MICE Results

NUFACT 2018

Blacksburg (VA), 16 August 2018

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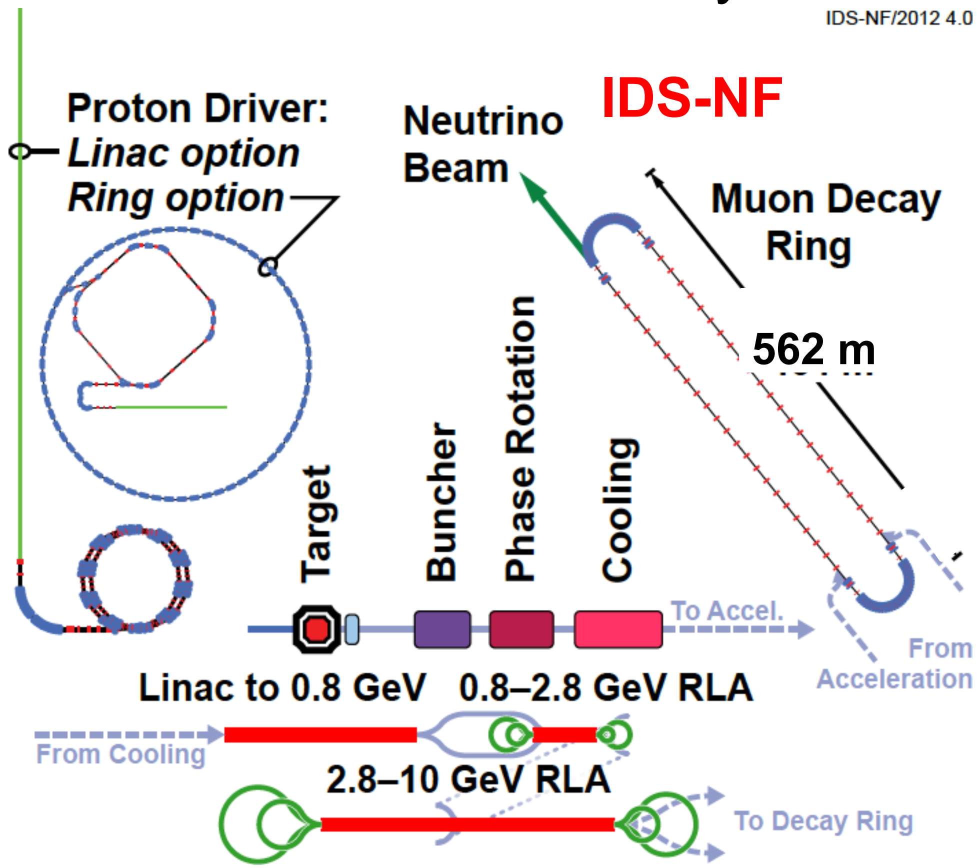
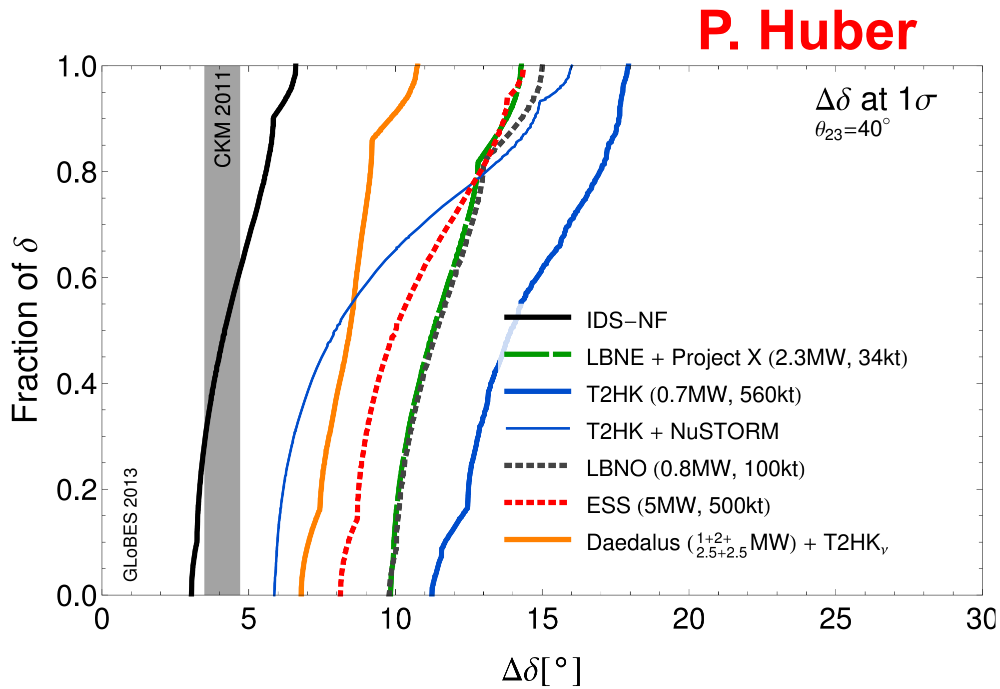
University of Glasgow

Neutrino Factory

- International Design Study for a Neutrino Factory (IDS-NF):
  - Most sensitive facility for the study of CP violation in neutrinos

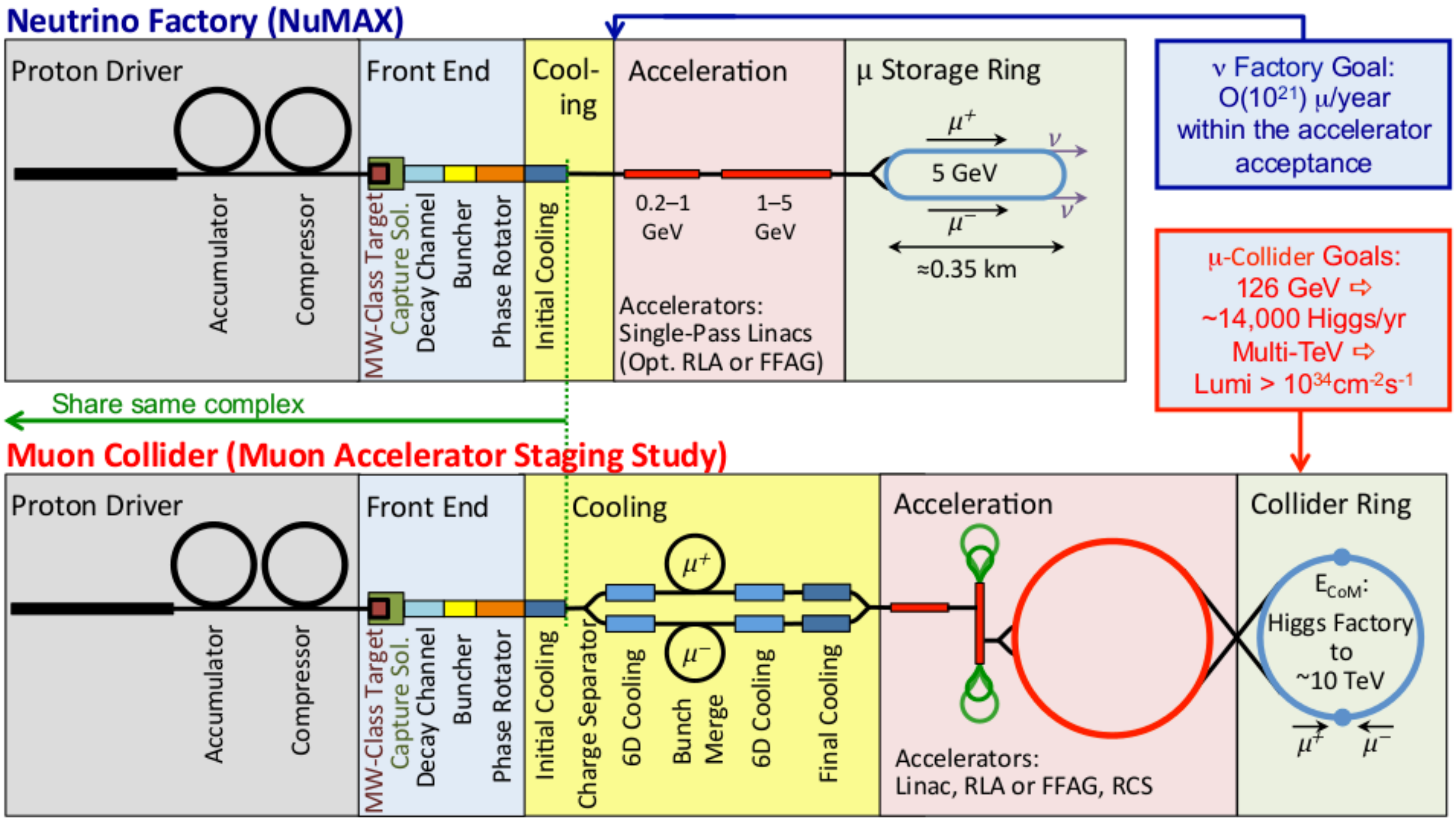




Can reach uncertainty in δ_{CP} of 5°

From Neutrino Factory to Muon Collider

- Staging of Neutrino Factory, leading to a Muon Collider, carried out within the US Muon Accelerator Programme (MAP)

