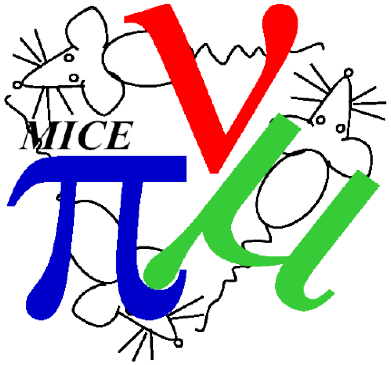
Emittance Evolution



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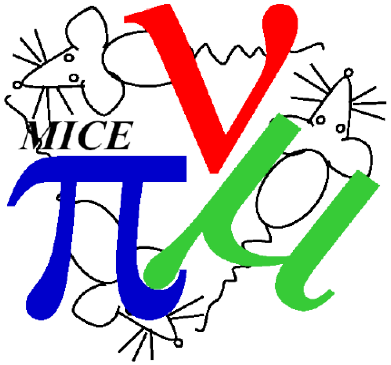
Overview

- Paper “First demonstration of ionization cooling using the Muon Ionization Cooling Experiment”
- Present the paper first
  - Plan is to submit article to Nature Physics (fall-back PRL or PRX)
  - 4-6 figures, 2000-3000 words
  - Bullets explaining gist of the words
  - Pause for comments
  - Nb: still working through details of paper
- Then go into details
  - Systematics studies

Paper



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First demonstration of Ionization Cooling

- Particle accelerators for protons, electrons and ions have been used in many areas of science
- Muon beams have been used for particle physics and material physics
  - Muon beams produced by putting protons onto a target
- Accelerated and stored muon beams have been proposed for a Neutrino Factory and Muon Collider
  - Muon beam phase space must be compressed for acceleration
  - Note LEMMA concept in addition to proton-based muon beams
- Four cooling techniques are in use at particle accelerators: synchrotron radiation cooling, laser cooling, stochastic cooling and electron cooling
  - Note also frictional cooling for low energy muon beams
- MICE seeks to demonstrate phase space compression using ionization cooling

