Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

HFOFO study
Review MICE experiment

Katsuya Yonehara

5/2/2025

I referred Drielsma's thesis, Nature Physics, and Phys. Rev. D.106.092003

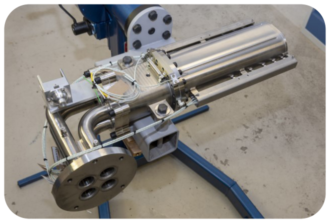
Muon Ionization Cooling Experiment MICE

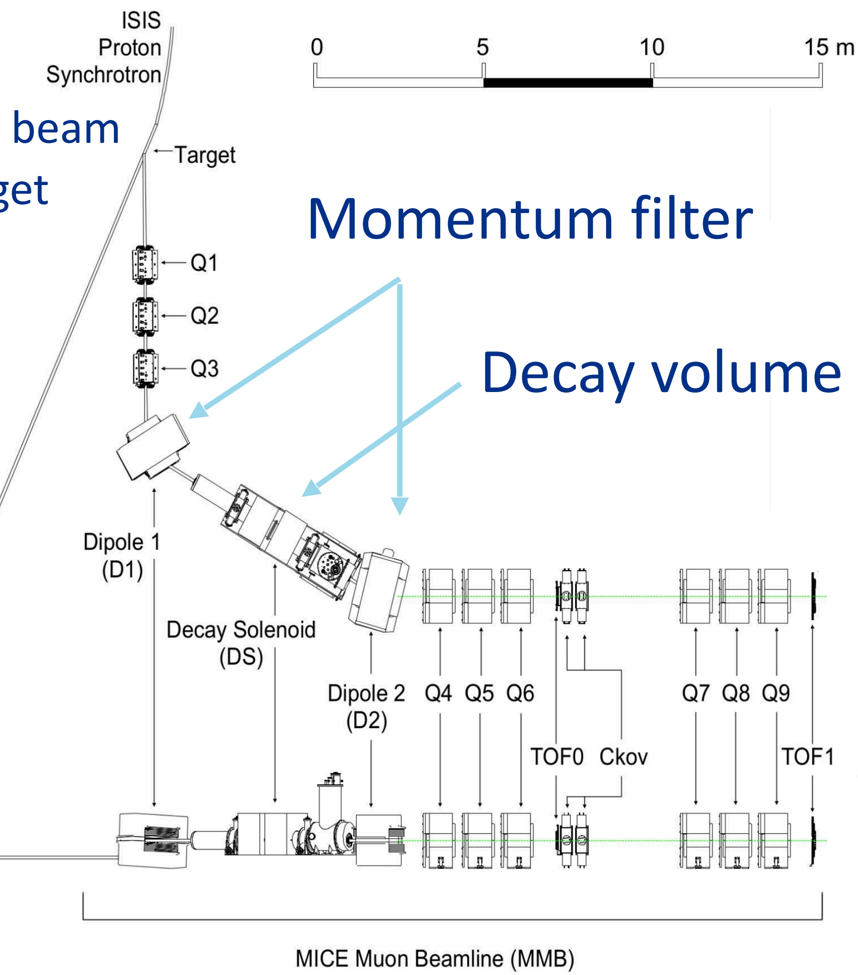
- The aims of the International Muon Ionization Cooling Experiment are (2003)
  - To show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - To place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling

MICE beamline at Rutherford Appleton Lab (RAL)

