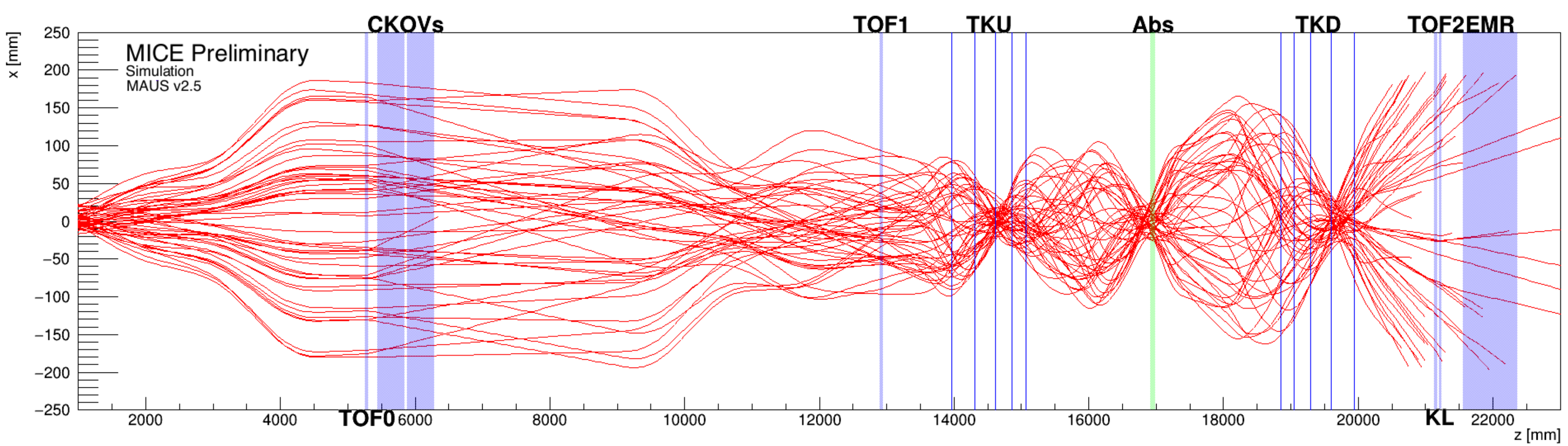


- Includes the two solenoidal spectrometers (5 coils each), an absorber focus coil (AFC 2 coils) and an absorber (liquid-hydrogen, lithium-hydride etc);
- Detectors: Time Of Flight, 2 cherenkov counters, a downstream calorimeter and 2 scintillating fibre trackers.
- allows normalised emittance change of beam passing through an absorber to be measured (before and after the absorber by the Trackers),
- over a range of momenta and under a variety of focusing conditions.
- **Data taking well underway and many papers in progress!!!**

Single Particle Experiment

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

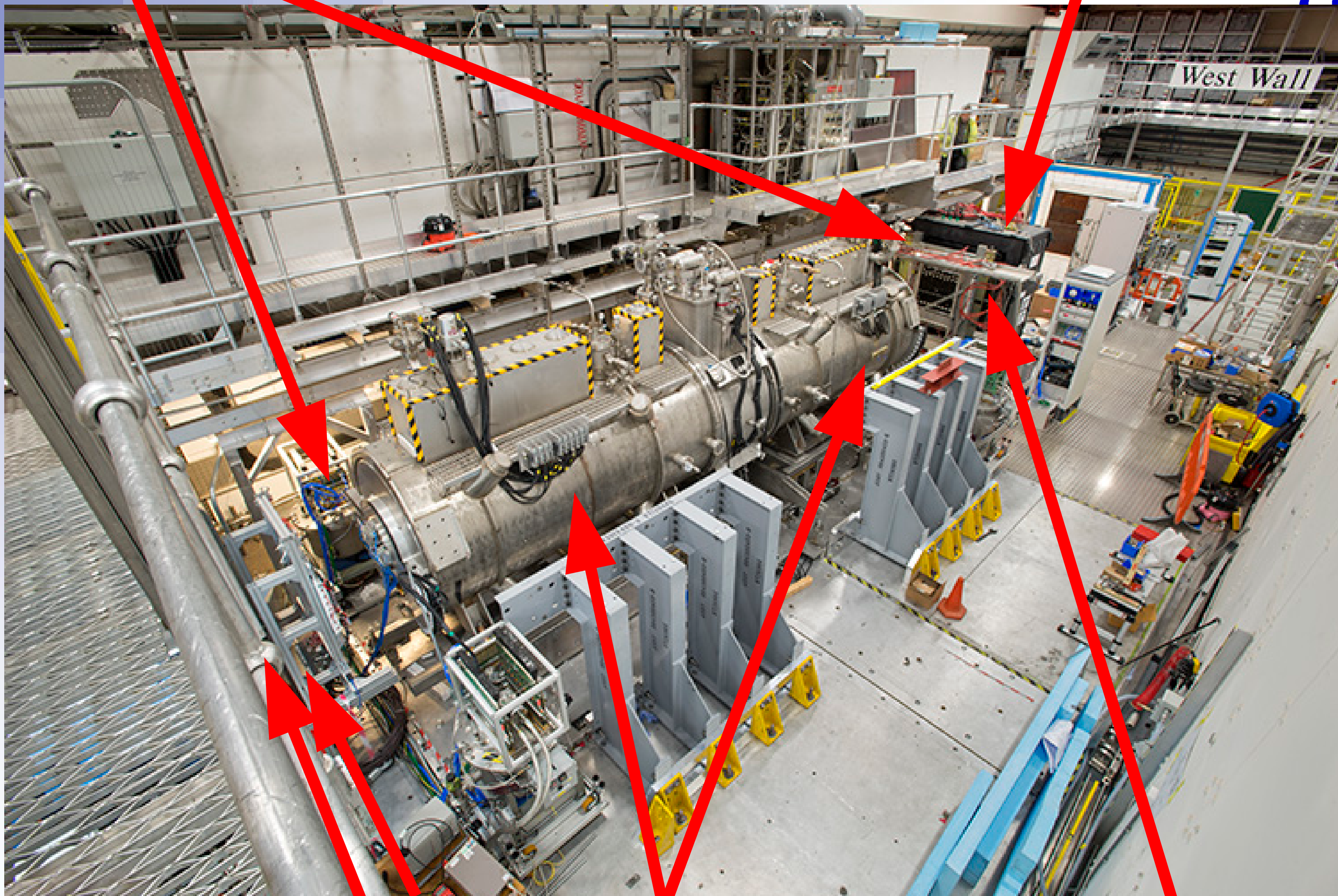
- There is no “beam” as such, instead, particles go down the beam line one by one
- At each DAQ cycle, a single particle track is recorded
- Particle tracks are bunched at the analysis level from which the emittance is computed.
- First direct measurement of emittance of muon beams by a scintillating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



The Detectors

Time of flight:
TOF0,1 and 2

Electron Muon
Ranger:
EMR



Cerenkov:
CkoVa CkoVb

Trackers

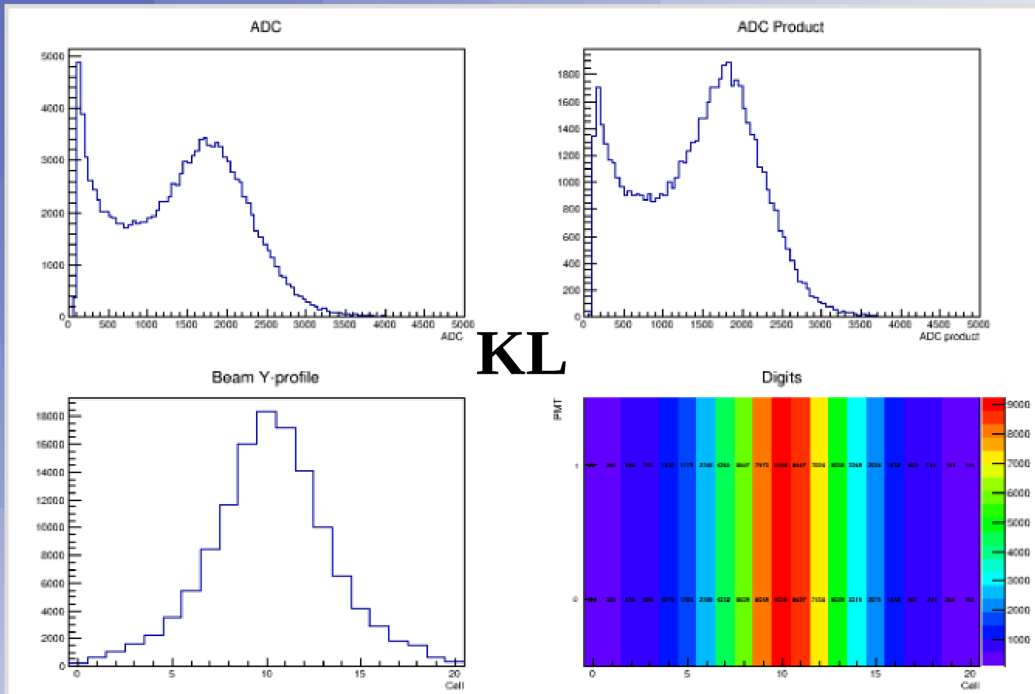
KLOE-Light:
KL

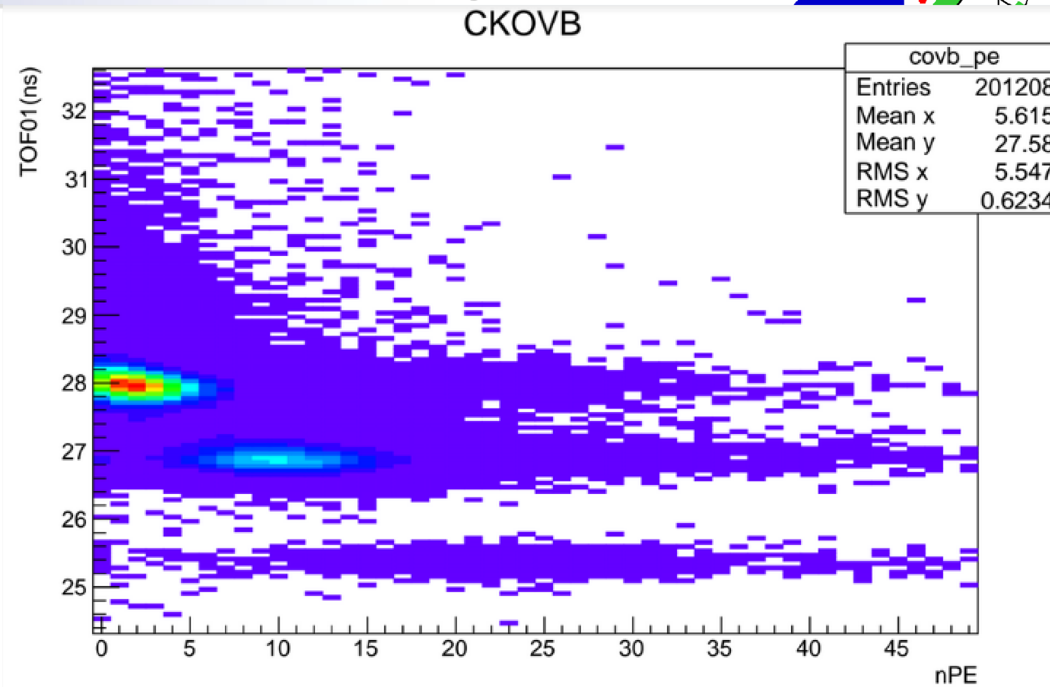
The Detectors

- Time Of Flight: TOF0, TOF1 and TOF2
  - precise timing and time of flight measurements.
- Electron Muon Ranger: EMR
  - to separate muons from decay electrons in collaboration with the..
- KLOE-Light: KL
  - based on the Kloe calorimeter design
- Cerenkov: CkoVa CkoVb
  - Threshold Cerenkov counters
- Trackers
  - 2 Tracker detectors upsteam and downstream of cooling section, each immersed in a uniform magnetic field of 4T.
  - Measure the normalised emittance reduction with a precision of 0.1% (beam emittance measured before and after cooling).
- Provide π/μ separation up to 300 MeV/c.