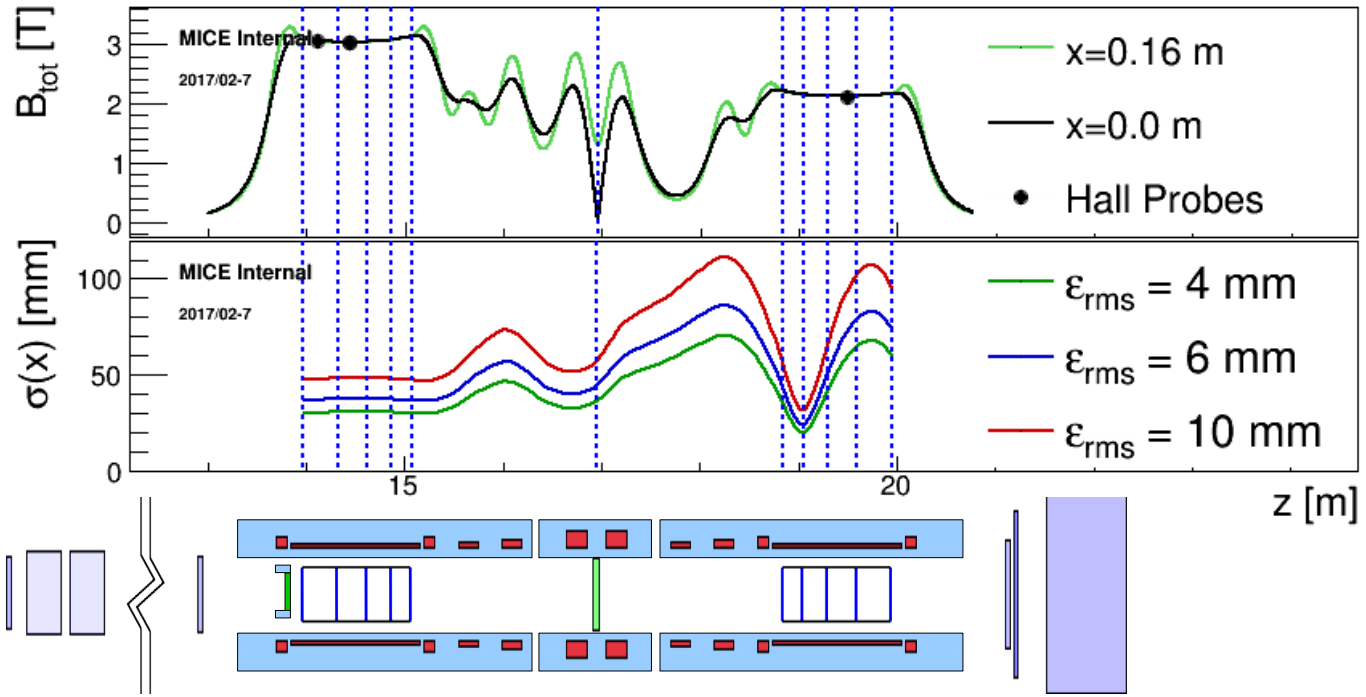
Observables

- Intensity of accelerator beams can be described by phase space volume and rate
- Phase space volume is conserved quantity
- Characterised by RMS emittance and amplitude
  - Define emittance and amplitude
  - Discuss expected change in amplitude on passage through an absorber
- RMS emittance is biased by scraping and optical aberrations
  - 9^{th} centile amplitude is numerically equal to RMS emittance, for Gaussian beam, in absence of scraping
- k Nearest Neighbour algorithm provides direct observable of phase space density
  - Describe kNN algorithm

MICE

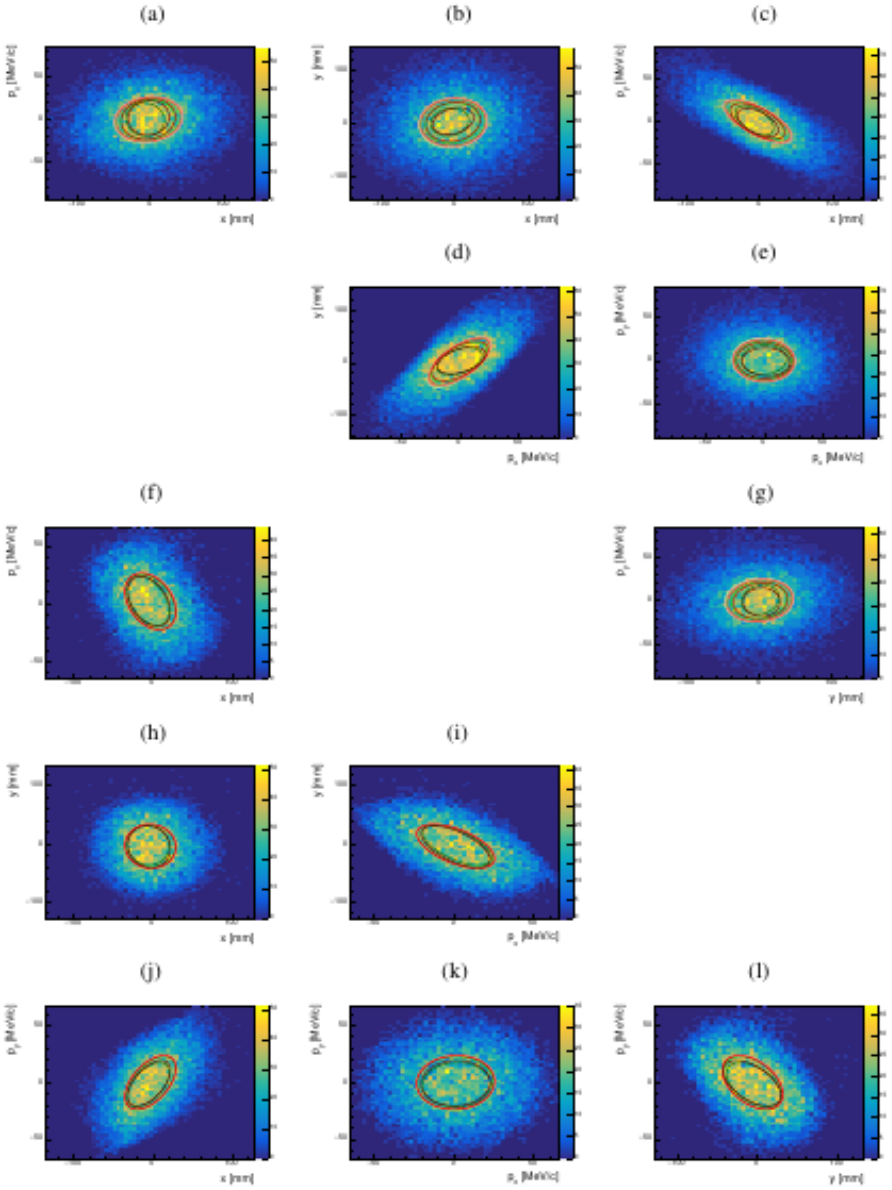
- MICE built to cool the beam and measure amplitude and phase space density
- Transfer line brings a few particles per second to the experiment; ensemble accumulated over ~ hours
- Particles contained by superconducting solenoids
- LiH and lH2 absorber studied here
- ToF, tracker and PID detectors measure the beam
- SciFi measures momentum
- ToF measures time of flight → velocity and, together with tracker, PID
- Simulation using GEANT4
- Consider an upstream sample that is well reconstructed, 135-145 MeV/c momentum and consistent with muon hypothesis
- Consider a downstream sample that is well reconstructed and subset of upstream sample

