A novel emittance measurement technique for the first analysis of the MICE muon beams

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on behalf of the international Muon Ionization Cooling Experiment

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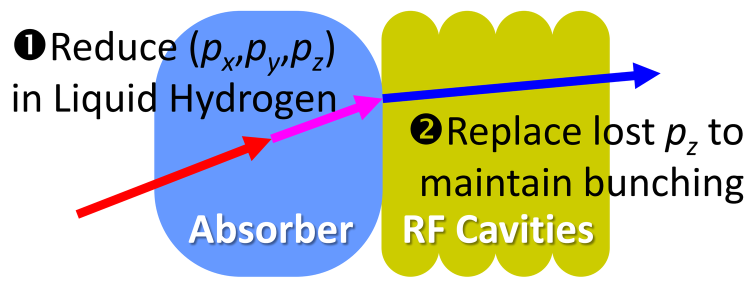
Demonstrating the fast emittance reduction required at a Neutrino Factory

Ionization Cooling

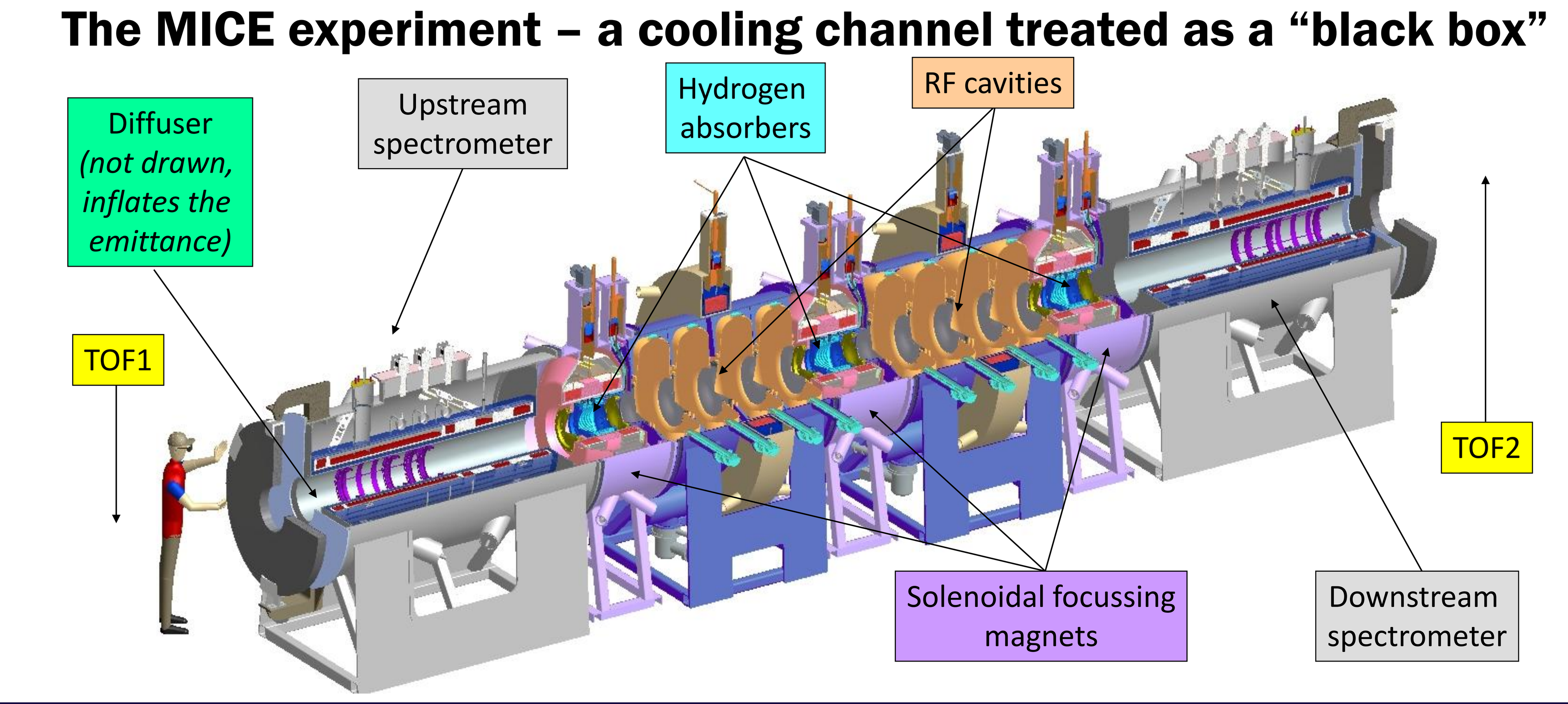


Emittance (focus): $\varepsilon_n = \frac{1}{mc}\sigma_x\sigma_{p_x} \propto \langle A \rangle$

