MICE STEP 1: FIRST MEASUREMENT OF EMITTANCE WITH PARTICLE PHYSICS DETECTORS

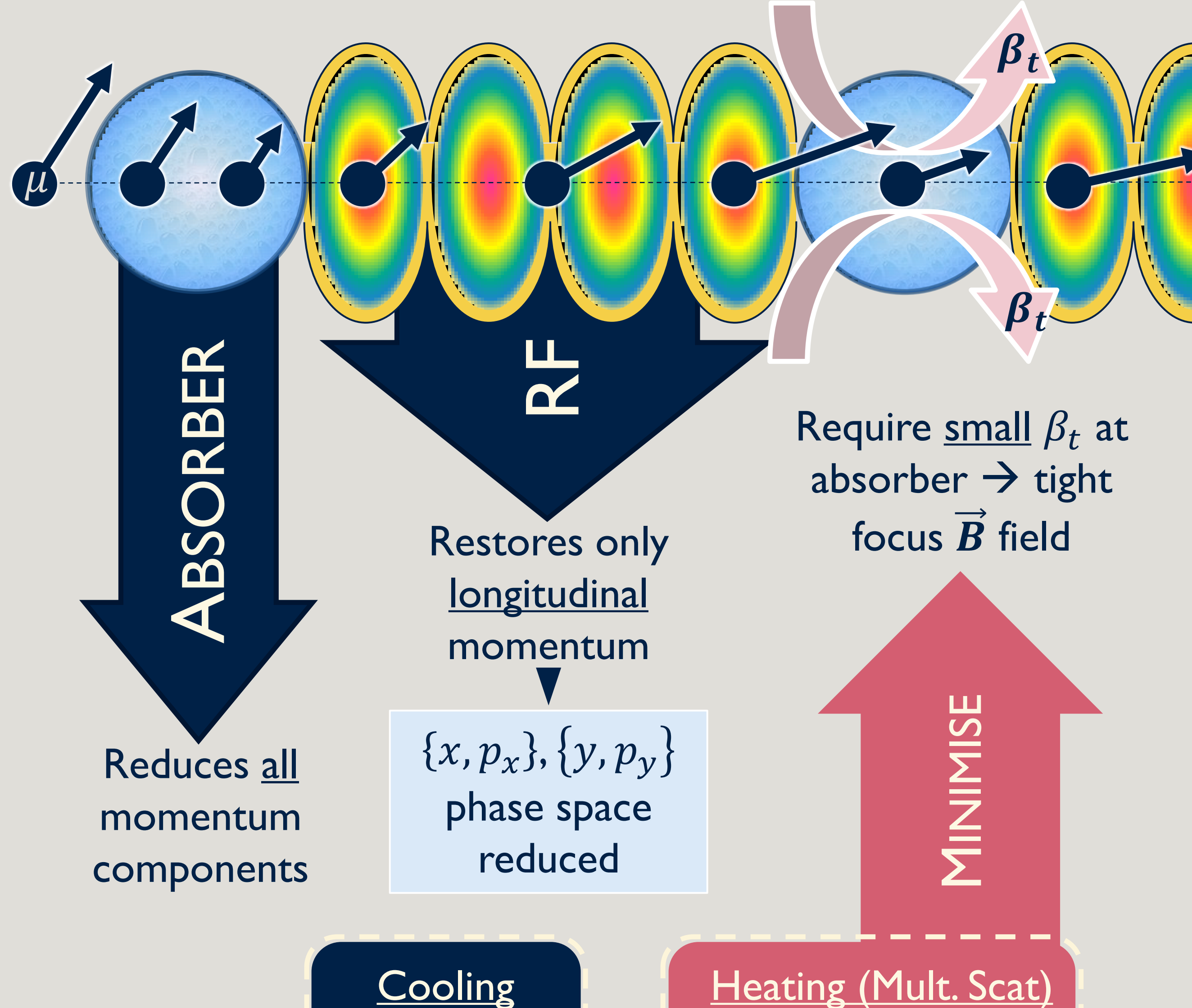
V. Blackmore, University of Oxford,
on behalf of the MICE Collaboration

About MICE

- Ionisation cooling
- The Muon Ionisation Cooling Experiment (MICE)
- The beam line

Ionisation Cooling

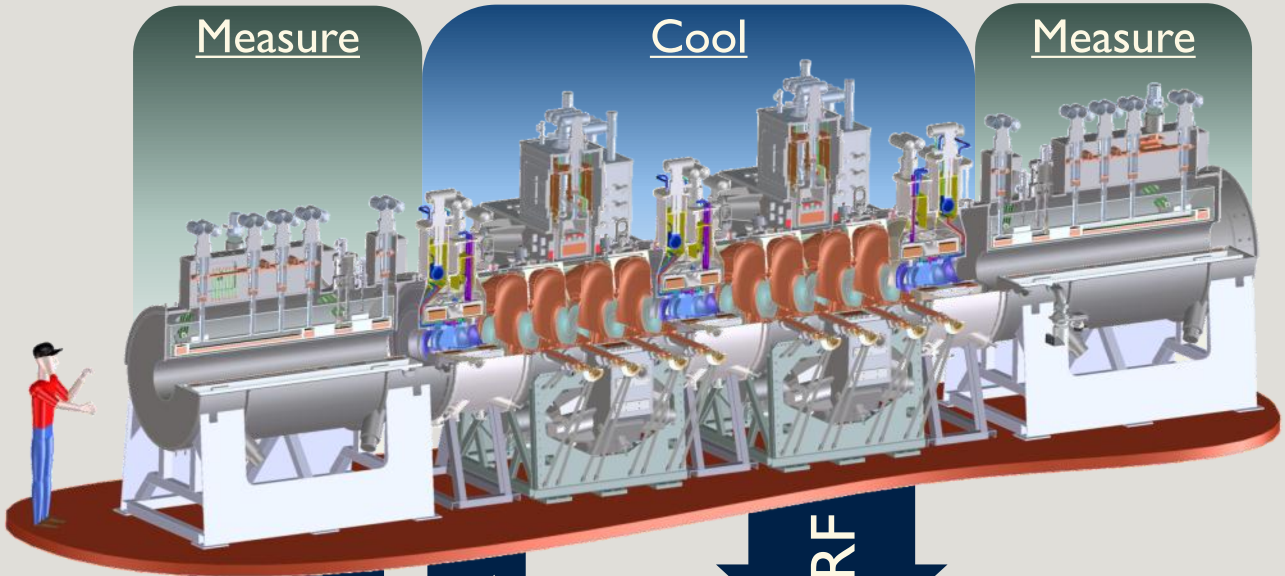
- **Cooling**: reduction of the beam volume in 2, 4, or 6 dimensional phase space.
- Light-to-moderate 4D cooling required for Neutrino Factory.
- Intense 6D cooling required for Muon Collider.
- Begin with ionisation cooling.



$$\frac{d\varepsilon_n}{dX} \approx \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

The Muon Ionisation Cooling Experiment (MICE)

- In construction at Rutherford Appleton Laboratory, UK.
- Full cell of ionisation cooling lattice.
- Test performance in different operational modes.
- Require relative precision of $\frac{\Delta\varepsilon_n}{\varepsilon_n} \sim 1\%$ → use particle physics detectors.
- Muon-by-muon measurement.



