Emittance Evolution in MICE: the Muon Ionization Cooling Experiment

Belgium / Bulgaria / China / Italy / Japan / Korea / Netherlands / Serbia / Switzerland / UK / USA

Daniel M. Kaplan
ILLINOIS INSTITUTE OF TECHNOLOGY
for the MICE Collaboration

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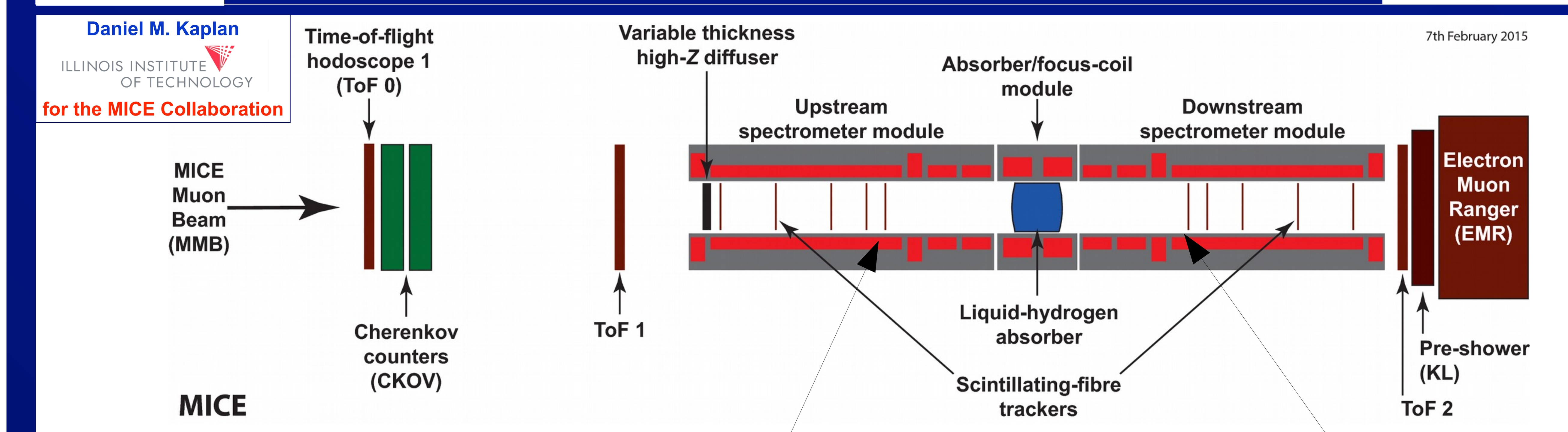
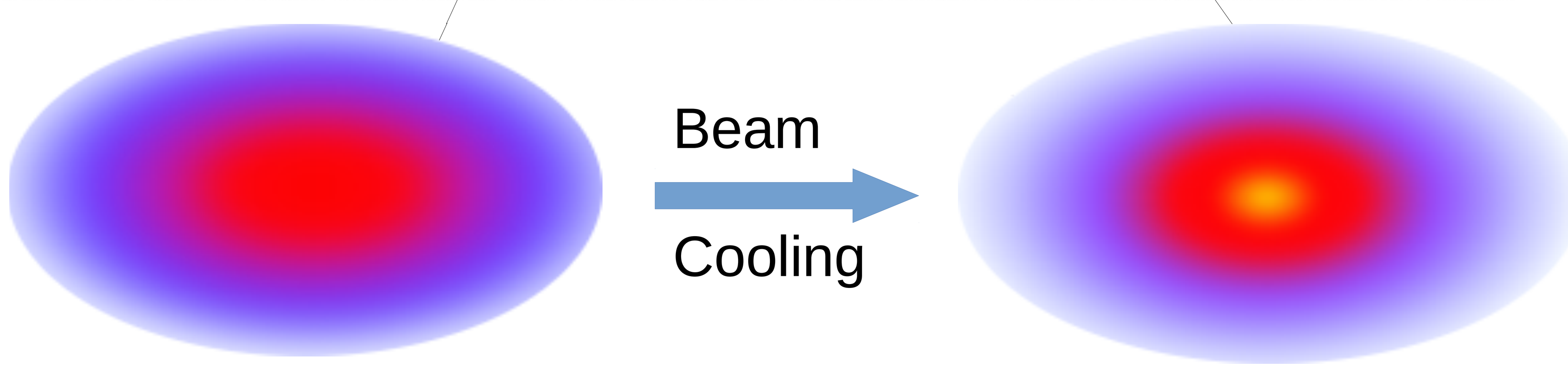
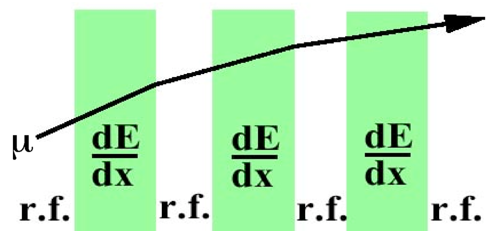