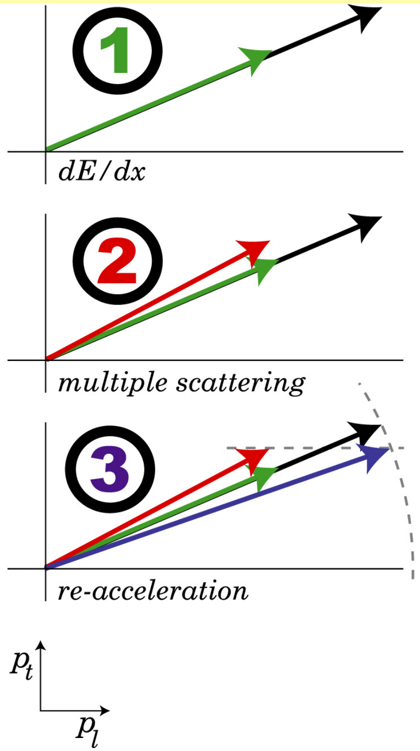


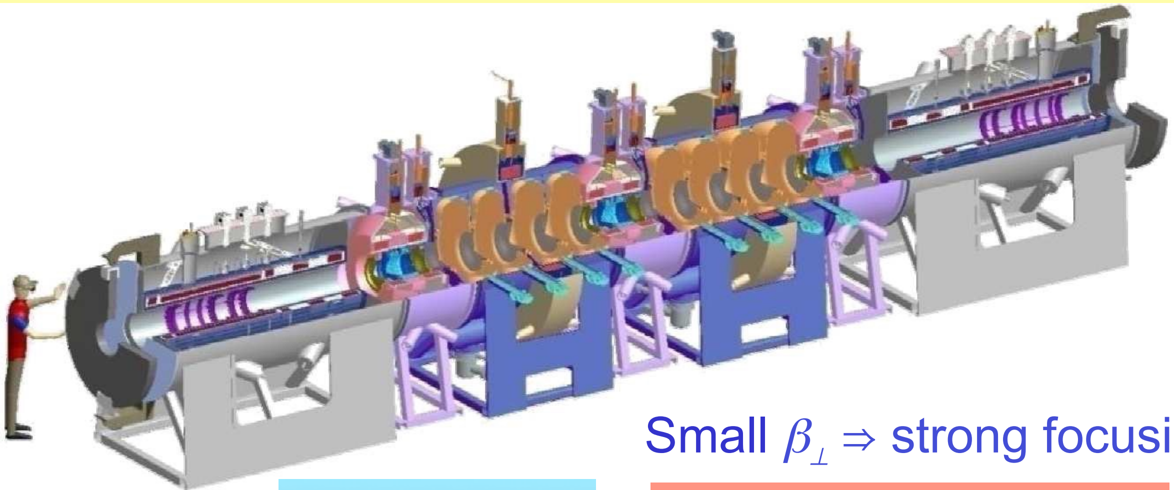
Only high energy lepton collider that can reach ~10 TeV

Muon Cooling

- Muon Ionization Cooling:
  - Muon Ionization Cooling is the key technology required to be able to realise a Neutrino Factory and a Muon Collider (similar to stochastic cooling for proton-antiproton collider in the 1980s)

Principle | **Practice**





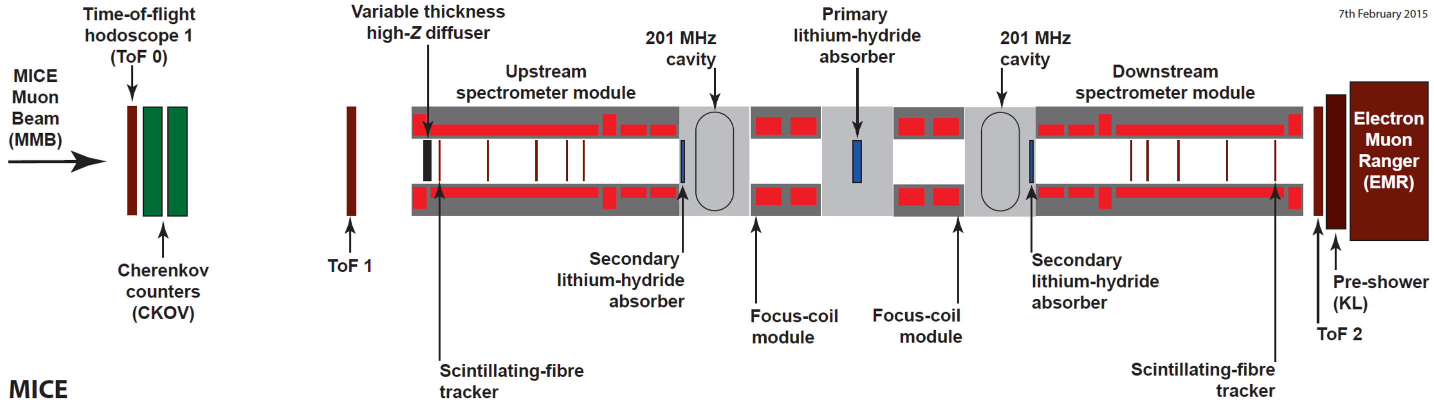
Small $\beta_\perp \Rightarrow$ strong focusing

$$\frac{d\varepsilon_T}{dz} \approx -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

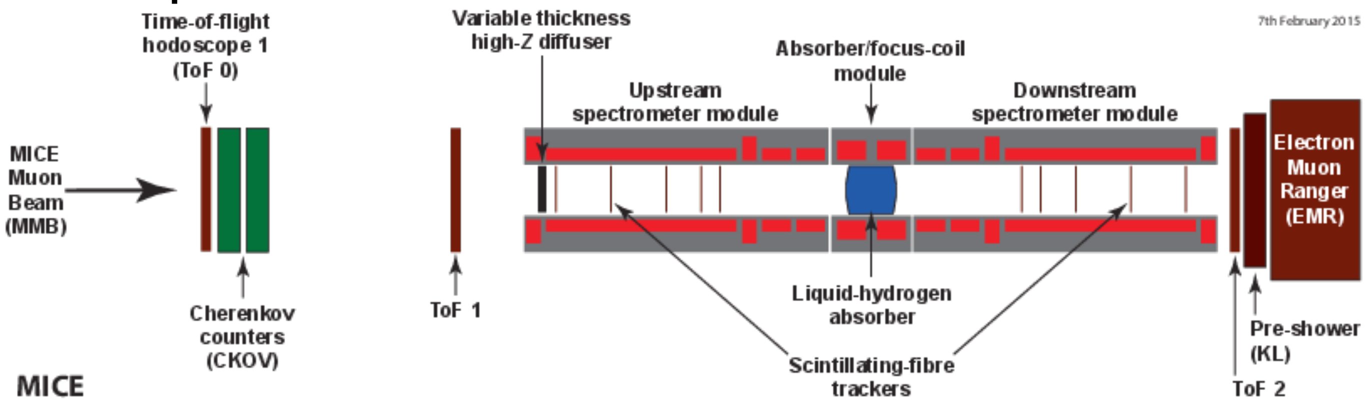
Ionization: cooling   Multiple scattering: heating

Muon Ionization Cooling Experiment

- Muon Ionization Cooling Experiment:
  - Letter of Intent: **November 2001**
  - Proposal at Rutherford Appleton Laboratory (RAL): **January 2003**
  - International collaboration formed to build experiment at RAL