MICE

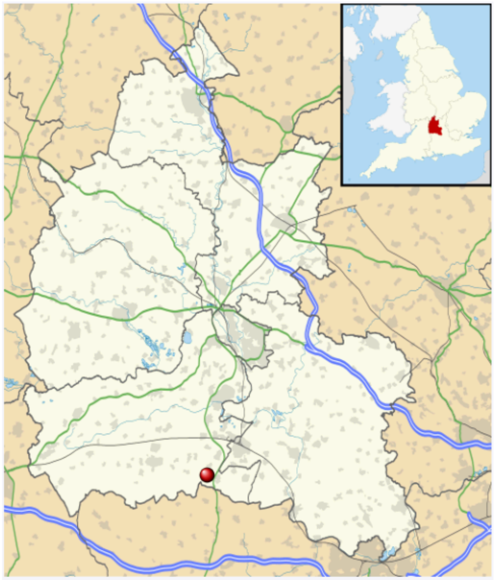
800 MeV proton beam hitting on W target





Momentum filter

Decay volume



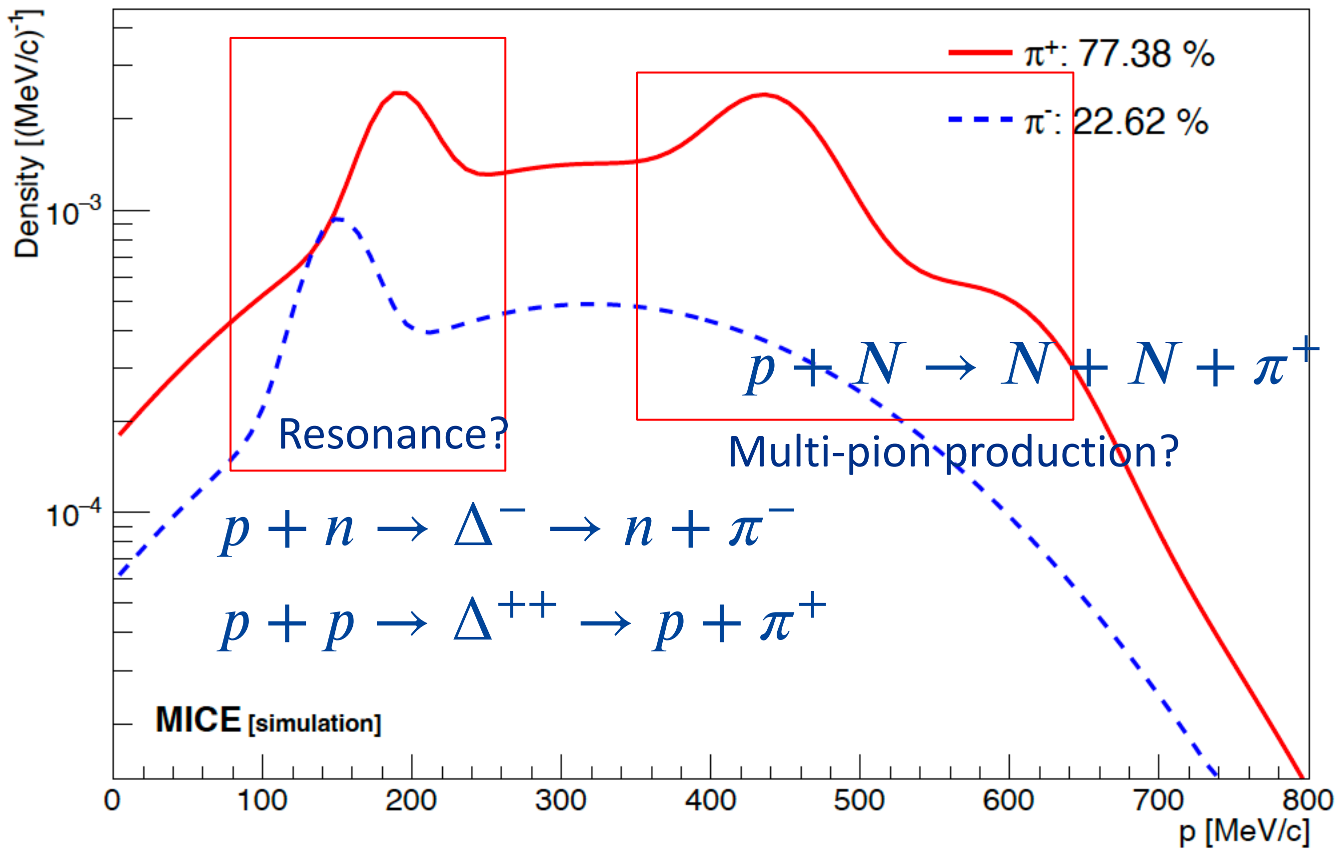
Location in Oxfordshire

Pion production

π^+ is dominant at low energy proton beams

$$p + W \to \pi^{\pm} + X$$

Simulated pion spectrum from W target



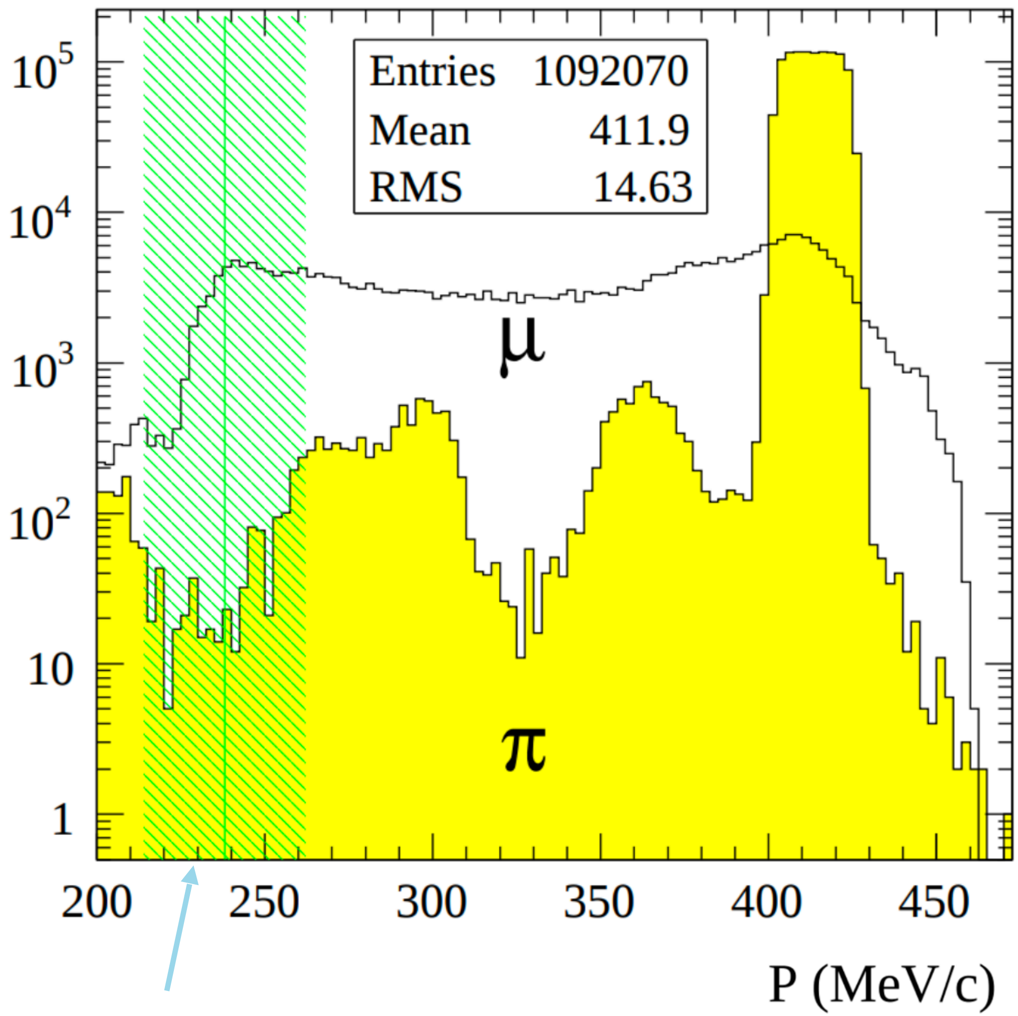
$$p + N \to N + N + \pi^+ + \pi^-$$

$$p + n \to \Delta^- \to n + \pi^-$$

$$p + p \to \Delta^{++} \to p + \pi^+$$

Fermilab

Selected muons after D1/D2 dipole magnet



$$m\frac{v^2}{r} = qvB_{dipole}$$

$$\rightarrow \frac{p}{r} = qB_{dipole}$$

$$\rightarrow r = \frac{p}{qB_{dipole}}$$

A collimator to select specific momentum

$$\rightarrow \Delta r = \frac{\Delta p}{qB_{dipole}}$$

Green shadow area shows selected muons after D2 magnet

MICE cooling section and detectors

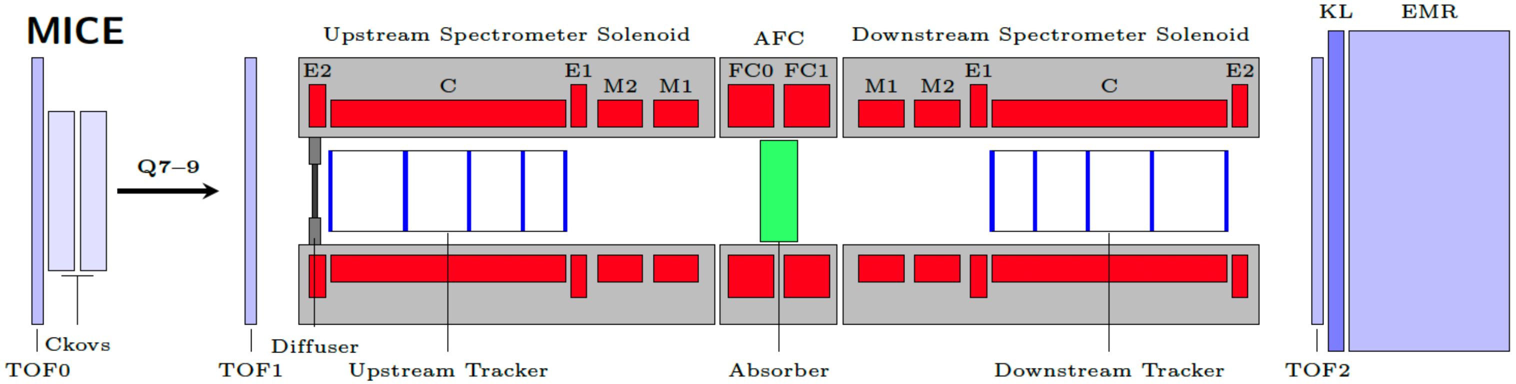


Figure 3.11: Layout of the MICE experiment in its Step IV configuration.

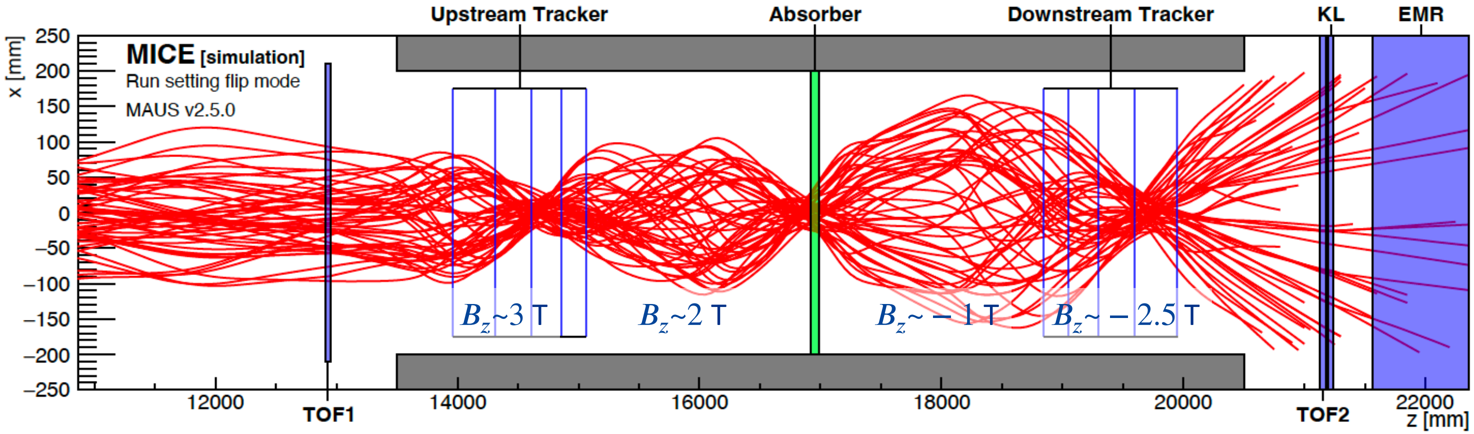


Figure 3.12: Single particle trajectories in the MICE Step IV configuration.

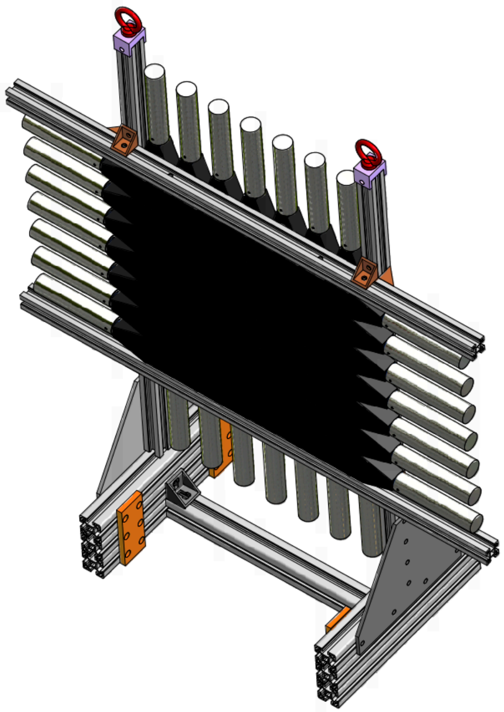
MICE is single particle tracking experiment

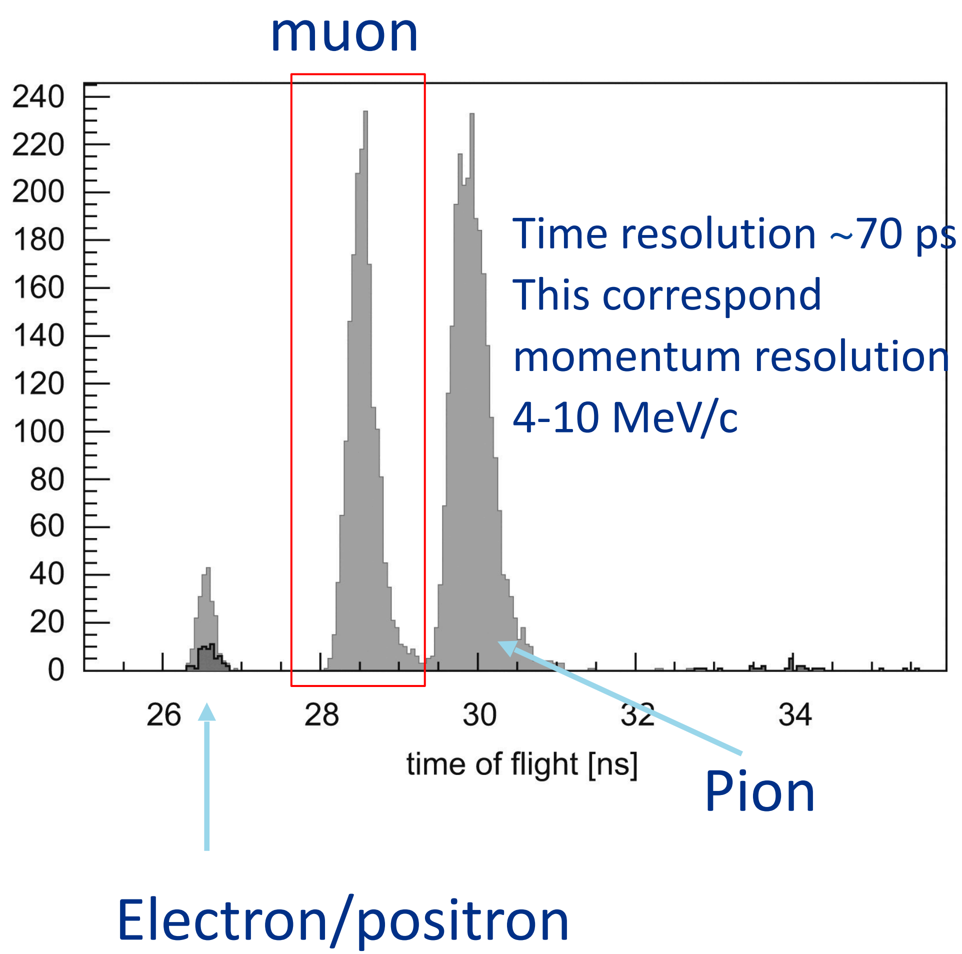
- Produce muons which has momentum around 140 MeV/c
  - These muons are most cooled in the MICE channel
  - The initial beam emittance is adjusted by using a diffuser, e.g. the initial normalized emittance is 3 (4), 6, and 10 mm
- MICE detectors achieved high precision particle ID system
  - Because pions and electrons/positrons contaminate the phase space measurement
- MICE detectors designed to measure 10 % transverse emittance reduction with 1 % measurement error
  - It means that the acceptable measurement error for absolute transverse emittance measurement is 0.1 %

MICE is single particle tracking experiment

- High precision Particle ID is achieved using Time of Flight (TOF), Cherenkov, and calorimeter measurements
- Initial particle momentum is observed in Upstream scifi Tracker and TOF
- After cooling, the final particle momentum is observed in Downstream scifi Tracker
  - KLOE-Light (KL) is used to identify electrons from measurements
  - Total kinetic energy is observed in Electron Muon Ranger

Time of Flight counter





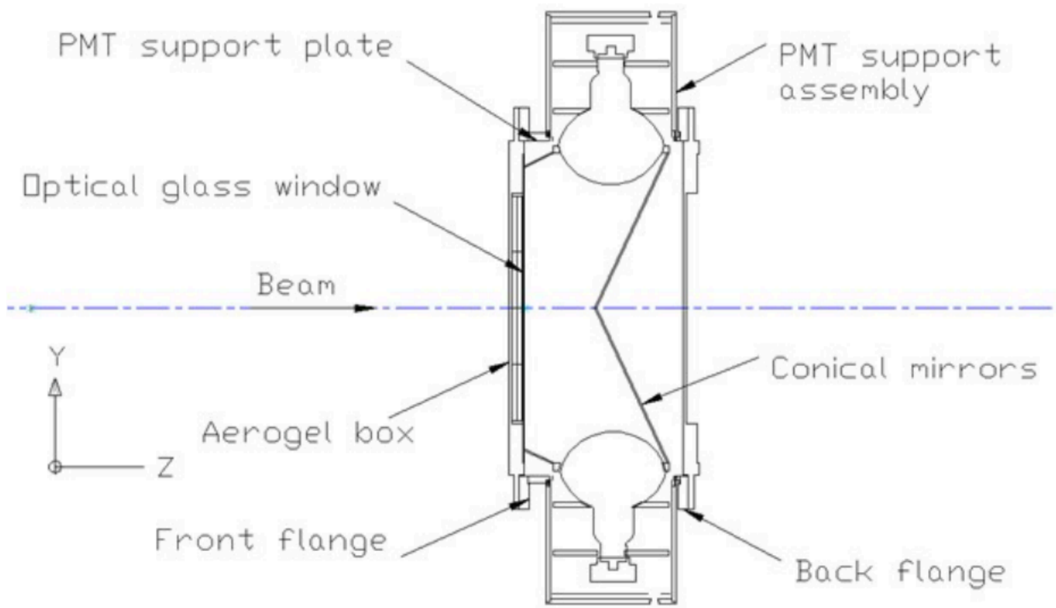
Use TOF counter (plastic scintillating counter) for PID and observing kinetic energy