Beam cooling causes migration of particles (in beam phase space) towards beam core



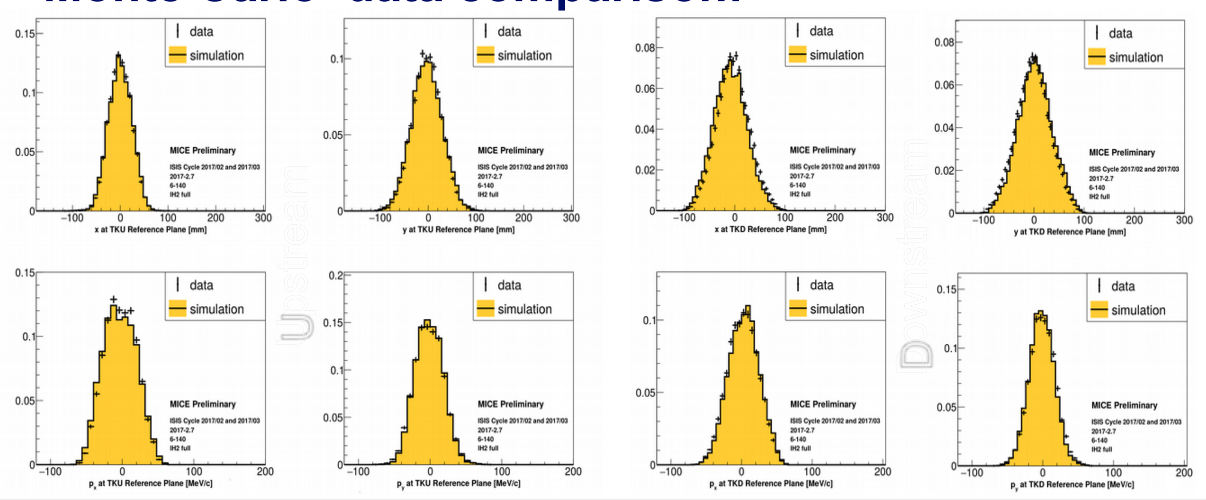
Abstract: The Muon Ionization Cooling Experiment (MICE) is a feasibility demonstration of a crucial emittance-reduction technique for future muon colliders and neutrino factories. Using a muon beam derived from the ISIS synchrotron at the UK's Rutherford Appleton Laboratory, MICE has studied the effect on the beam of ionization energy loss in low-Z absorber materials. Muons were focused on lithium hydride and liquid hydrogen absorbers using a large-aperture solenoid. Particle tracking and identification detectors upstream and downstream of the absorber enabled the reconstruction of the phase-space coordinates of individual muons. The evolution of beam emittance was measured by studying the properties of ensembles of single muons using muon beams with varying input emittances and momenta. Data taken in 2016 and 2017 are currently being analyzed. The current status and most recent results are presented.