Cooling: $\frac{d\varepsilon_n}{dz} = -\frac{\varepsilon_n}{\beta^2 E}\frac{dE}{dz} + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E m X_0}$

Larmour frame: $x(z) = \sqrt{A\beta(z)}\sin\psi(z)$

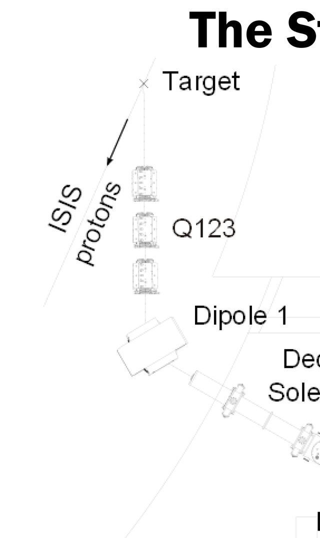
The MICE experiment – a cooling channel treated as a "black box"



The Scintillating Fibre Trackers

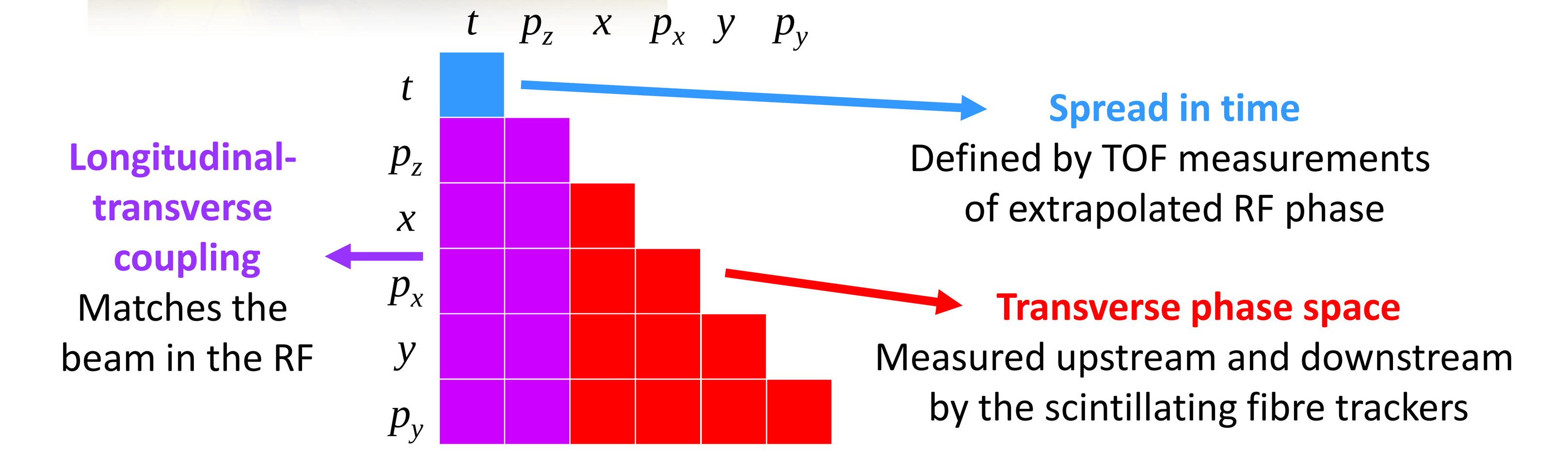
Reconstructs transverse phase space to ½ mm and 1 MeV by fitting helical muon trajectories