Fig. 1



- (Top) Solenoid field model
- (middle) Nominal RMS beam width
- (bottom) cooling channel schematic
- Add labels to schematic

Fig 2



Upstream

Downstream

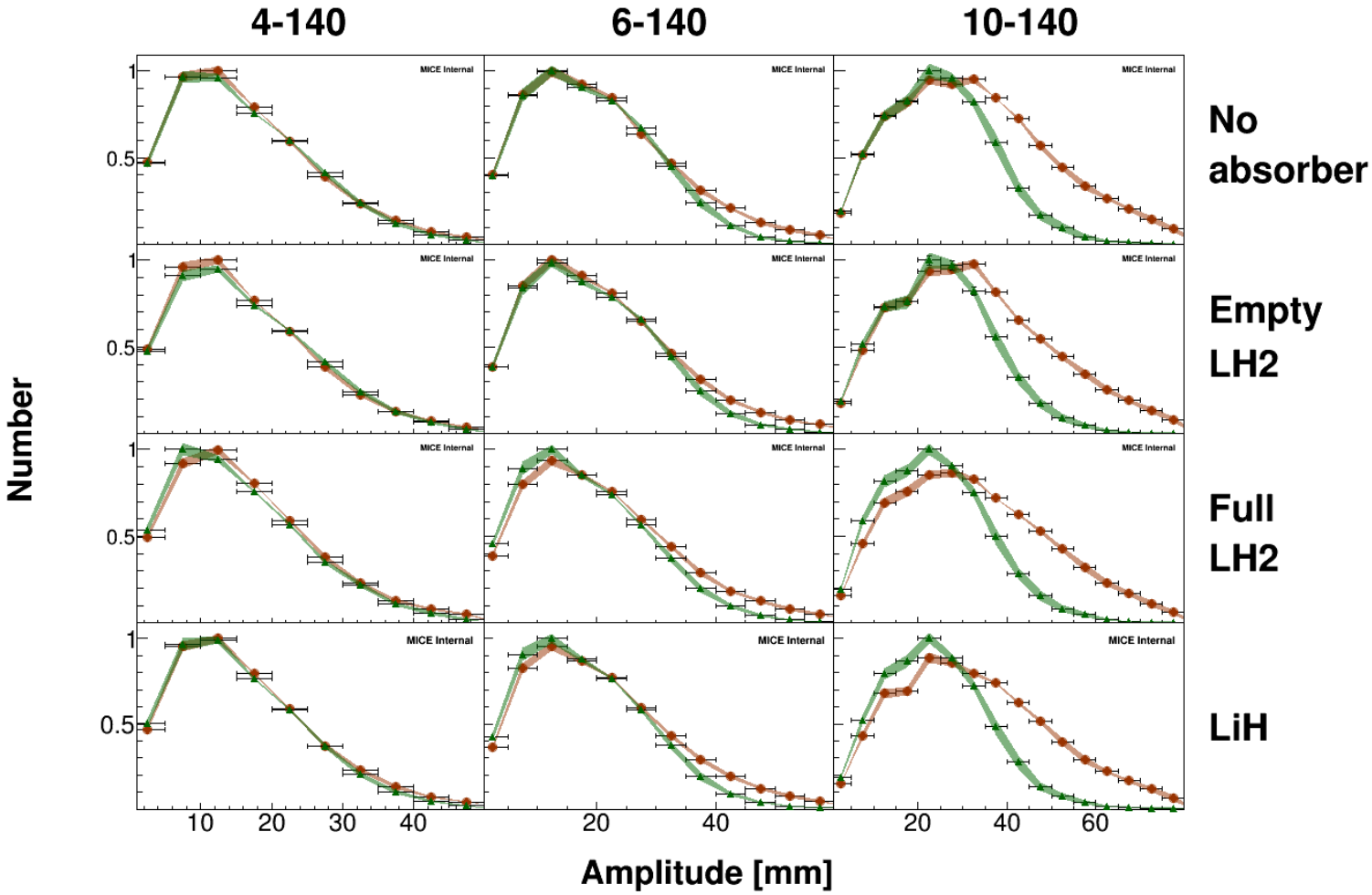
Amplitudes

- Distribution of amplitudes upstream and downstream
  - Note correction has been made for detector efficiency/resolution
- Note increase at low amplitude when absorber installed
- Note more increase with higher amplitude beams