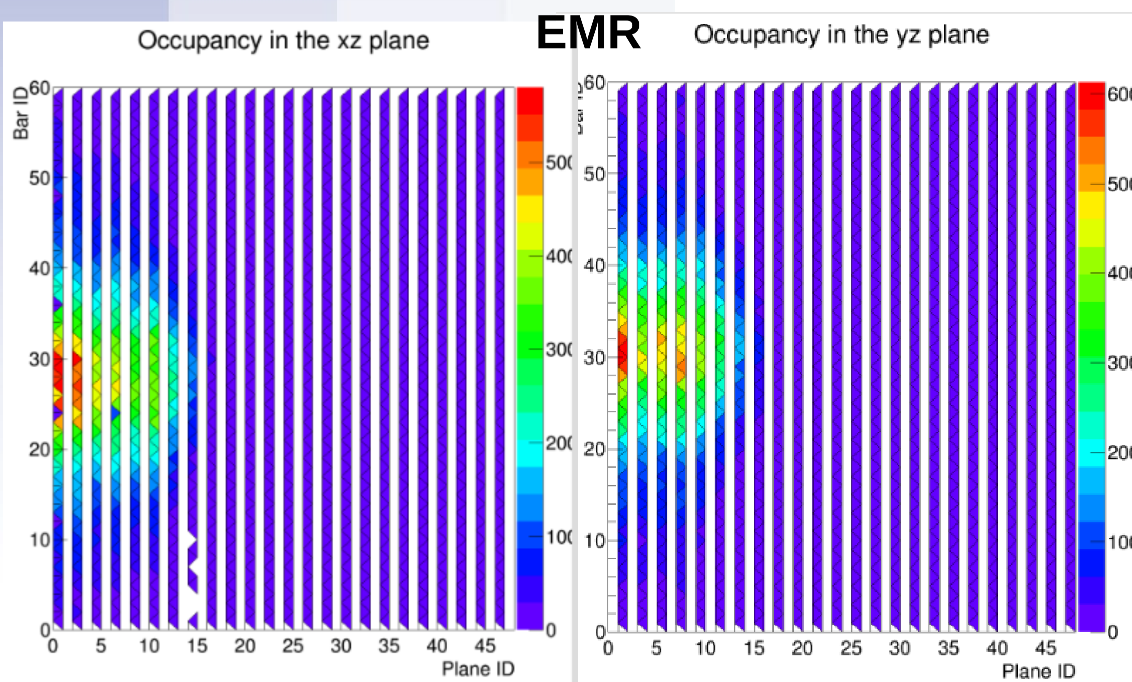
All Detectors Performing Well

KL

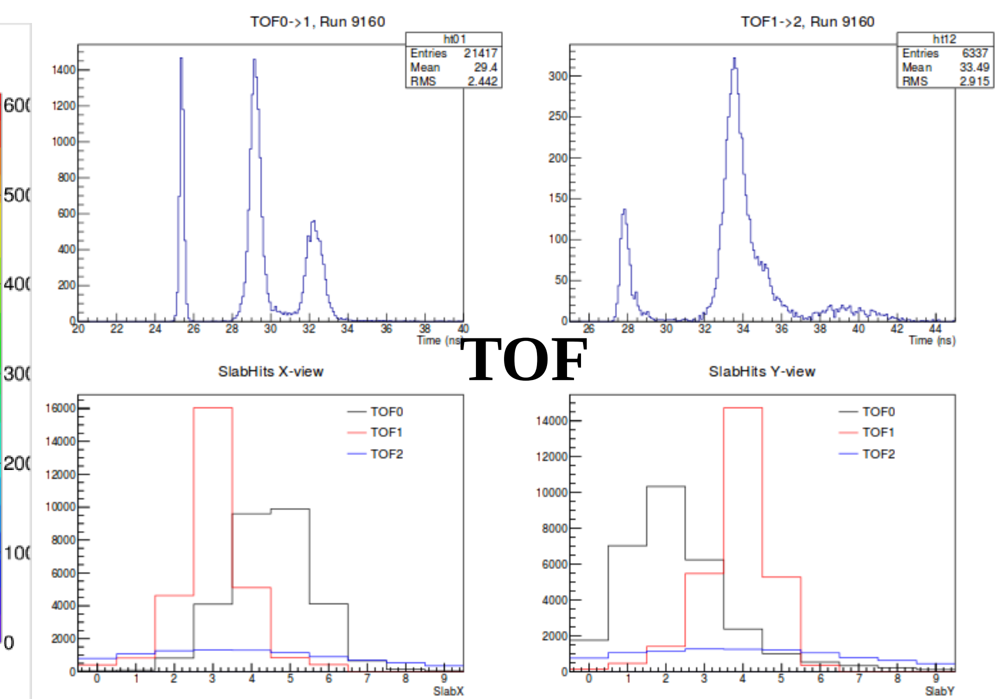




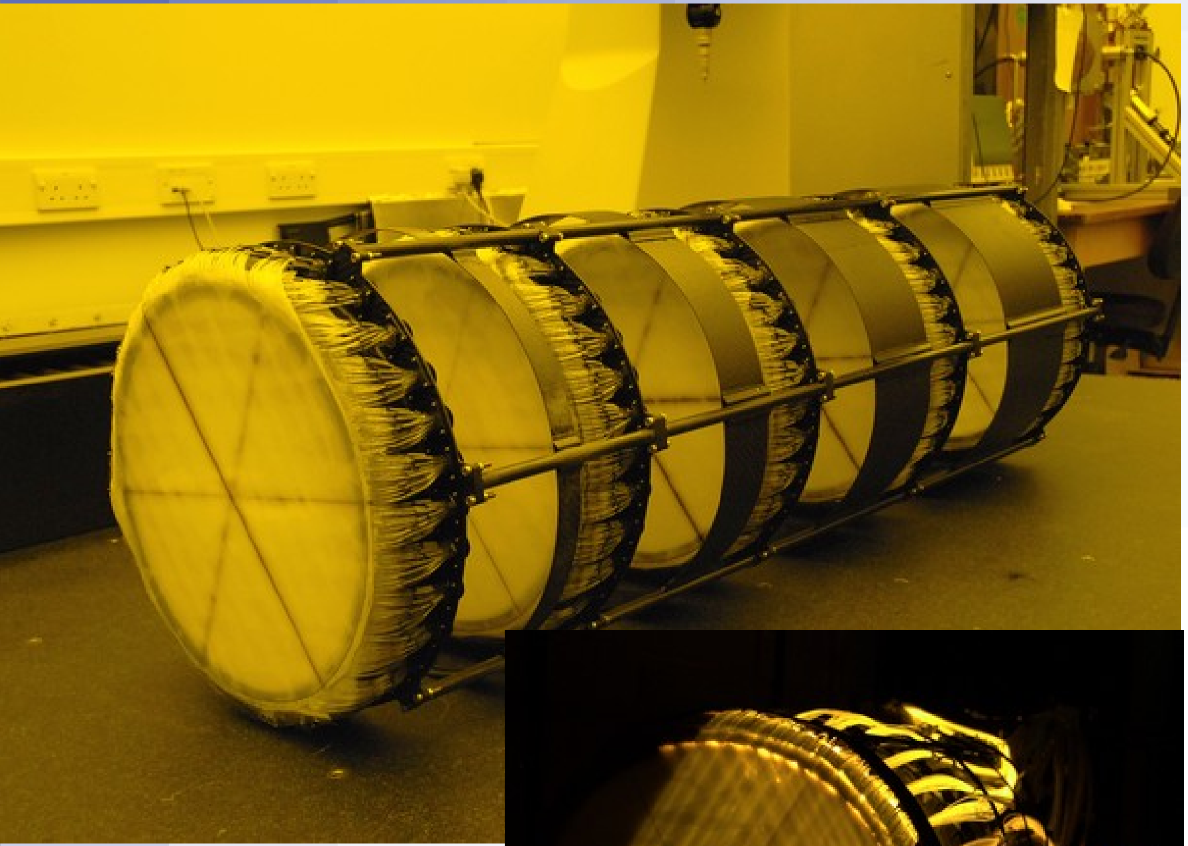
EMR

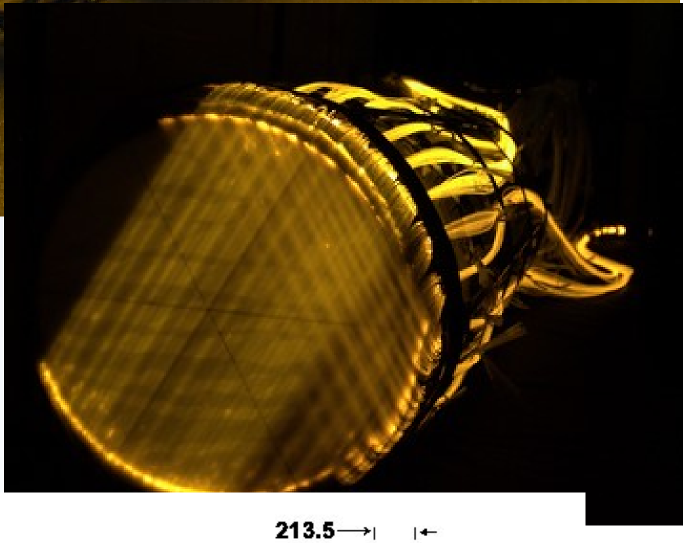


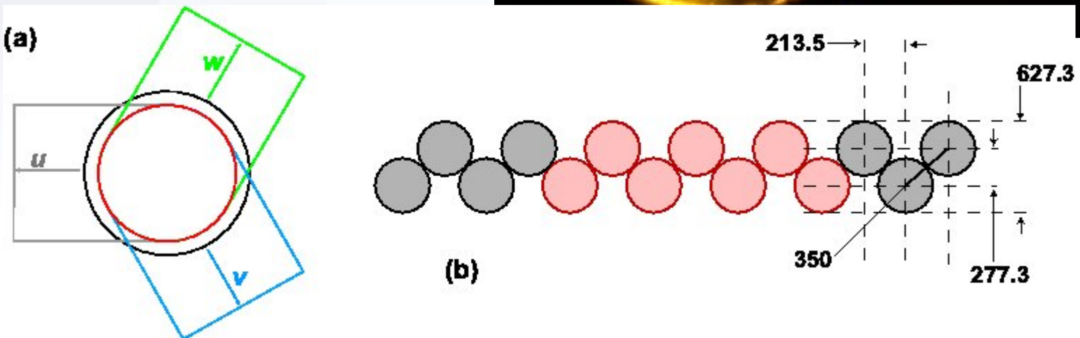
TOF



The Trackers



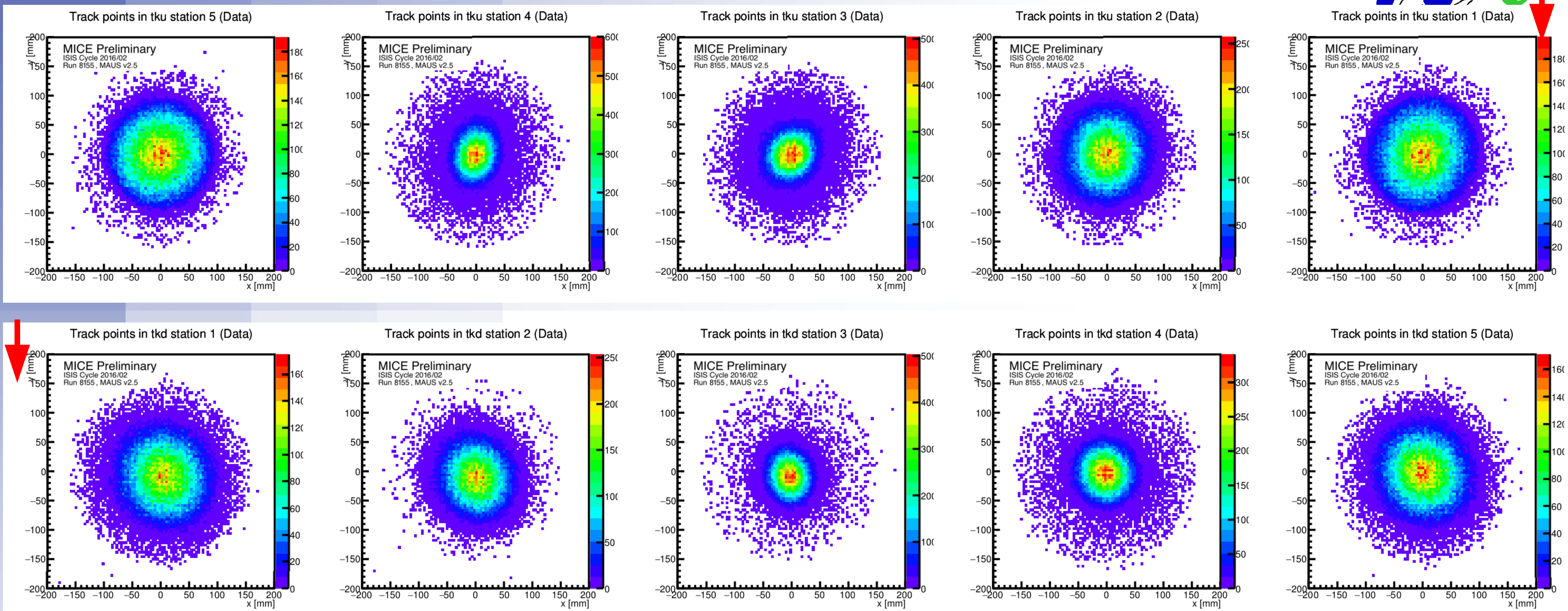




- Two scintillating fibre trackers, one upstream, one downstream of the cooling channel.
- Each within a spectrometer solenoid producing a 4T field.
- Each tracker is 110 cm in length and 30 cm in diameter.
- 5 stations
  - varying separations 20-35 cm (to determine the muon p_T).
- 3 planes of fibres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