Ionization Cooling

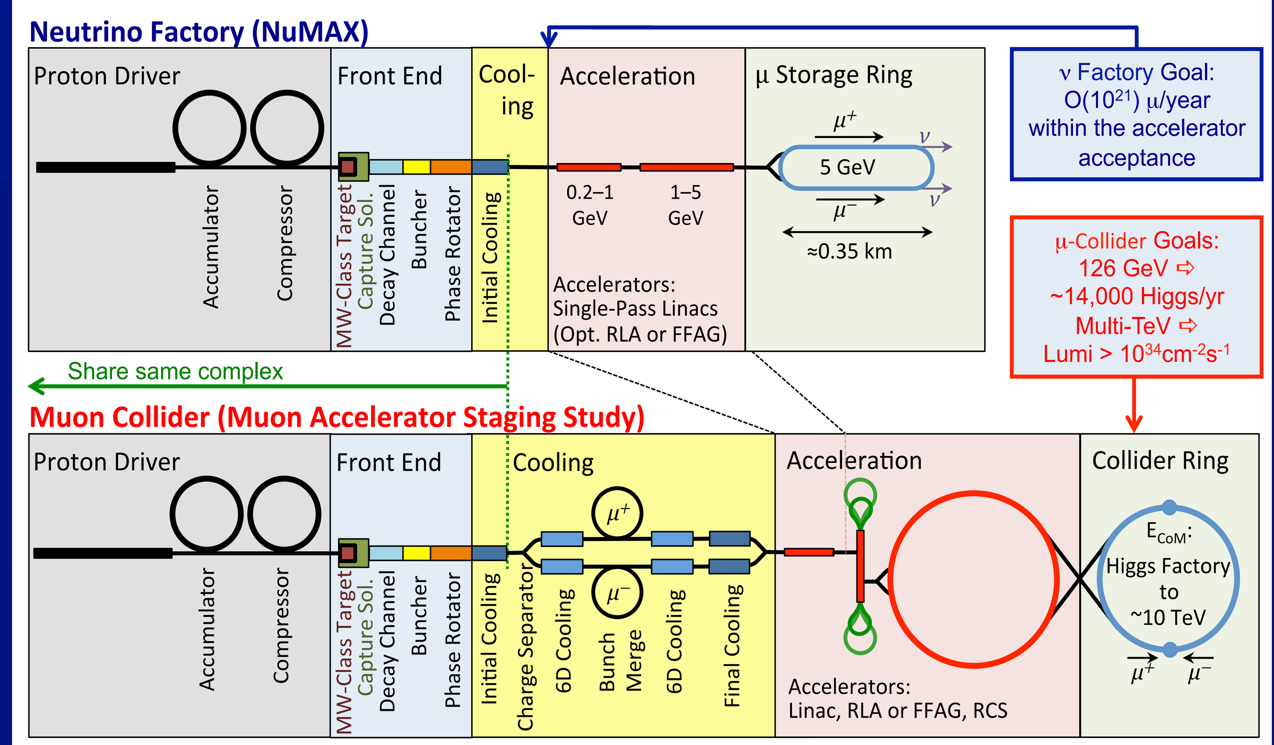


G.I. Budker & A.N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A.N. Skrinsky & V.V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)
D. Neuffer, Part. Acc. **14**, 75 (1983)

- **Energy loss in liquid hydrogen or LiH**
  - **muons lose both transverse and longitudinal momentum**
- **Acceleration in radio-frequency (RF) cavity:**
  - **restores *only* longitudinal momentum**
- **Result: transverse cooling**
  - **competition between dE/dx cooling & MCS heating**
- **MICE measures individual muons crossing:**
  - **empty absorber**
  - **35 cm LH_2**
  - **65 mm LiH disk**
- **Muons measured before and after absorber in a uniform 3 T magnetic field**
- **Beam emittance change in absorber measured by comparing upstream and downstream muon phase space volumes**
- **Monte Carlo–data comparison:**