Fig. 3

Downstream

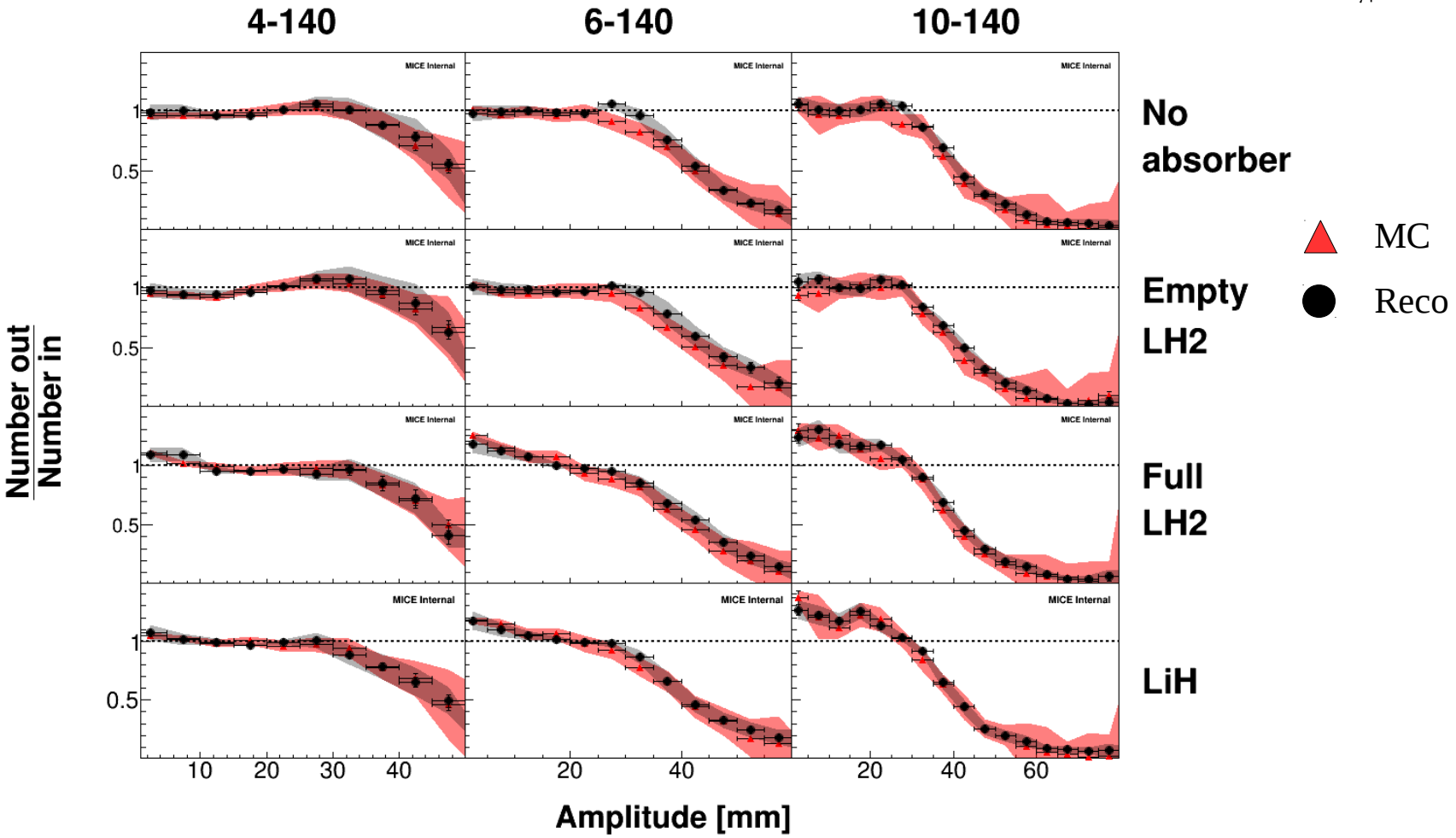
Upstream



Amplitude pdf ratio

- Ratio of upstream amplitude to downstream amplitude
- Note that ratio is 1 at low amplitude for empty absorber indicating no cooling
- Note that ratio is < 1 above 30 mm → scraping aperture
- Note that ratio is > 1 at low amplitude for full absorber indicating cooling

Fig. 4


4-140
6-140
10-140
MICE Internal
No absorber
Empty LH2
Full LH2
LiH
MC
Reco
Number out / Number in
Amplitude [mm]

Amplitude cdf ratio

- Define cdf ratio
- Note that a ratio > 1 at low amplitude indicates cooling
- Note that ratio at high amplitude is transmission
- Note that cooling is observed when absorber is installed

Fig. 5 (a)