The Step 1 Beam Line



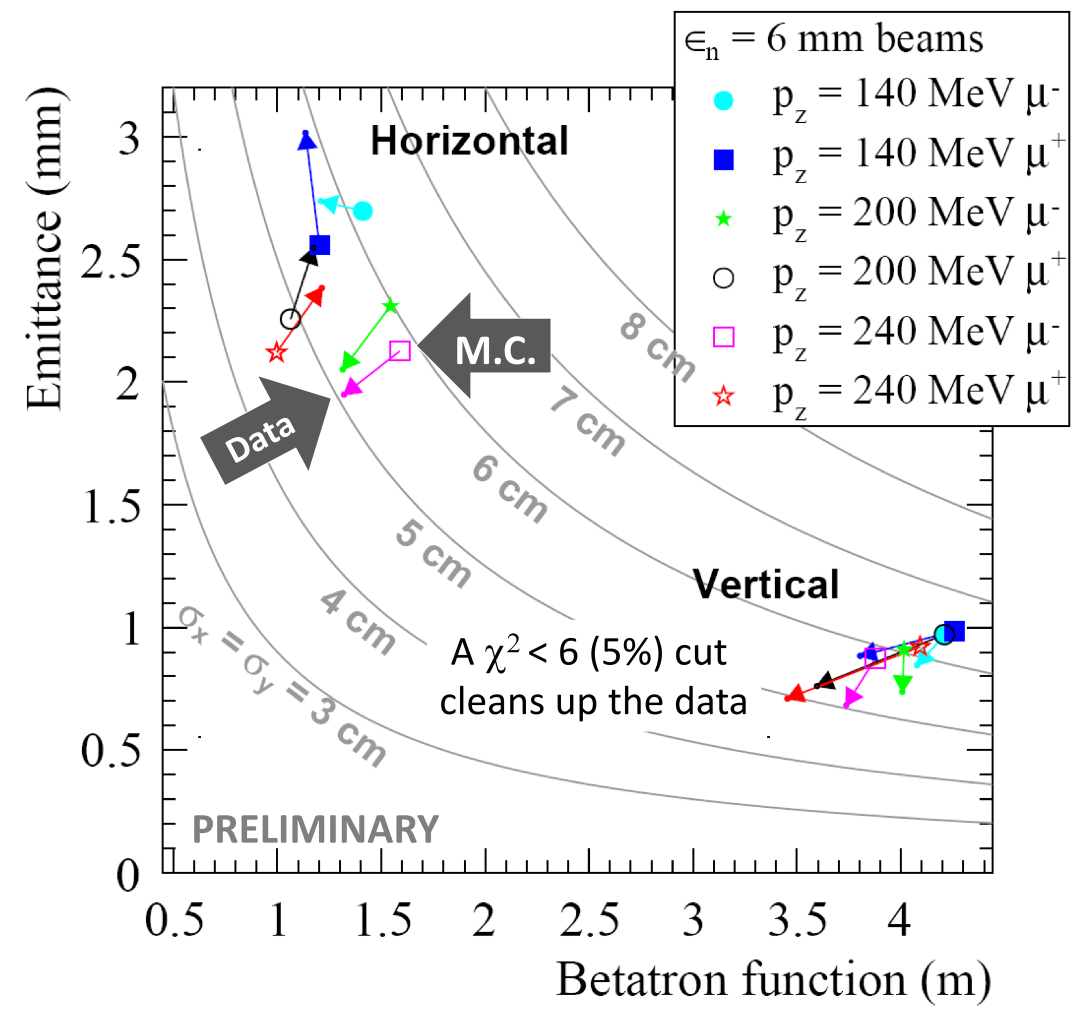
Goal of Step 1:
Produce muon beams which will be matched in the tracker ($\beta' = 0$) with ε_N = (3,6,10) mm and p_z = (140,200,240) MeV/c