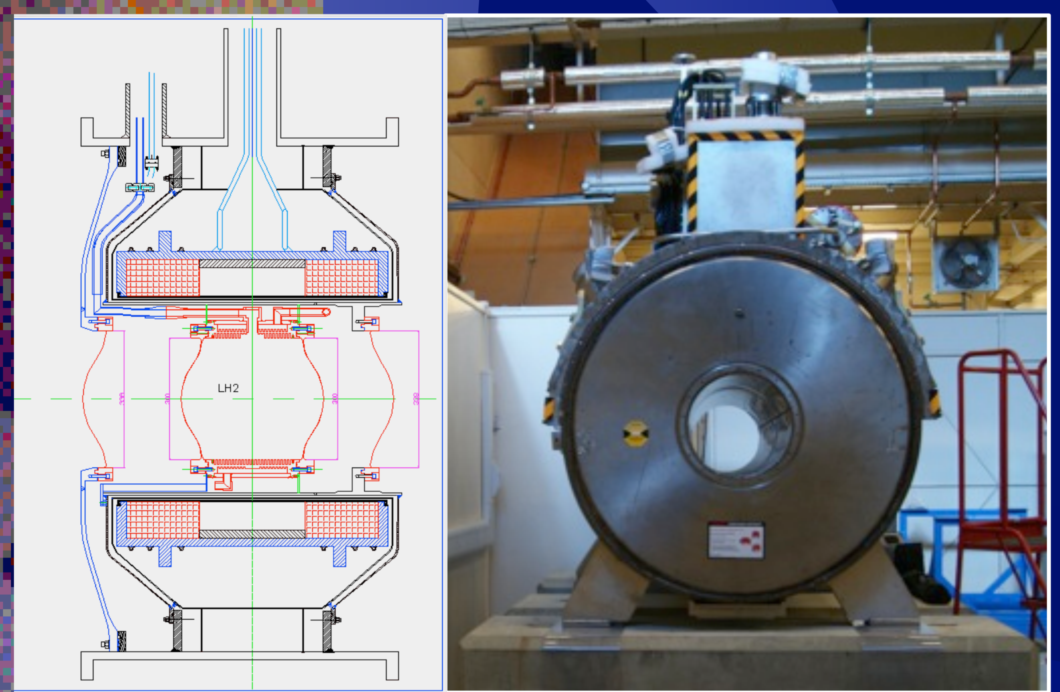


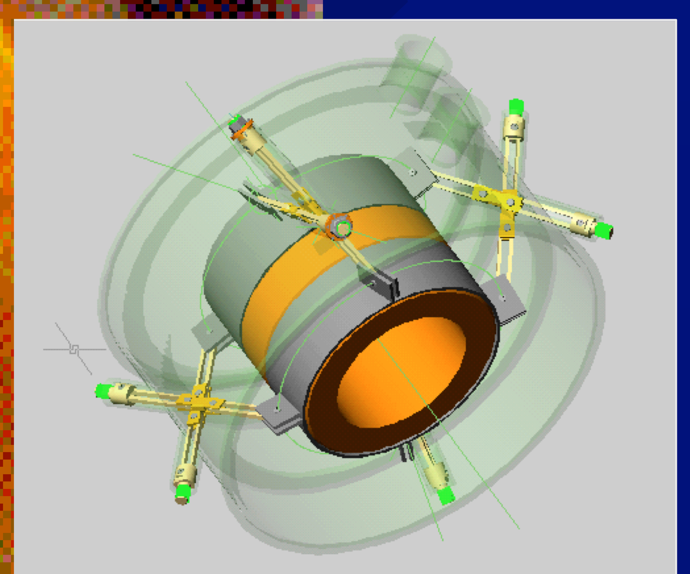
Future Stored-Muon Beam Accelerator Facilities



- **Neutrino Factory**
  - **World's most sensitive neutrino-oscillation facility**
    - **ultra-clean ν_μ appearance in ν_e beam**
  - **Physics reach increases with neutrino flux**
  - **High flux requires cooled muon beam**
    - **emittance reduction by factor ~10**
- **Muon Collider:**
  - **CM energy up to ~10 TeV**
  - **Luminosity > 10^{34} $cm^{-2}s^{-1}$**
  - **High luminosity requires cold muon beams**
    - **emittance reduction by factor ~10^6**