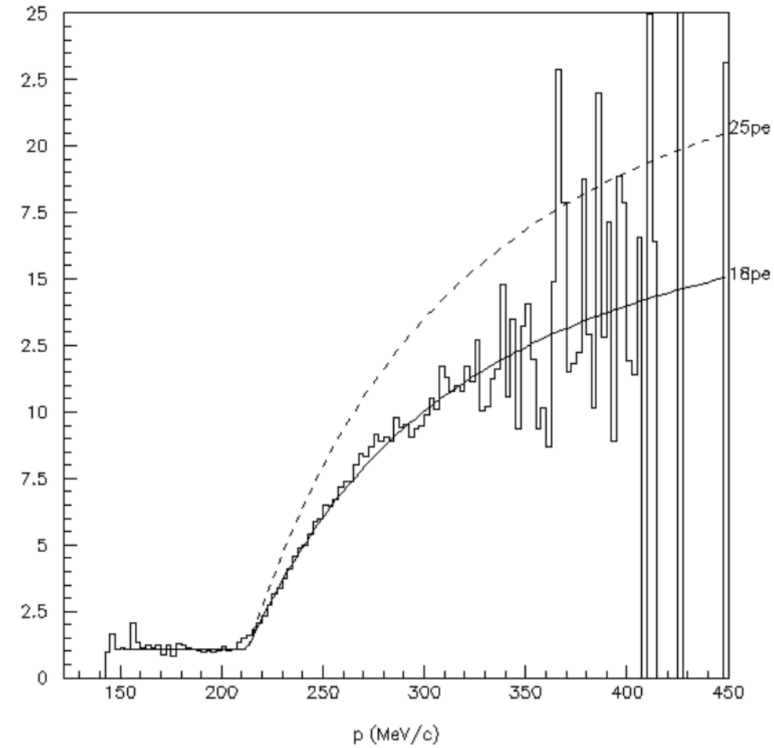
$$\Delta t_{TOF} = \frac{L}{v}$$

L: Gap between two TOF counters

v: particle velocity

Cherenkov Detector





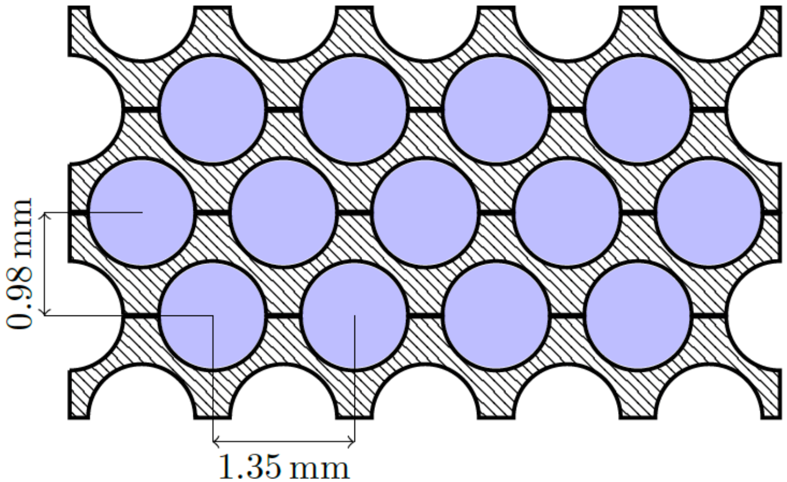
Use Cherenkov Detector for PID
Aerogel as a radiator

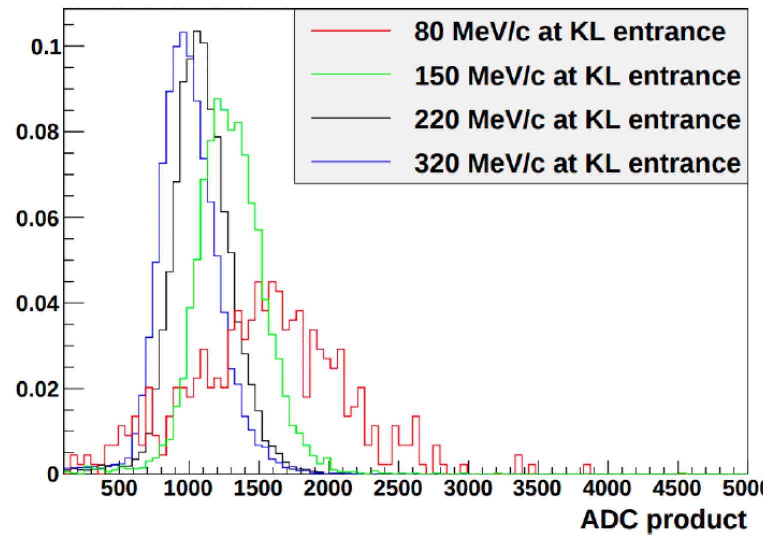
$$cos\left(\theta_c\right) = \frac{c}{nv}$$

n: Refractive index
v: particle velocity

Low energy threshold monitor
Detecting muons which has p > 213 MeV/c
They also have other CD which is a threshold momentum 272 MeV/c

KLOE-Light preshower sampling calorimeter



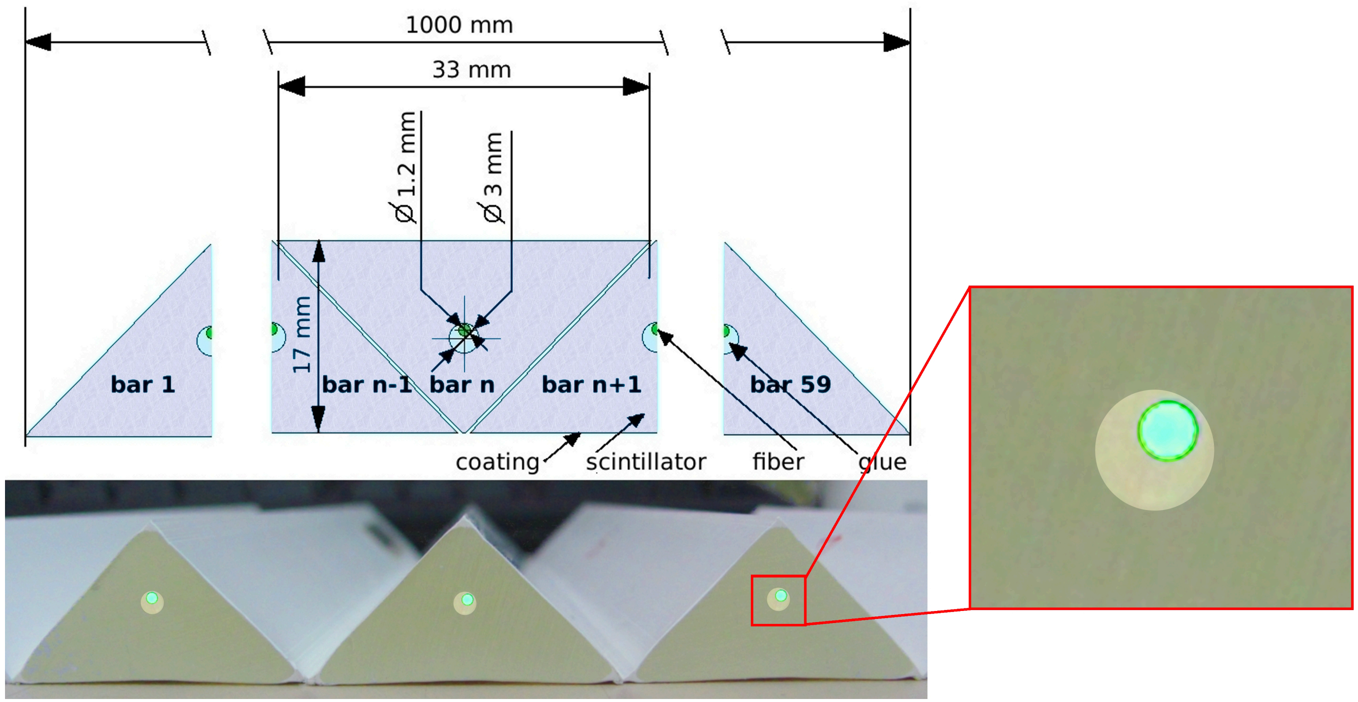


1-mm diameter scifi in lead layers to form calorimeter and other TOF counter

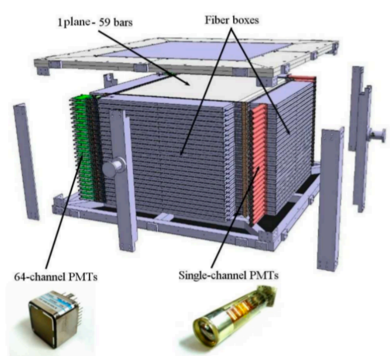
Energy resolution is $\frac{\sigma_E}{E} = 7\ \%/\sqrt{E}$ (GeV)

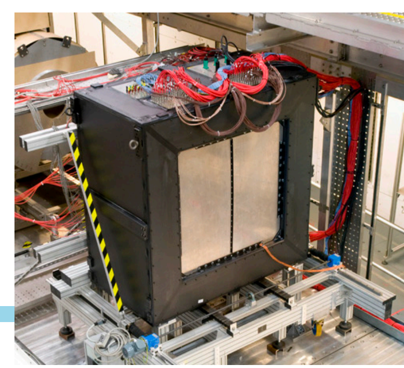
Time resolution is $\sigma_t = 70$ ps/$\sqrt{E}$ (GeV)