  - MICE Step IV built at RAL: first demonstration of ionization cooling

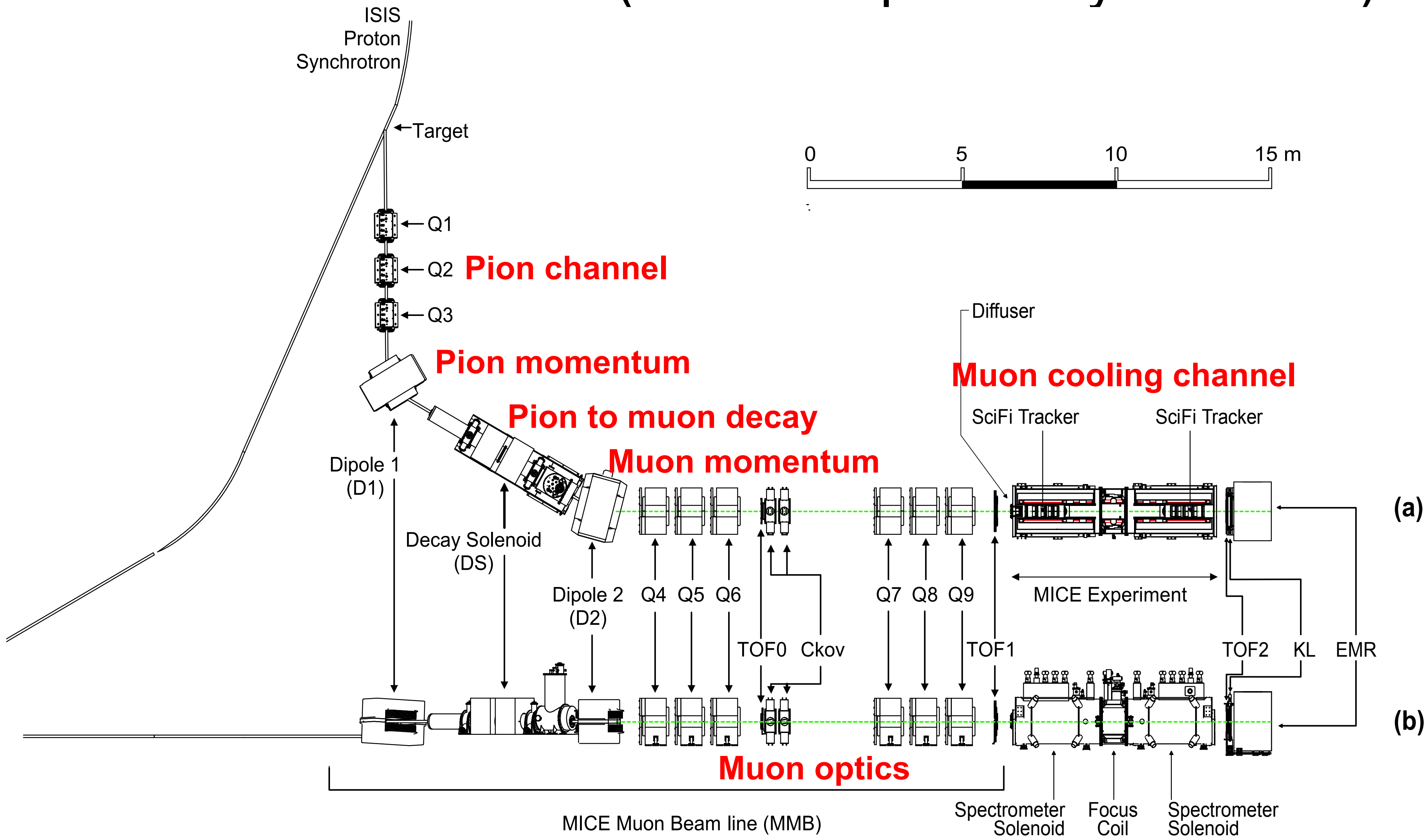


Muon Ionization Cooling Experiment

- We are extremely grateful to all the funding agencies that are contributing and have contributed to MICE
  - STFC from UK
  - NSF and DoE from USA
  - INFN in Italy, Swiss National Science Foundation, European Community, Institutional Funding in Bulgaria, Netherlands, Serbia
  - Japan Society for the Promotion of Science, Chinese Academy of Sciences, institutional funding South Korea

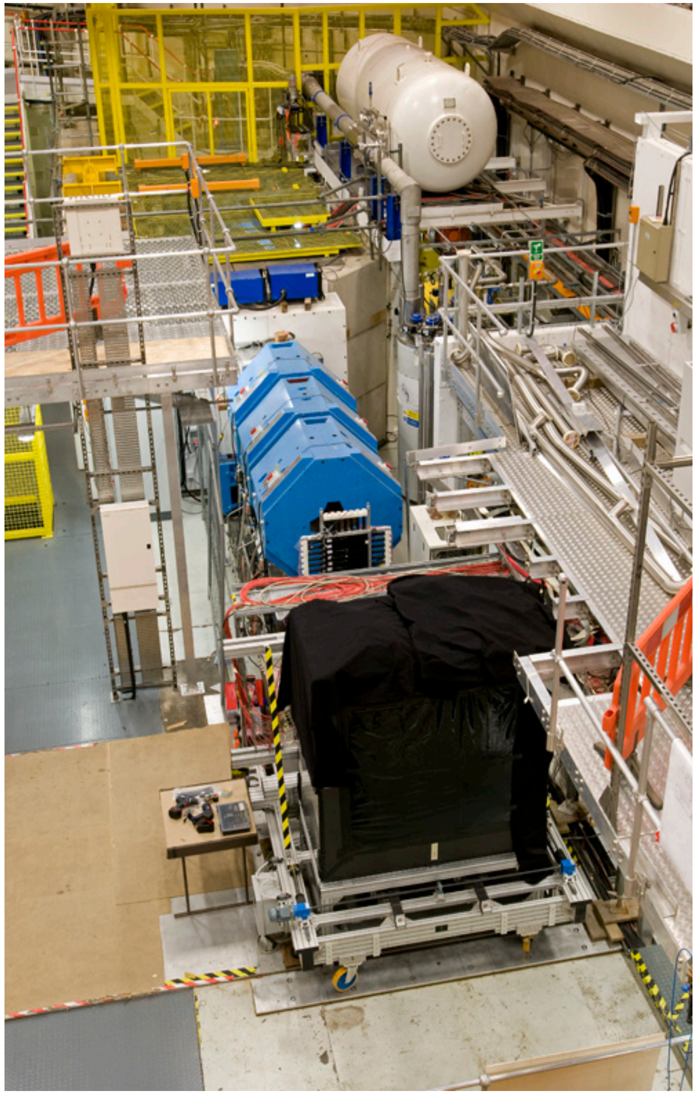
MICE Beam

- Muon beam from ISIS (800 MeV proton synchrotron)