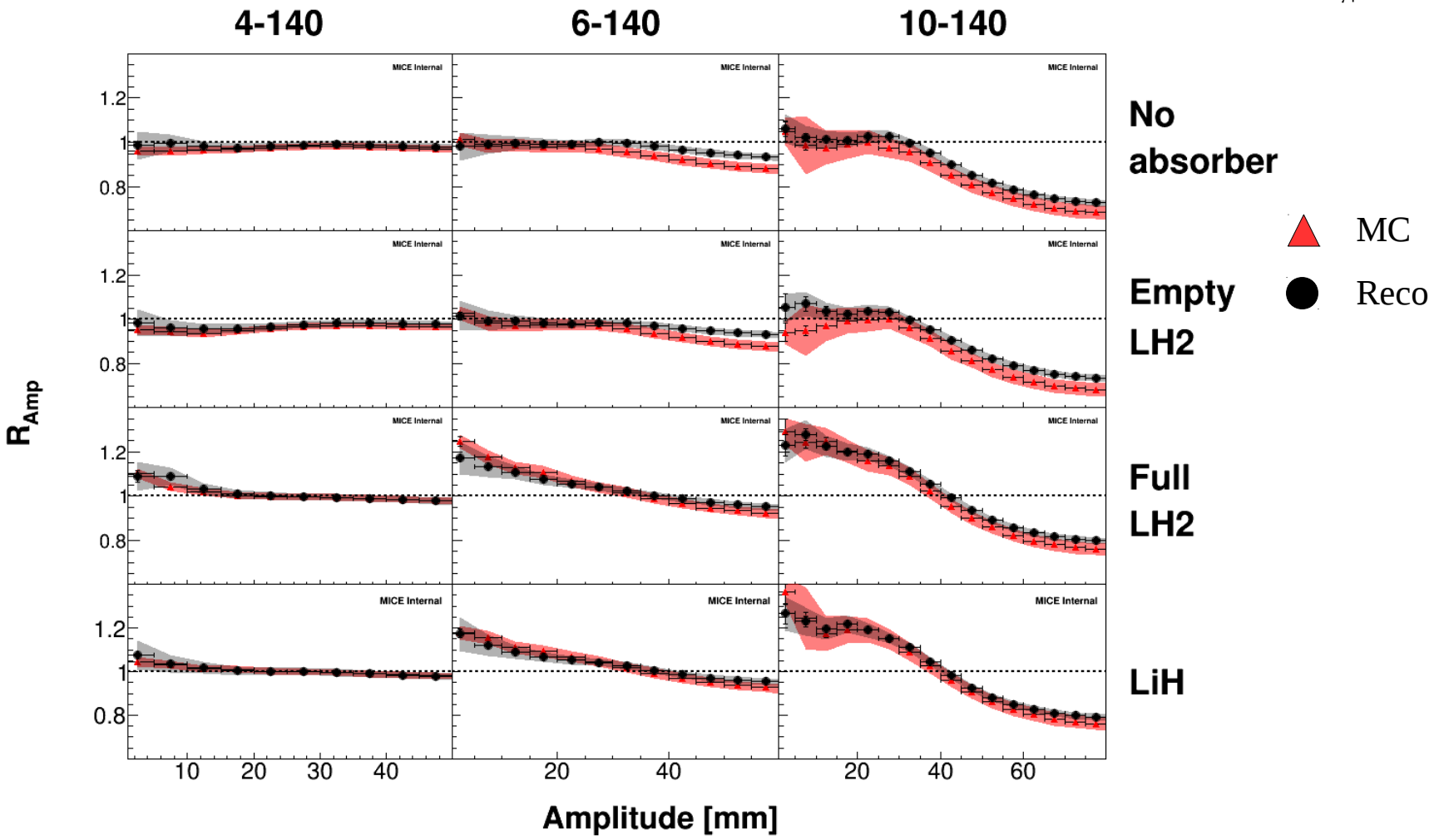
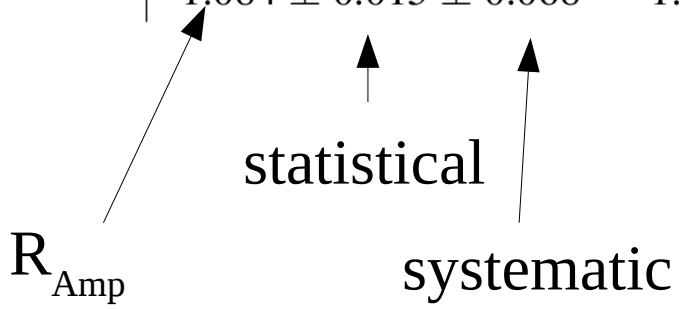

4-140
6-140
10-140
MICE Internal
R_{Amp}
1.2
1
0.8
10
20
30
40
60
Amplitude [mm]
No absorber
Empty LH2
Full LH2
LiH
MC
Reco

Fig. 5 (b)

	4-140	6-140	10-140
No absorber	$0.993 \pm 0.0064 \pm 0.038$	$0.9987 \pm 0.0048 \pm 0.016$	$1.028 \pm 0.0088 \pm 0.024$
Empty LH2	$0.9821 \pm 0.012 \pm 0.061$	$1.011 \pm 0.019 \pm 0.066$	$1.036 \pm 0.014 \pm 0.025$
Full LH2	$1.086 \pm 0.015 \pm 0.04$	$1.108 \pm 0.0074 \pm 0.033$	$1.169 \pm 0.011 \pm 0.026$
LiH	$1.084 \pm 0.015 \pm 0.068$	$1.069 \pm 0.0062 \pm 0.024$	$1.185 \pm 0.011 \pm 0.032$