RF

Reaccelerates muon, restoring lost energy

ABSORBER

Liquid hydrogen or solid Lithium Hydride. Reduces muon momentum vector

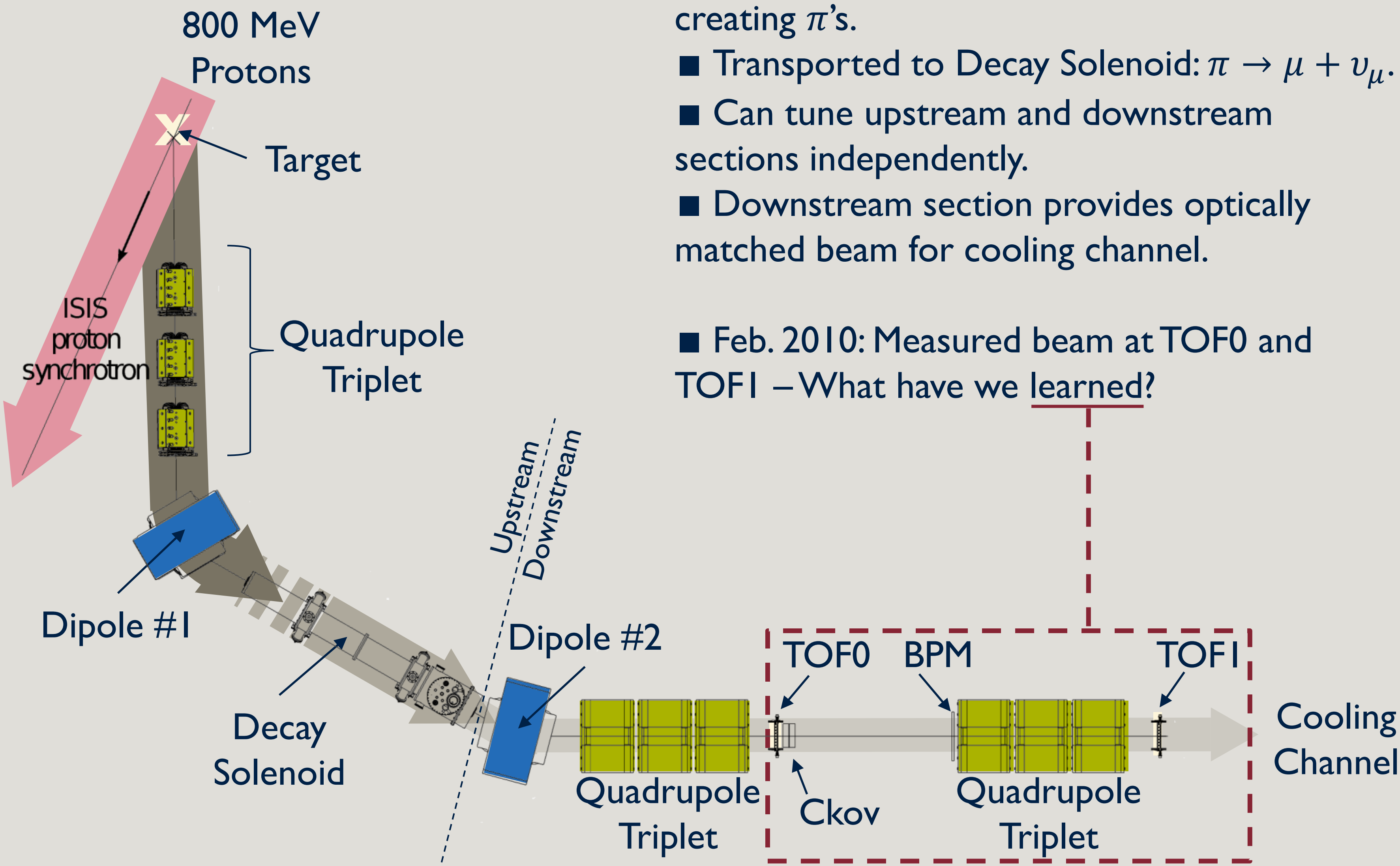
SPECTROMETER SOLENOID

4T Solenoid containing scintillating fibre tracker. Measures muon components: $\{x, y, z, p_x, p_y\}$

The Beam Line

■ Target samples 600 – 800 MeV protons, creating π's.
■ Transported to Decay Solenoid: $\pi \rightarrow \mu + \upsilon_{\mu}$.
■ Can tune upstream and downstream sections independently.
■ Downstream section provides optically matched beam for cooling channel.

■ Feb. 2010: Measured beam at TOF0 and TOF1 – What have we learned?