The beam's covariance matrix from measurements of individual muons

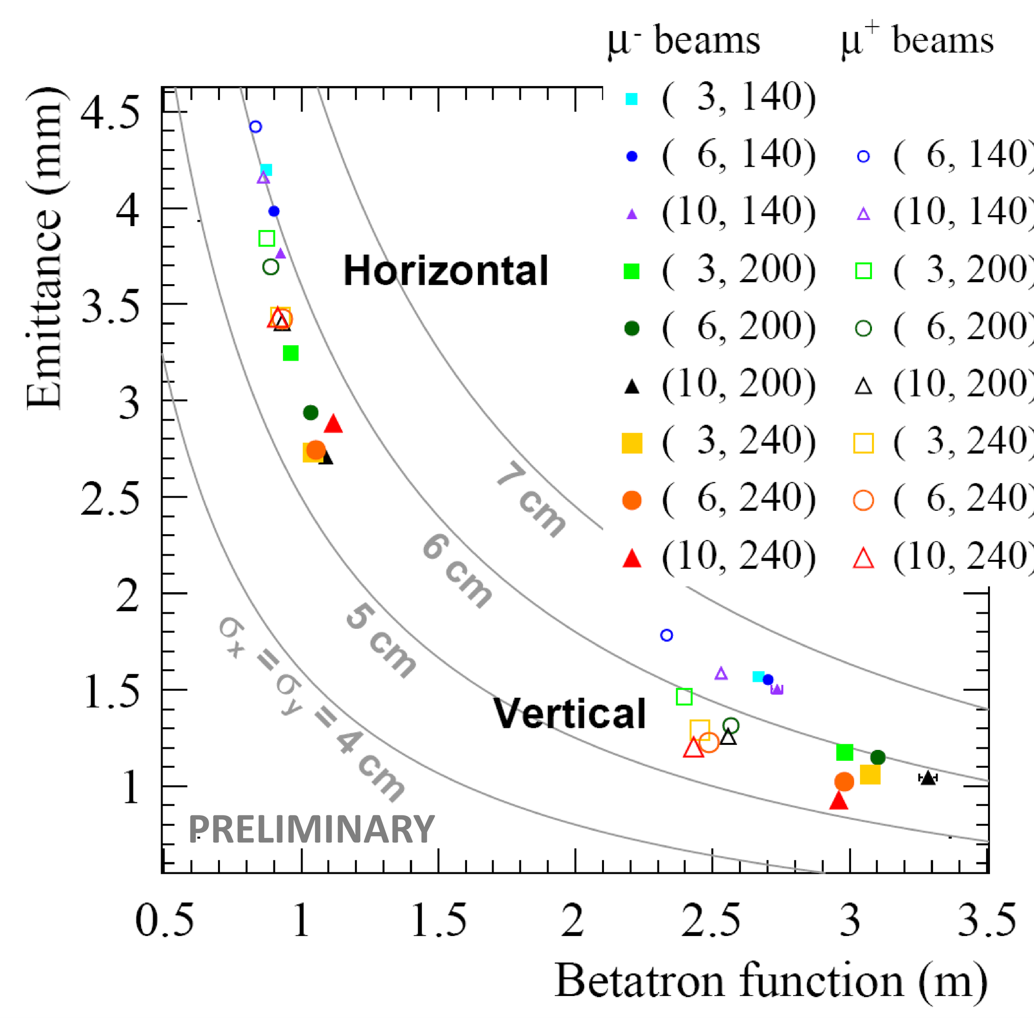


The first MICE beam measurements and a glimpse into the future

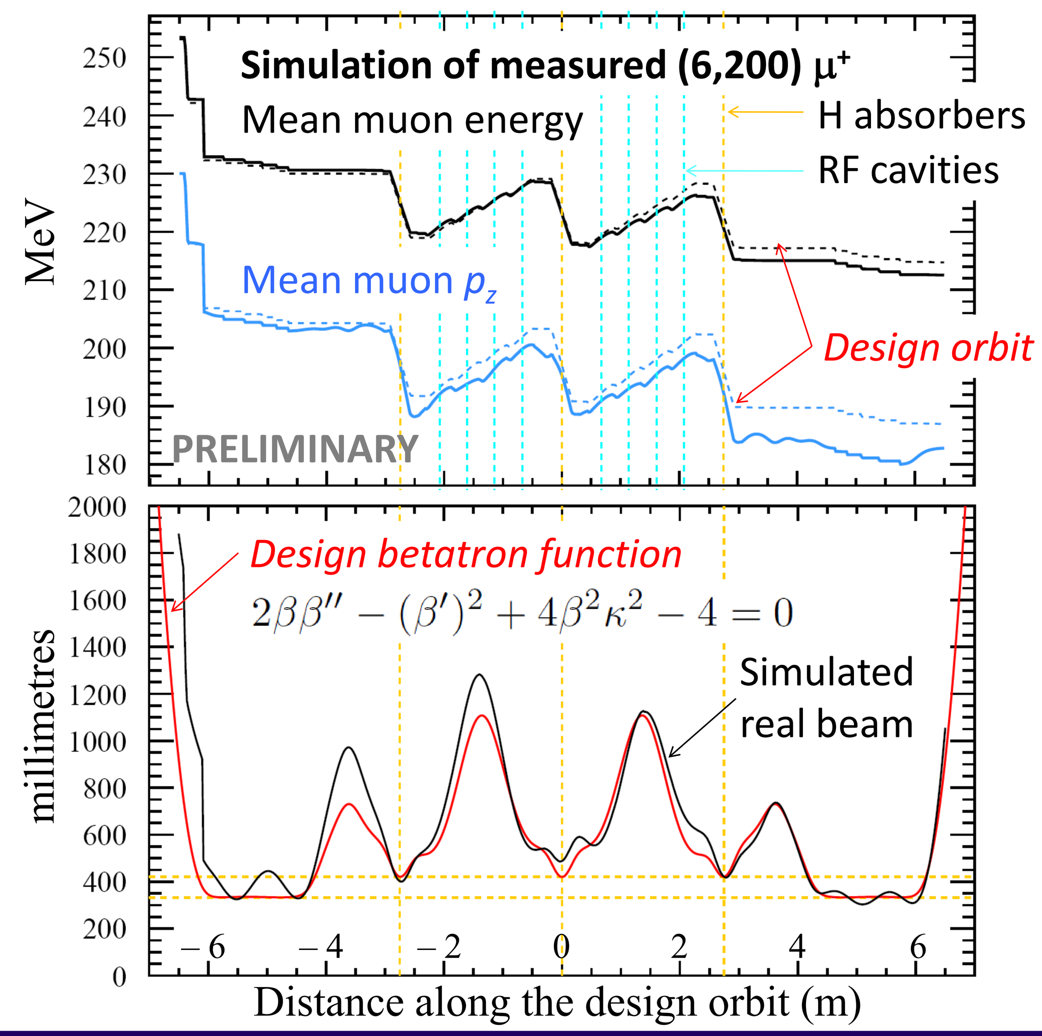
The measured beams are quite well matched