Nearest to absorber

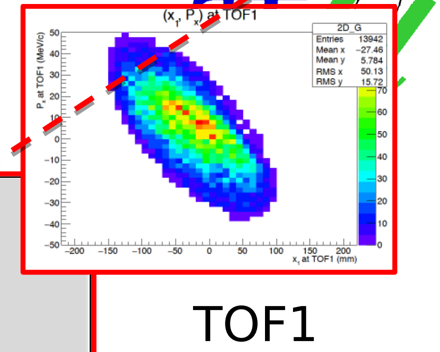
Tracker Reconstruction

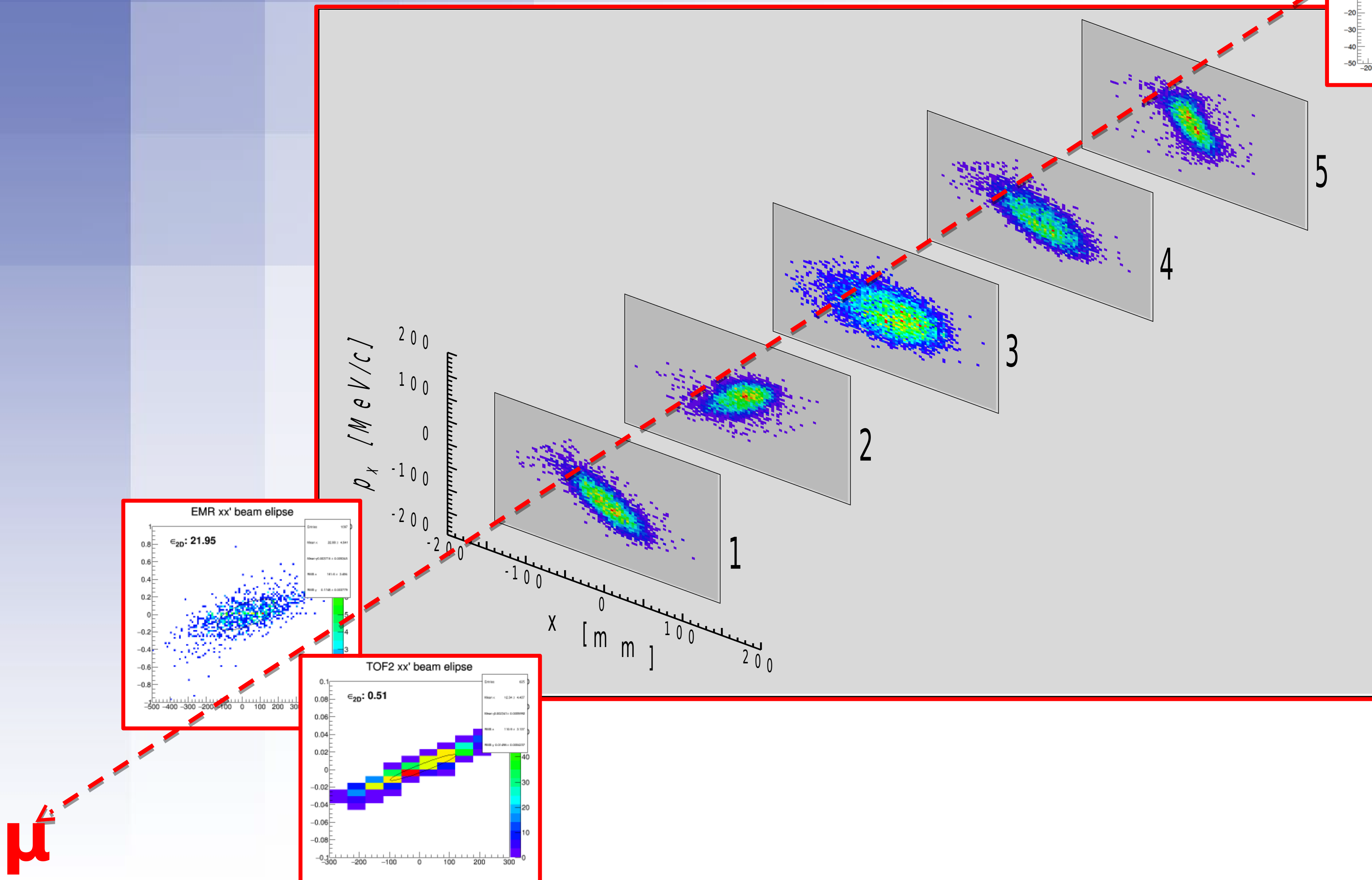


Space point distributions in both trackers.
The stations are ordered from the most upstream to the most downstream, i.e. from 5 to 1 upstream and from 1 to 5 downstream.
The red arrows denote the stations nearest to the absorber

