JAI Fest 2019, Oxford

Progress on Muon Ionisation Cooling Demonstration with MICE

The MICE Collaboration

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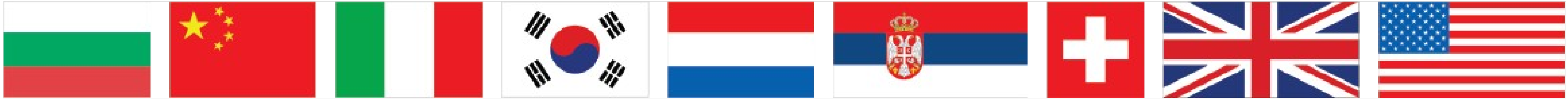
Outline

- **Motivation**
- **Ionisation cooling and MICE**
- **Highlights of the data taking**
- **Current status and results**
- **Next steps**



The MICE collaboration

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Progress on Muon Ionisation Cooling with MICE

MOTIVATION

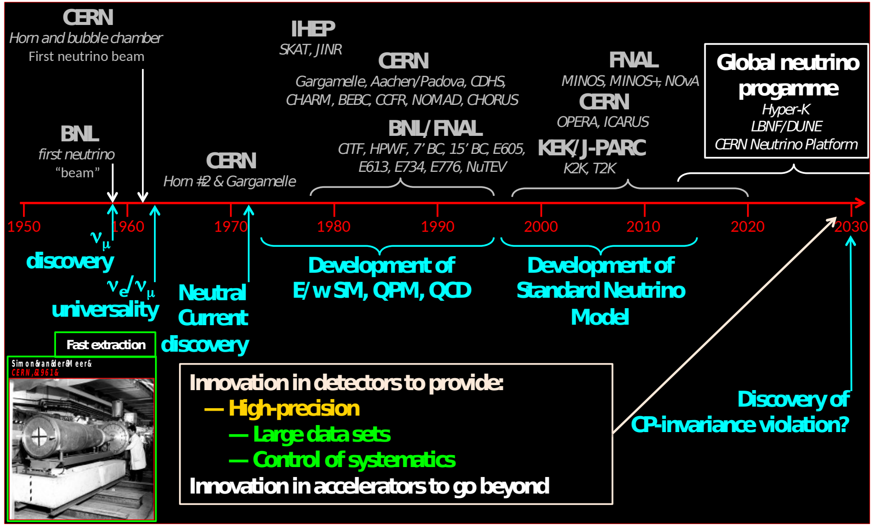
Unique advantages of muon accelerators

Energy frontier lepton-antilepton collider:

- No brem-/beam-strahlung
  - Rate $\propto m^{-4}$
$[5 \times 10^{-10}$ cf $e]$
- Enhanced Higgs coupling
  - Production rate $\propto m^{2}$
$[4 \times 10^{4}$ cf $e^{+}e^{-}]$

Neutrino beams

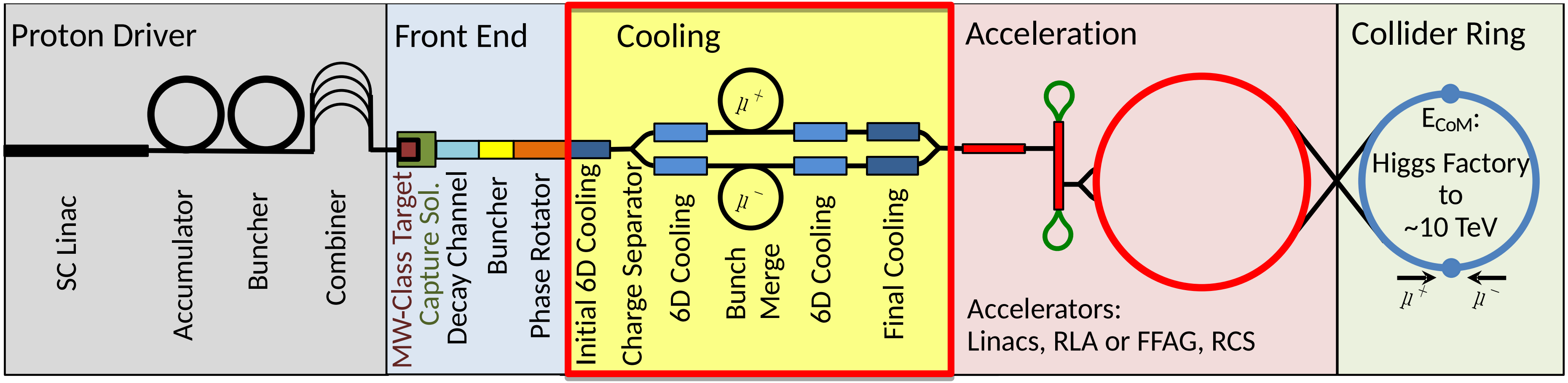
- ν_e, ν_μ
- Precisely known energy spectrum