A summary of the MICE Step 1 beam line data

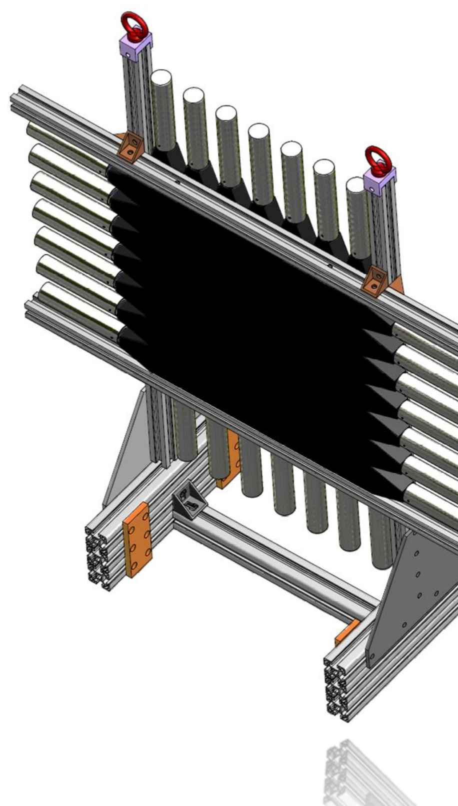


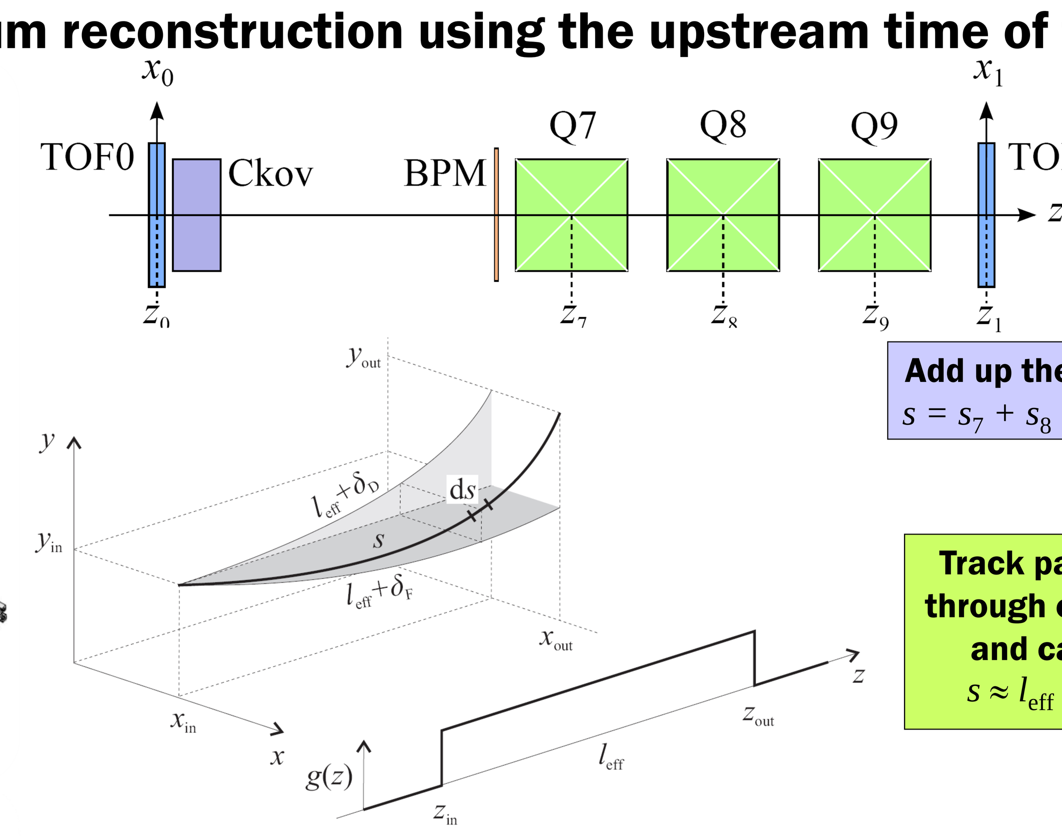
The beams should perform well in Step 6



Reconstructing longitudinal momentum from the time of flight

Momentum reconstruction using the upstream time of flight detectors





Assume the path length $s \approx z_{TOF1} - z_{TOF0}$