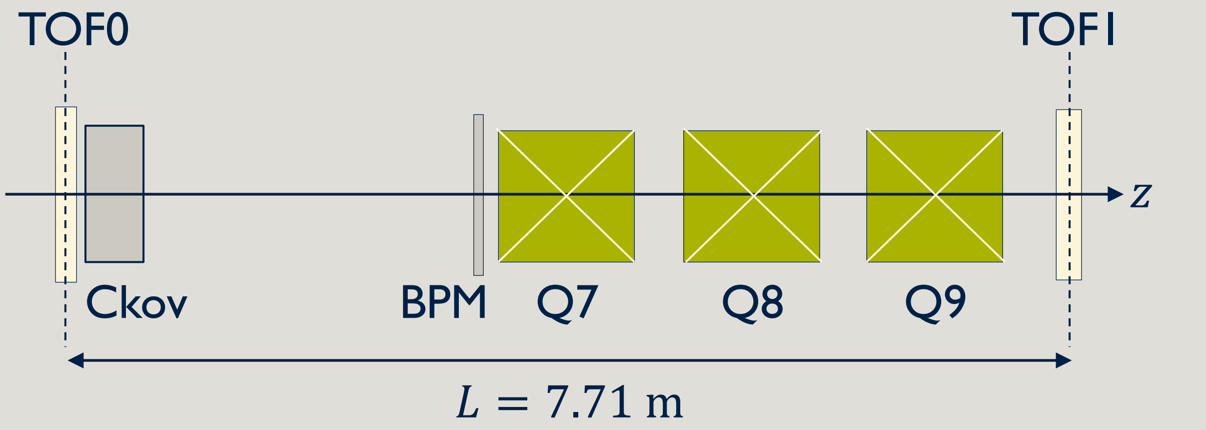
Emittance & Momentum Reconstruction

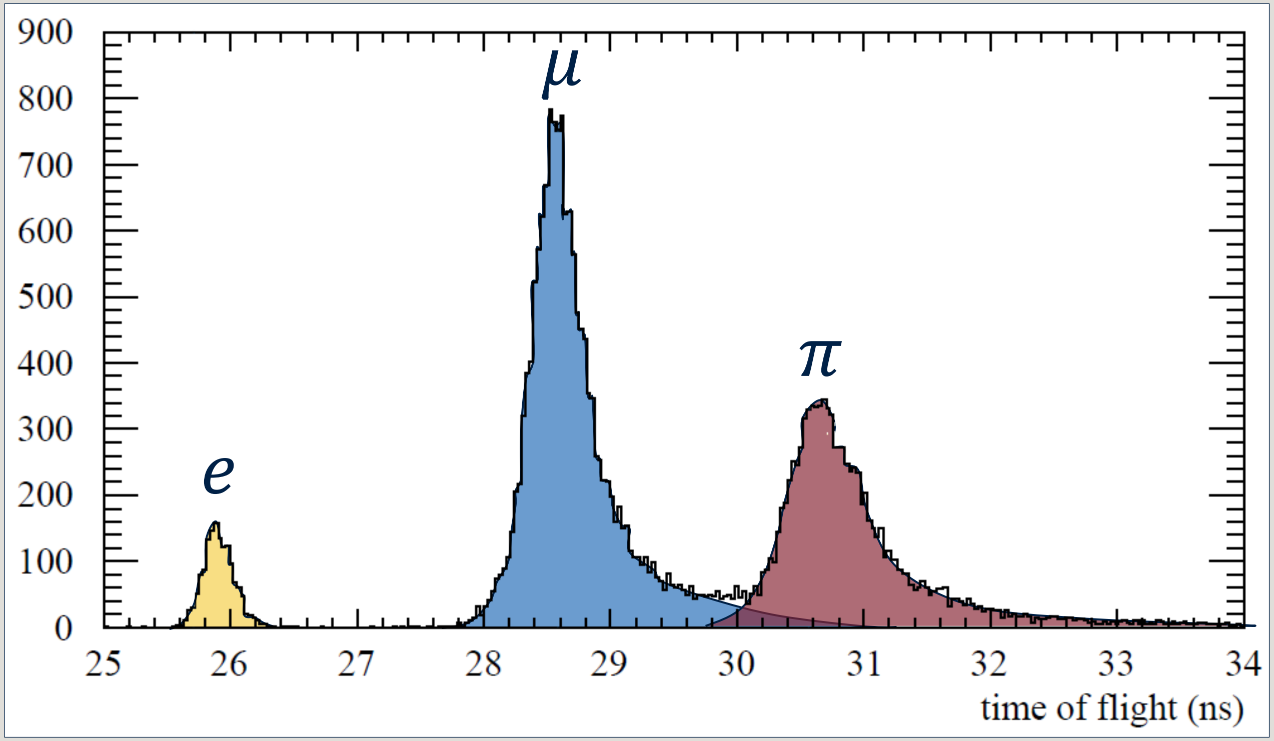
- The Time Of Flight (TOF) system
- Measuring position components
- Reconstruction of muon paths
- Accuracy of the reconstruction technique

The Time Of Flight (TOF) System

- Two detectors, each with two orthogonal planes of scintillator slabs.
- Measure particle crossing time to 50 ps
- Dipole selects mean momentum of beam.
- Time-of-flight depends on particle mass – PID possible.

$$t = \left(\frac{L}{c}\right)\sqrt{1 + \frac{(mc)^2}{p^2}}$$





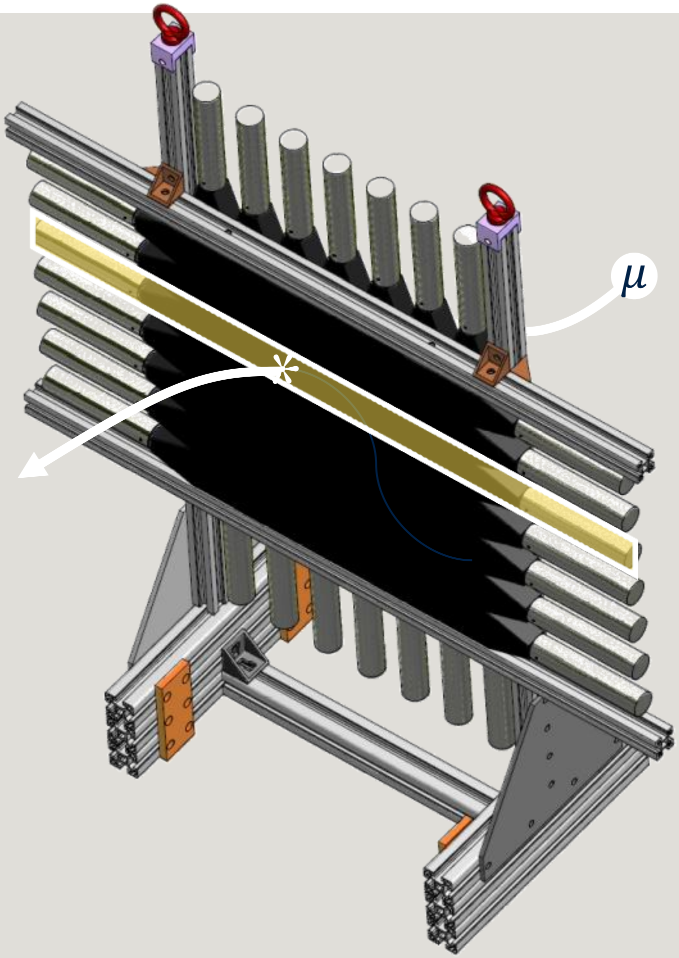
Measuring Position Components

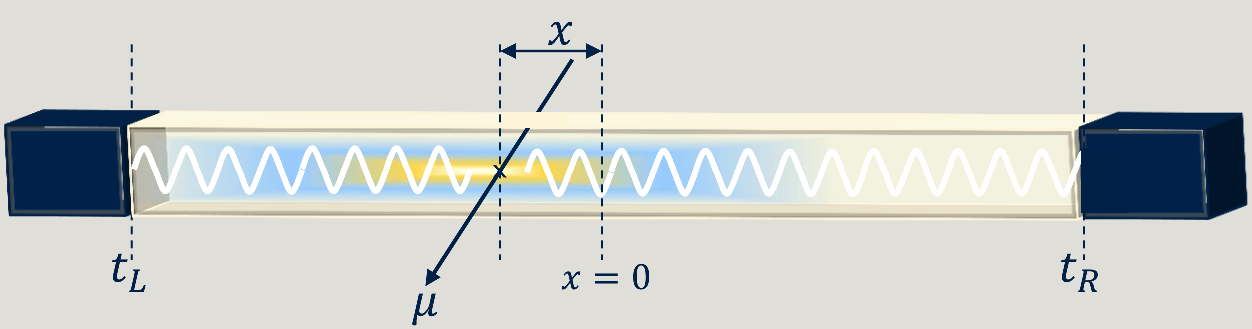
- Two independent methods of measuring position:
  1) Measure pixel position,
  2) Measure position according to signal arrival time at PMTs.

$$x = \frac{c_{\text{eff}}(t_L - t_R + \Delta)}{2}$$

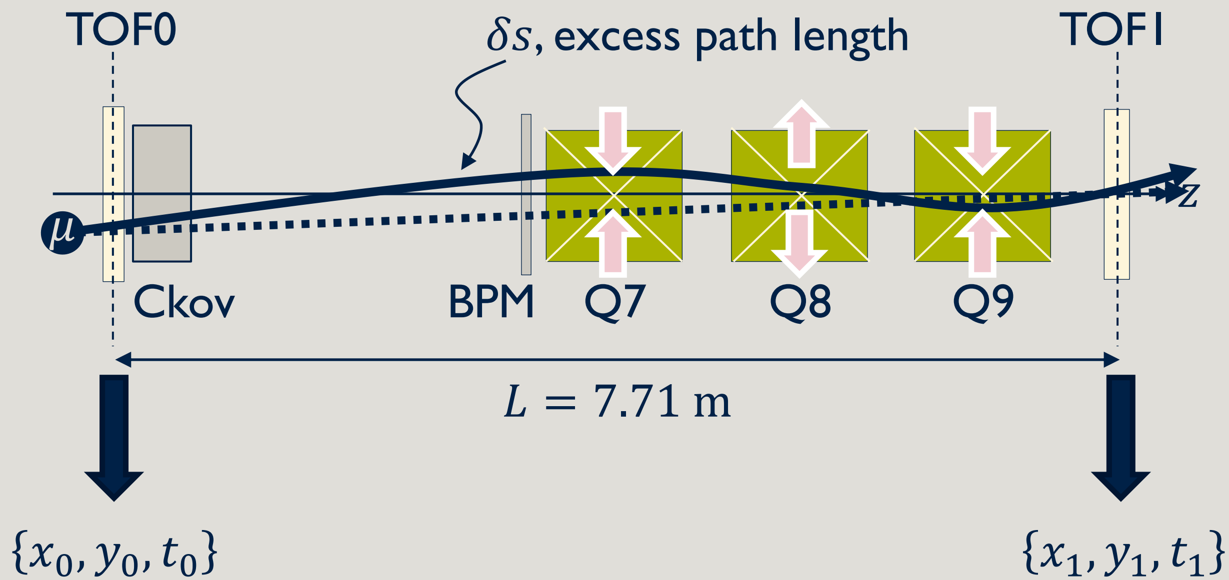
- Position resolution, TOF0: 9.8 mm
  TOF1: 11.4 mm

- For each particle crossing the TOF stations, we know $\{x, y, t\}$
- To learn more about the beam line we must <u>also</u> know $\{x', y', p_z\}$, where $x' = \frac{p_x}{p_z}$ etc.
- Reconstruct particle trajectories.