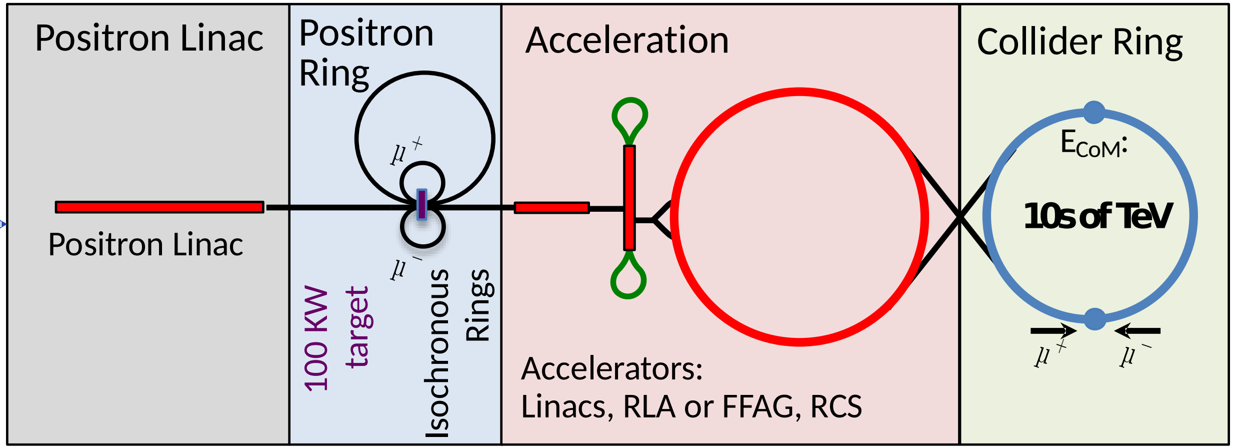
Innovation in detectors to provide:
- High-precision
  - Large data sets
  - Control of systematics

Innovation in accelerators to go beyond

Resurgence of interest: Pastrone Panel



Low EMmittance Muon Accelerator (LEMMA):
10^{11} ∝ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Pastrone et al.