Estimate the momentum $p / E = s / t$

Calculate the transfer matrix

Deduce (x', y') **at TOF0 from** (x, y) **at TOF1**

Deduce (x', y') **at TOF1 from** (x, y) **at TOF0**

Track path length through each quad, and calculate $s \approx l_{eff} + \delta_F + \delta_D$

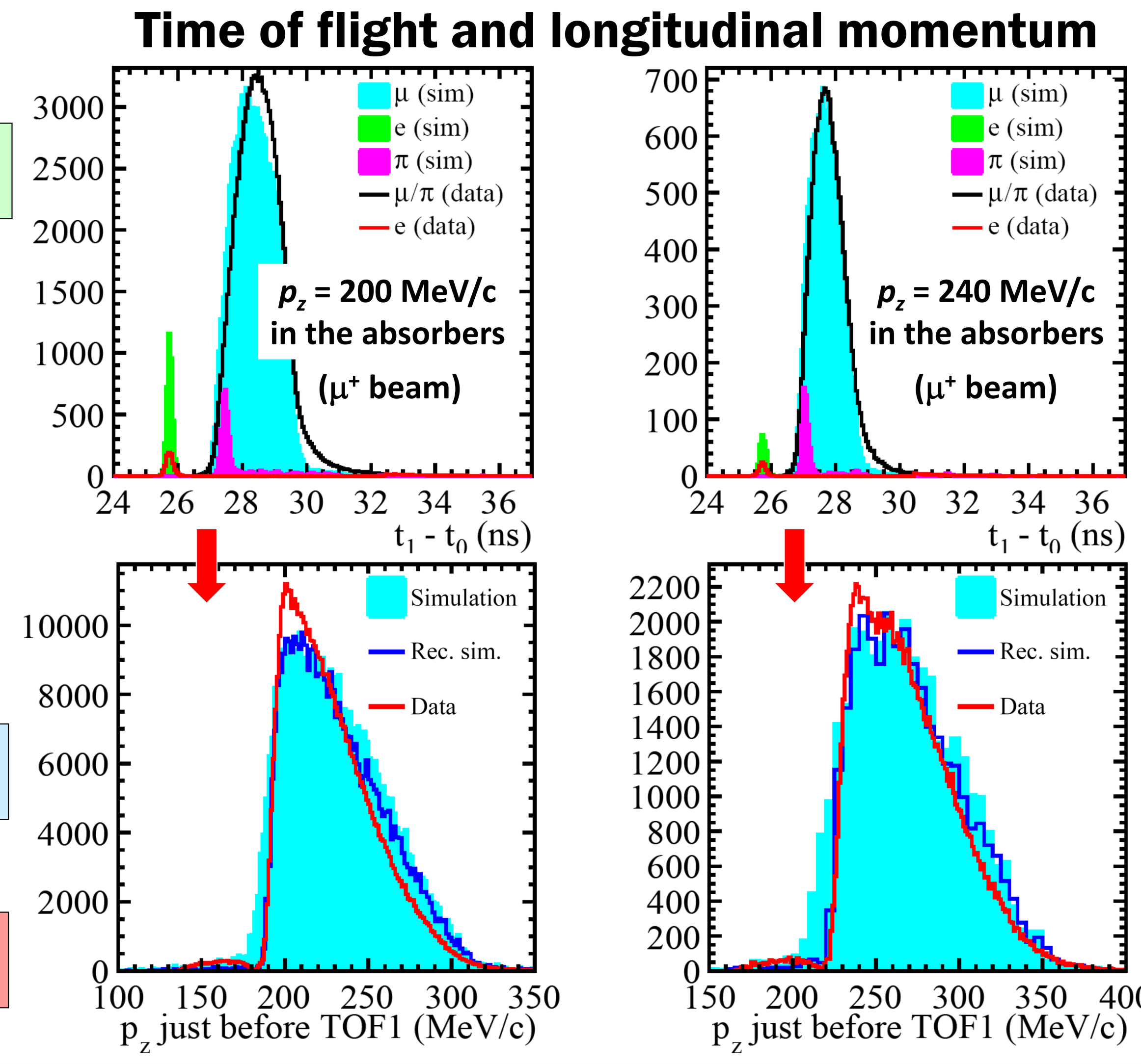
Add up the total path $s = s_7 + s_8 + s_9$ + drifts