Reconstructing Muon Paths



- Begin with position measurements of muon at TOF0 and TOF1.

REPEAT

1) Calculate p_z from time of flight.

2) Assume linear beam transport*:

*$\underline{M}$ depends on p_z

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} \Rightarrow \begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$

- $\underline{M_x}$ and $\underline{M_y}$ vary quickly at low p_z.

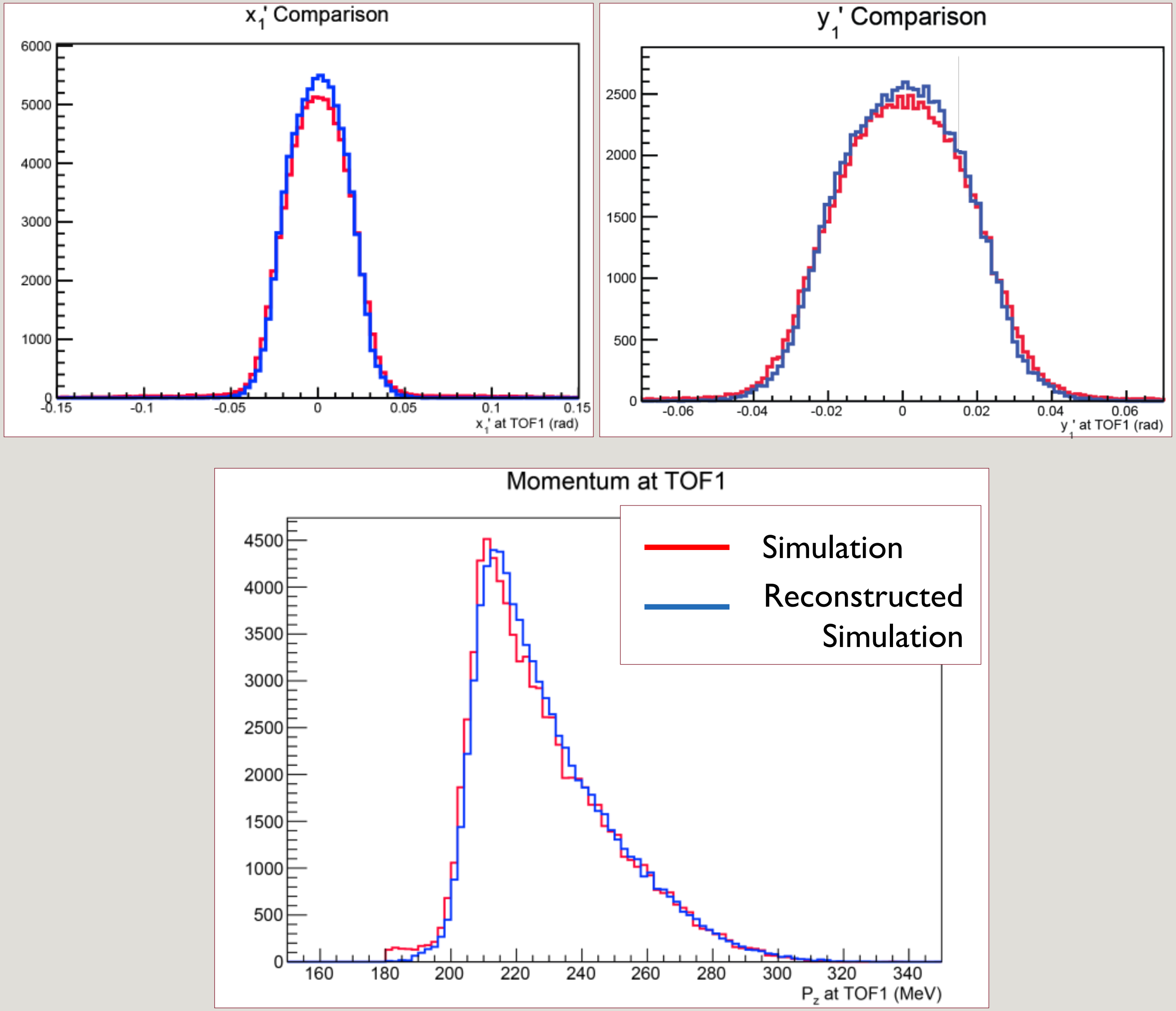
3) Track through quadrupoles to calculate δs,

$$\underline{M_x} = \underline{O}_{Q9\rightarrow TOF1}\, \underline{F}_{Q9}\, \underline{O}_{Q8\rightarrow Q9}\, \underline{D}_{Q8}\, \underline{O}_{Q7\rightarrow Q8}\, \underline{F}_{Q7}\, \underline{O}_{TOF0\rightarrow Q7}$$