Electron Muon Ranger



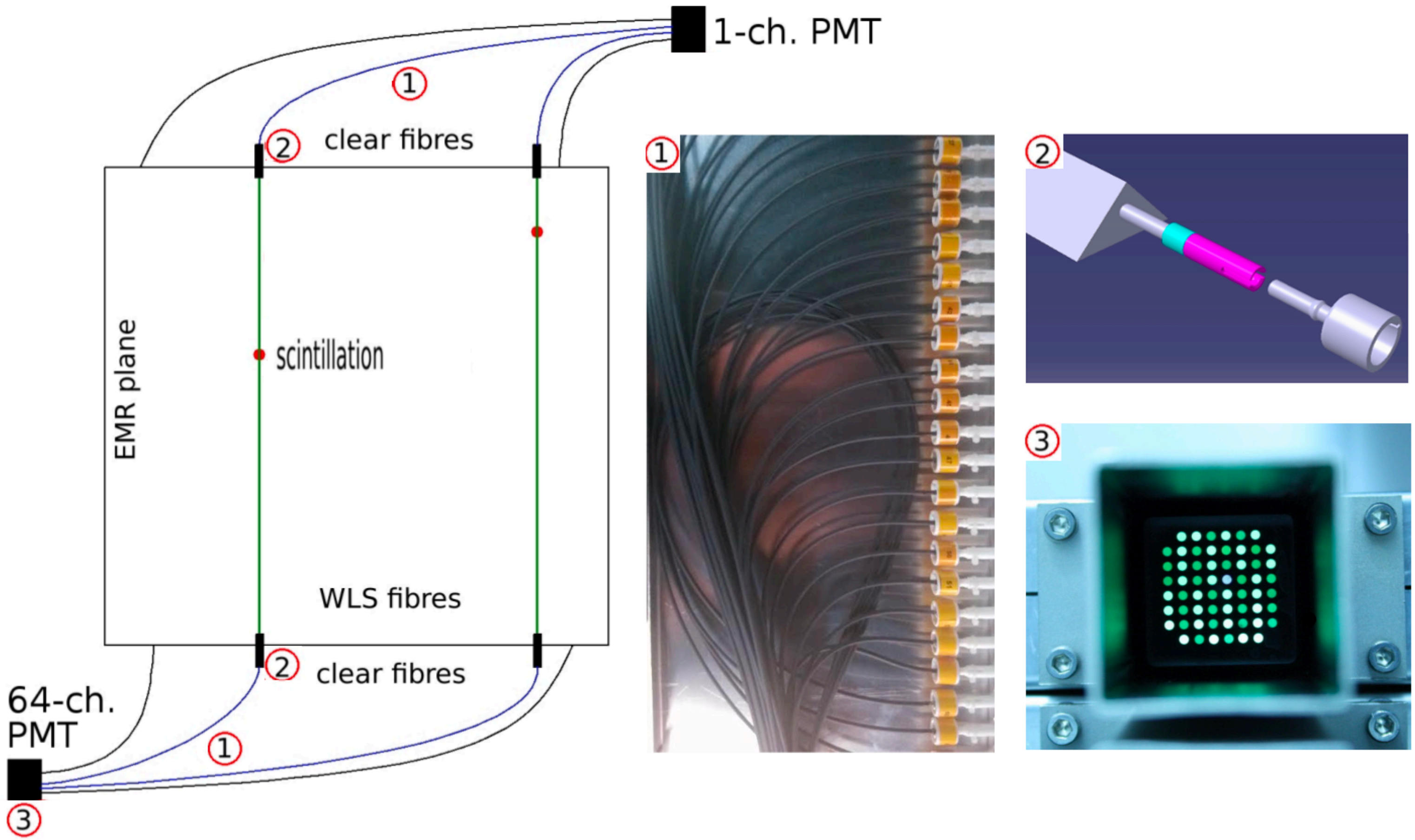
Scintillating bar and wavelength shifting (WLS) fiber glued inside





Fermilab

Electron Muon Ranger

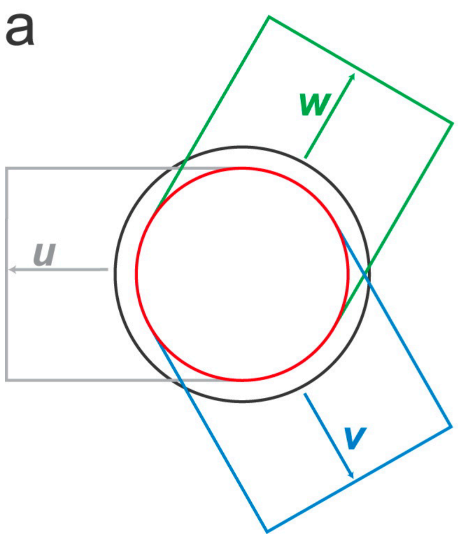


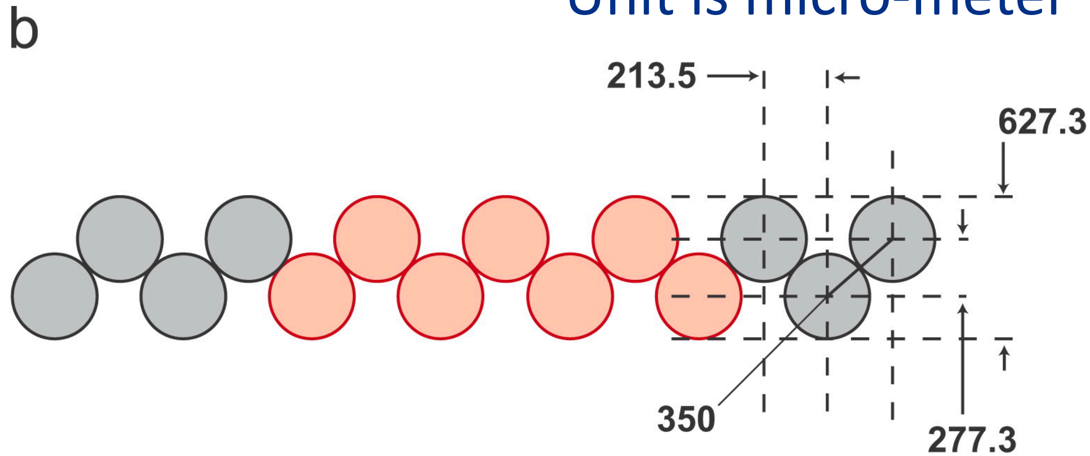
Dual light output couplers, one is for integrated light yield for calorimetry and other is for processing multiplexed signals for further analysis (which I do not know the detail)

Scifi Tracker

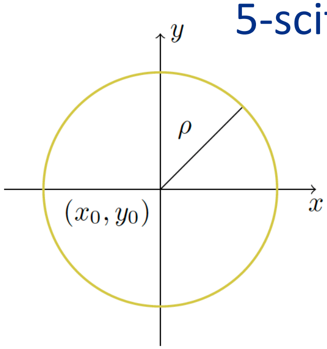
Radius of sense area is 150 mm

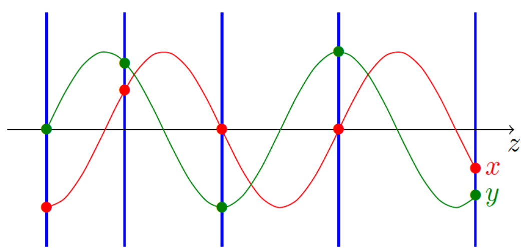
Unit is micro-meter





5-scifi stations along beam direction





$$\rho = \frac{p_T}{qB_z}$$

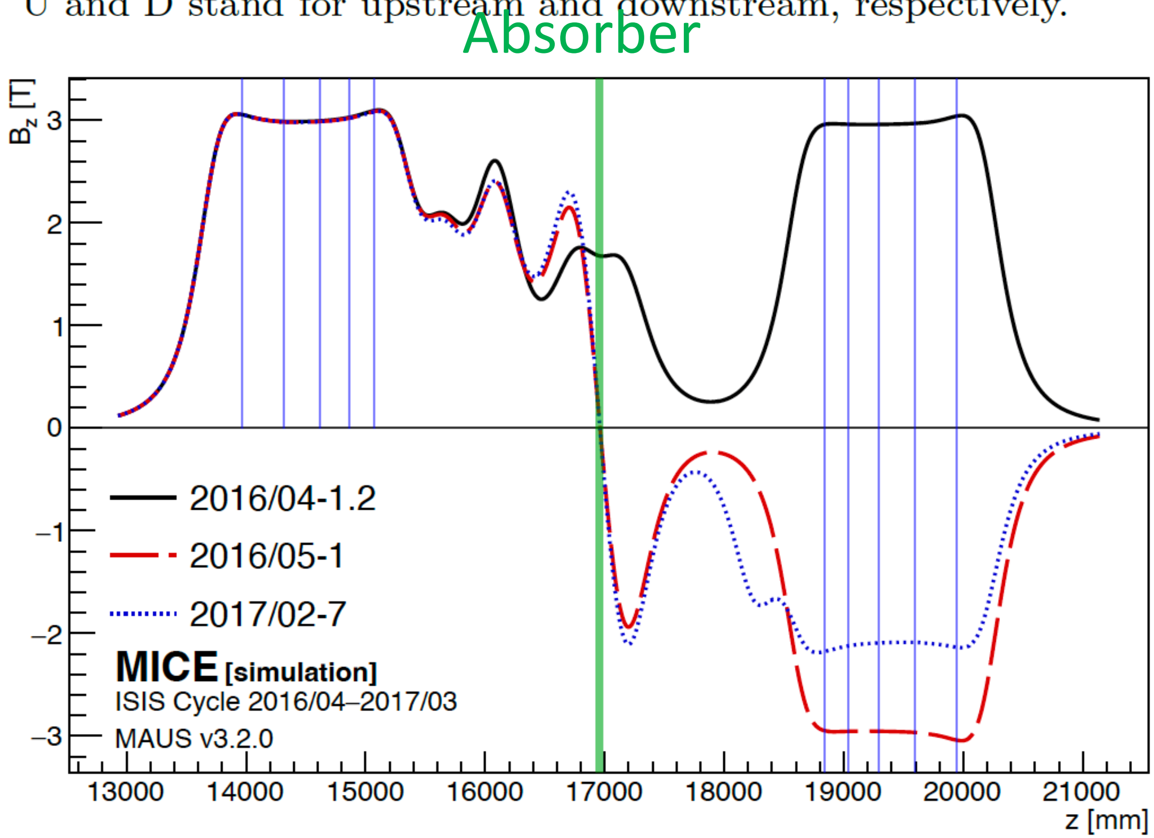
$$\frac{ds}{dz} = \sqrt{1 + \left(\frac{p_T}{p_L}\right)^2}$$

Resolution is typically 1.264 MeV/c in transverse and 3.974 MeV/c in longitudinal

Three different magnetic field configurations

Tag	Polarity	ECEU	M2U	M1U	FC	M1D	M2D	ECED
2016/04-1.2	Sol.	205.9	171.9	211.7	57.9	**0**	**0**	205.9
2016/05-1	Flip	205.7	174.9	190.3	119.4	**0**	**0**	205.7
2017/02-7	Flip	205.7	168.3	191.0	129.2	**0**	190.7	144.0

Table 6.1: Current in the MICE coils as represented in figure 3.11, quoted in amperes. U and D stand for upstream and downstream, respectively.

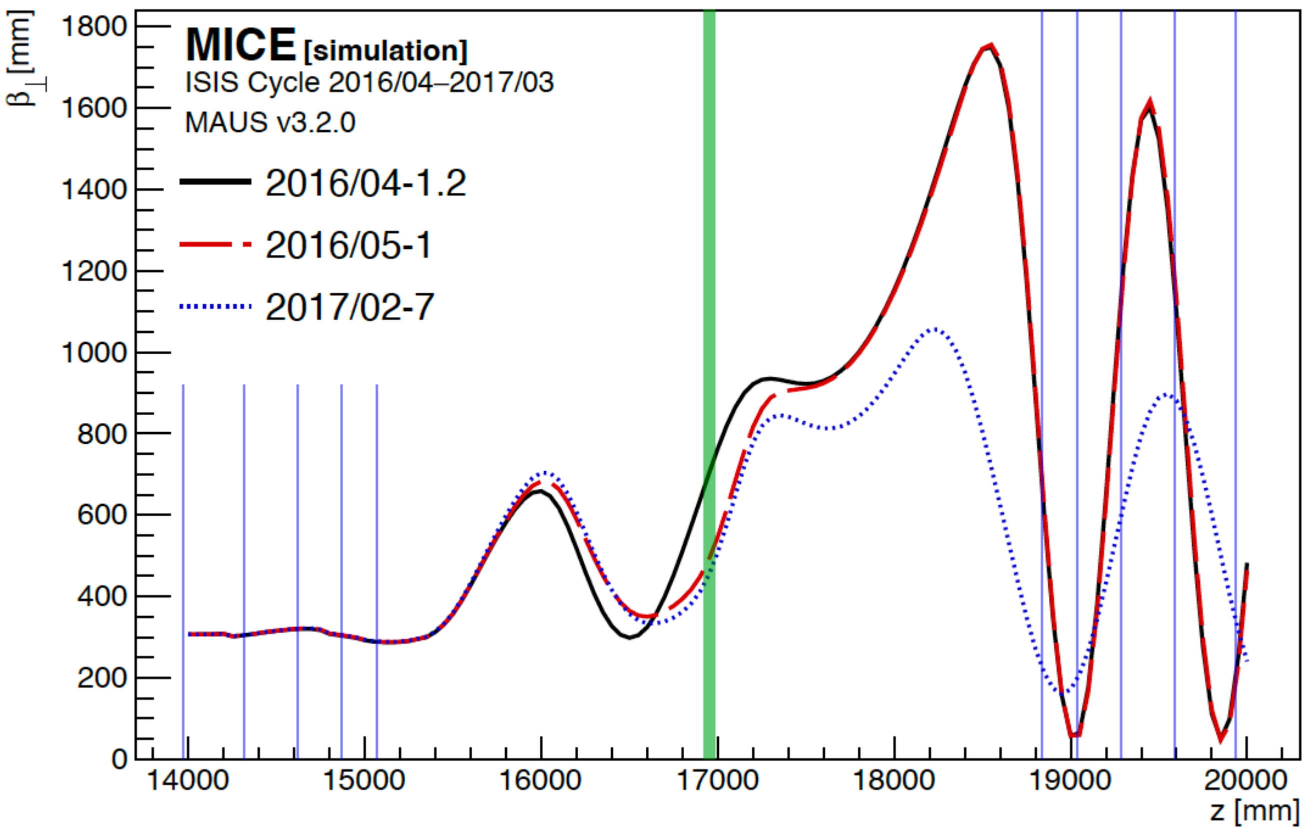


- They lost M1D magnet before running cooling demo test
- They found a new magnetic field configuration to mitigate the missing magnet issue
- They ran three different magnet configurations
- One is that all magnets have same polarity
- Second is that downstream magnets polarity is flipped
- Third is M2D magnet is turned on