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IONISATION COOLING AND MICE

The principle of ionisation cooling

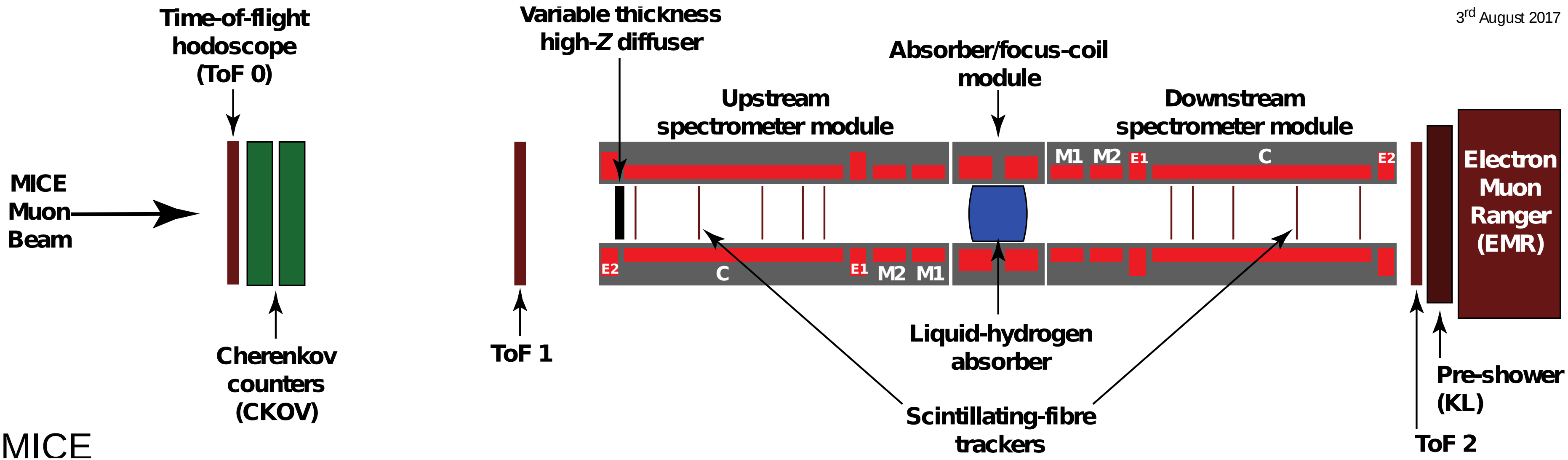
Ionisation cooling

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

- Competition between:
    - dE/dx [cooling]
    - Multiple Coulomb Scattering [heating]

- Optimum:
    - Low Z, large X_0
    - Tight focus (small β_t)
    - H_2 gives best performance

Schematic of the experiment



MICE

PID and tracking detectors

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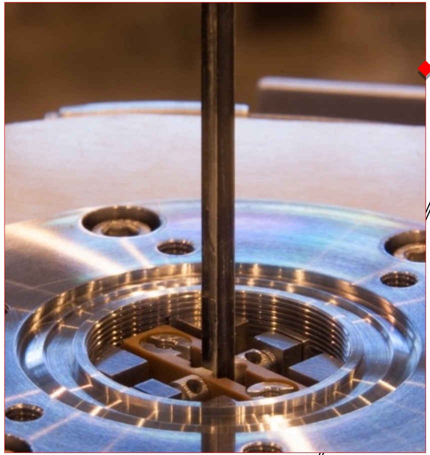
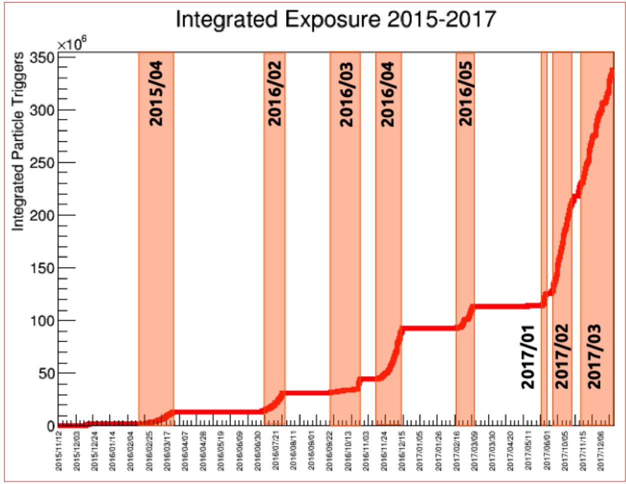
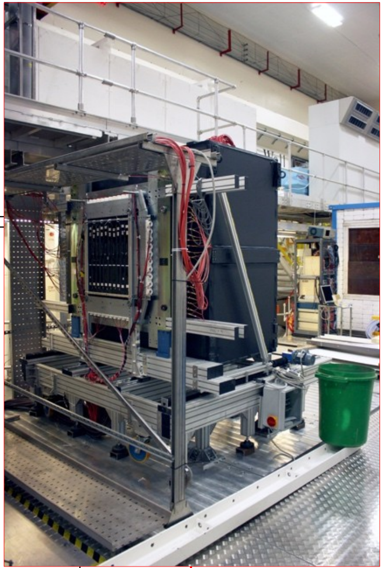
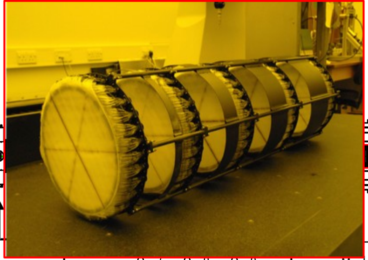
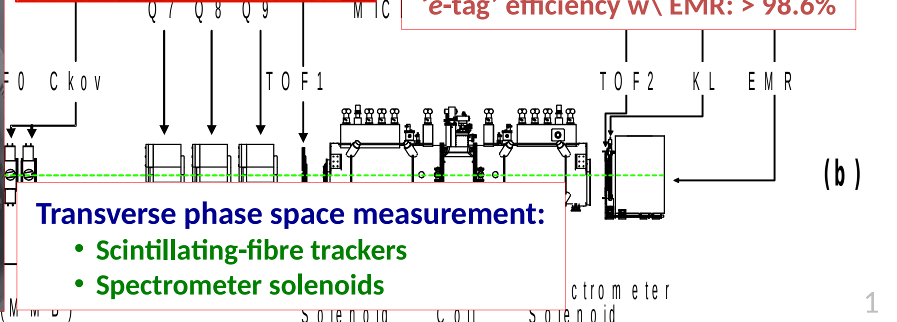
HIGHLIGHTS OF THE DATA TAKING