- Correct for energy lost between TOF0 and TOF1

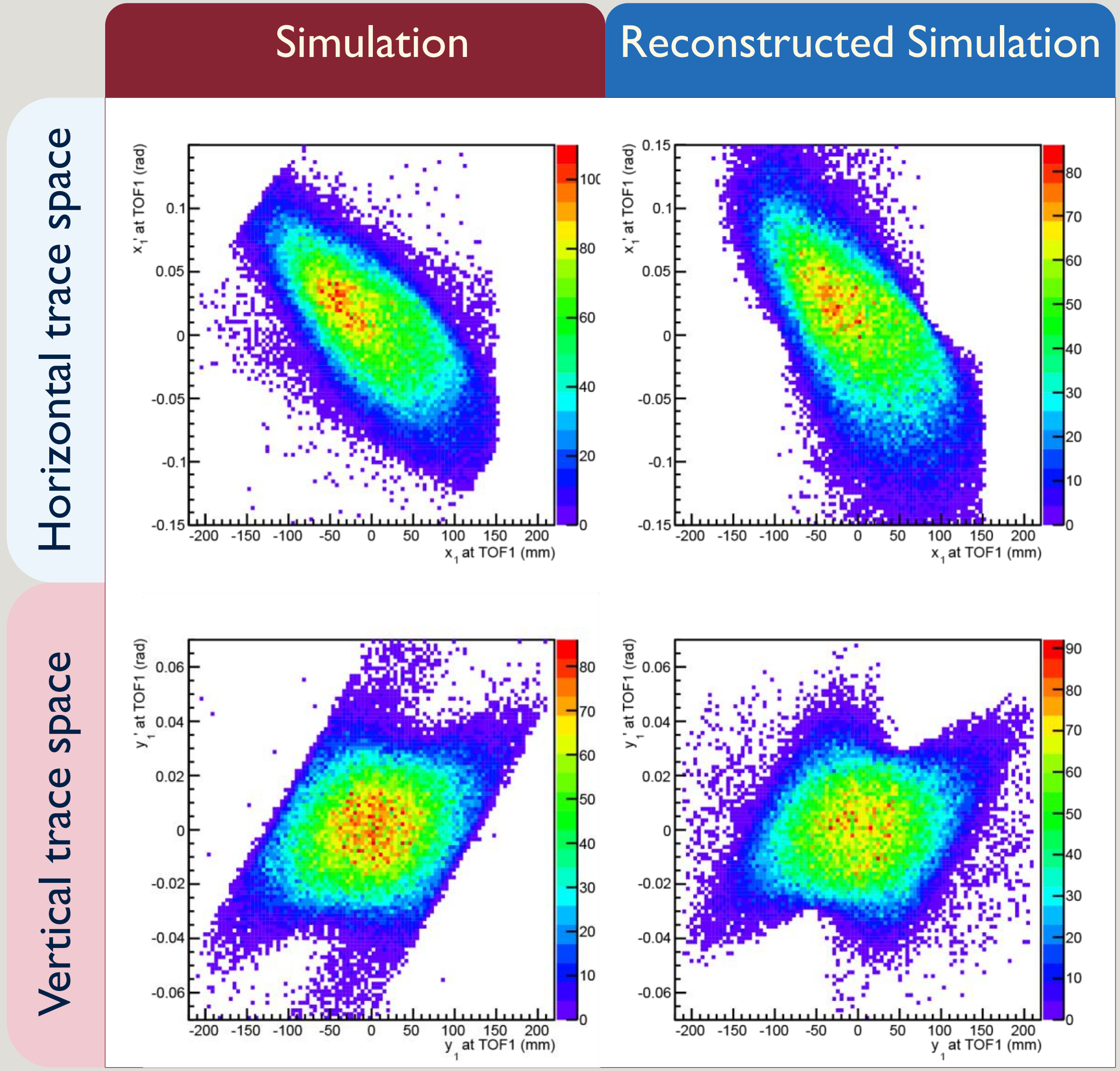
Accuracy of Reconstruction Technique

- (x, y, t) from Monte Carlo (G4beamline, G4MICE) simulation are smeared by the TOF resolution.
- Trace-space components and momentum reconstructed.



Accuracy of Reconstruction Technique

- (x, y, t) from Monte Carlo (G4beamline, G4MICE) simulation are smeared by the TOF resolution.
- Trace-space components and momentum reconstructed.
- Good qualitative agreement:
  - Core reproduced well.
  - Good reproduction of high amplitude particles.



Step 1 Data

- Step 1 data sets
- Expectations versus reality

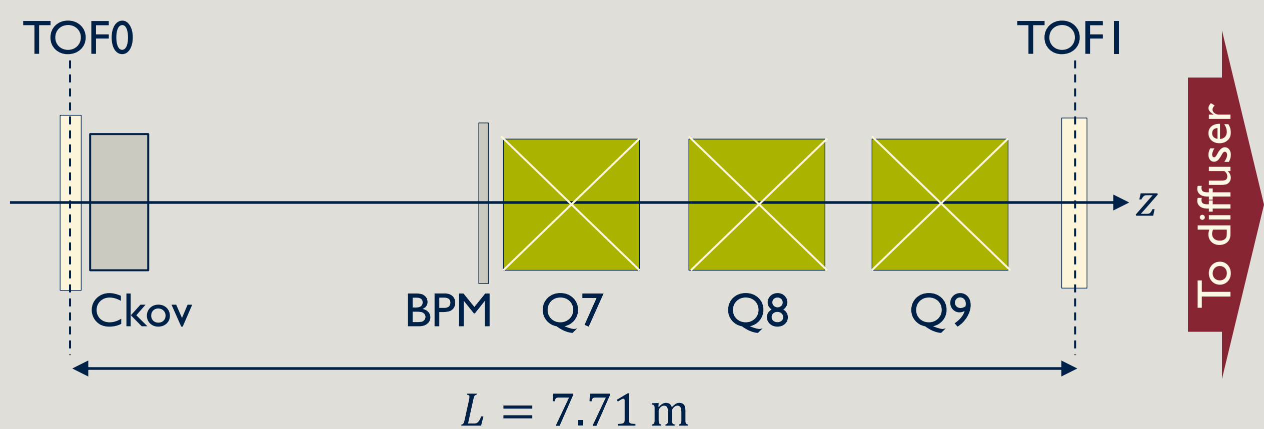
Step 1 Data Sets

- MICE investigates cooling potential of lattice cell for different beam settings.
- Categorise beam settings by their values at the **centre of an absorber**.
- Nominal test beams given in an "emittance-momentum" matrix.
- 9 beam settings x 2 muon polarities = 18 beams [17 measured].

	$p_z = 140\text{MeV}$	$p_z = 200\text{MeV}$	$p_z = 240\text{MeV}$
$\varepsilon_N = 3$ mm	$D = 0$ mm	$D = 0$ mm	$D = 0$ mm
$\varepsilon_N = 6$ mm	$D = 5.0$ mm	$D = 7.5$ mm	$D = 7.5$ mm
$\varepsilon_N = 10$ mm	$D = 10$ mm	$D = 15.5$ mm	$D = 15.5$ mm

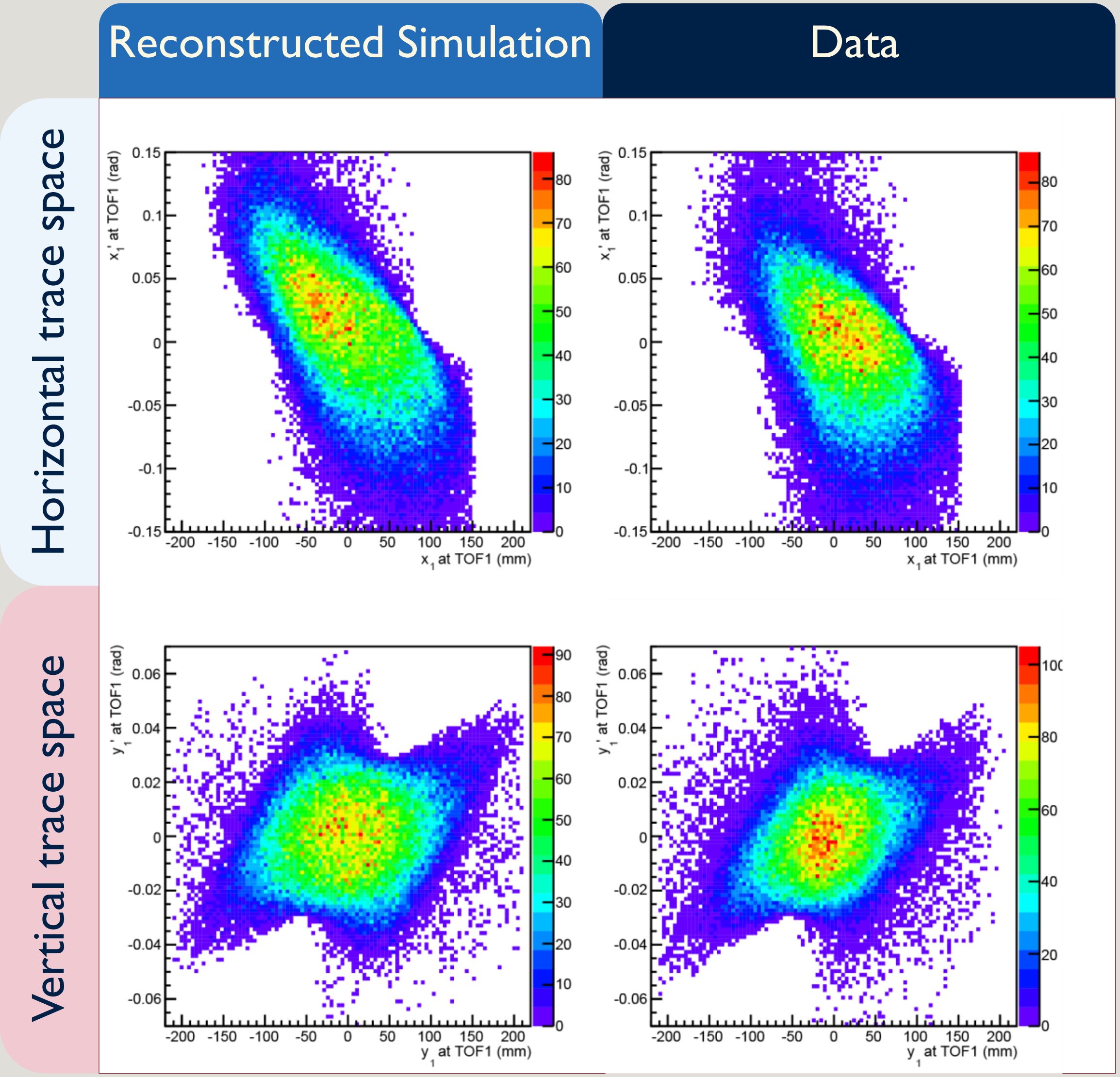
Thickness of Pb required to achieve this emittance and momentum upstream of cooling channel ("diffuser")