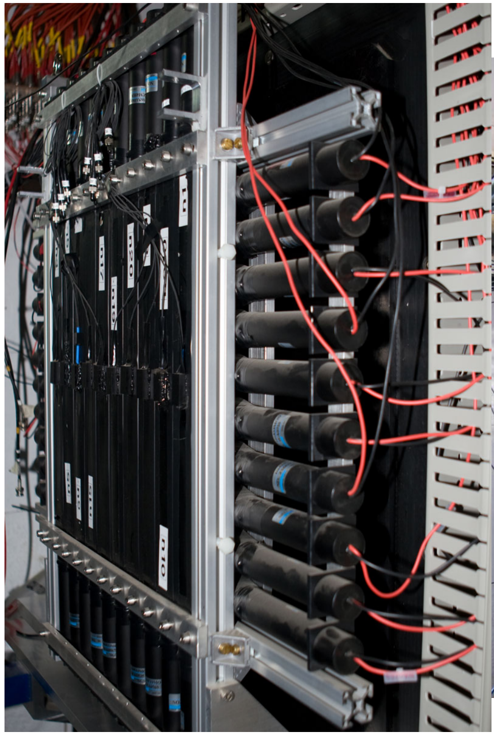
MICE Beam

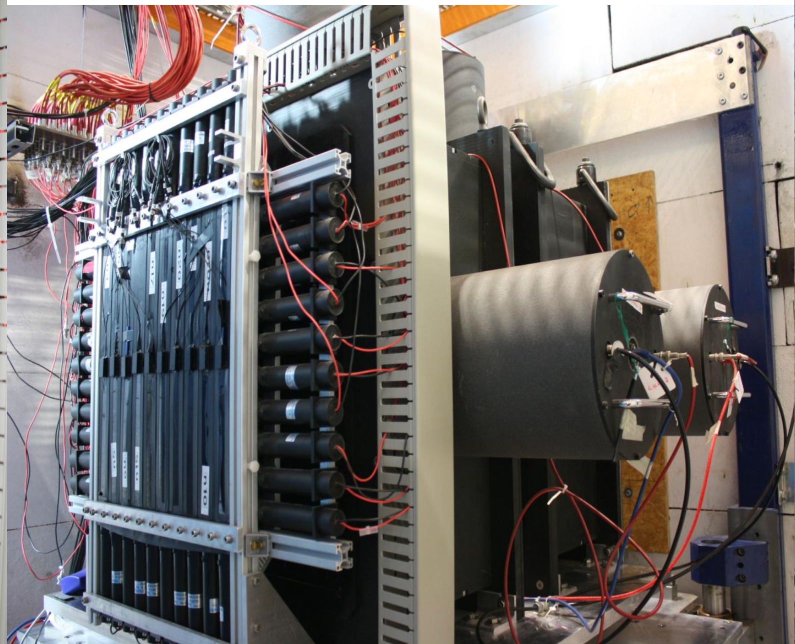
- Muon beam from ISIS

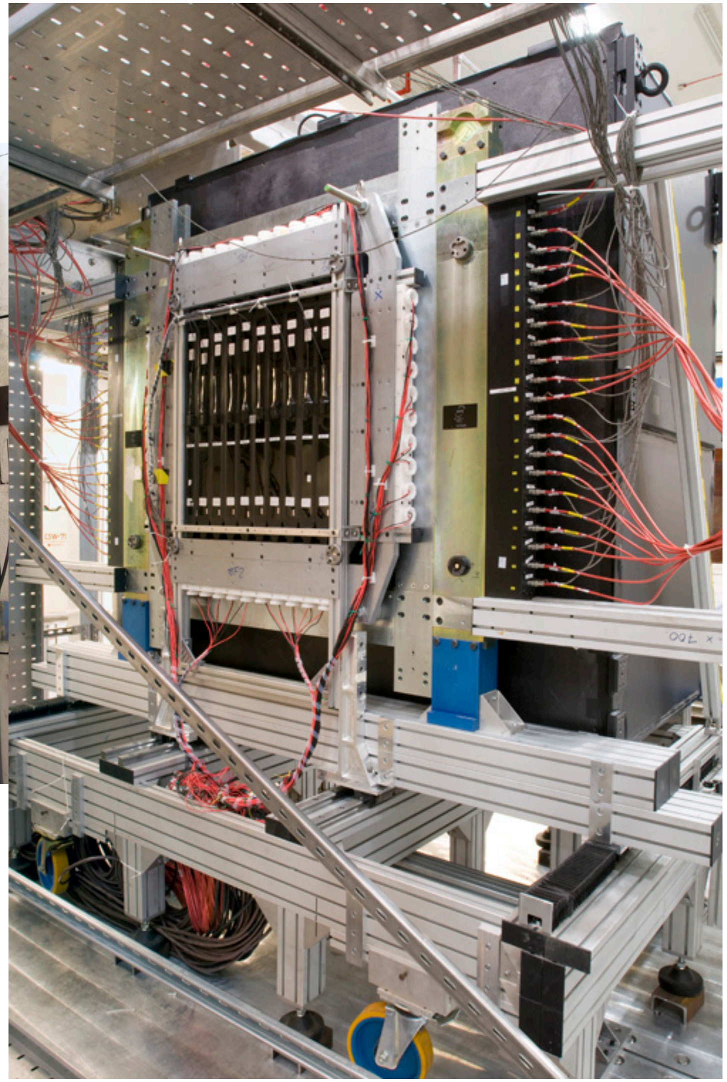


MICE Particle Identification Detectors

- Time-of-Flight, Cherenkov and KL-preshower detectors

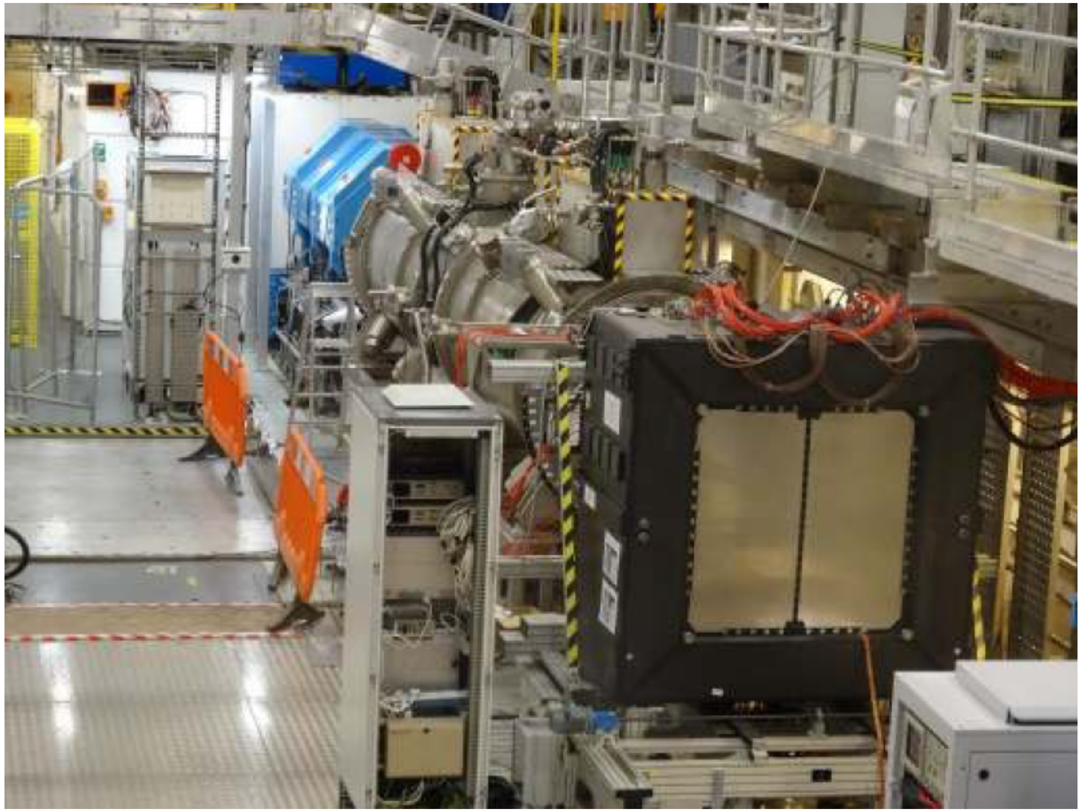


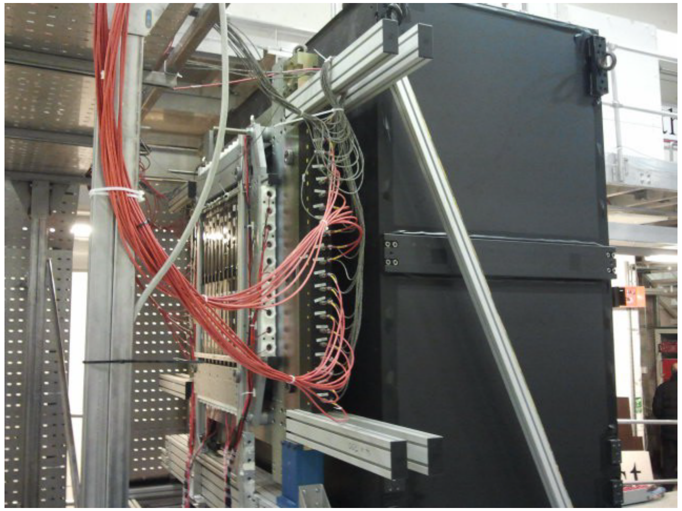




EMR and Absorbers

- Electron Muon Ranger





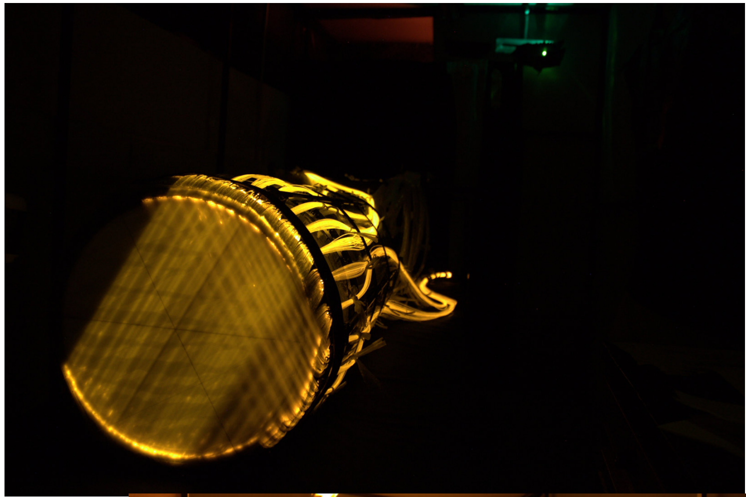
- Hydrogen absorber module

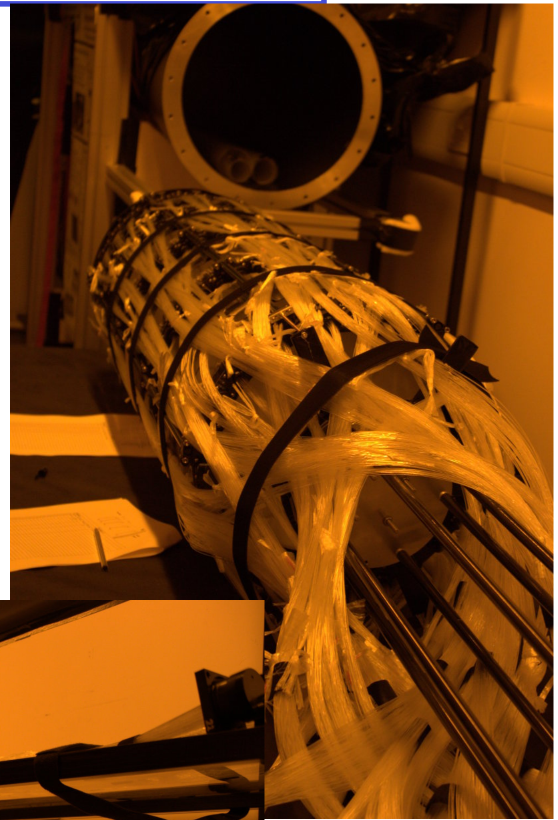
Muon Ionization Cooling Experiment

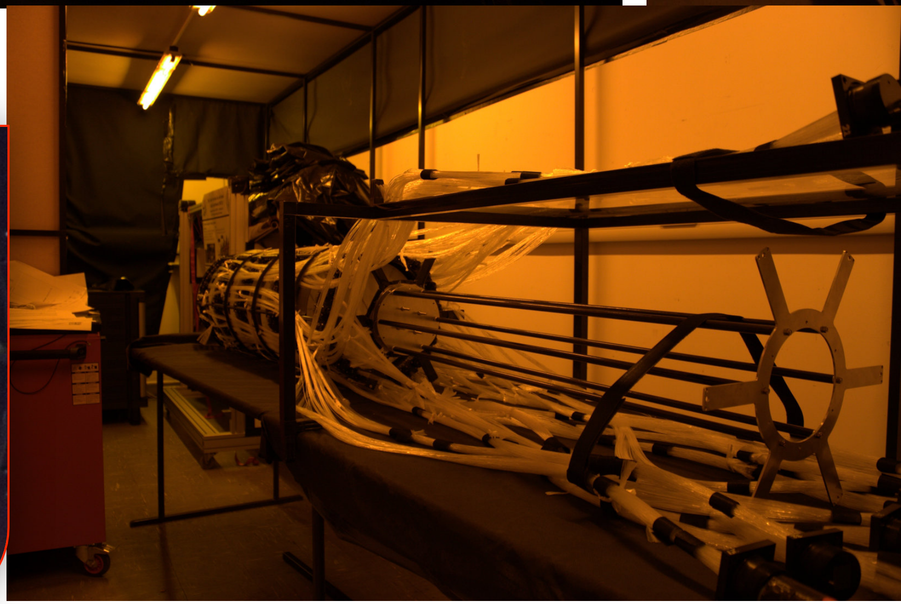
- Focus Coils and Spectrometer Solenoids