Beta functions

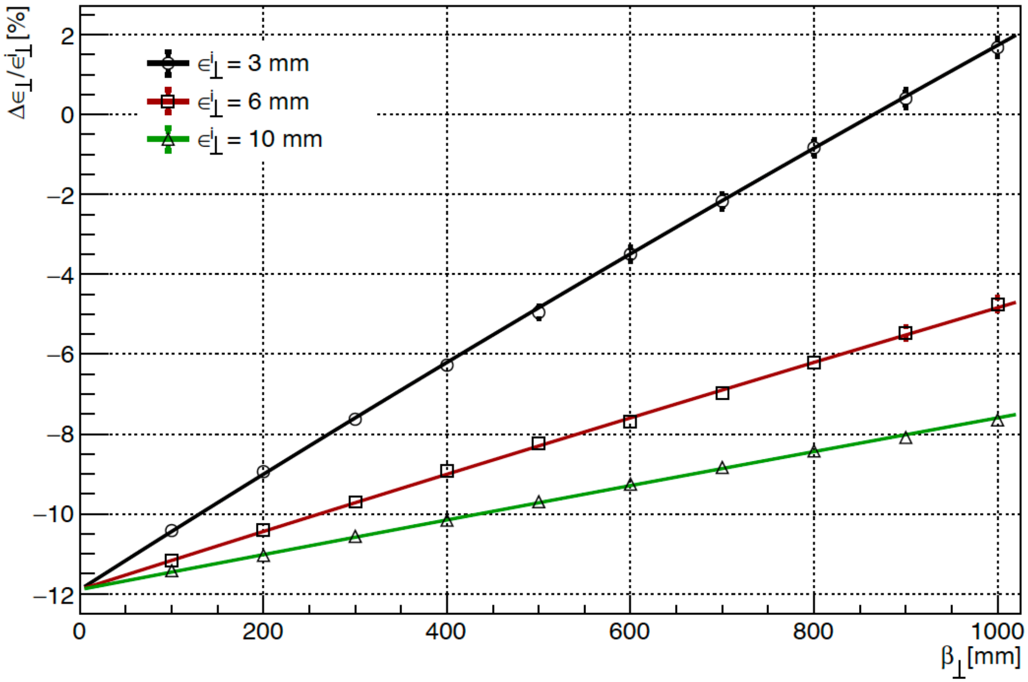
Setting	2016/04-1.2	2016/05-1	2017/02-7
$\beta^*_\perp$ [mm]	760	550	510

Absorber



Beta function is significantly improved with third field configuration

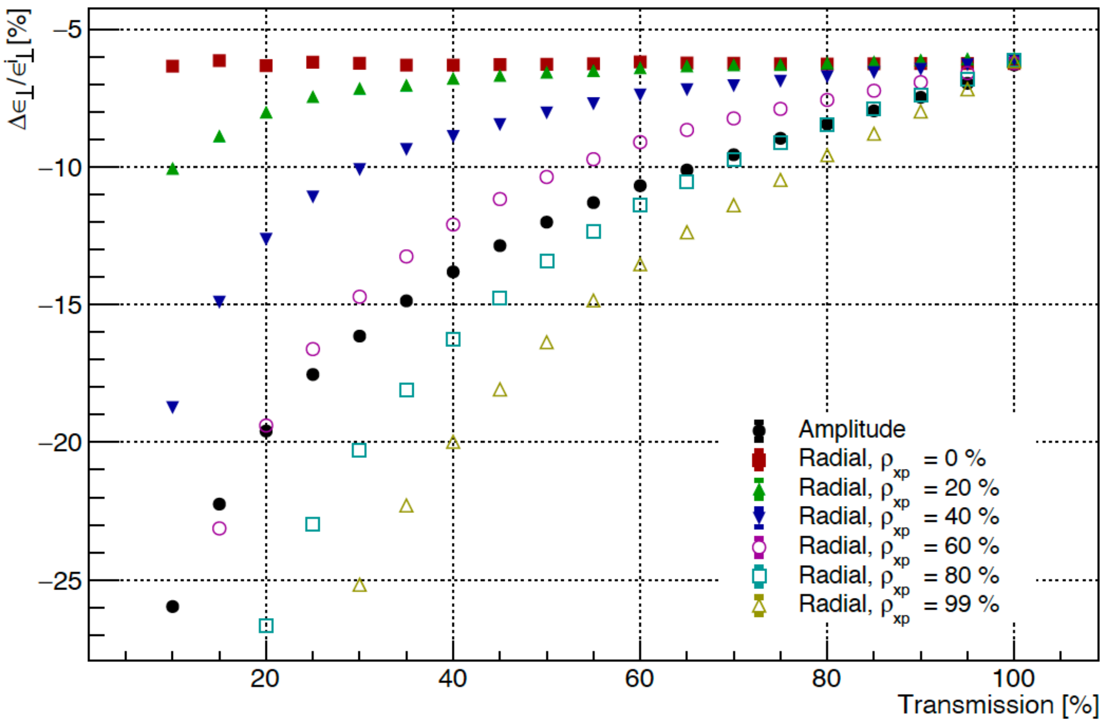
Expected emittance reduction and particle loss



$$\beta_\perp^* \sim \frac{\sigma_r^2 p}{mc\varepsilon_\perp}$$

$$\delta = \frac{\varepsilon_{t,downstream}}{\varepsilon_{t,upstream}} - 1 \sim \left(1 - \frac{\Delta p}{p}\right)\sqrt{1 + \frac{\theta_s^2}{mp\beta^2 c^3}\frac{\beta_\perp^*}{\varepsilon_{t,up}}} - 1$$

Expected emittance reduction and particle loss

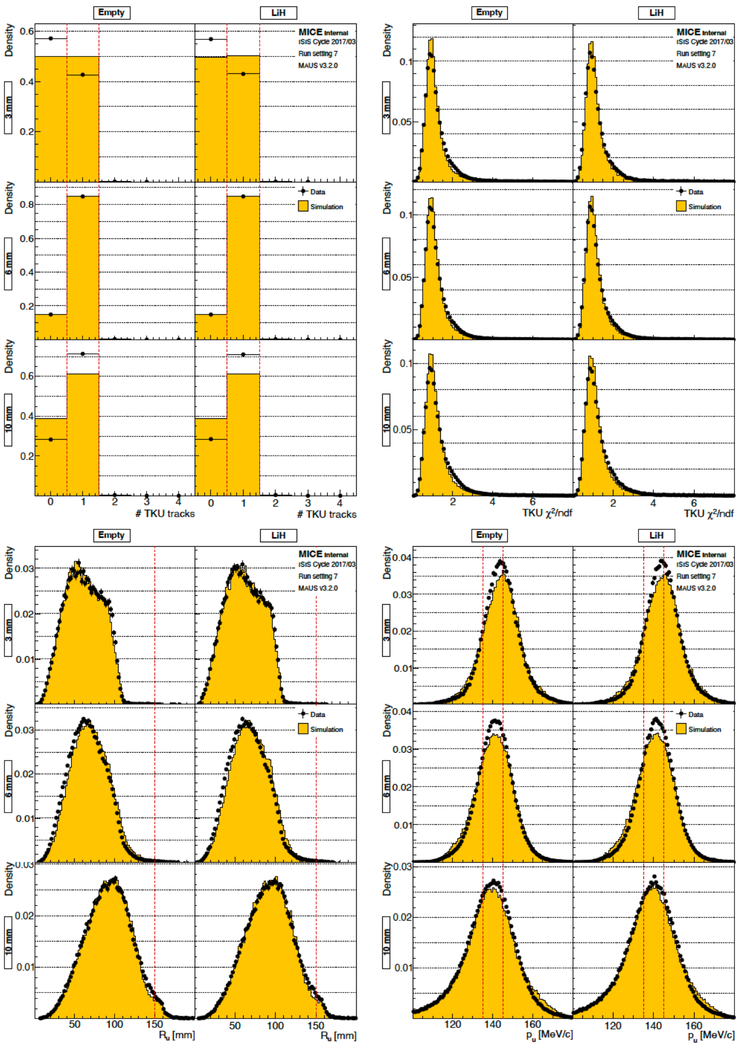


Because the MICE channel has a finite bore (so called dynamic aperture), they expect significant particle loss which seems to be contributed as emittance reduction

<u>They have developed the sophisticated particle selection algorithm</u>
I do not cover here since it is too complicated, and I do not fully understand yet…

Fermilab

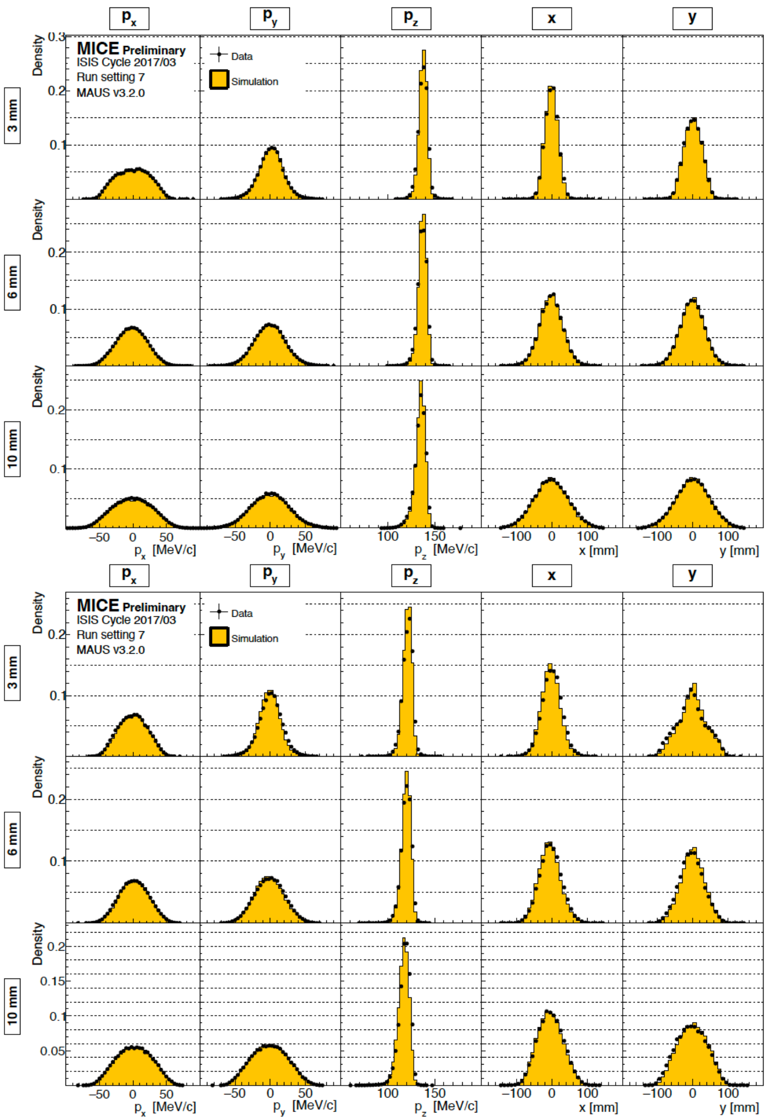
Observed phase space and MC comparison for 2017/02-7