Complication: Our beam line measurements exist upstream of the diffuser: higher momentum and lower emittance.



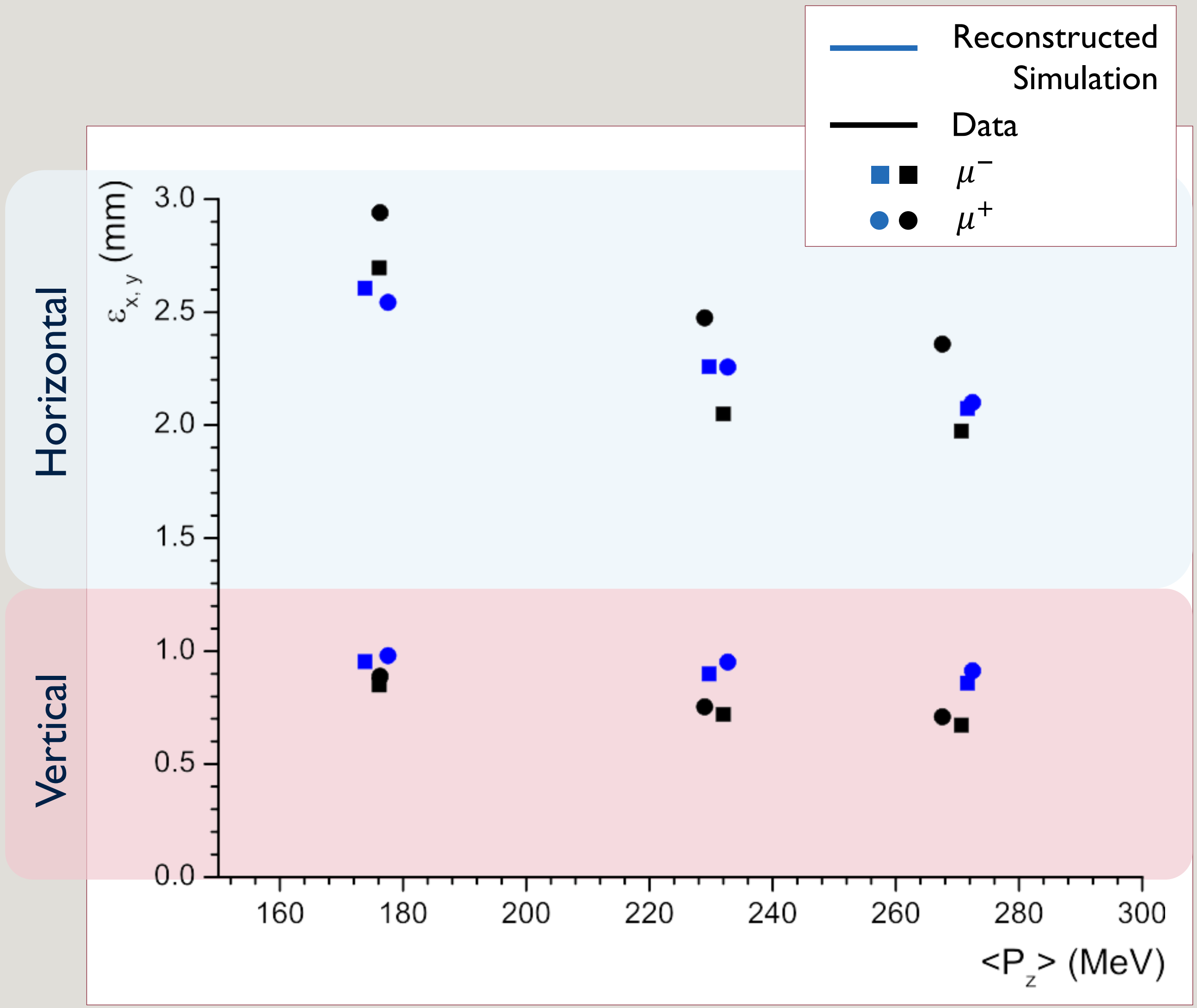
Expectation versus Reality

- Compare data to reconstructed simulation.
- Overall good qualitative agreement.