Rejection of decays:

- TOF2
- KLOE Light 'preshower' (KL)
- Electron Muon Ranger (EMR)

'*e*-tag' efficiency w\ EMR: > 98.6%

Pure muon beam selection:

- High precision (55 ps) time-of-flight hodoscopes (TOF0, TOF1)
- Threshold aerogel Cherenkov counters

Measured π contamination < 1.4% (90% C.L.)

(w\ KL)

Transverse phase space measurement:

- Scintillating-fibre trackers
- Spectrometer solenoids

Characterisation of the cooling equation

- Evolution of normalised transverse emittance:

$$\frac{d\varepsilon_T}{ds} \approx -\frac{\varepsilon_T}{\beta_R^2 E}\left\langle \frac{dE}{ds} \right\rangle + \frac{\beta_T\,(13.6\mathrm{MeV})^2}{2\beta_R^3 E m_\mu X_0}$$

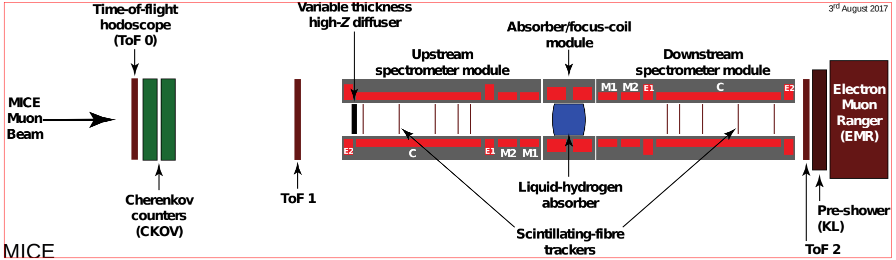
  - Measured dependence on:
    - Input emittance:
      - Vary beam optics/diffuser;
    - Material:
      - Absorber LH2; LiH
    - *p*, *E* and β:
      - Vary beam momentum, optics

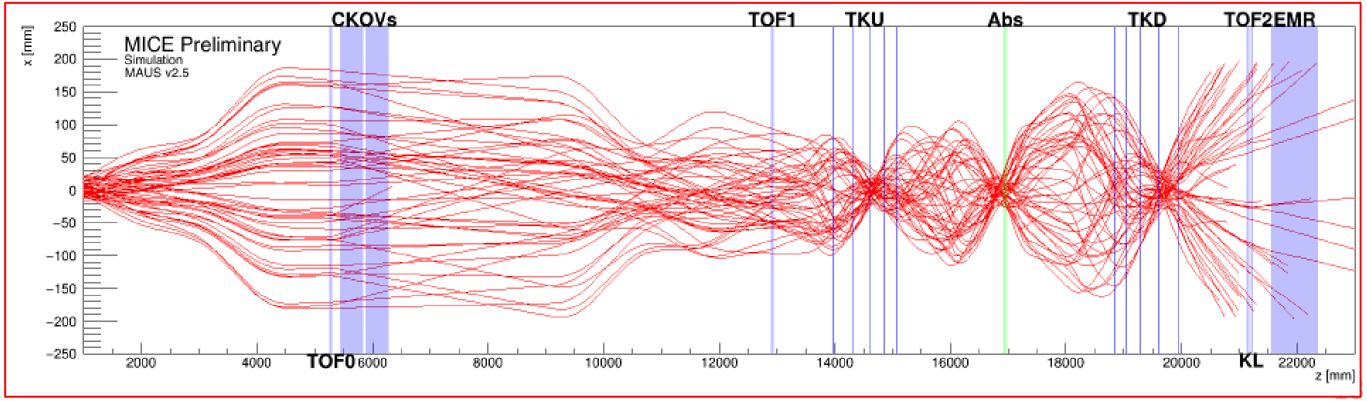
<u>Absorbers:</u>

65 mm thick lithium hydride disk
350 mm thick liquid hydrogen vessel
45° polythene wedge absorber