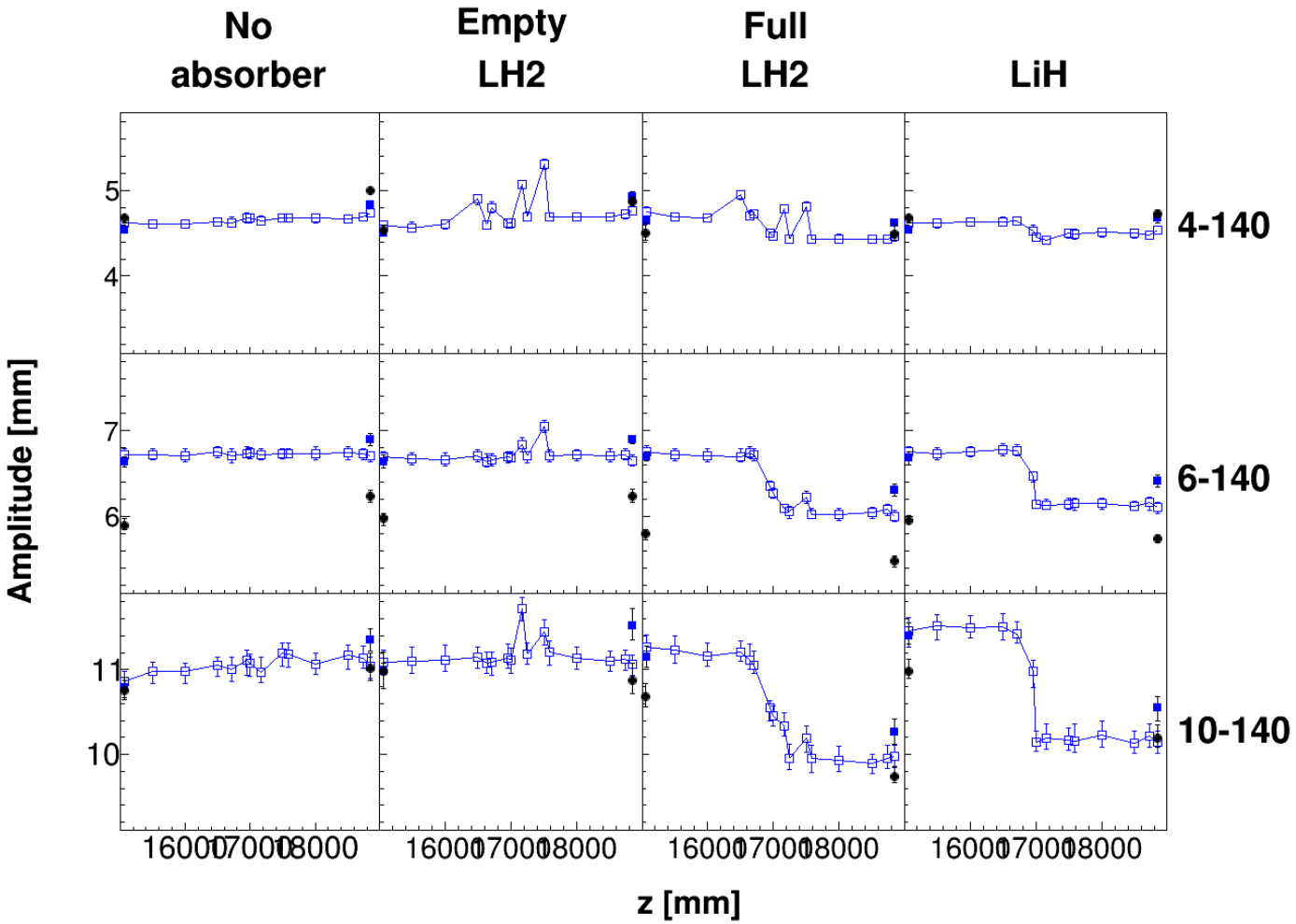
- R_{Amp} and uncertainty on most significant CDF bin

Fractional emittance

- Amplitude of 9th centile particle
- Demonstrates emittance reduction in the absorber (but not much in the fields)

- Caveat: plot needs work!