Principles of MICE Phase Space Reconstruction

- Data from 7th October: SSU(E-C-E) 4T

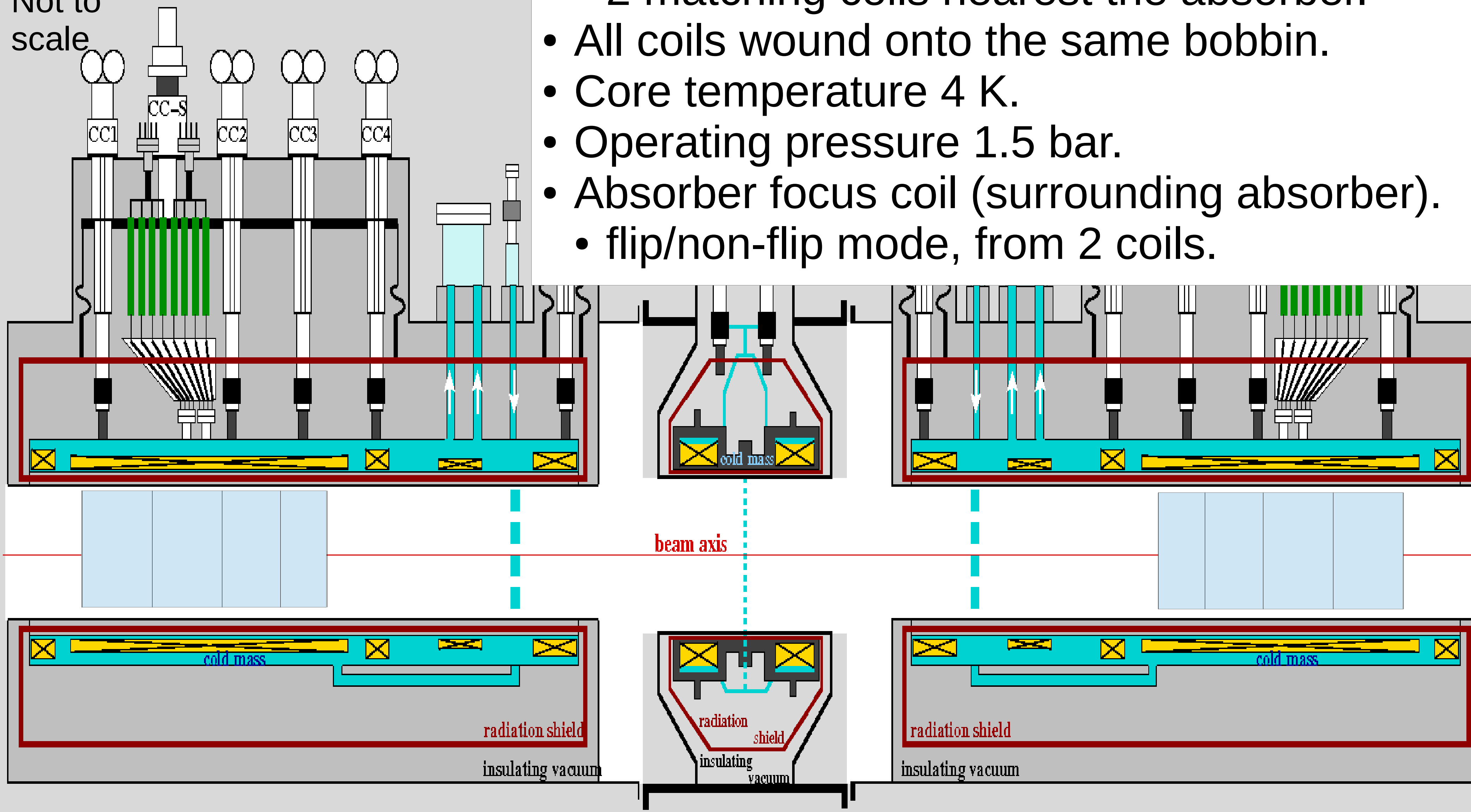




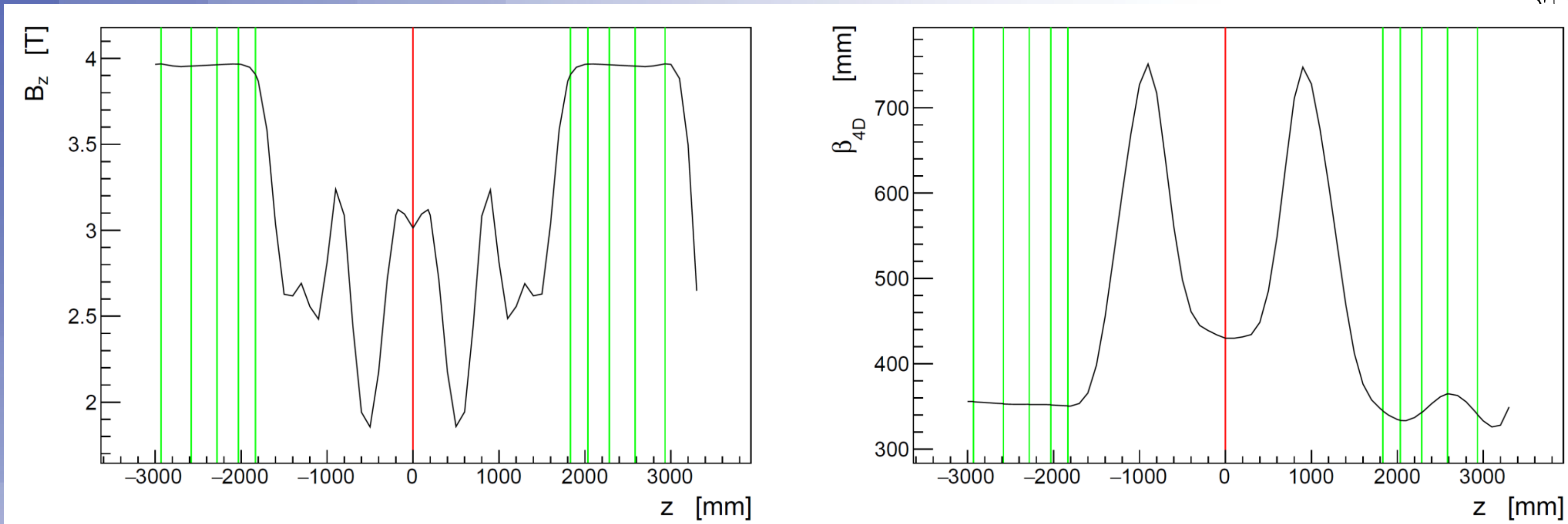
The Magnets

- 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



Design Of Beam Optics in Cooling Channel



Bz and Beta in solenoid mode at 4T

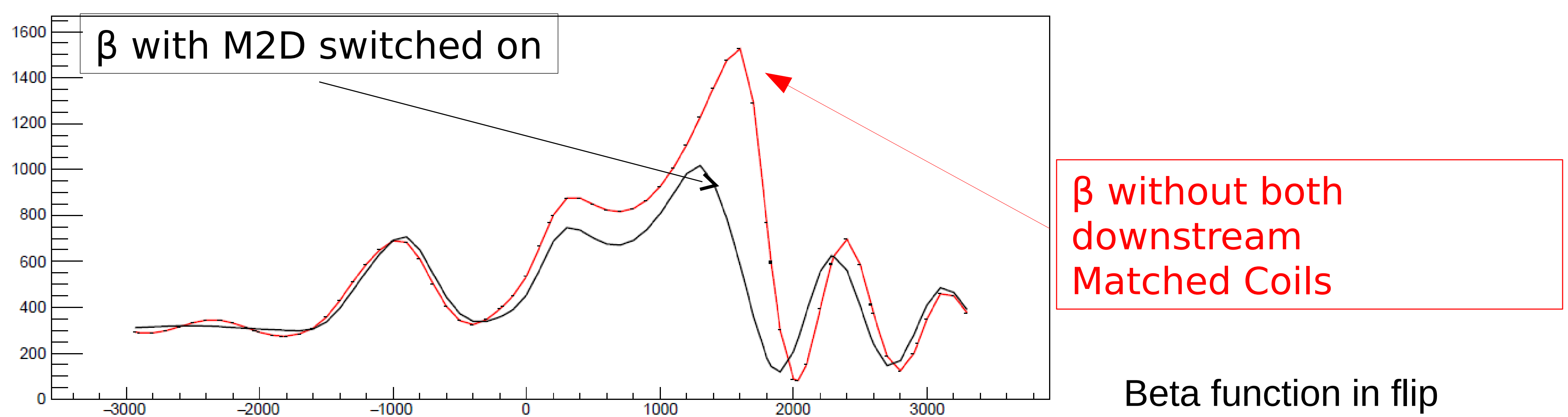
C. Hunt (IC) Thesis 2017

Beam incoming from beam line, optimised for transmission, passes through variable thickness high-Z diffuser to increase emittance above the equilibrium value in a controlled way at the entrance to the Channel.

- Optics of the channel assumes matched beam (α=0) in both upstream and downstream solenoids.
  - To maximise transmission.
  - To minimise emittance growth due to mismatch.
  - In practice this condition is met only approximately, but a matched beam sample can be selected with sufficient statistics.
- Small beta waist is created with the help of Matched Coils and AFC at absorber (centre).
  - Solenoid and flip modes are proposed and used for data taking.
- Optics can only be approximately symmetric due to energy loss and large momentum spread.

Beam Optics: Data Taking

- Failure of QPS during training caused one of the Matching Coils in SSD to be inoperable.
- This caused beam mismatch and a decrease in transmission, which could be partially compensated.
  - Compensation required operation with reduced field in SSs (4T→3T)
  - As an effect the optics is non-symmetric
- In the downstream solenoid, the second match coil (M2D) was not operated as a precaution.
  - Operation with M2D on is foreseen in October.
- The flexibility of the lattice has allowed the optics to be tuned such that a cooling signal is expected.



Beta function in flip mode

Emittance Calculation

The 4D normalised RMS transverse emittance is defined as

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

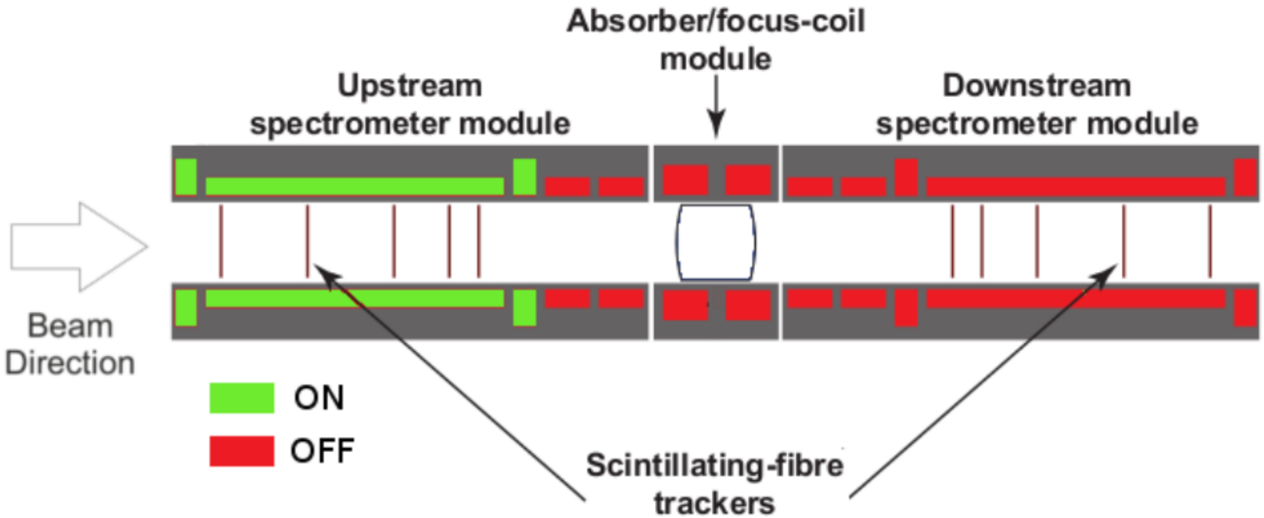
Where m_μ the muon mass and Σ the covariance matrix:

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

And $\sigma^2_{ij} = \langle ij \rangle - \langle i \rangle \langle j \rangle$ the covariance of i and j.

Emittance Measurement
First Direct Measurement

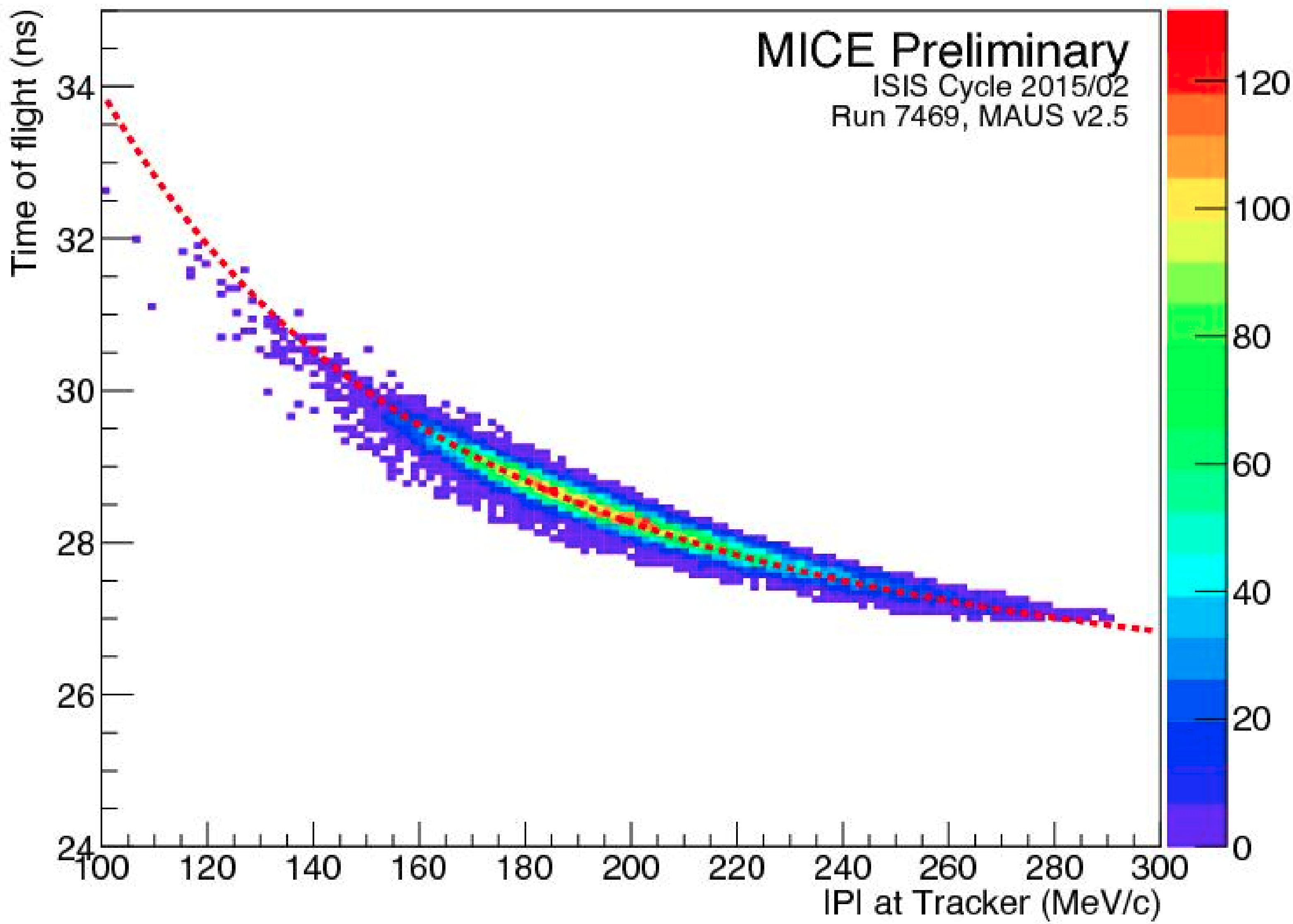
- Measurement only in Upstream Tracker: to measure the beam at the input to Step IV channel demonstrating the power of the technique.
- Data taken in October 2015
  - upstream spectrometer powered for the first time at its designed current.
  - 200 MeV/c positive muon input beam
  - 70 minutes of data taking
  - 19076 good muon tracks acquired
- This run was used to characterise the MICE muon beam and validate the tracker reconstruction.



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).

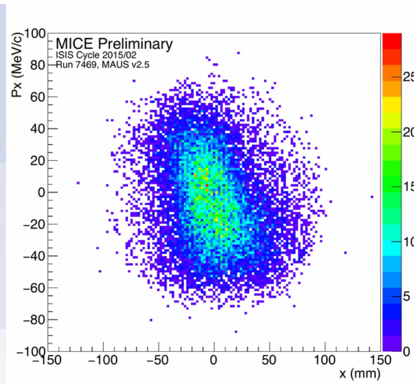
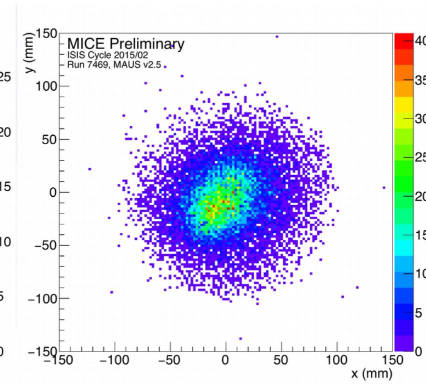
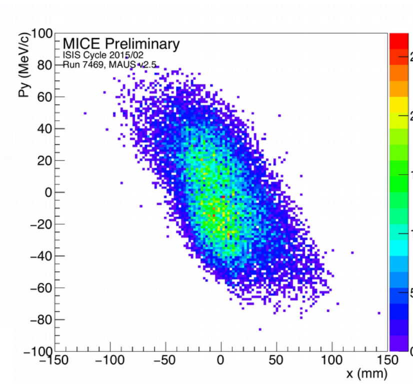
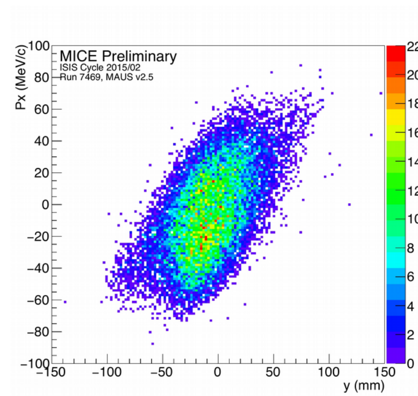
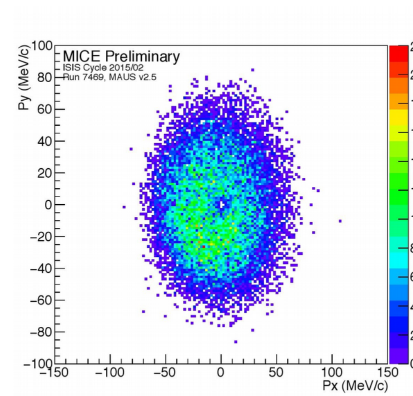
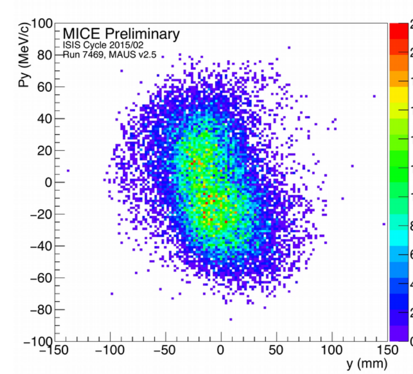
Emittance: Beam Selection