Single-particle technique

- Powerful! Fully measure one muon at a time:
  - Fast instrumentation, matched to beam intenstity:
    - Measure all 6D phase-space coordinates of each muon
  - Build muon ensemble offline:
    - Calculate ensemble properties
      - E.g. ε_T





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CURRENT STATUS AND RESULTS

Emittance and amplitude

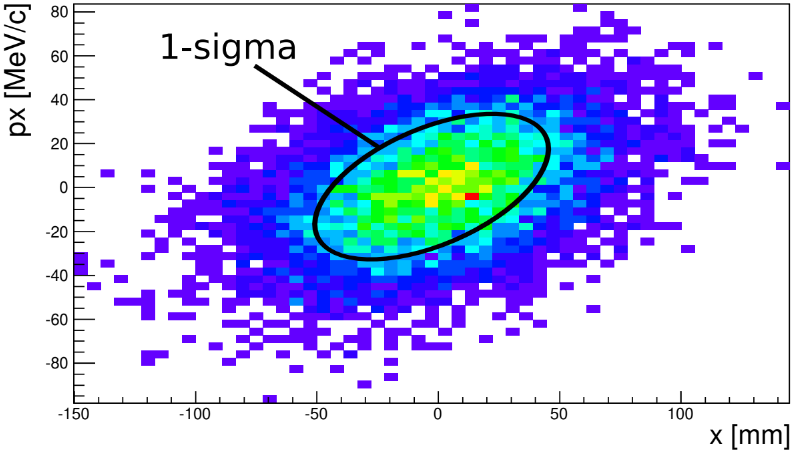
Phase space, covariance, emittance and amplitude

Phase space: $\mathcal{P} = (x, p_x, y, p_y)^{\mathrm{T}}$

Covariance: $\mathcal{C} = \left\langle \Delta\mathcal{P}\Delta\mathcal{P}^{\mathrm{T}} \right\rangle$

Normalised transverse emittance: $\varepsilon_T = \frac{|\mathcal{C}|^{\frac{1}{4}}}{m_\mu}$

Transverse amplitude: $A_T = \varepsilon_T \mathcal{P}^{\mathrm{T}}\mathcal{C}^{-1}\mathcal{P}$