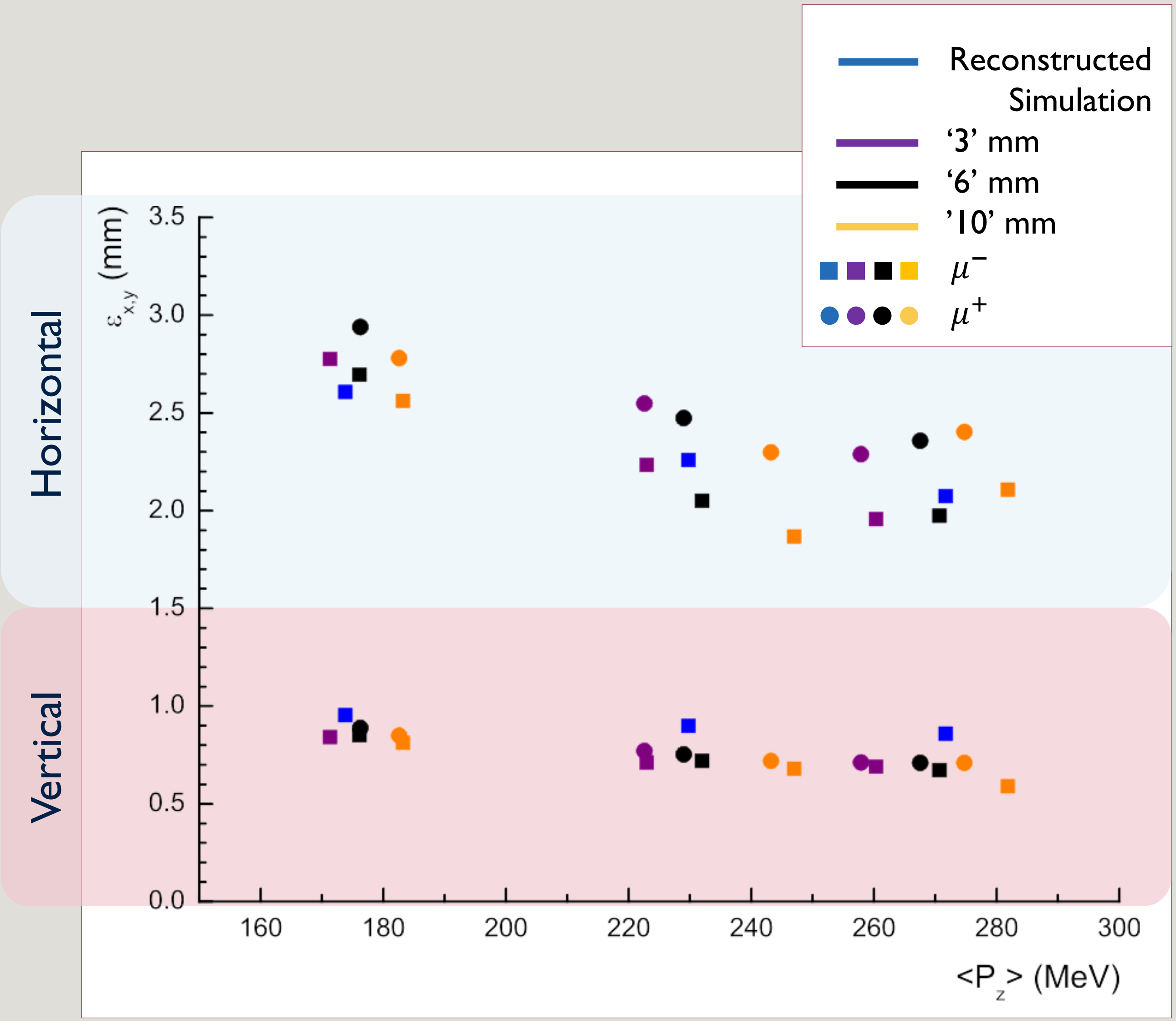
Expectation versus Reality

- Compare data to reconstructed simulation.
- Overall good qualitative agreement.
- Larger difference in horizontal plane



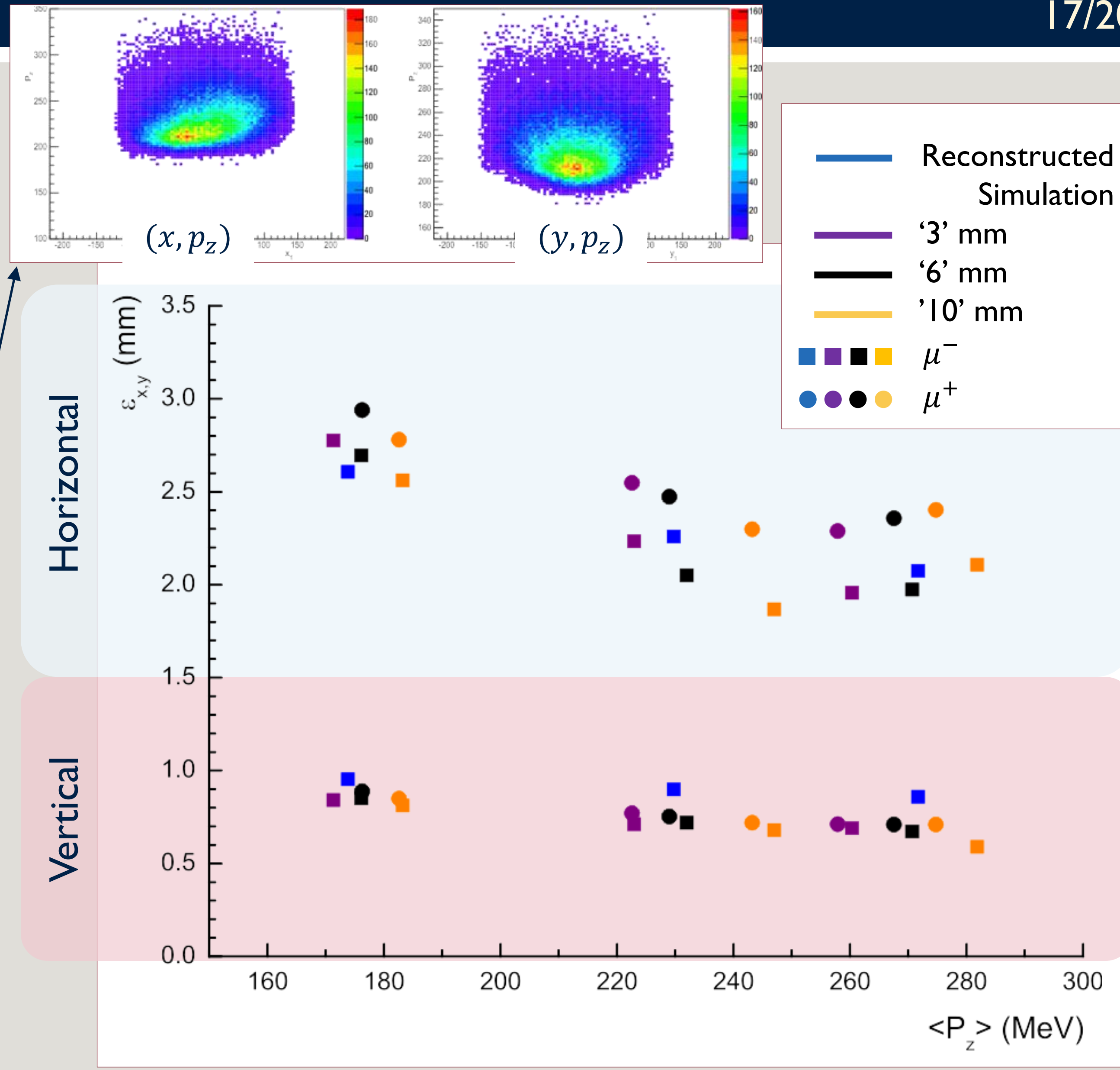
The Full Data Set

- Measured, and reconstructed emittances of 17 of the beam line settings.
- Note: The nominal '3', '6' and '10' mm emittance is after the diffuser.
- Good agreement with simulation.



Summary

- Constant vertical emittance of 0.8 mm.
- Horizontal emittance varies depending on dispersion from D2, ~2.5 mm.
- Resolution of reconstruction method has not been removed.
- Beam is asymmetric in x and y.
- Limited by quadrupole apertures.



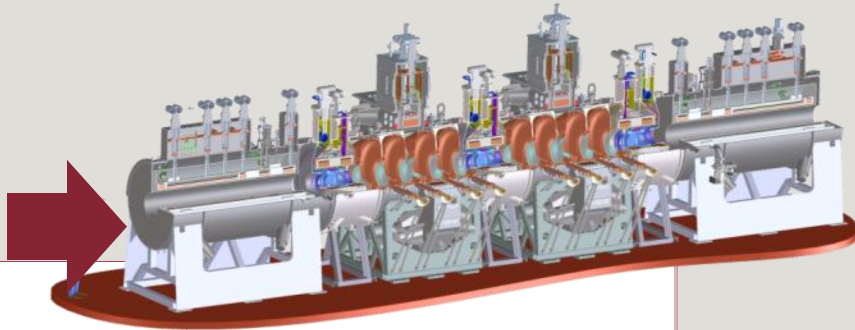
What would happen if we put our measured muons through a simulation of the full cooling channel?