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

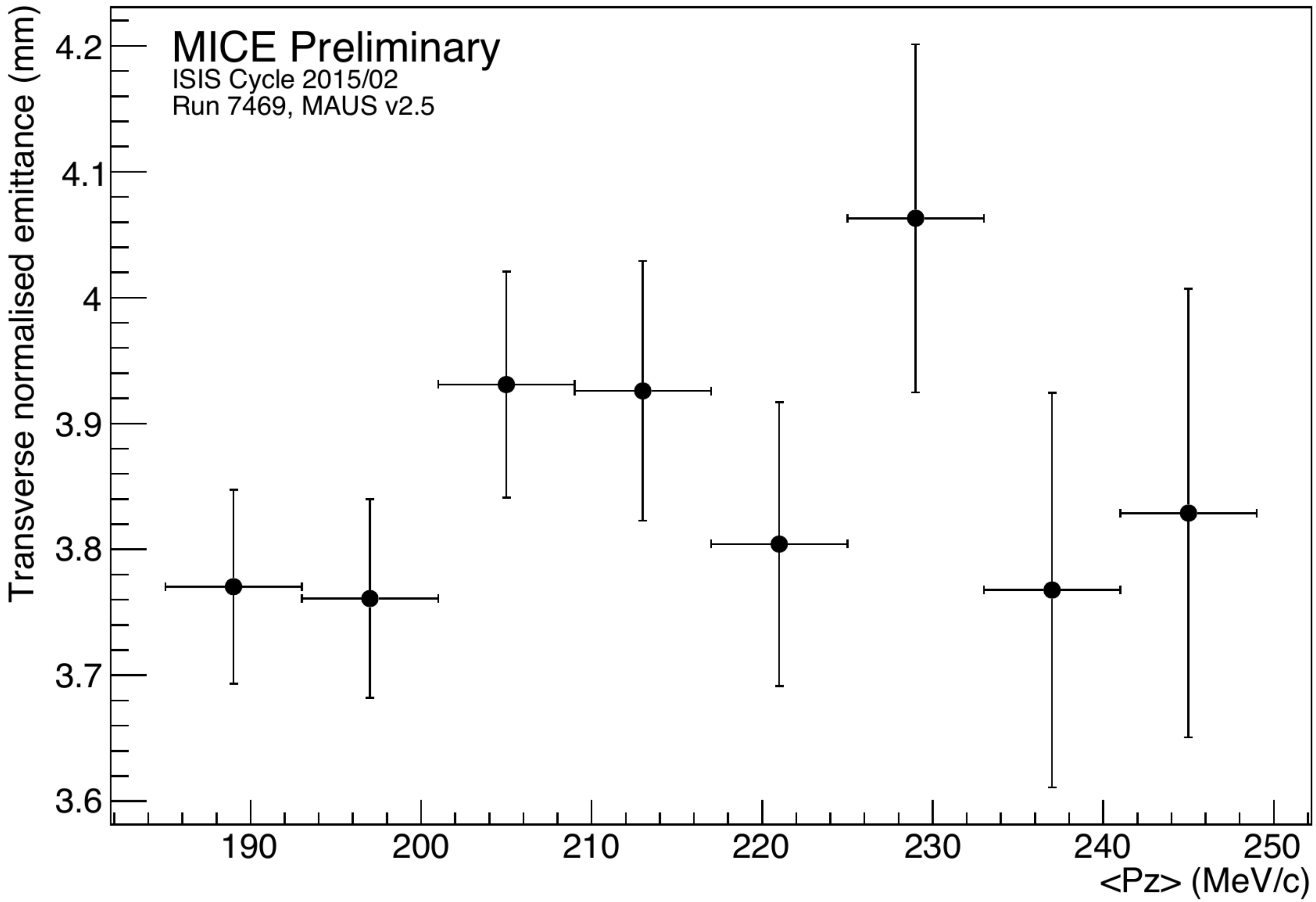
- The absence of other populations indicates selection of a pure muon sample.
- The (red) dotted line is the trajectory of a muon that loses the mean momentum (20 MeV/c) between TOF1 and the Tracker.

Emittance: Covariance Elements

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

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

First Direct Measurement of Emittance



See My Talk this afternoon for:

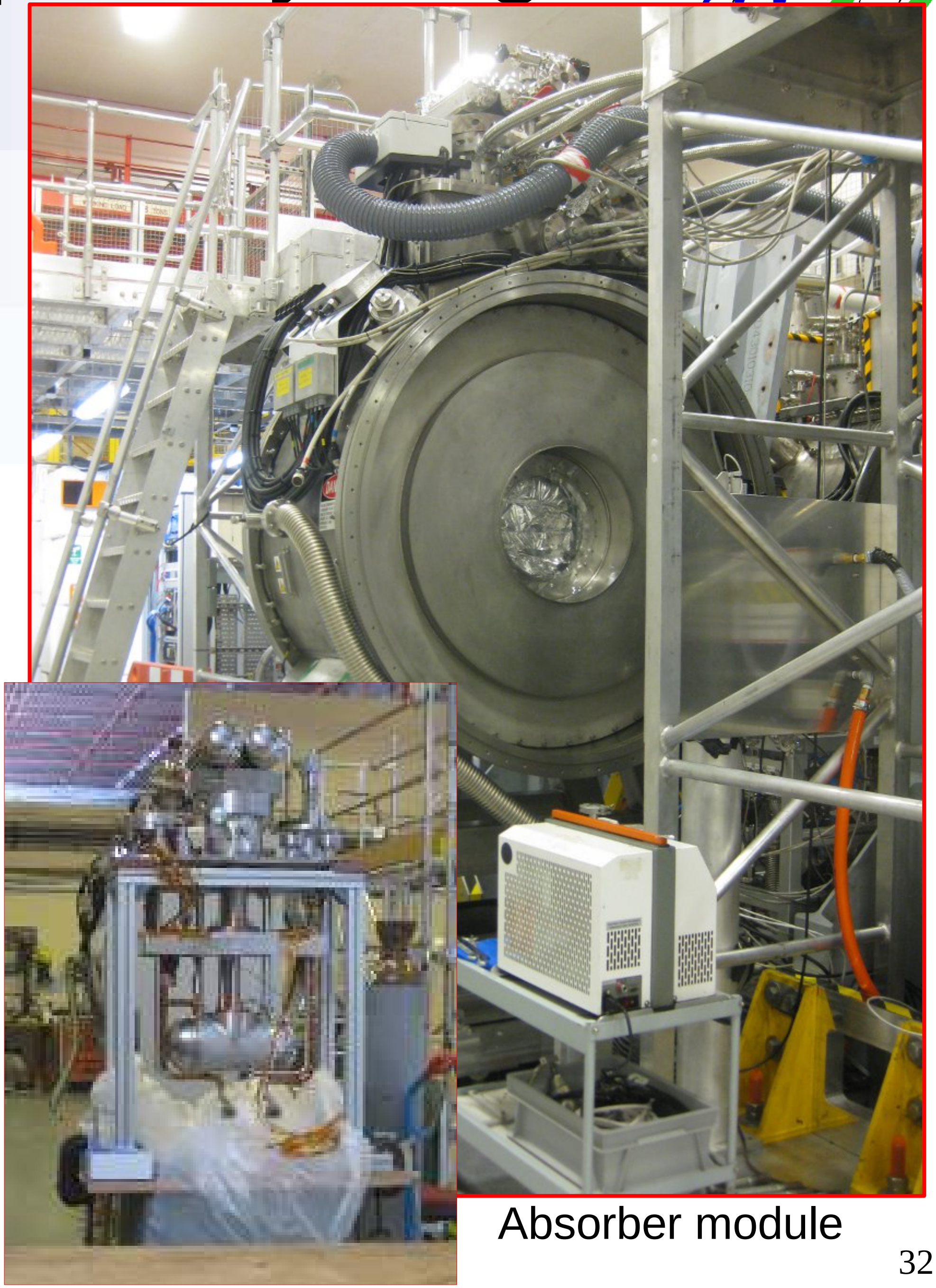
Recent results from the study of emittance evolution in MICE

See Dimitrije Maletics talk this afternoon for:

Measurement of phase-space density evolution in MICE

Cooling With Liquid Hydrogen

- LH_2 system installed and commissioned with Neon.
- Filling for data taking started yesterday!!
- Data taking with LH_2 starts Wednesday!
- Exciting publications in preparation and to come!

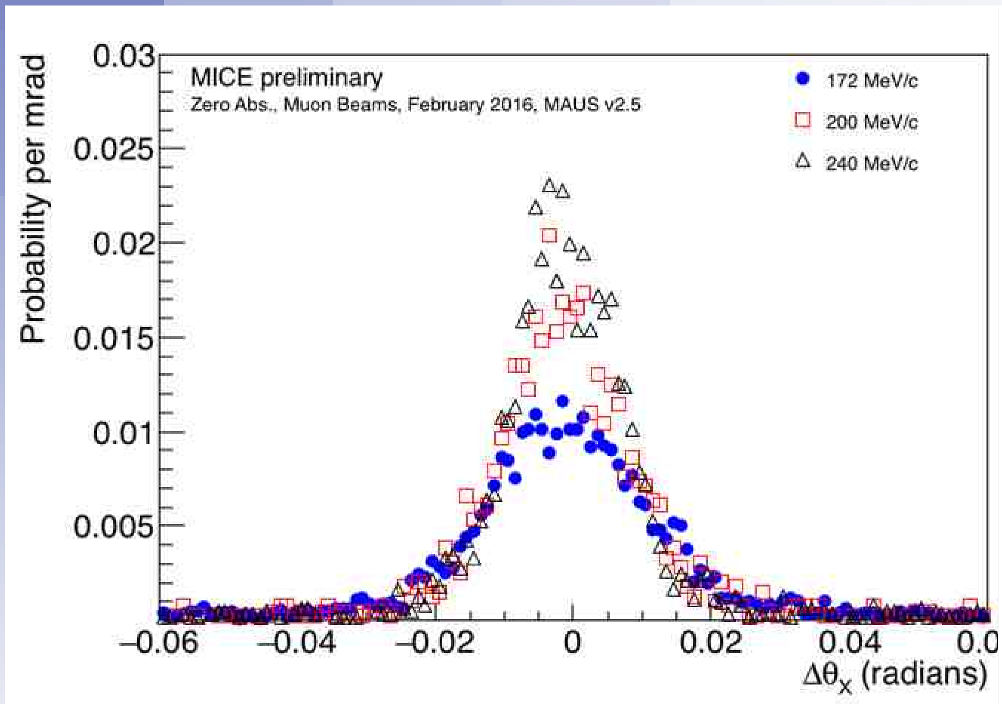


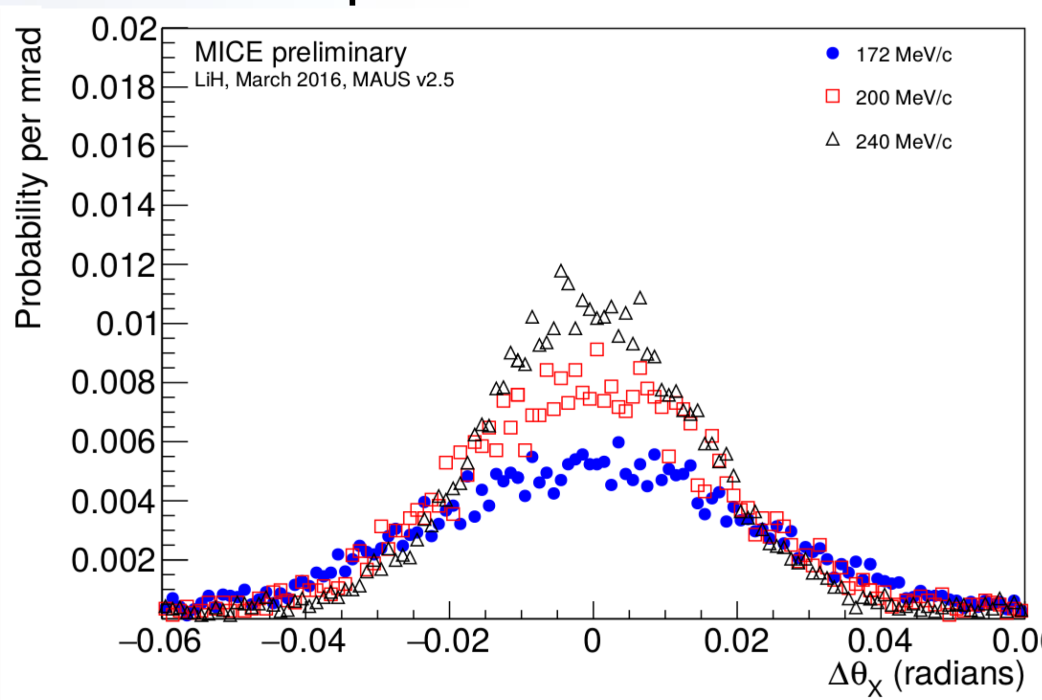
Absorber module

Production condenser

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.