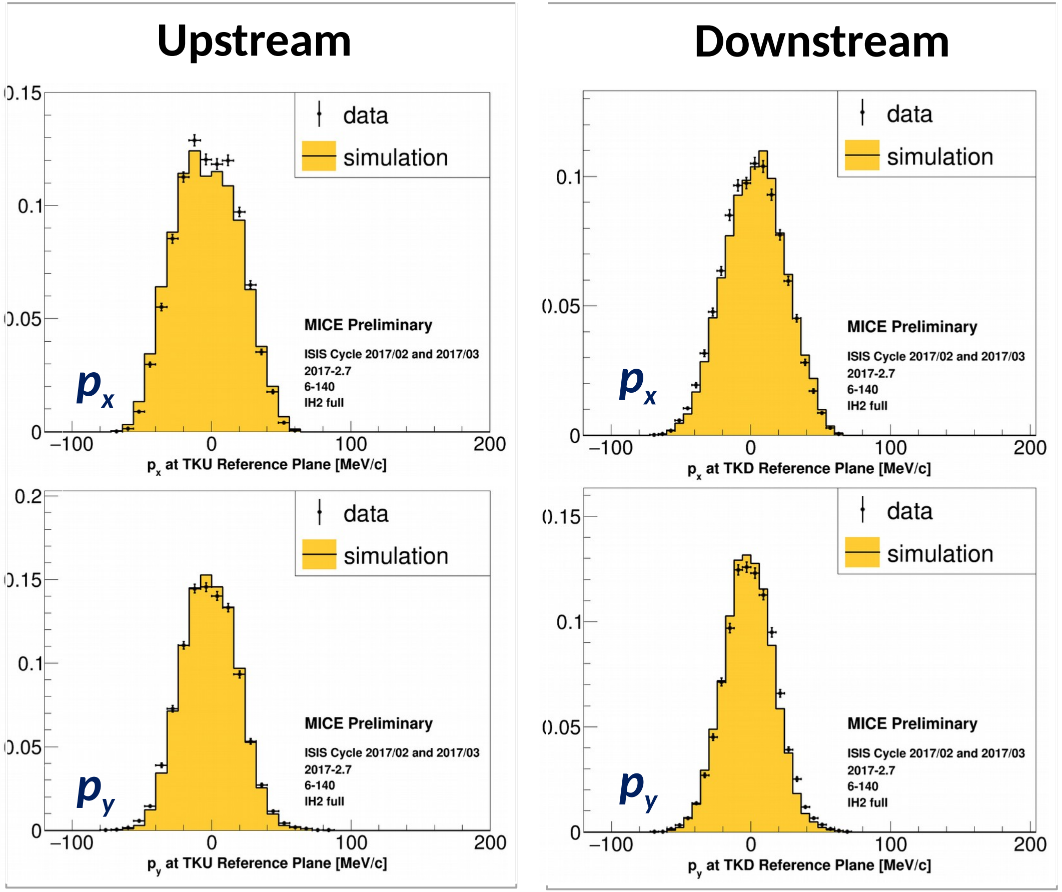


- Emittance:
  - Evaluated from RMS beam ellipsoid
- Amplitude:
  - Distance from core of beam
- Mean amplitude ~ RMS emittance

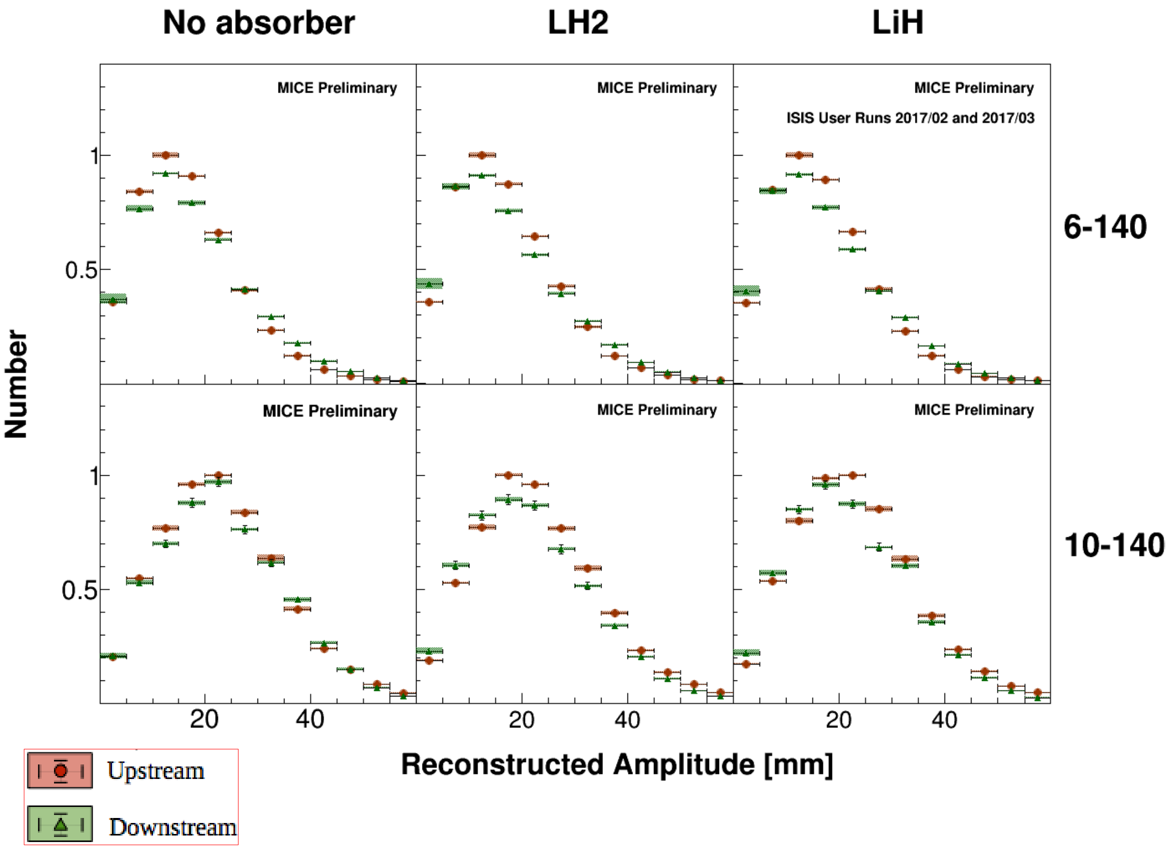
Effect of absorber

- Simulation in good agreement with data
  - Example:
    - ε_T = 6 mm
    - P = 140 MeV/c