The plots show the event cut (a red dashed line is the range)

- Track cut
  - Observed position must have a χ^2 over the number of degrees-of-freedom of 10 or less $\frac{\chi^2}{ndf} \leq 10$
  - Particle hits all five planes
  - Reconstructed momentum is in the range 135-145 MeV/c
- Aperture cut
  - 150 mm
- Momentum cut
  - 135-145 MeV/c

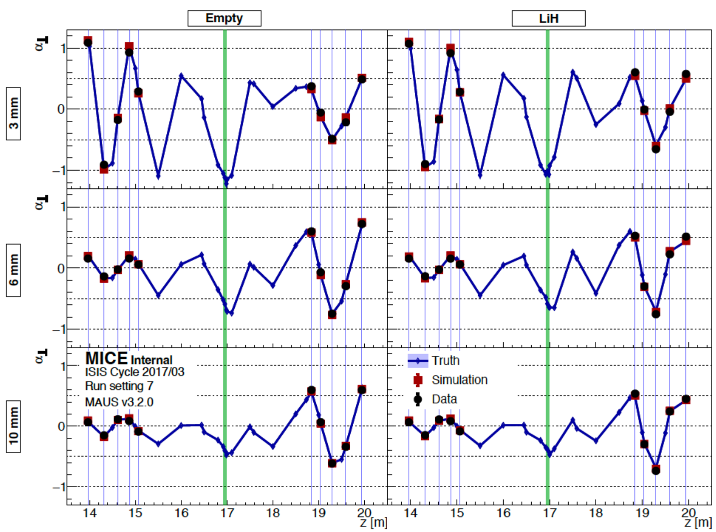
Phase space profiles and transmission efficiency of 3, 6, 10 mm for 2017/02-7

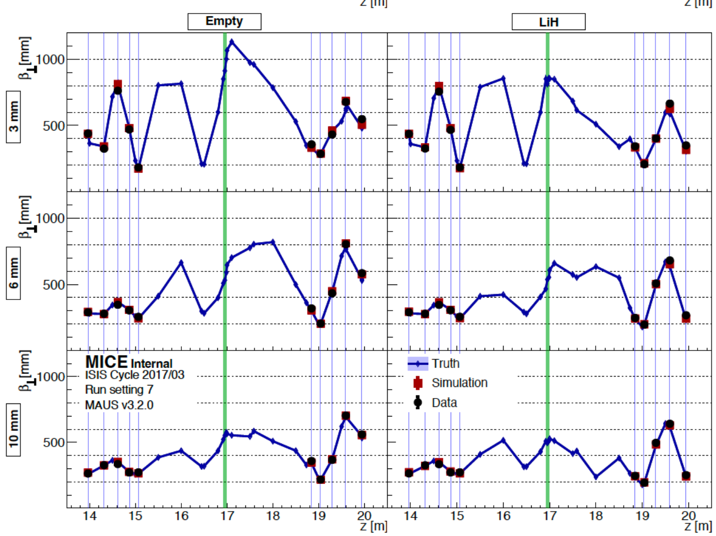


The observed phase space vs Monte Carlo simulation

- Both agree reasonably well

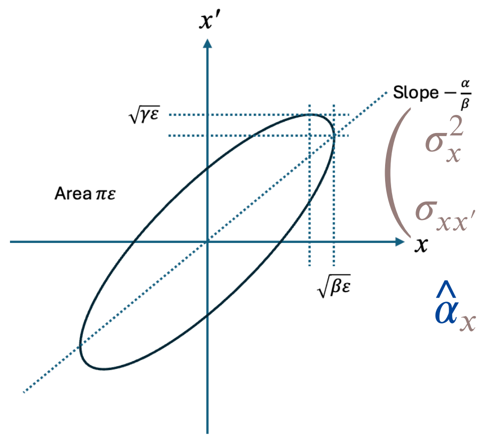
Phase space profiles and transmission efficiency of 3, 6, 10 mm for 2017/02-7





The observed Twiss parameters $\beta_\perp$, $\alpha_\perp$ (we used $\hat{\beta}$, $\hat{\alpha}$ in this lecture)

- $\alpha_\perp$ represents the average correlations in the (x, p_x) and (y, p_y)
- $\beta_\perp$ relates to the beam spot size
- Both are scaled by the geometric emittance (we called mechanical emittance in this lecture)

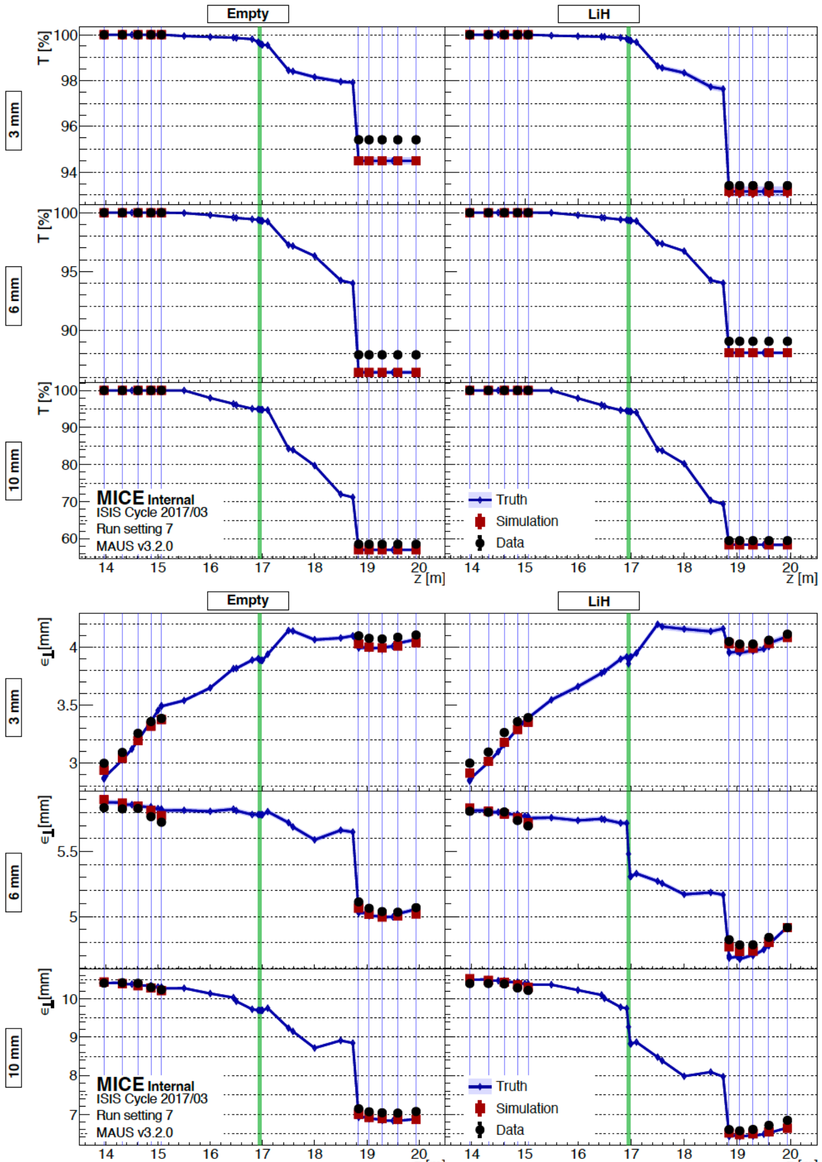


$$\begin{pmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{pmatrix} = \varepsilon_{rms} \begin{pmatrix} \hat{\beta} & -\hat{\alpha} \\ -\hat{\alpha} & \hat{\gamma} \end{pmatrix}.$$

$$\hat{\alpha}_x = -\frac{1}{2}\hat{\beta}_x'$$

Fermilab

Phase space profiles and transmission efficiency of 3, 6, 10 mm for 2017/02-7



The raw RMS emittance

- A large non-linearity at 3-mm beam
- A large particle loss at 10-mm beam, transmission efficiency is below 60 %

These significantly influence on the RMS emittance

- 3-mm beam emittance increased more than ionization cooling due to non-linear effct
- 10-mm beam emittance reduced more than ionization cooling due to particle loss
- They referred the emittance with external effect, as “biased emittance”

Fermilab

Event selection technique

Covariance matrix in solenoid B

$$\boldsymbol{\Sigma}_\perp = mc\epsilon_\perp^* \begin{pmatrix} \beta_\perp/p_z & -\alpha_\perp & 0 & -(\beta_\perp\kappa - \mathcal{L}) \\ -\alpha_\perp & \gamma_\perp p_z & (\beta_\perp\kappa - \mathcal{L}) & 0 \\ 0 & (\beta_\perp\kappa - \mathcal{L}) & \beta_\perp/p_z & \alpha_\perp \\ -(\beta_\perp\kappa - \mathcal{L}) & 0 & \alpha_\perp & \gamma_\perp p_z \end{pmatrix}$$

Transverse amplitude

$$A_\perp = \varepsilon_\perp^* \left(x - \langle x \rangle\right)^T \Sigma^{-1} \left(x - \langle x \rangle\right) \sim \varepsilon_\perp^* \bullet \chi_4^2 \qquad x = x, p_x, y, p_y$$

$$\langle A_\perp \rangle = \varepsilon_\perp^* \langle \chi_4^2 \rangle \sim 4\varepsilon_\perp^*$$

If a new one event is added in the amplitude, each component varies

$$\langle x_\alpha \rangle_{n-1} = \frac{1}{n-1}\left(n\langle x_\alpha \rangle_n - x_\alpha^n\right) \qquad \alpha, \beta = x, p_x, y, p_y$$

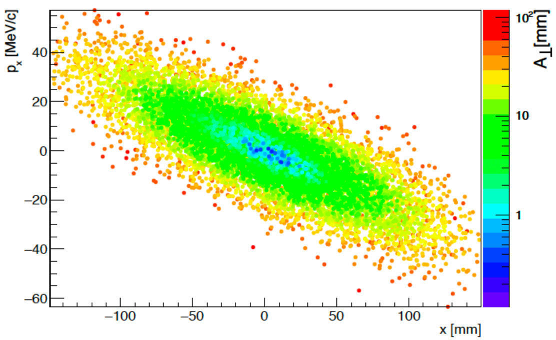
$$\Sigma_{\alpha\beta}^{n-1} = \frac{n-1}{n-2}\Sigma_{\alpha\beta}^n - \frac{n}{n-1}\left(x_\alpha^n - \langle x_\alpha \rangle_n\right)\left(x_\beta^n - \langle x_\beta \rangle_n\right)$$