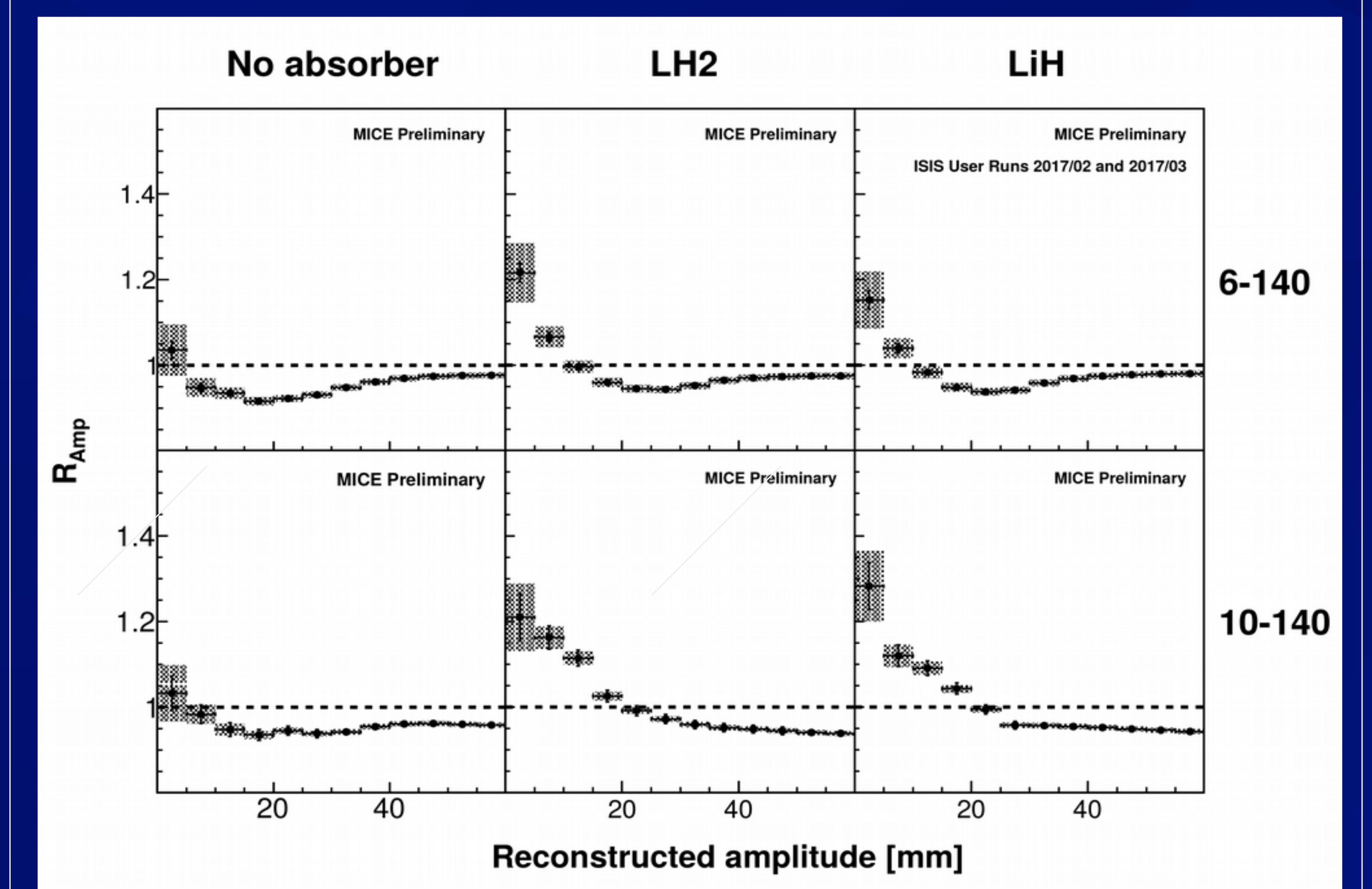
Absorber & focus-coil module





- **Liquid-hydrogen absorber:** (Japan, USA)
  - **Large ionization energy-loss rate (cooling)**
  - **Low multiple scattering (heating)**
  - **First prototype built and bench-tested**
- **LiH disk absorber** (USA)
- **Focus-coil assembly:** (UK)
  - **Superconducting magnets Two coils; up to 5 Tesla**

Initial MICE Cooling Results



The ratio of the downstream to upstream cumulative amplitudes for two input beam configurations with nominal momenta of 140 MeV/c and nominal emittance of 6 (top) and 10 (bottom) mm. Cooling is observed where R_{Amp} > 1, showing migration of muons from high to low amplitude.

- Beam size expressed as 4-D transverse, normalized emittance
  - $\varepsilon_{4D,N} = \sqrt[4]{|\det\Sigma_\perp|} / m_\mu$
  - $\Sigma_\perp$ = covariance matrix of muon ensemble in (x, y, p_x, p_y) space
- Transverse amplitude: $A_\perp = \varepsilon_N\, \boldsymbol{\Delta}_\mu{}^T\, \Sigma_\perp\, \boldsymbol{\Delta}_\mu$
  - $\boldsymbol{\Delta}_\mu = (\mathbf{v} - \langle \mathbf{v} \rangle)$ distance of muon from beam center

Instrumentation

- **Particle identification:** (EU, USA)
  - **Upstream: π/μ separation**
    - **Aerogel Cherenkovs, 50ps time-of-flight (TOF)**
  - **Downstream: e/μ separation**
    - **TOF, calorimeter, e/μ Ranger**
- **Muon momentum measurement:** (UK, USA, Japan)
  - **Five-station planar scintillating-fiber trackers**
    - **in 3 T superconducting solenoids**
  - **350 μm fibers, three stereo views**
  - **Cryogenic solid-state photodetectors (VLPCs)**
- **Emittance resolution: 0.1%**