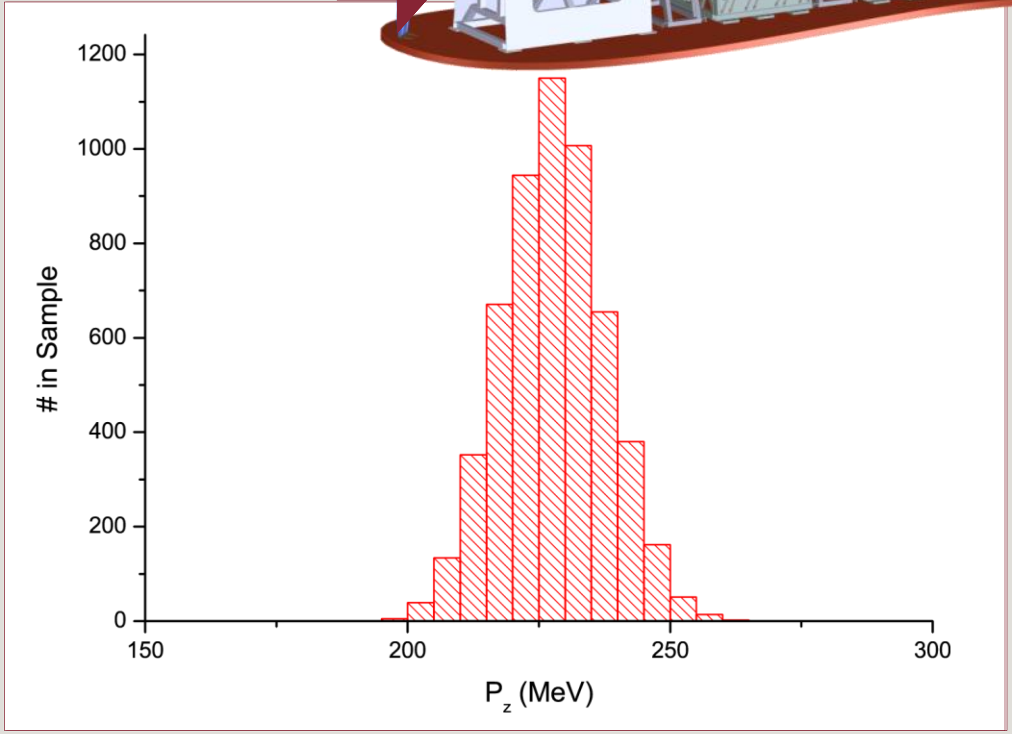
EVOLUTION THROUGH STEP VI

- Expected performance of the cooling channel
- Conclusions

Expected Performance of the Cooling Channel

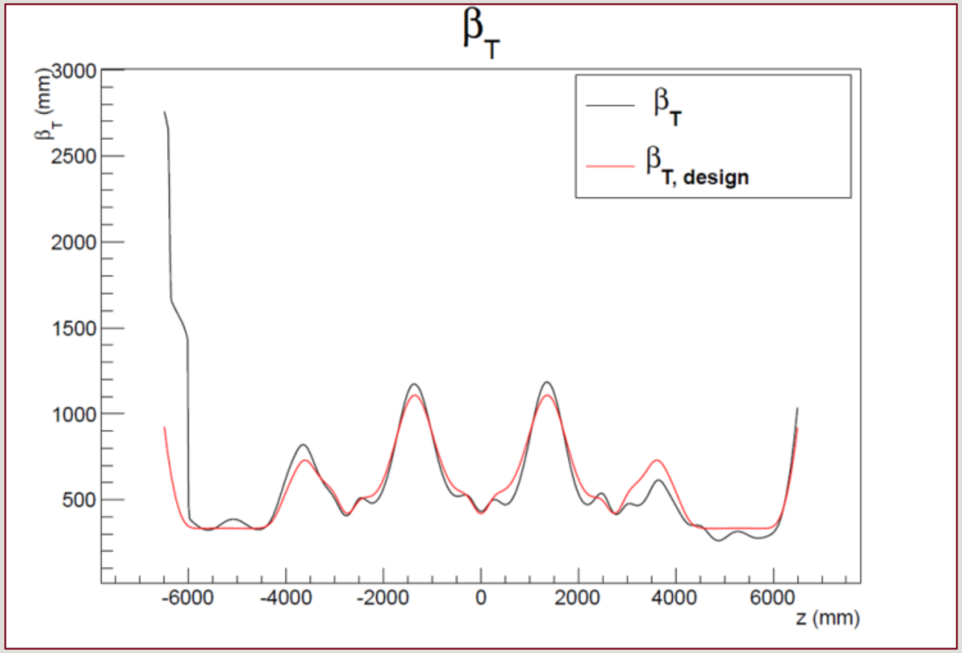
- Propagate measured beams forward through full cooling channel simulation
- Select a 'NF-like' Gaussian p_z distribution of muons to send down the channel.

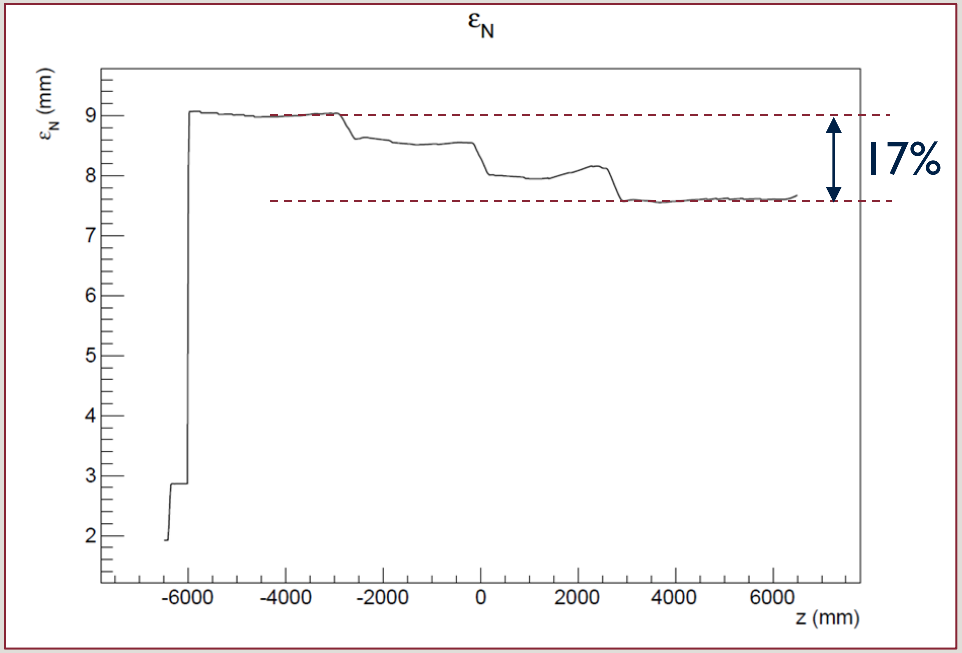




Expected Performance of the Cooling Channel

- Propagate measured beams forward through full simulated cooling channel.
- Select a 'NF-like' Gaussian p_z distribution of muons to send down the channel.
- Track matching through channel.
- Track emittance reduction across the channel.





Conclusions

- First single-particle emittance measurements of the MICE beam line.
- Good agreement with simulations.
- Propagating a sub-selection of real measured muons through cooling channel demonstrates excellent beam matching and cooling performance.
- MICE Step VI promises to be very exciting!