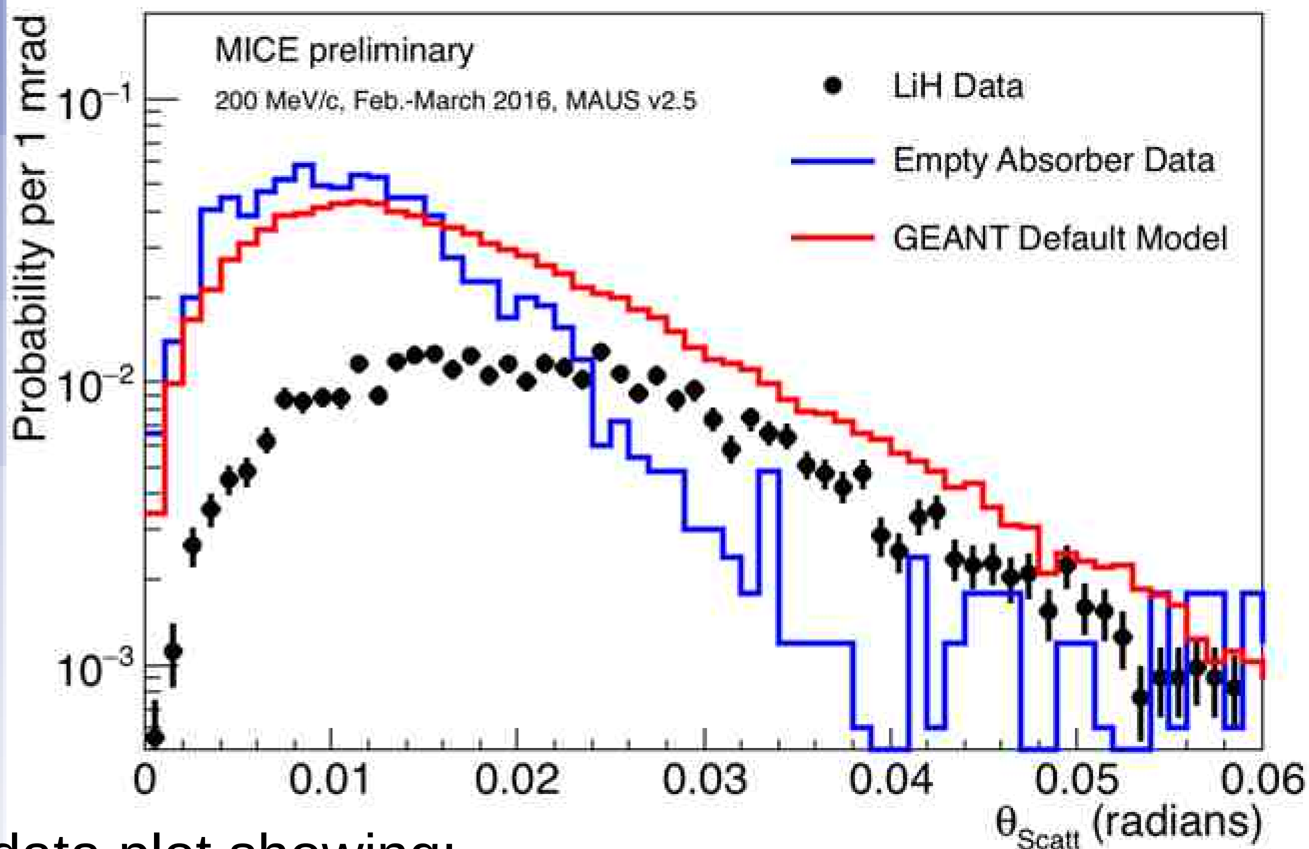




Scattering distributions from data taken at three momenta with a null/empty absorber (left) and lithium hydride absorber (right).

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

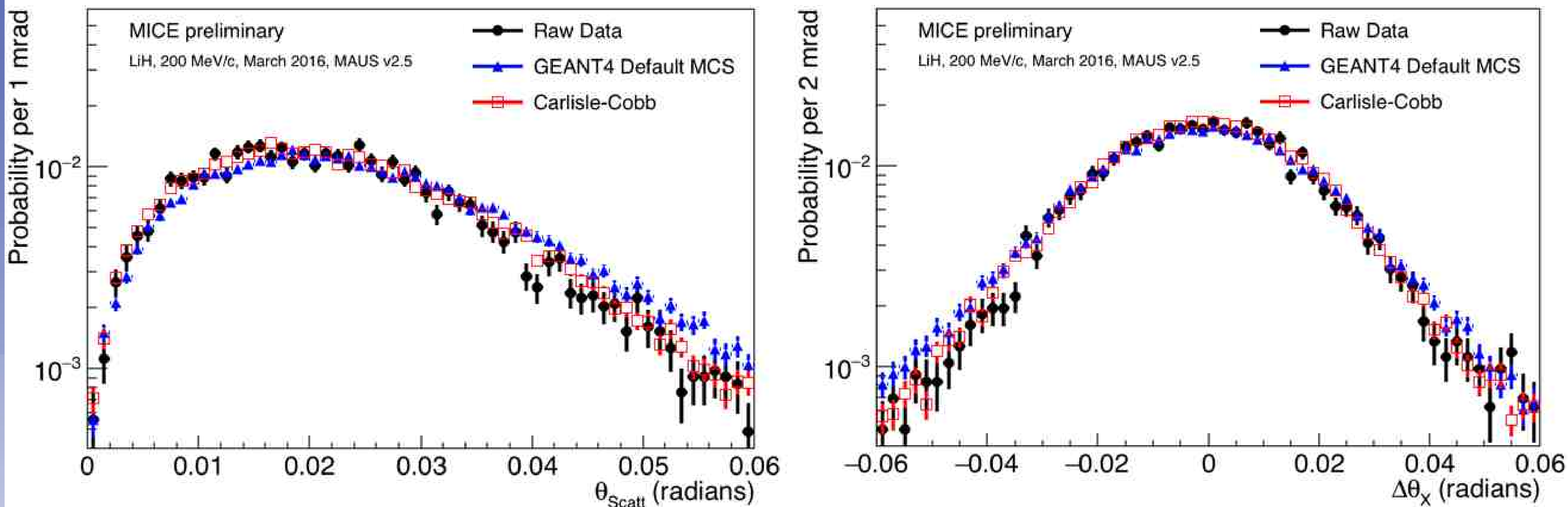
LiH Scattering Data vs Models



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.

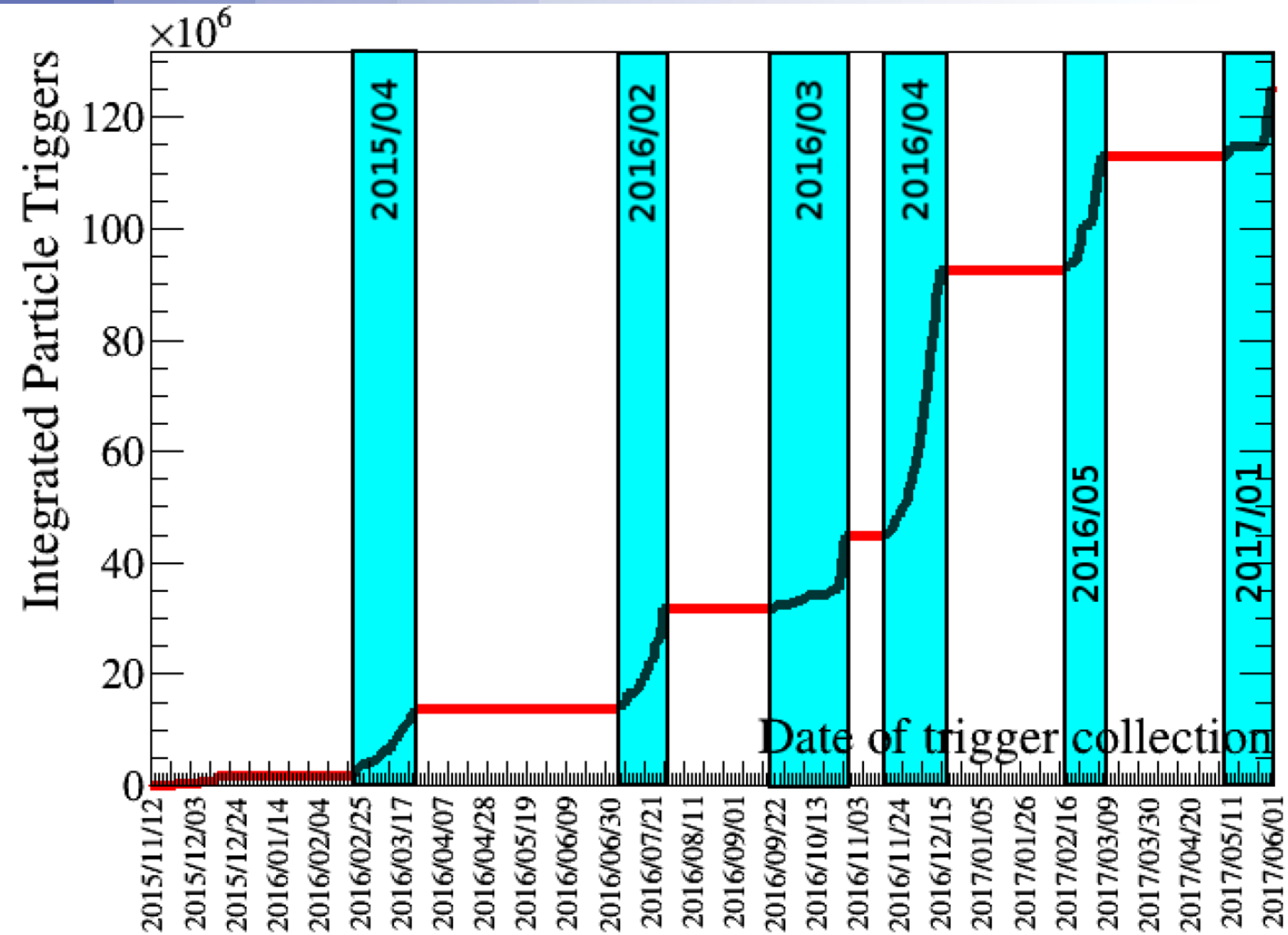
See Dimitrije Maletics talk this afternoon for:

Recent results from MICE on multiple Coulomb scattering and Energy Loss

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 taken.
- Diffuser data taken and analysis in progress.
- First direct measurement of emittance in progress.
- Field on absorber and emittance data taken and analysis nearing publication.
- Liquid Hydrogen absorber installed and filling as we speak.

Particle Triggers Over Time



The integrated number of particle triggers collected by the MICE experiment.

The shaded bands highlight the ISIS user cycles during which the ISIS machine was operational.