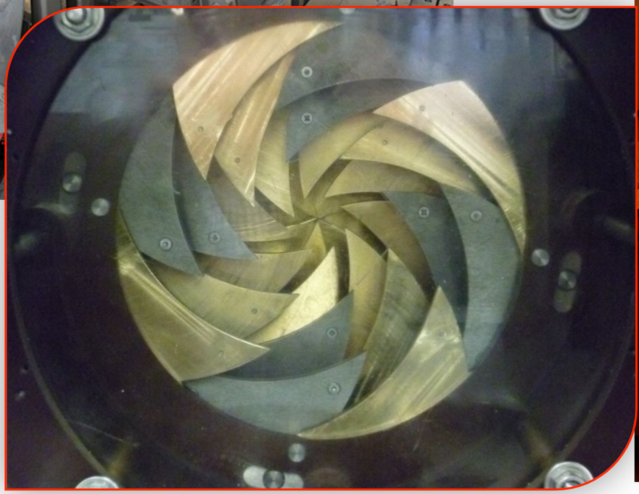
Muon Ionization Cooling Experiment

- Scintillating Fibre Tracker and diffuser





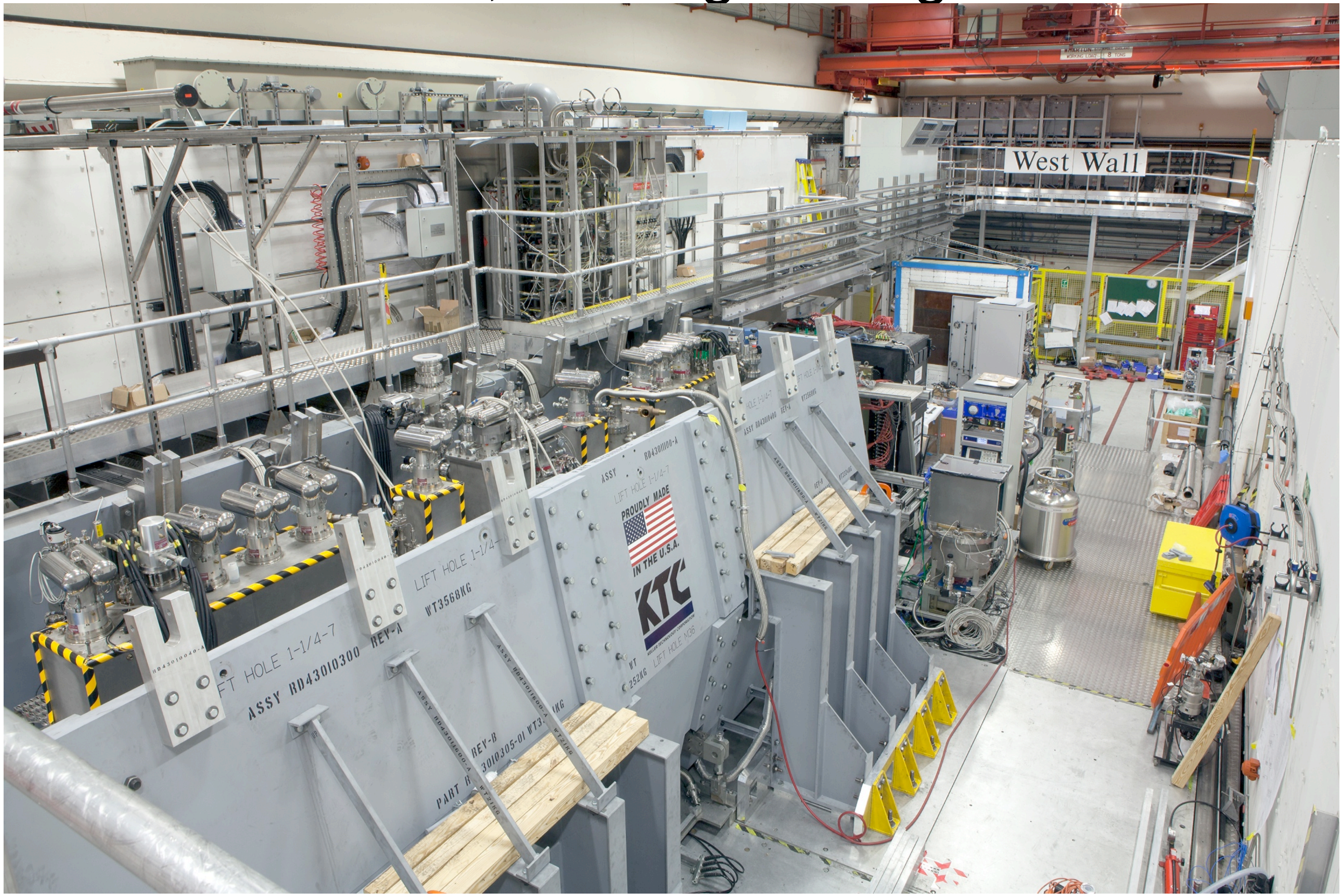




Diffuser

Muon Ionization Cooling Experiment

- Partial Return Yoke, housing cooling channel



MICE Step IV

- MICE Step IV goals: make first measurement of ionization cooling and explore change of emittance as a function of:
  - Input emittance: vary beam optics and diffuser thickness
  - Absorber material: liquid hydrogen (350mm), lithium hydride (65 mm) and 45° polyethylene wedge absorber
  - Momentum and optical beta function
- Change parameters of cooling formula to explore potential cooling performance of future facilities in detail

$$\frac{d\varepsilon_T}{dz} \approx -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