Notation: ε_T–P = 6-140



Change in amplitude across absorber

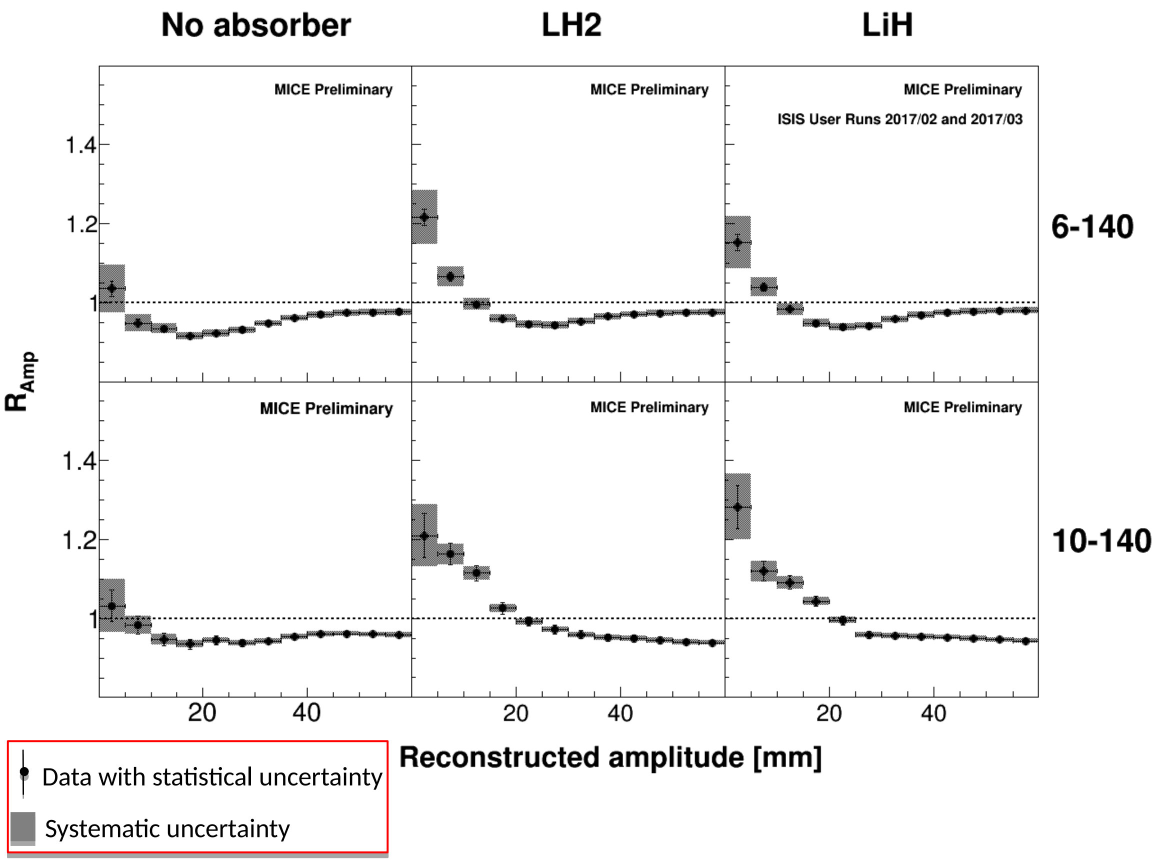


Muons in beam core:

- *Decrease with no absorber*
- *Increase* with LiH and LH2 absorbers

Ionisation cooling signal

Core-density change across absorber



R_{amp} = ratio of cumulative density downstream to upstream

Core-density:

- *Increases* with LiH and LH2 absorbers
- *Consistent with 'no change'* for no absorber