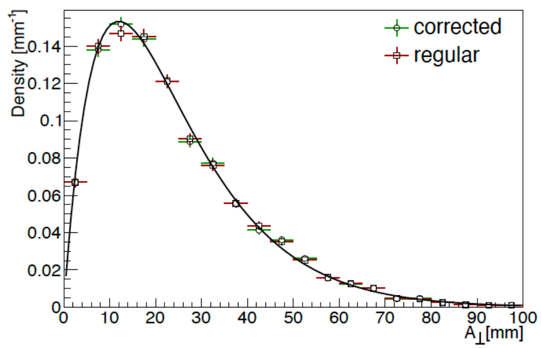
They can find if the added event makes $A_\perp$ only true particle amplitude (sounds that they remove any particles which causes non-linear behavior or particle loss)

Event selection technique

If the beam transport line is linear,

$$\begin{cases} q \to q \\ q' \to q' - \frac{q}{f} \end{cases}$$

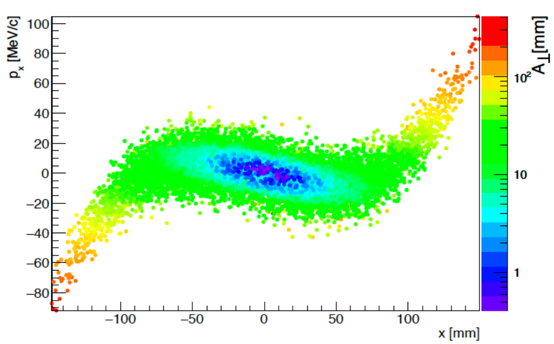


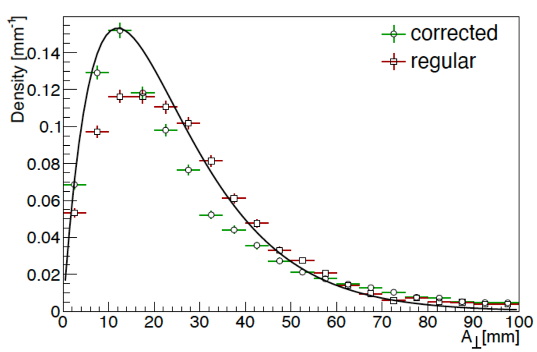


Transverse amplitude does not need correction

If the beam transport line is non-linear,

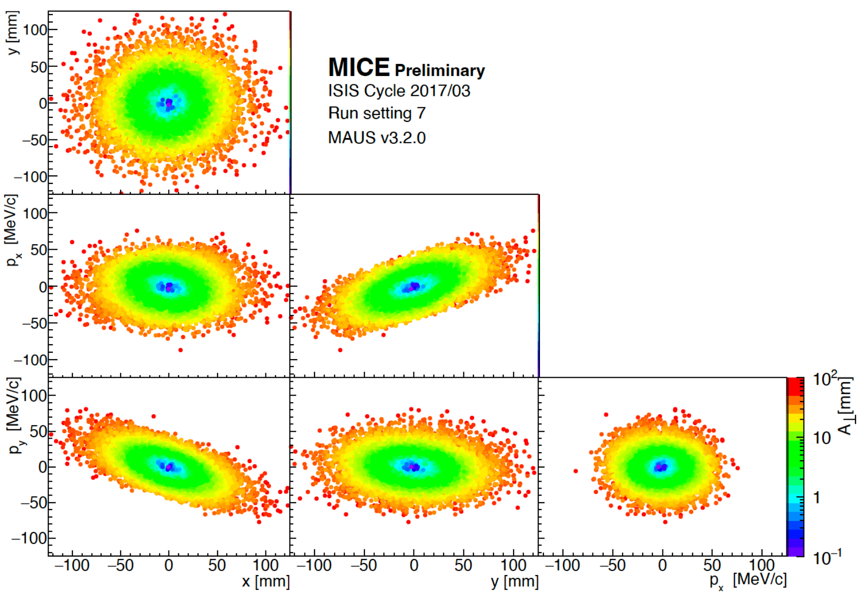
$$\begin{cases} q \to q \\ q' \to q' - \frac{q}{f}\left(1 + C_\alpha q^2\right) \end{cases}$$

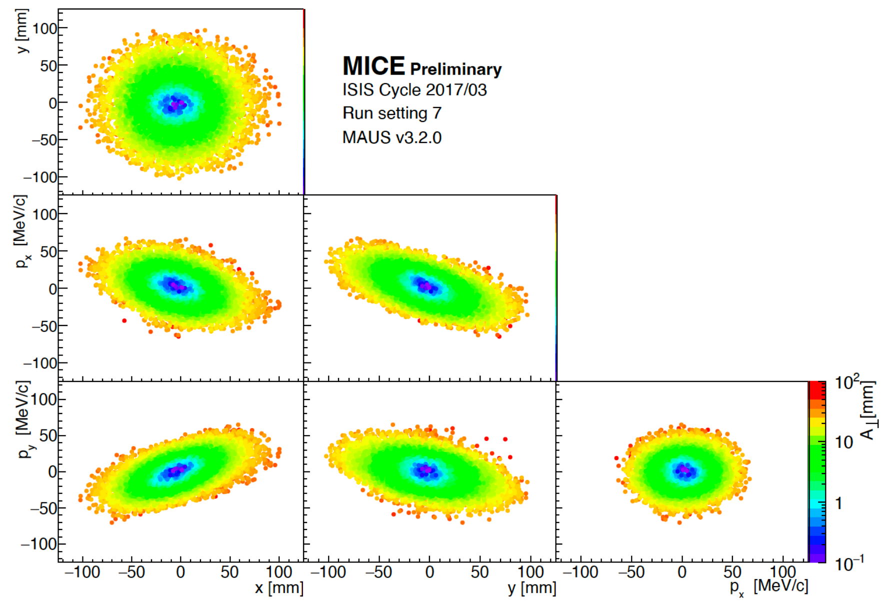




Corrections applied to reconstruct true amplitude

Poincare Sections





These plots show the six Poincare sections of transverse emittance

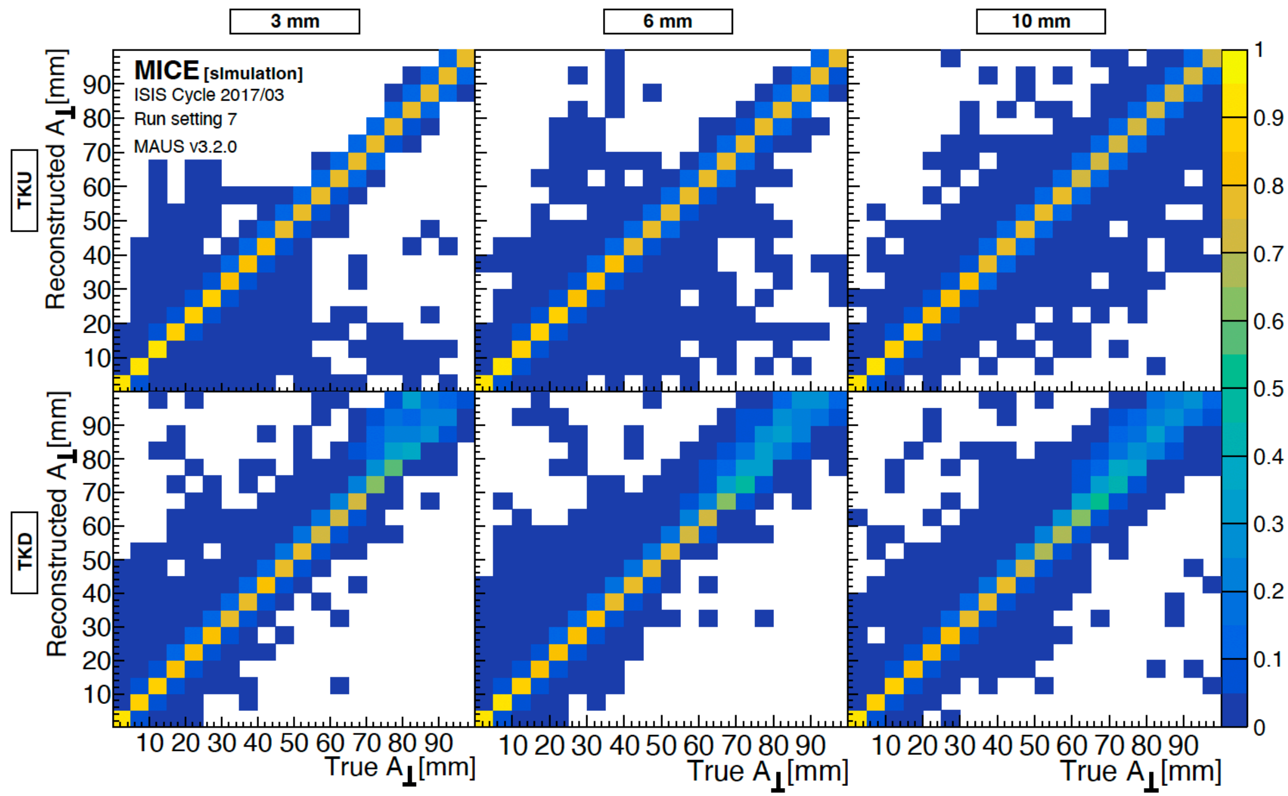
The amplitude correction is applied

Color code shows the size of amplitude (Does this mean that they cut high amplitude points?)

Additional correction

- To reconstruct the observed particle position and momentum, they simulate the particle tracking and apply the exact value to calibrate the detector resolution

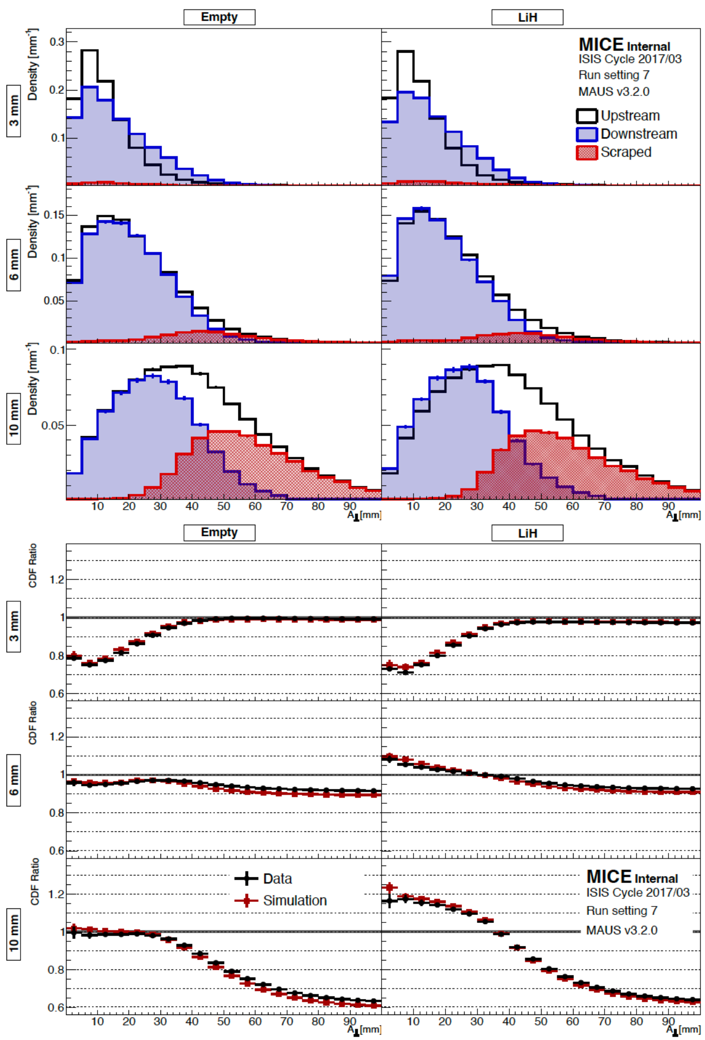
$$N_\perp^i = e_i^{-1} \bar{N}_\perp^i = e_i^{-1} \sum_{j=1}^{n} M_{ij} \tilde{N}_\perp^j.$$