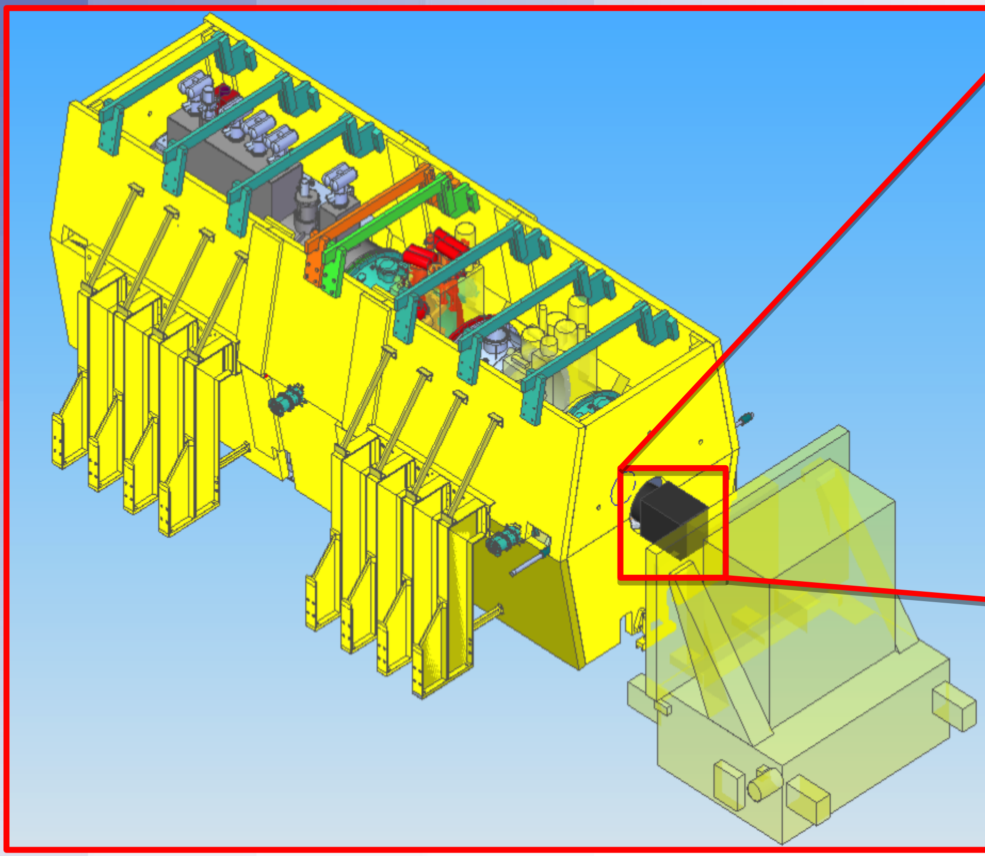
MICE has collected just under 120×10^6 particle triggers so far.

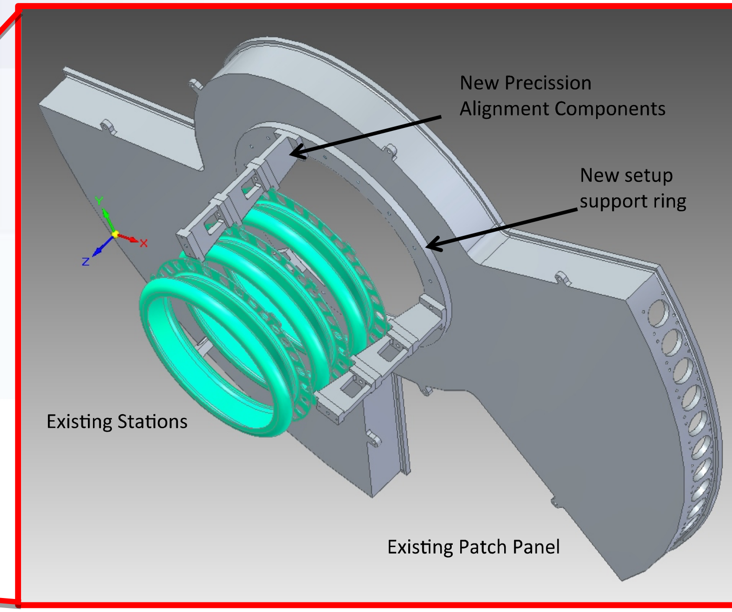
A Year In Papers

Title	Status
The reconstruction software for the MICE scintillating fibre trackers	arXiv:1610.05161
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
Direct Measurement of Emittance Using the Scintillating fibre Tracker	Paper in preparation
Measurement of Scattering Distributions in MICE	Paper in preparation

The Future

MICE Step IV Upgrade



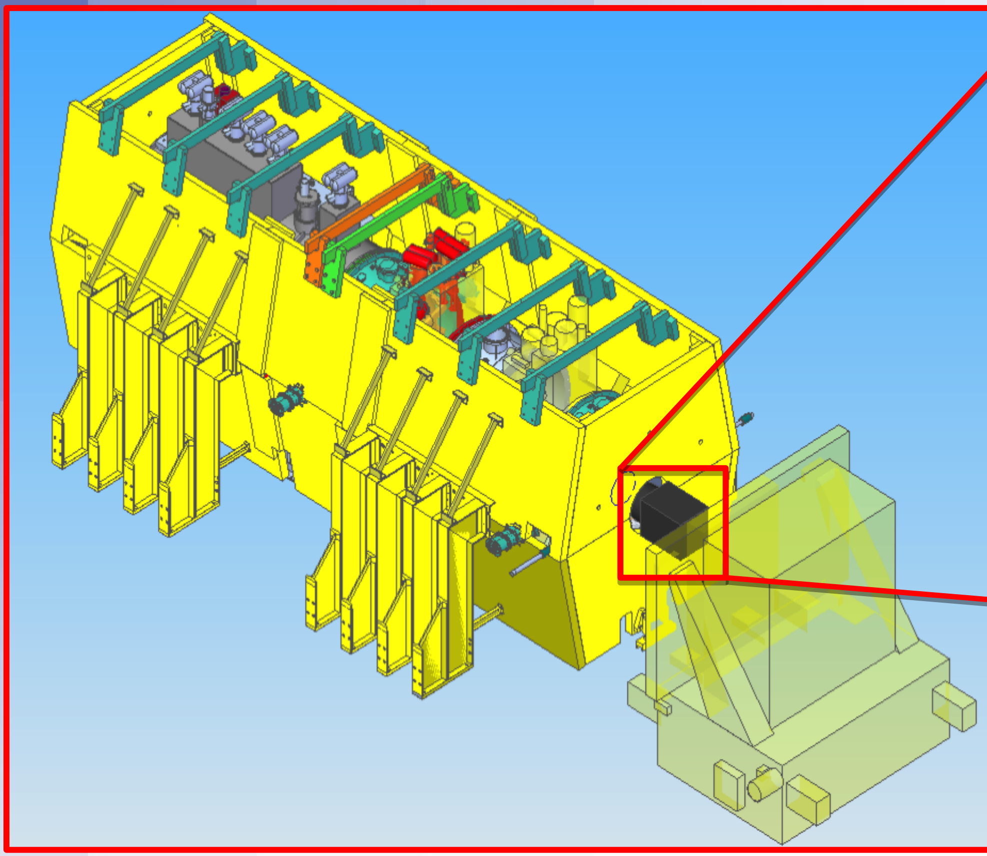


- RF cavity built and fully tested in Fermliab.
- Available to ship to RAL.
- Tracker support vessel, first build stage complete.

- 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 Upgrade



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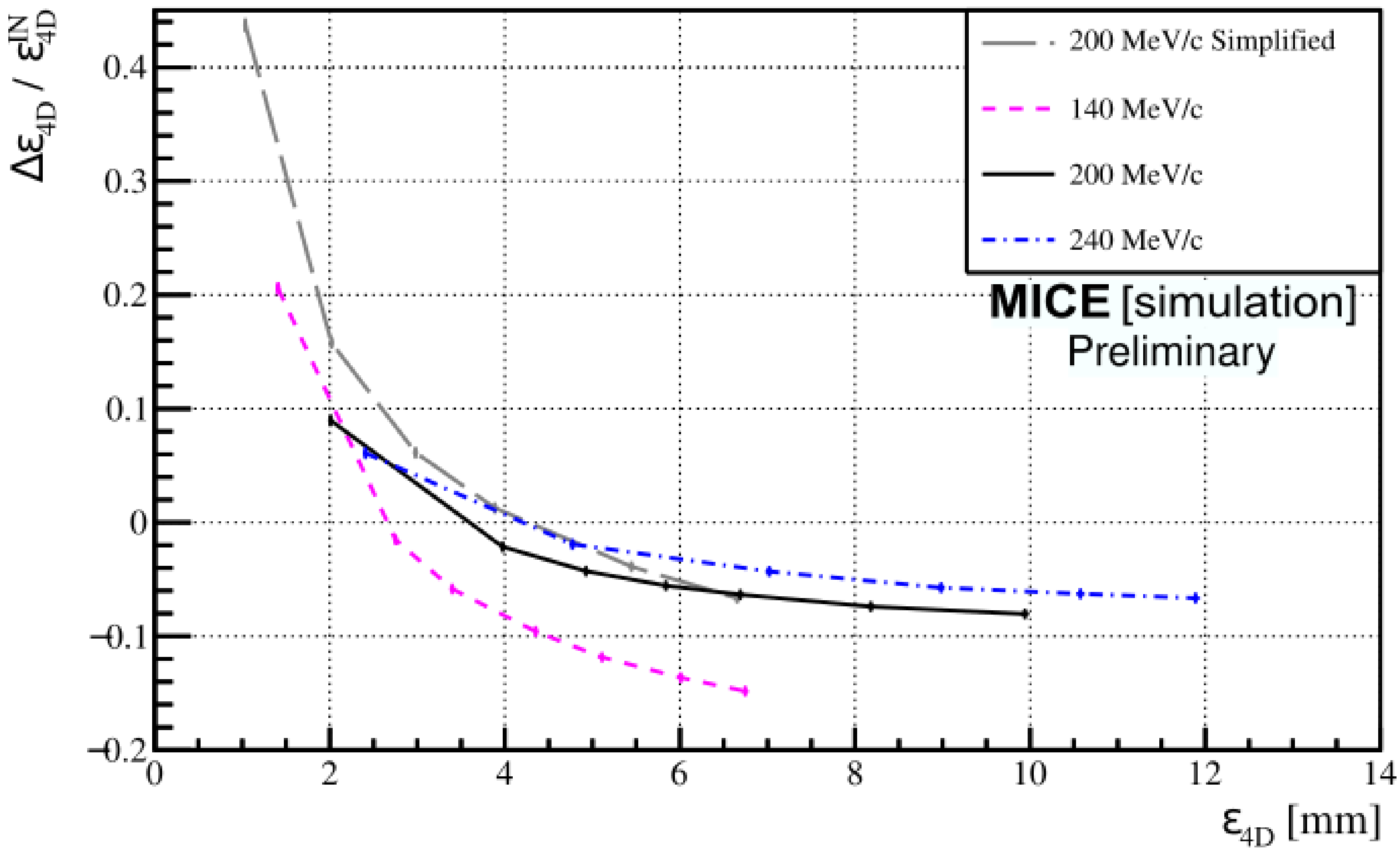


Fractional change in transverse emittance.

Conclusions

- MICE Step IV has been taking data since 2015.
- LiH scattering data complete.
- Cooling channel magnets operated and data taken in flip and solenoid modes successfully.
- Diffuser data taken and analysis underway.
- Liquid Hydrogen running starting in two days!
- The first direct measurement of emittance has been made in MICE.
  - The emittance was measured and chromatic effects were understood.
  - Paper is in preparation.
- First emittance change measurement to come in the near future.
  - MICE expects to observe normalised transverse muon beam emittance reduction.
- Multiple scattering results progressing well and publication coming soon.
- More to come!

Further Talks

Monday, 18 September 2017

10:00 - 11:00	Registration
11:00 - 11:30	Coffee Break
11:30 - 12:50	Registration
13:00 - 14:00	Lunch Break
14:00 - 16:00	Muon I

Convener: Dieter Prasuhn

14:00 **Welcome** *20'*
Speaker: Dieter Prasuhn

14:20 **MICE muon ionization cooling – progress and first results** *50'*
Speaker: M.A. Uchida

15:10 **Measurement of phase-space density evolution in MICE** *50'*
Speaker: D. Maletic

16:00 - 16:30	Coffee Break
16:30 - 17:50	Muon II

Convener: Yuhong Zhang

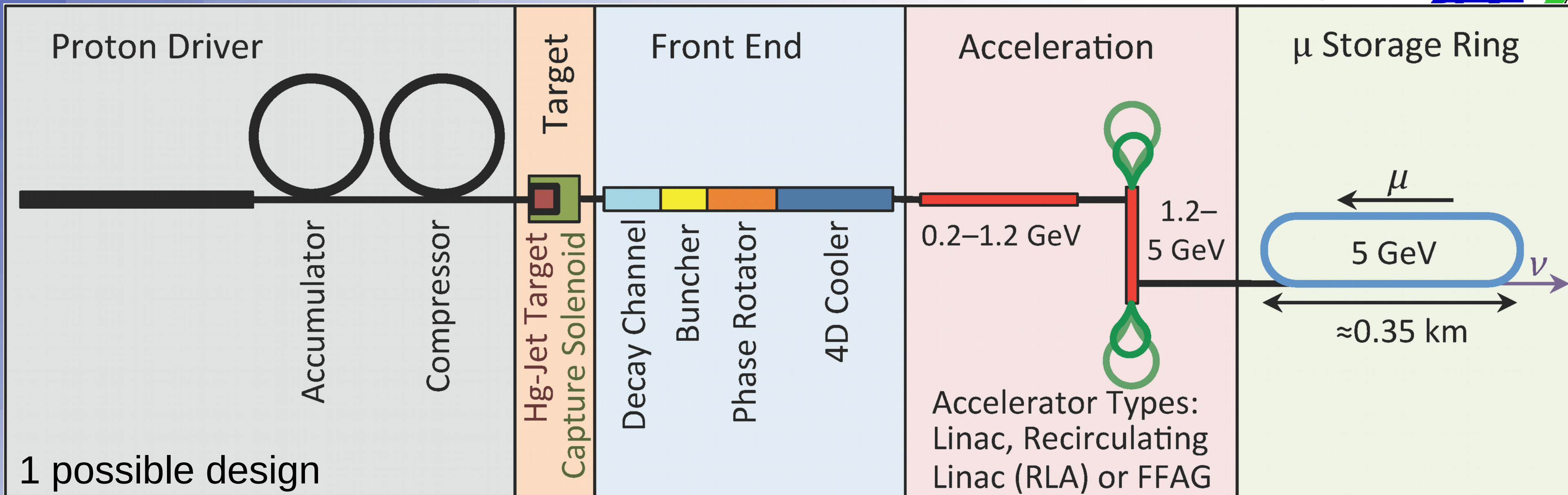
16:30 **Recent results from the study of emittance evolution in MICE** *40'*
Speaker: M.A. Uchida

17:10 **Recent results from MICE on multiple Coulomb scattering and energy loss** *40'*
Speaker: D. Maletic

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.