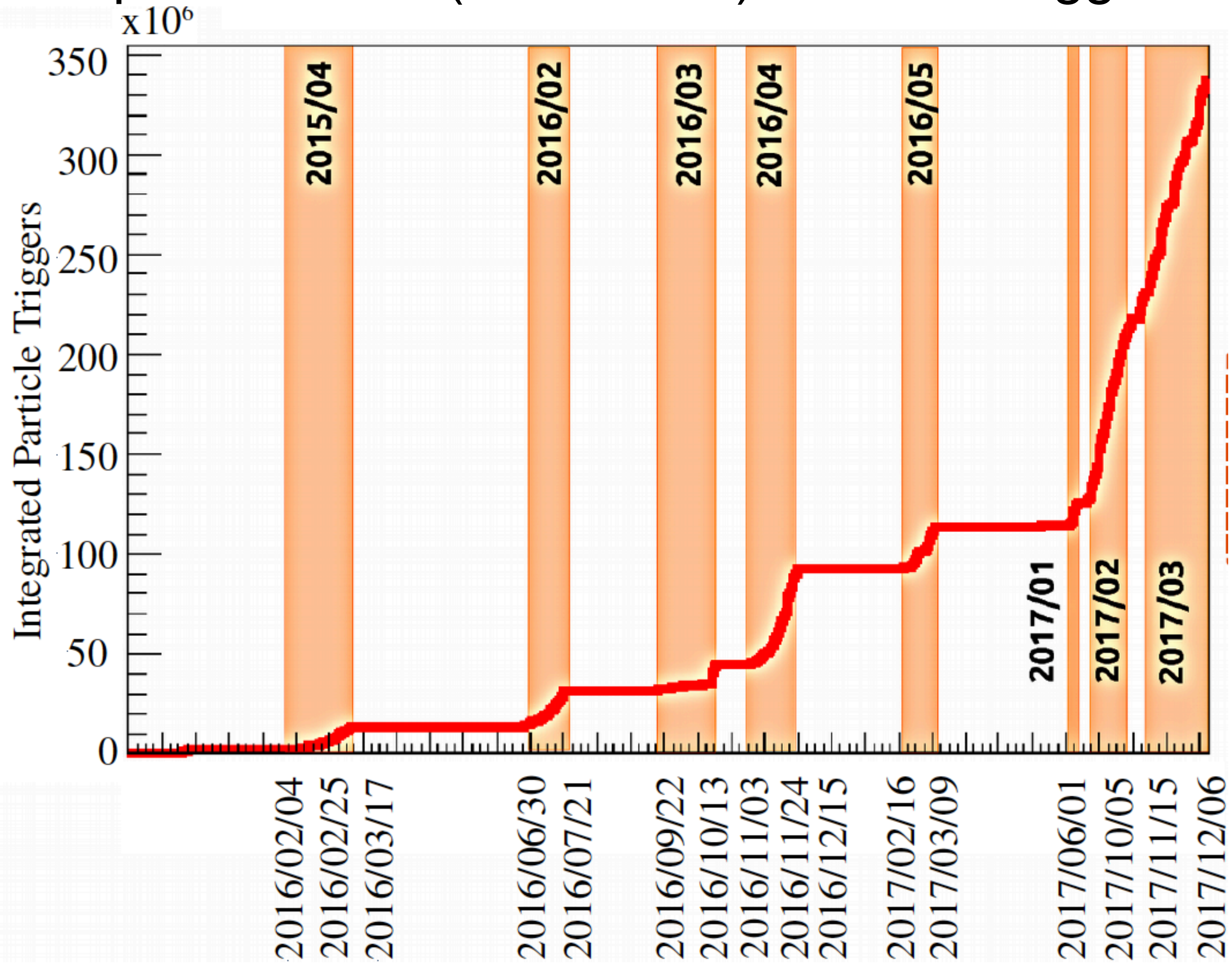
ε_T = 3 mm – 10 mm

$X_0(LH_2)$ = 890 cm, $X_0(LiH)$ = 102 cm, $X_0(CH)$ = 47.9 cm

p_μ= 140 – 240 MeV/c

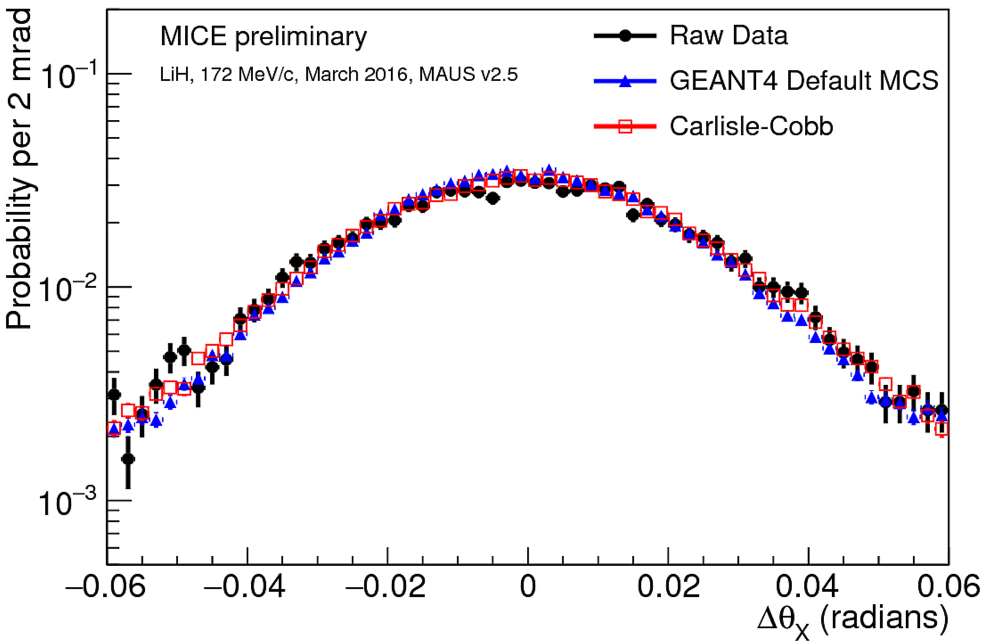
MICE Step IV

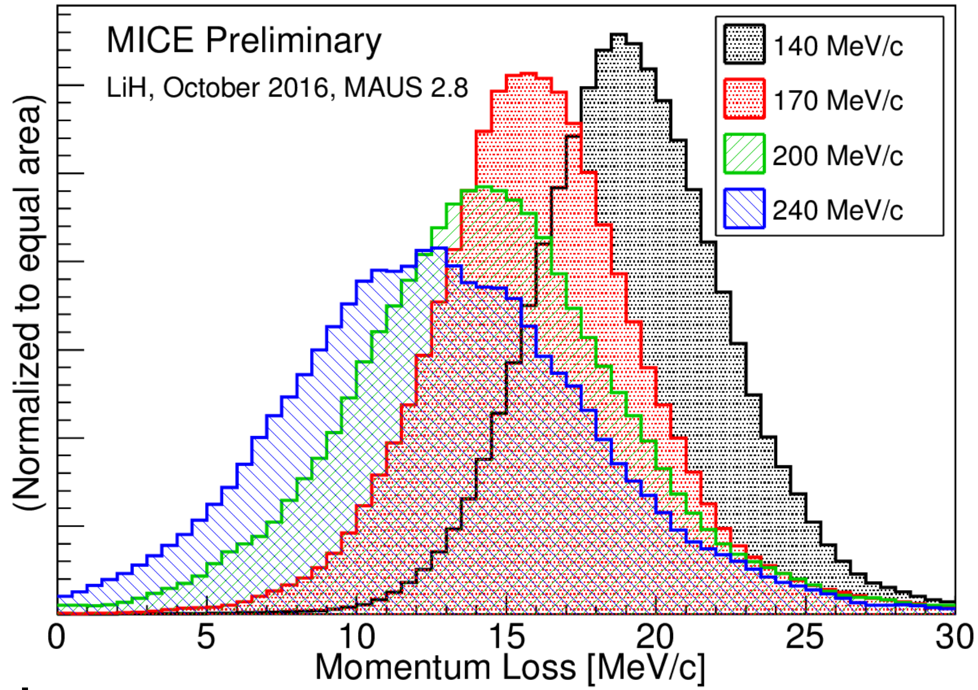
- MICE Step IV data set (2015-2017): 350×10^6 triggers



Multiple Coulomb Scattering

- First measurement of muon Multiple Coulomb Scattering in lithium hydride at 140-240 MeV/c: **see Monday WG3 parallel talk by John Nugent**
  - Validation of Molière scattering model and GEANT4





- Validation of energy loss model

Measurement of beam emittance

- Emittance measured through single particle reconstruction, creating virtual beams by performing ensemble of all particles
- 4D-phase space of particles: (x, p_x, y, p_y)
- Normalised transverse emittance: $\varepsilon_T = \dfrac{\sqrt[4]{|V_{4D}|}}{mc}$