Ionisation cooling signal

Paper sent for publication

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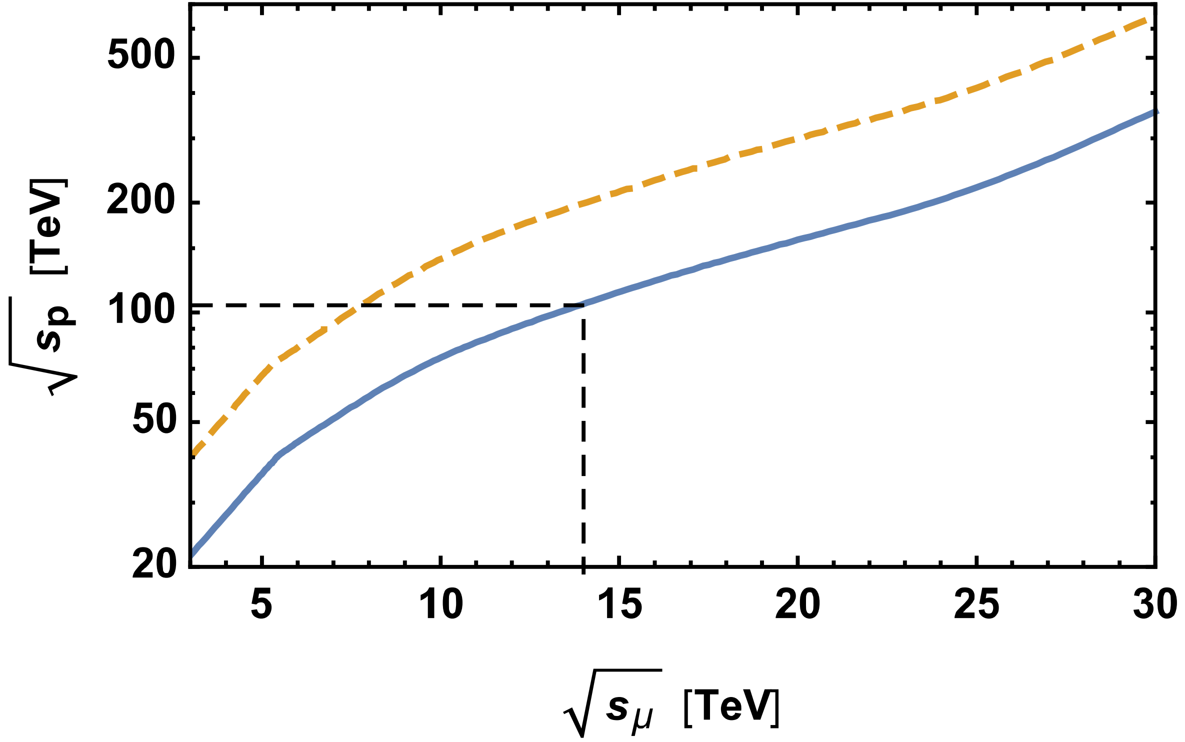
NEXT STEPS

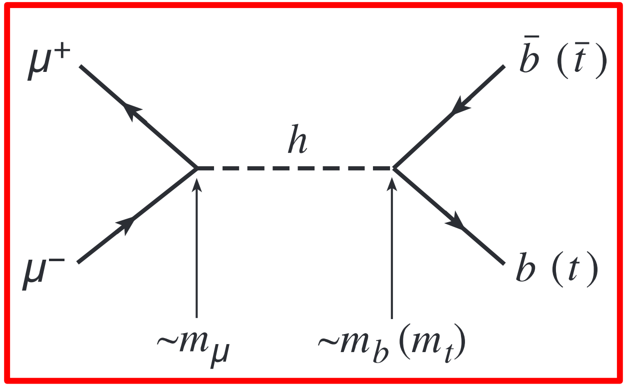
Next steps in study of ionisation cooling

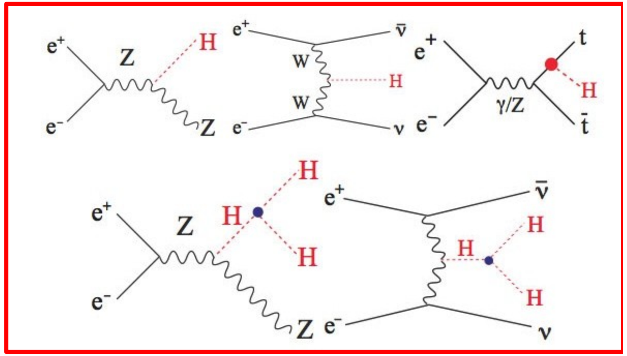
- MICE has:
  - Demonstrated principle of 4D ionisation cooling
- Analysis of MICE data will:
  - Study ionisation cooling as a function of:
    - Input beam emittance and momentum;
    - Lattice optics and absorber material (LiH and LH2);
  - Study emittance exchange with wedge absorber
- Ambitious next step:
  - Design and implement a 6D cooling experiment
    - Essential R&D for development of multi-TeV muon collider

Thank you

The Standard Model and beyond







Energy frontier: big advantage over pp because fundamental fermion

Future study of the Higgs:

- **Line width; establish single resonance (?) in s-channel with $\mu^+\mu^-$**
- **Couplings; requires > 1 TeV for complete, precise study**