This technique is standard for the neutrino oscillation experiment

Fermilab

Amplitude change in absorber



Upper plots show the amplitude variation by absorber

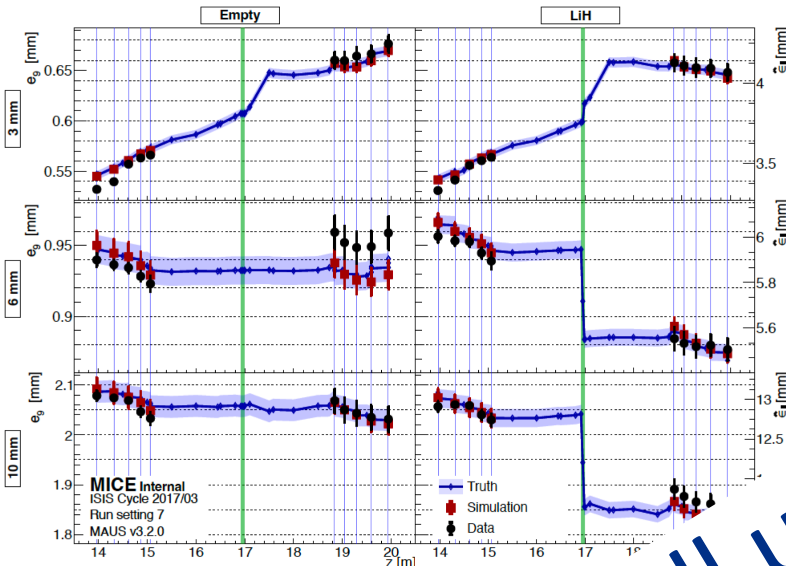
- Density at low amplitude for 10-mm increases which indicates beam cooling

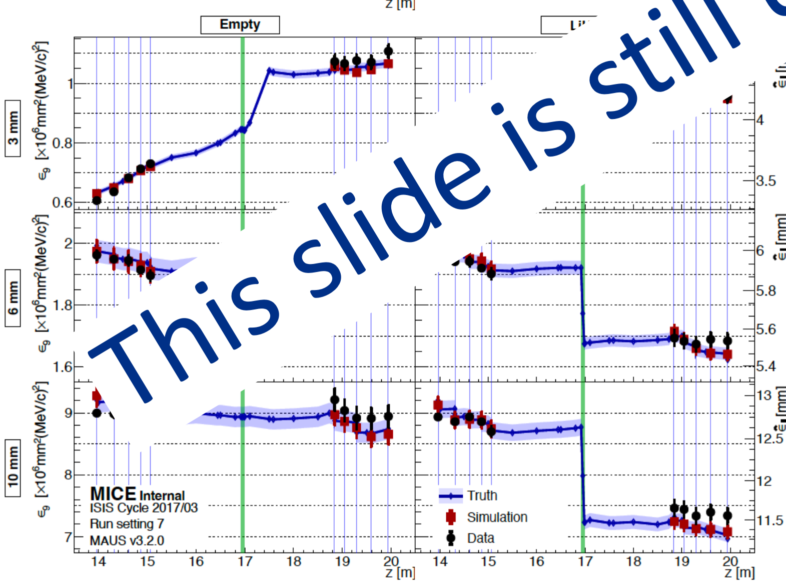
Lower plots show the Cumulative Density Function (CDF) ratio

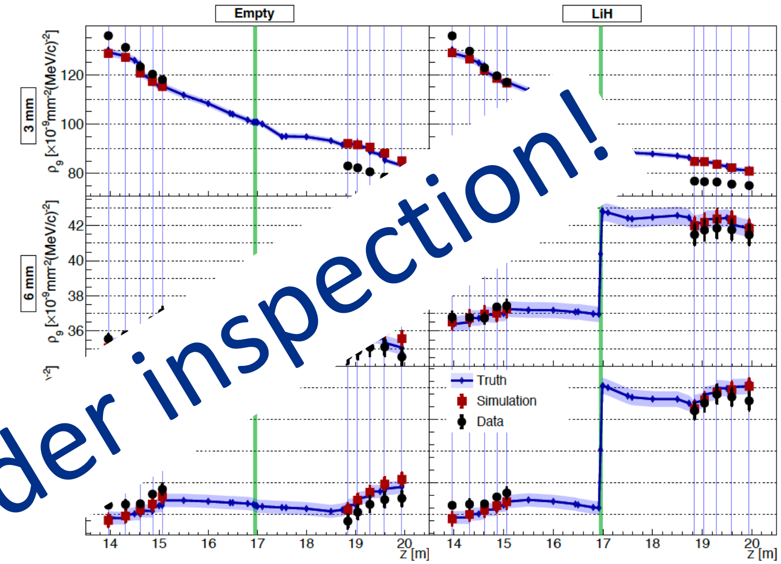
- As shown in 3-mm case, CDF ratio becomes 1 at high amplitude if beam is no cooling or heating
- CDF is above 1 if the beam density is increased
- 6-mm and 10-mm beams present that the beam density at low amplitude increases while that at high amplitude decreases
- It suggests beam cooling

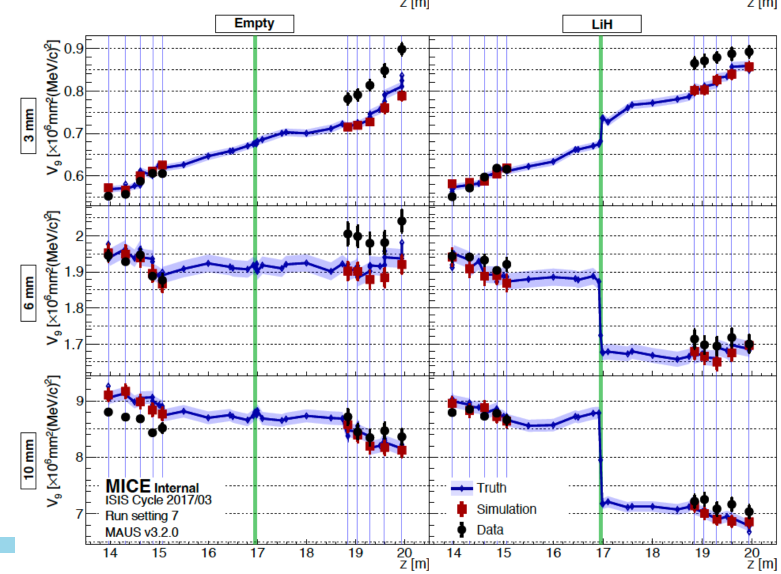
Using particle selection: 9%-subemittance and 9%-emittance evolutions

Using KNN selection algorithm









This slide is still under inspection!

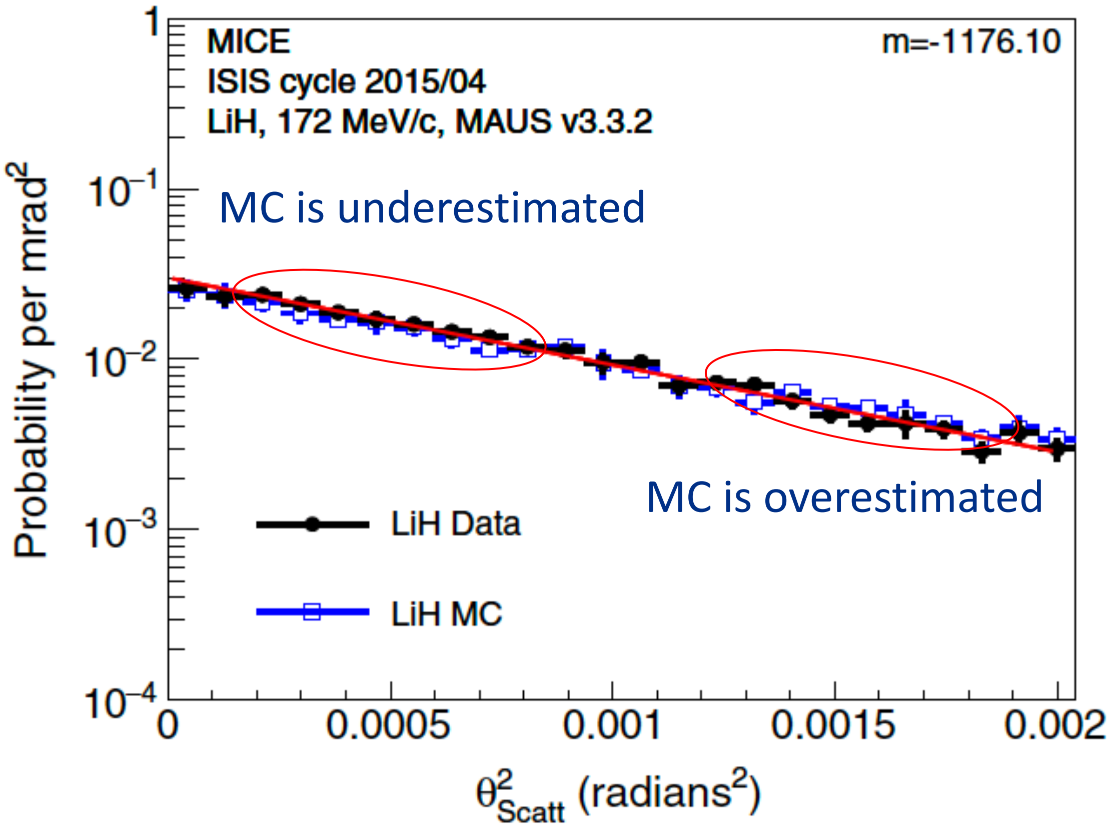
My Personal Inspections for MICE

- I agree that MICE has successfully demonstrated ionization cooling
  - Very careful systematic studies and analysis
  - Ionization cooling works for large phase space volume
  - I also notice that MICE analysis is based on a model dependent, similar as neutrino oscillation experiments
- MICE is not real cooling channel
  - Lost matching magnet, no correction magnets
  - No RF cavity to compensate kinetic energy of muons
  - Poor acceptance which causes large particle loss
- We still do not know the intensity effect from MICE
  - Space charge in ionization process
  - Emittance exchange (transverse and longitudinal coupling)
  - RF embedded in magnetic fields

Discussion

- I am also concerned about the accuracy of the cooling theory which should be based on
  - Multiple scattering
  - Energy straggling
  - Collective effect

Particle penetration in matters is refurbished using computer simulations to include microscopic structure of target material including electron behaviors



Goal of demo channel

- Primary goal is demonstrating the most critical component in muon collider complex
  - It includes not only ionization cooling but also target and muon acceleration
  - Also, there is no solid design for final cooling section
- For cooling section,
  - Try to design a direct emittance evolution measurement
    - I do not have enough confidence yet for the MICE analysis
  - It means that the beam diagnostics system could be challenging to reach fine accuracy (0.1 % level of emittance measurement), especially for longitudinal emittance measurements
  - We should also consider variation of cooling by tuning beta function