Volume of 4D phase-space hyper-ellipse

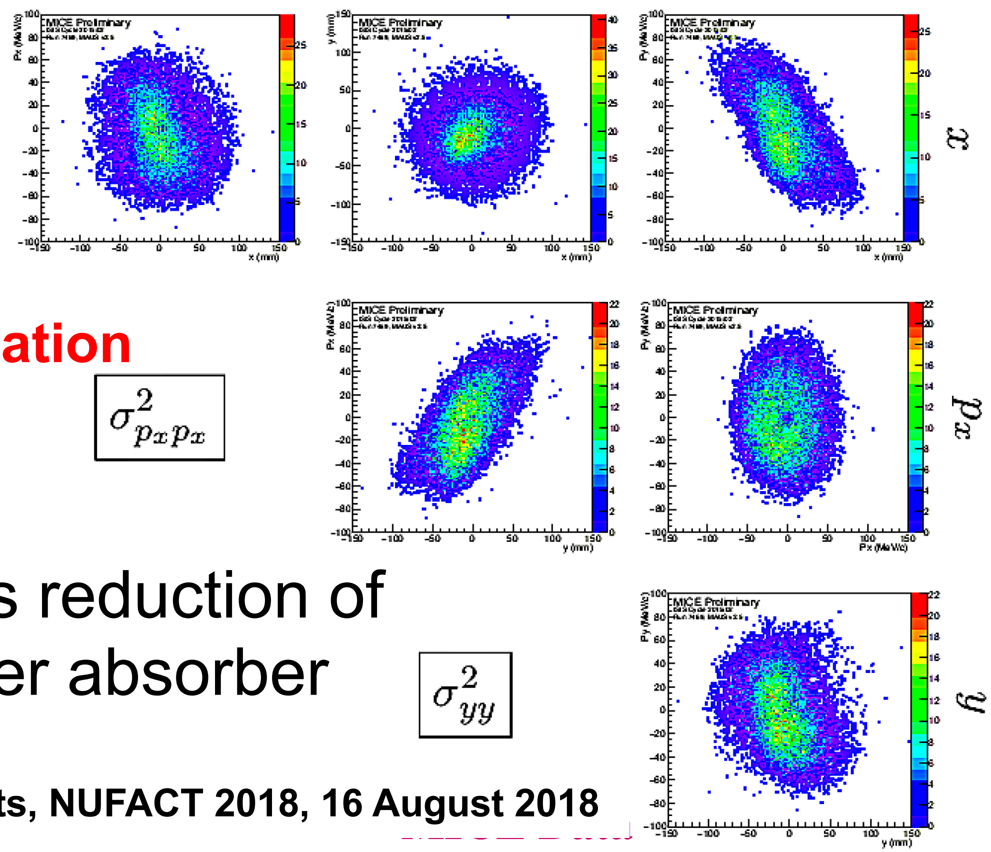
4D covariance matrix: V_{4D}

x p_x y p_y

σ^2_{xx}

$\sigma^2_{p_x p_x}$

σ^2_{yy}

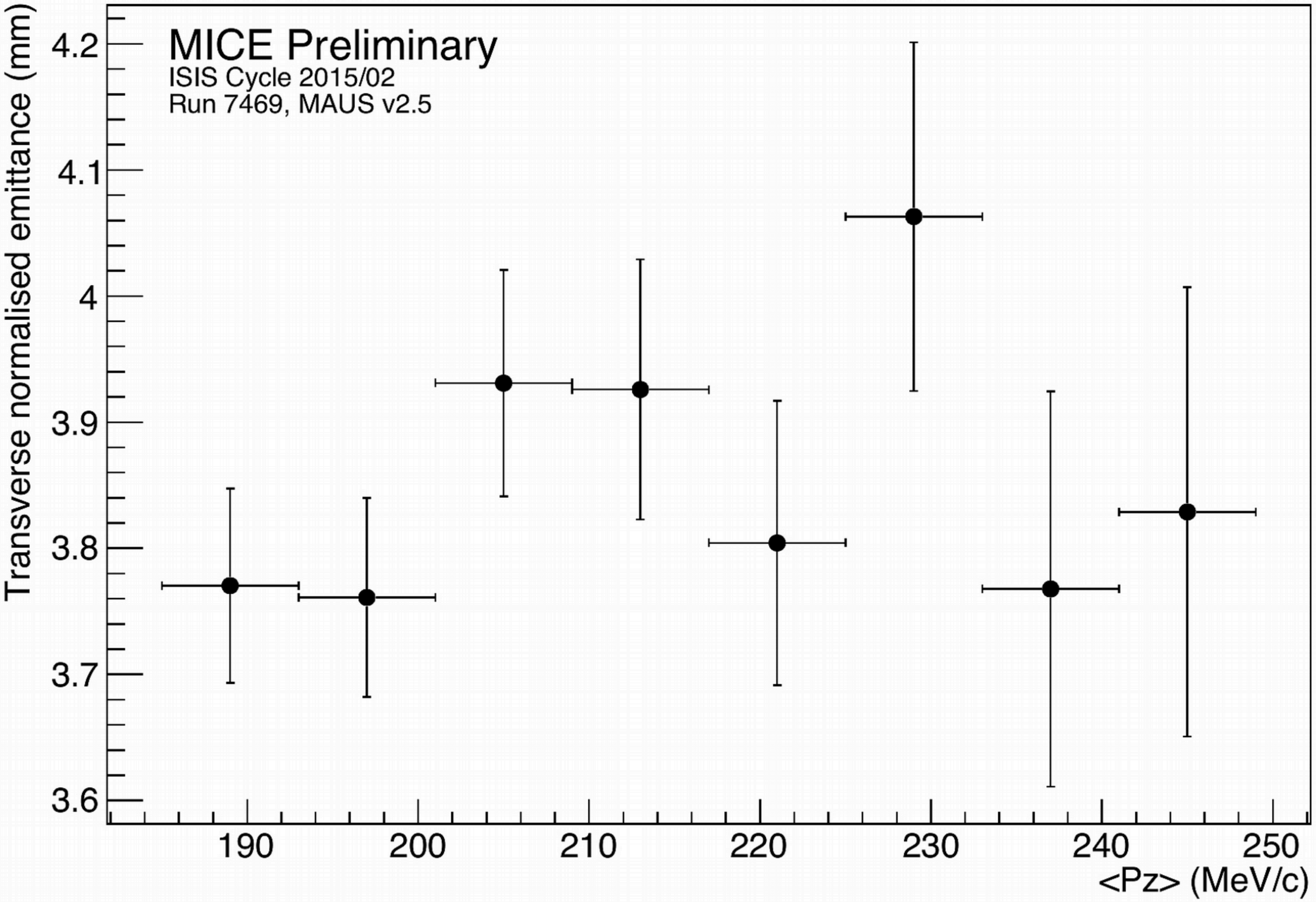


Reconstructed phase space shows coupling of different variables for emittance calculation

- Ionization cooling implies reduction of transverse emittance after absorber

Emittance evolution

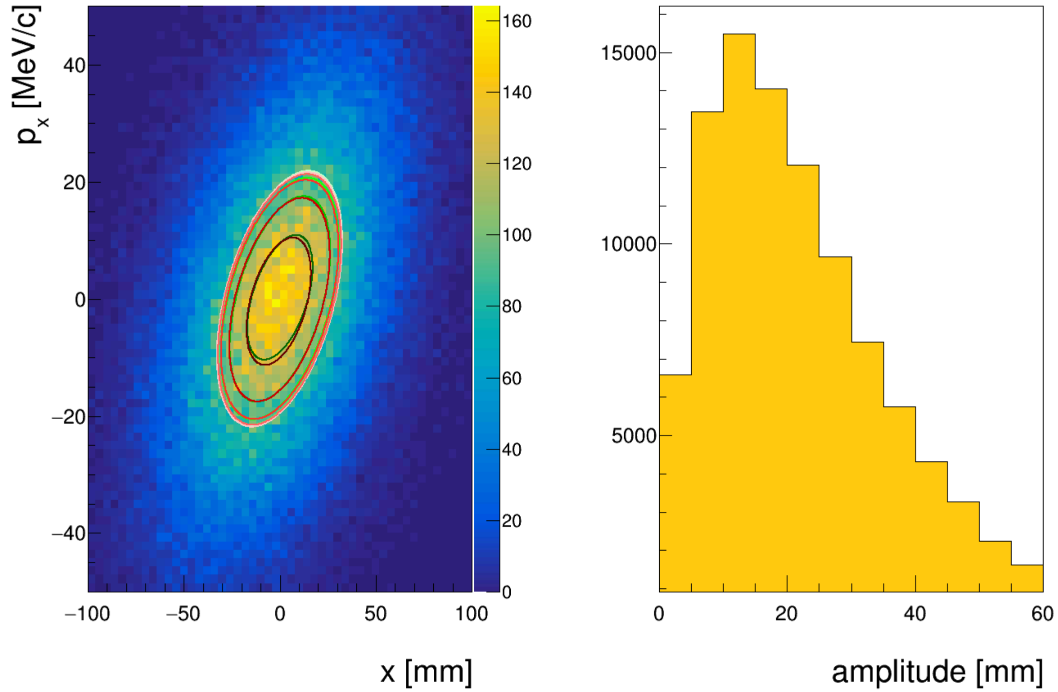
- Measurement of emittance using single-particle method:
  - MICE data shows dispersion of beam as function of momentum



See Chris Hunt's talk (Monday WG3)

Single particle amplitude

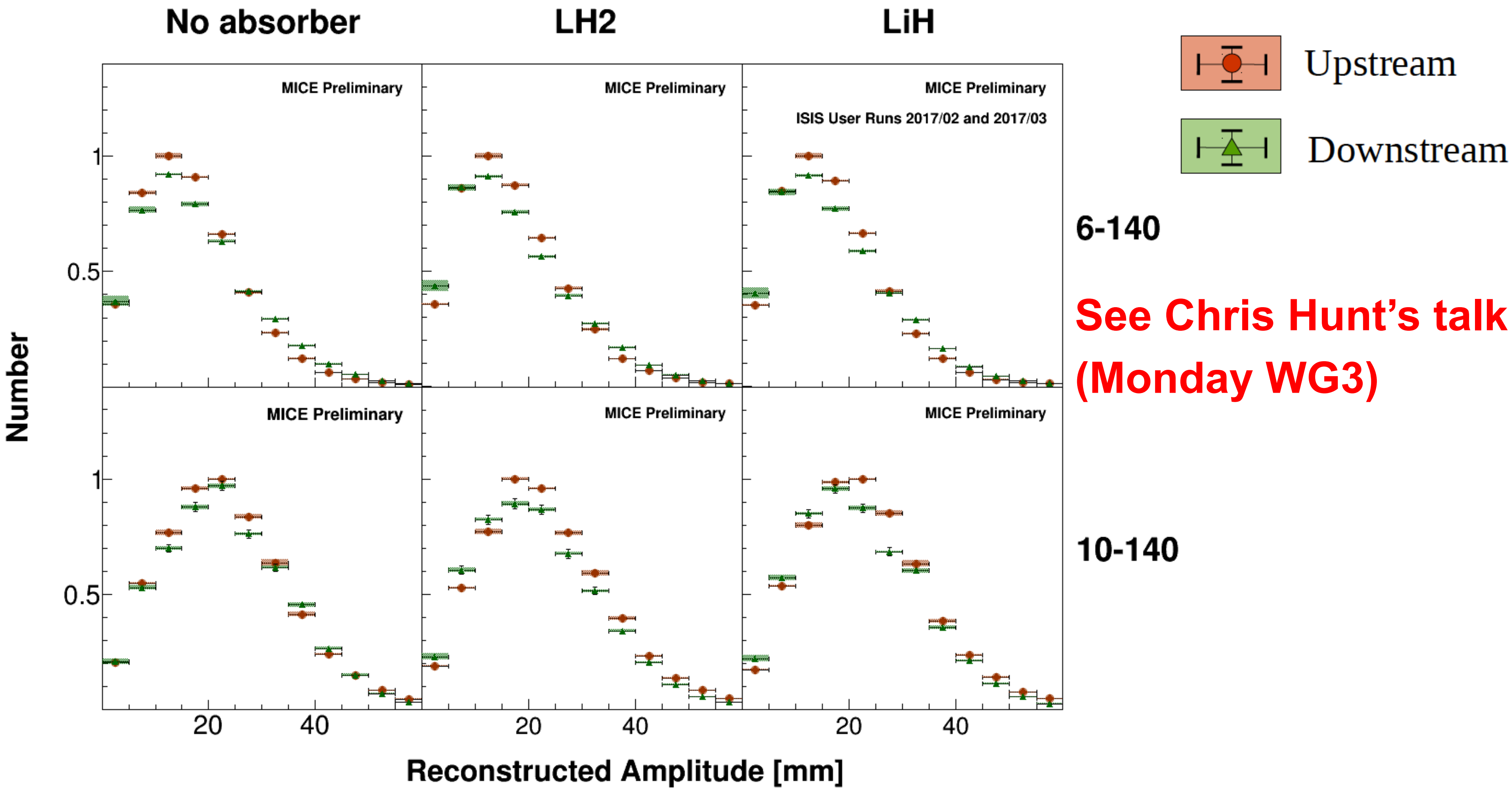
- Single particle amplitude:
  - Normalise phase space to RMS beam ellipse
  - Amplitude is phase-space distance of muon from beam core