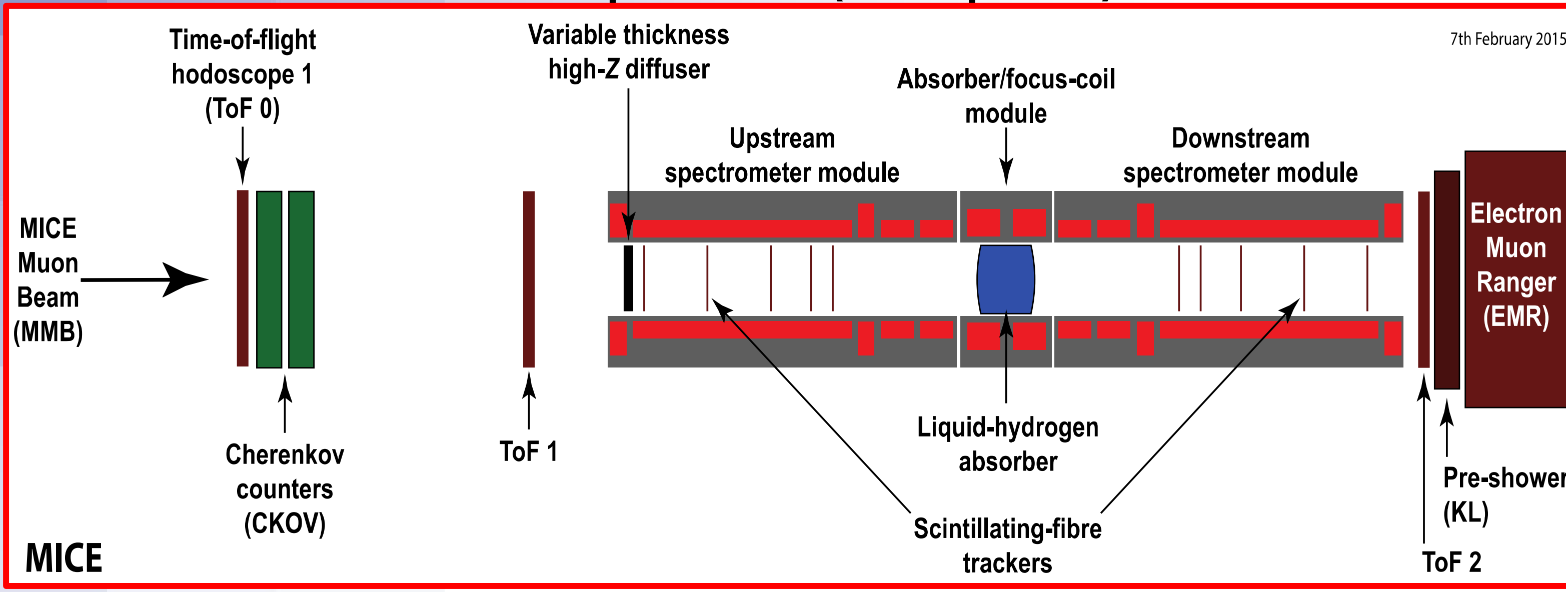
Motivation: Neutrino factory



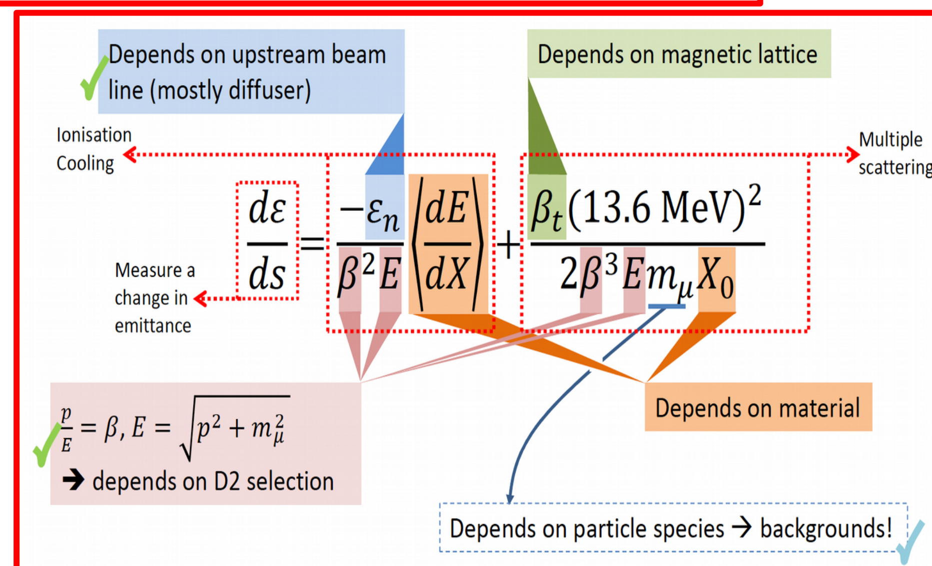
- In order to measure δ_{CP} to 5σ we must understand the neutrino cross section to the 1% level.
- A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \rightarrow e^- \nu_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
- Provides collimated, high-energy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

Characterisation of the Cooling Equation

- Acceleration not required (Step IV):



- Emittance:
  - Vary beam optics/diffuser;
- Material:
  - Absorber change (LH2; LiH);
- *p*, *E* and β:
  - Vary beam momentum, optics



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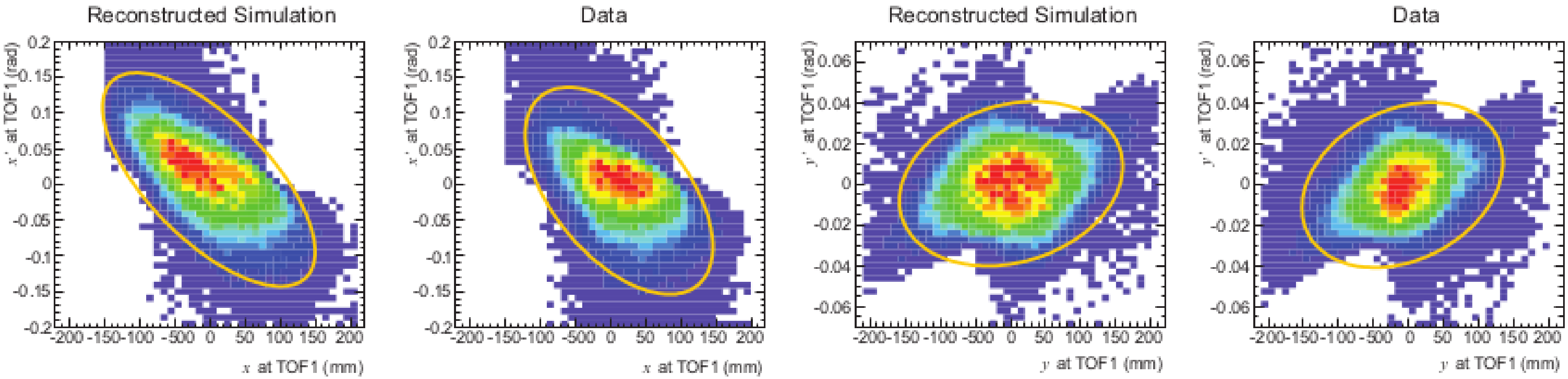
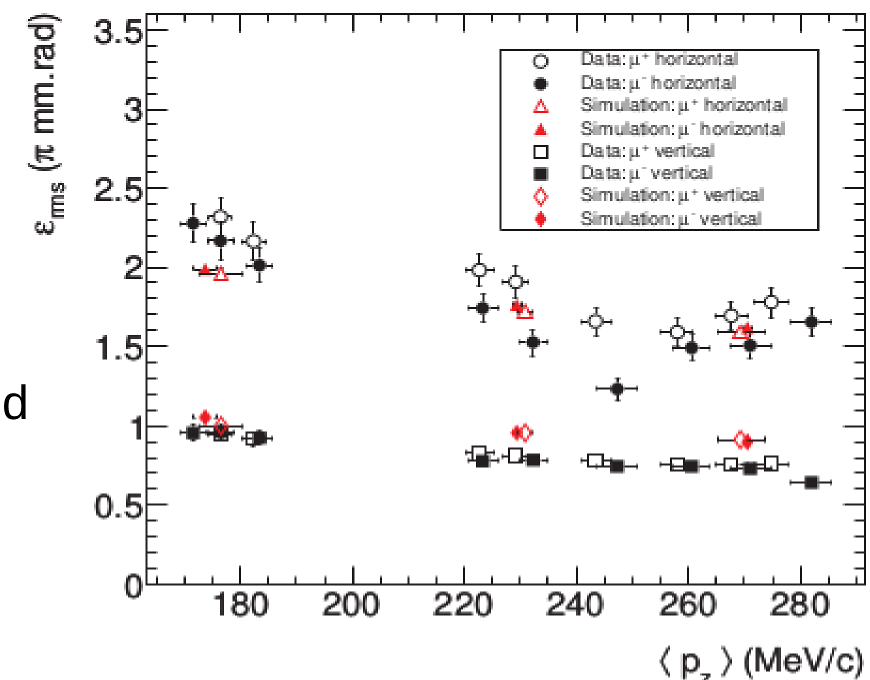
Step I

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

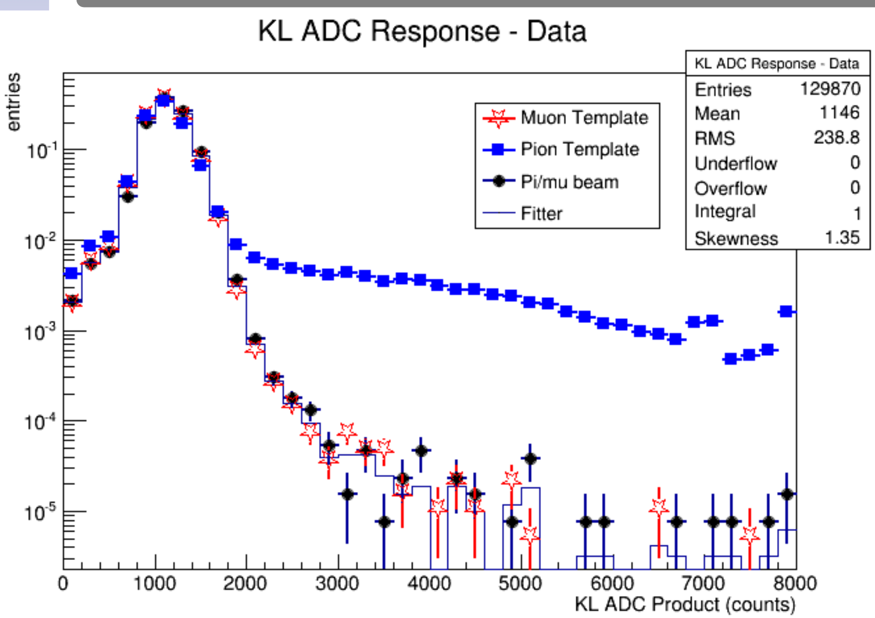
Muons per MICE target dip (spill) as a function of ISIS beam loss

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.