10 iterations

damping factor 0.5

TOF0 and TOF1 have been calibrated to measure time with 50 ps resolution and transverse position with a resolution of 1 cm. Longitudinal momentum is reconstructed to 3 MeV/c with its error dominated by the timing resolution. Multiple scattering limits the reconstruction of the angles x'=dx/dz and y' to 10 mrad.

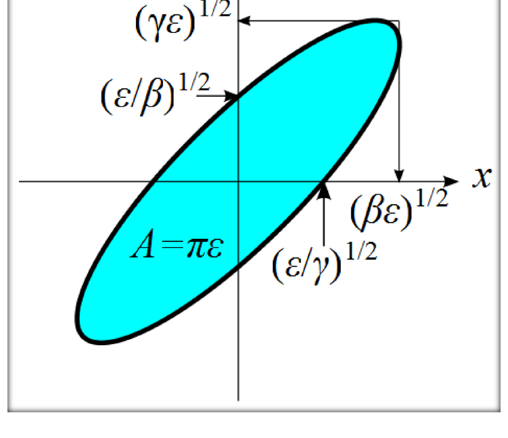
Time of flight and longitudinal momentum

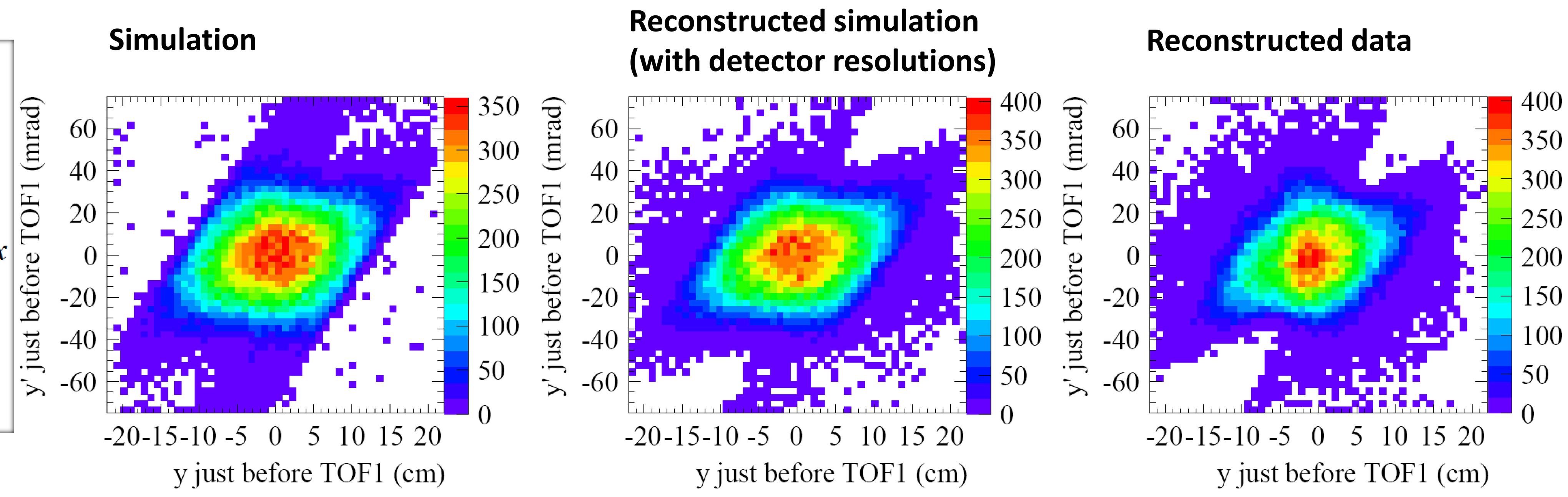


A new single particle technique for reconstructing transverse trace space

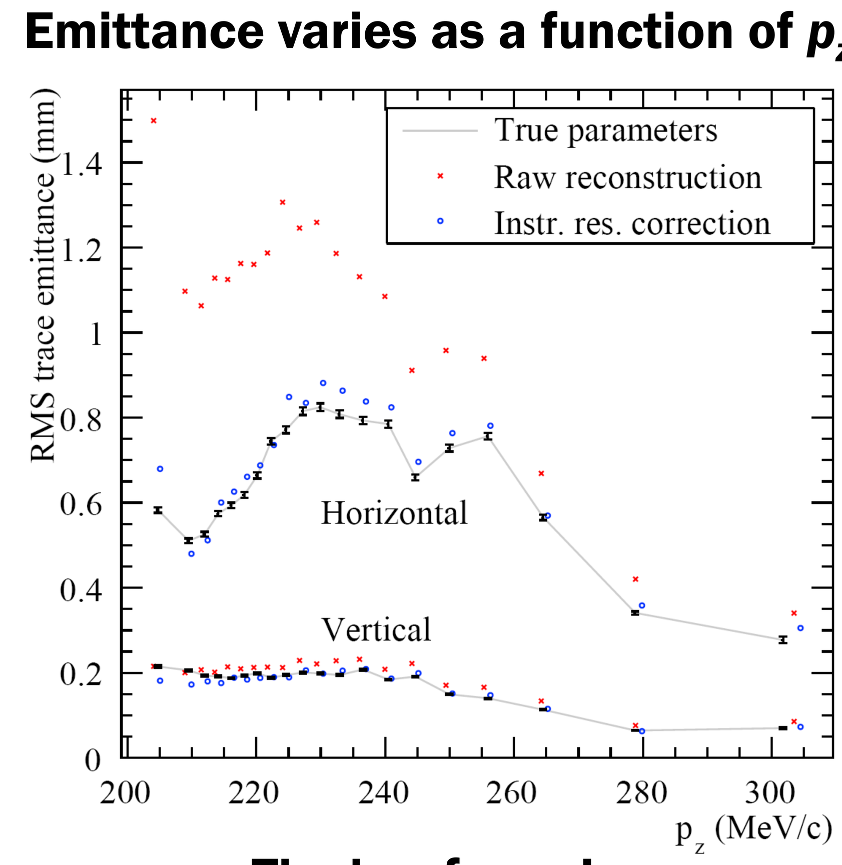
The covariance matrix is measured by reconstructing the trajectories of individual muons

Emittance is traditionally measured using observations of a beam's RMS size in three or more profile monitors. A beam's covariance matrix Σ = Cov[x, x'] is transformed as $\Sigma_1 = M\Sigma_0 M^T$ in the same fashion that position x and angle x' = dx/dz transform as $(x_1, x_1') = M(p_z) \cdot (x_0, x_0')$. One may solve for the $\sigma_{xx'}$ and $\sigma_{x'x'}$ given three or more measurements of σ_{xx} at different positions in the focusing channel. The emittance is given by $\varepsilon = (\det \Sigma)^{1/2}$. This technique is not possible for beams with wide momentum spectra, as the transfer matrices vary too much in the quadrupoles. Instead, $M(p_z)$ can be reconstructed individually for each muon, based on the a momentum measurement, and the angles deduced from the position measurements in TOF0 and TOF1.





Emittance varies as a function of p_z



The key formula

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