- Mean amplitude is RMS emittance
- Ionization cooling reduces amplitude in the core of the beam (higher amplitude density at low amplitudes)

Change in amplitude across absorber

- No absorber: decrease in number of core muons
- Absorber: increase in number of core muons (cooling signal)



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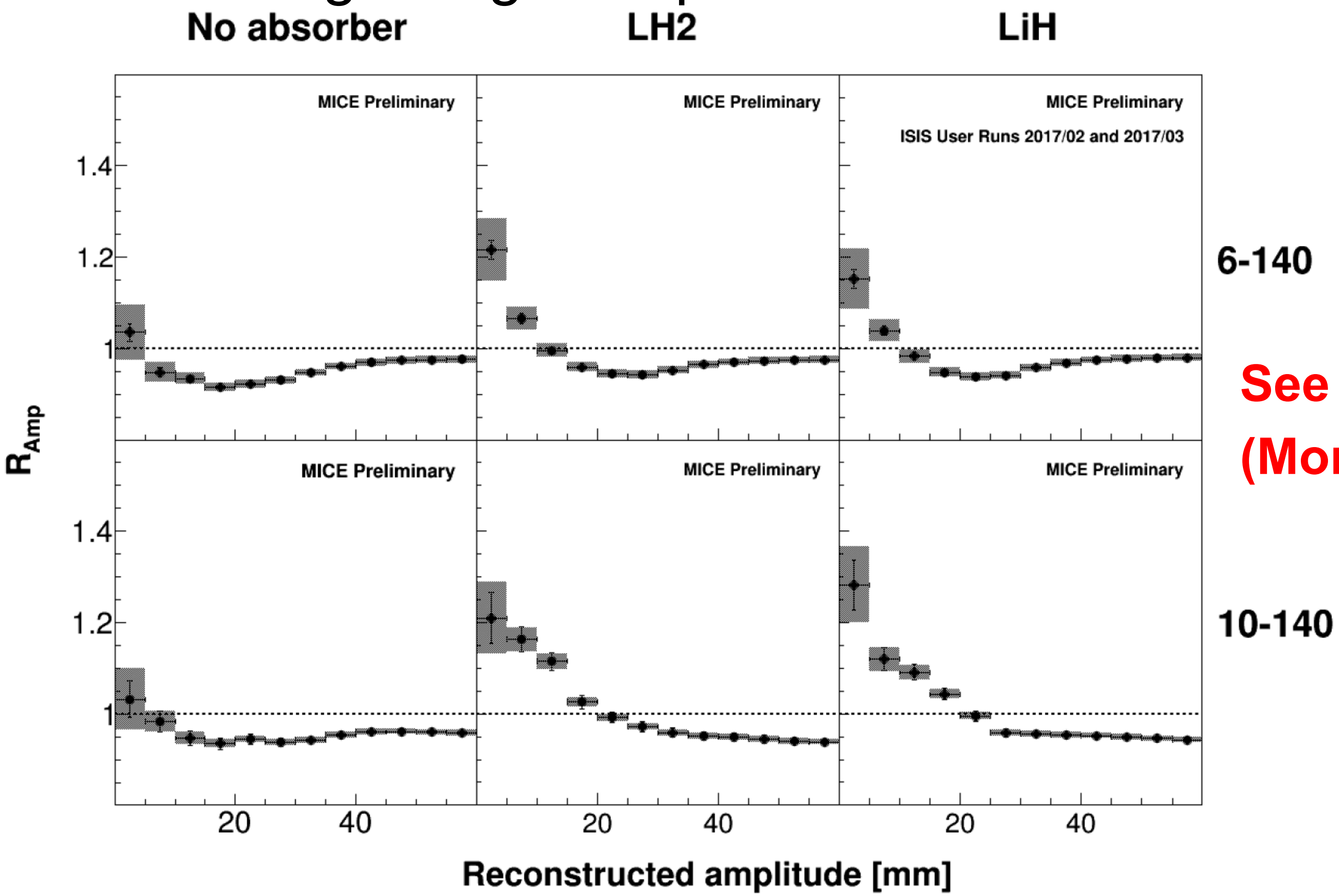
Ratio of core densities

- Core density increase for LH2 and LiH absorbers
- More cooling at higher input emittances

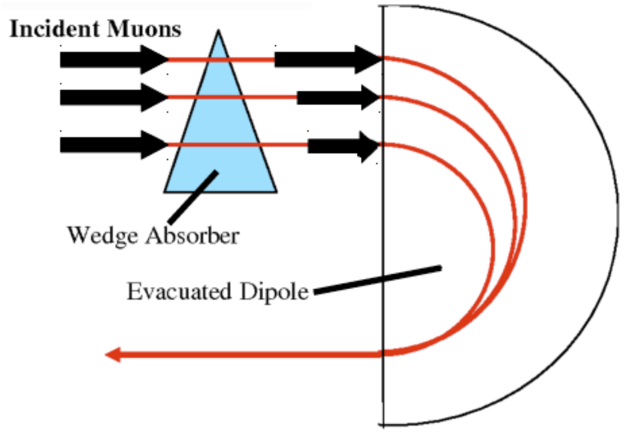


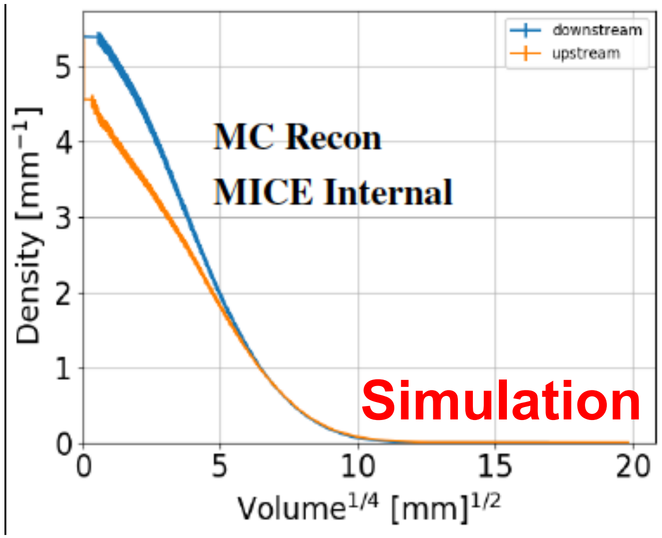
See Chris Hunt's talk (Monday WG3)

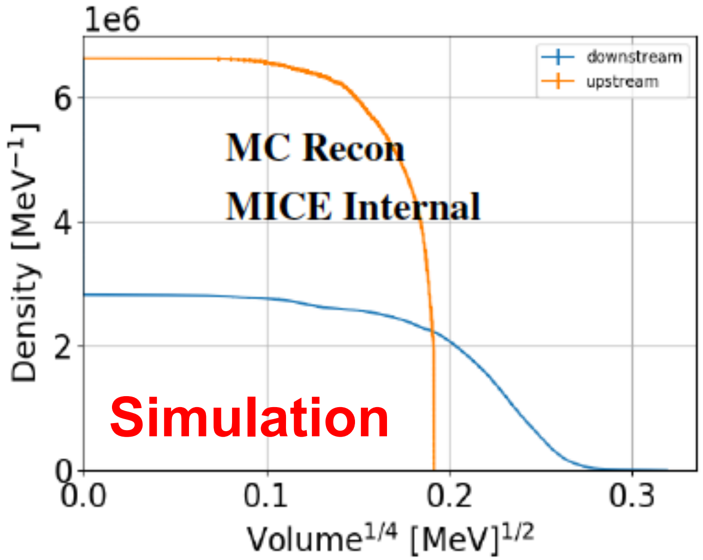
First demonstration and characterisation of ionization cooling!

Reverse emittance exchange

- Data taken with polyethylene wedge absorber
- Measure reverse emittance exchange: longitudinal heating and transverse cooling (used in muon collider 6D cooling)







See Yagmur Torun's talk (Monday WG3 parallel session)

Conclusions

- The Muon Ionization Cooling Experiment was constructed at RAL to show ionization cooling for the first time
- MICE collected 350 million triggers under different input configurations to fully characterise ionization cooling
- MICE analyses are ongoing, measuring material properties, such as Multiple Coulomb Scattering and Energy Loss
- The MICE apparatus has been used to perform accurate emittance measurements
- MICE has demonstrated ionization cooling for the first time
- Characterisation of ionization cooling to benchmark performance of future neutrino factory and muon collider