Fig. 6

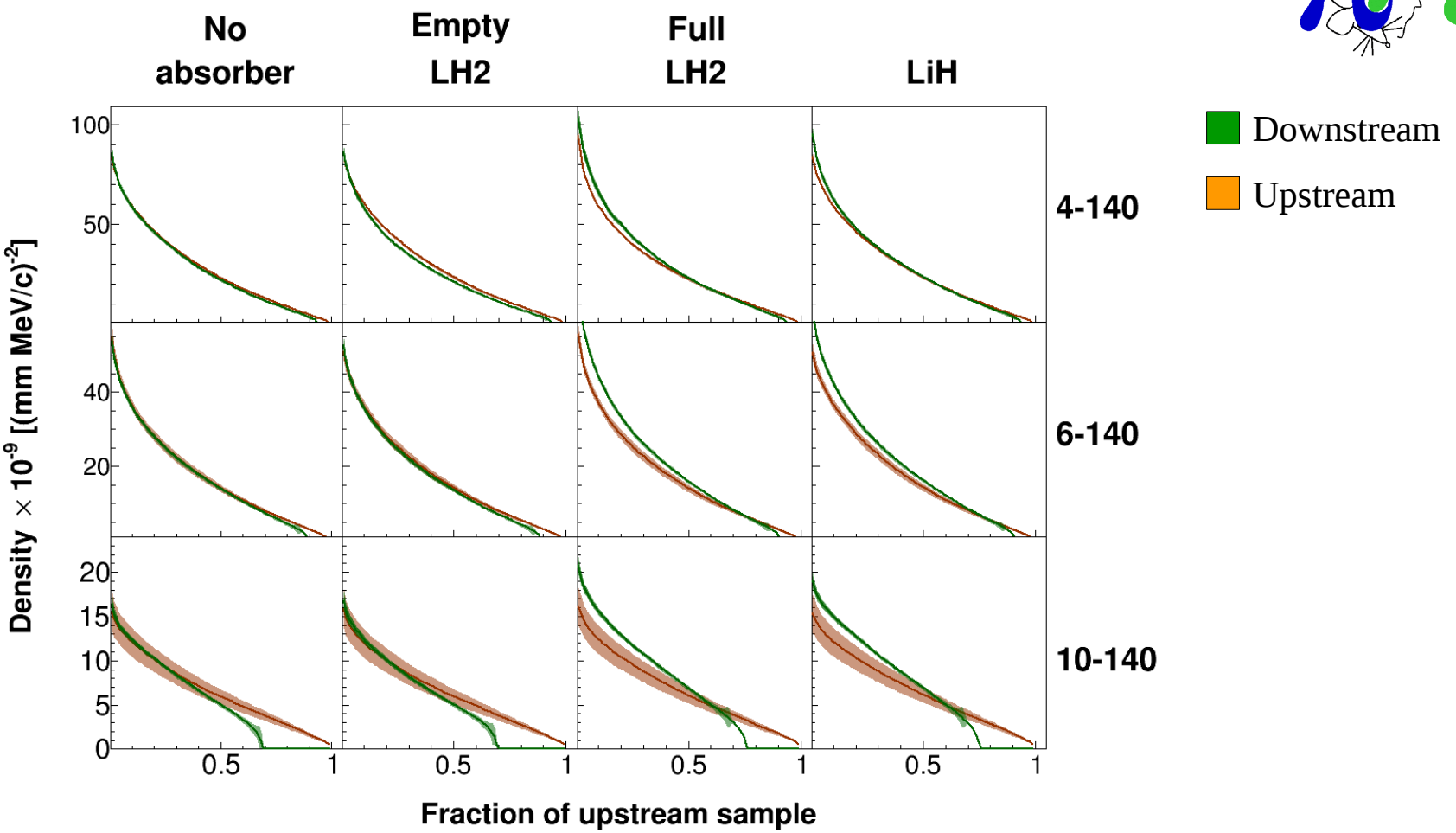


- Caveat: plot needs work!

Phase space density

- Phase space density is direct measure of beam brightness
- Phase space density is invariant
- Study phase space density for different beam settings

Fig. 7



- Error analysis needs to be understood

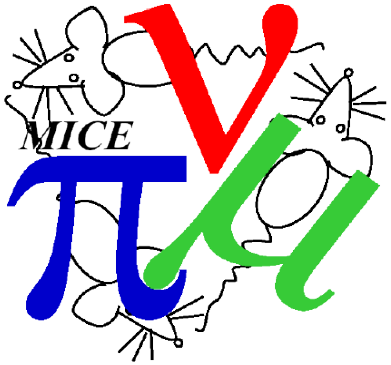
Conclusions

- Ionization cooling is a novel beam cooling technique
- Can e.g. enable preparation of a muon beam for acceleration
- MICE has demonstrated ionization cooling

Methods (In Progress)

- Describe sample selection in more detail
- Describe correction algorithm in more detail

Details



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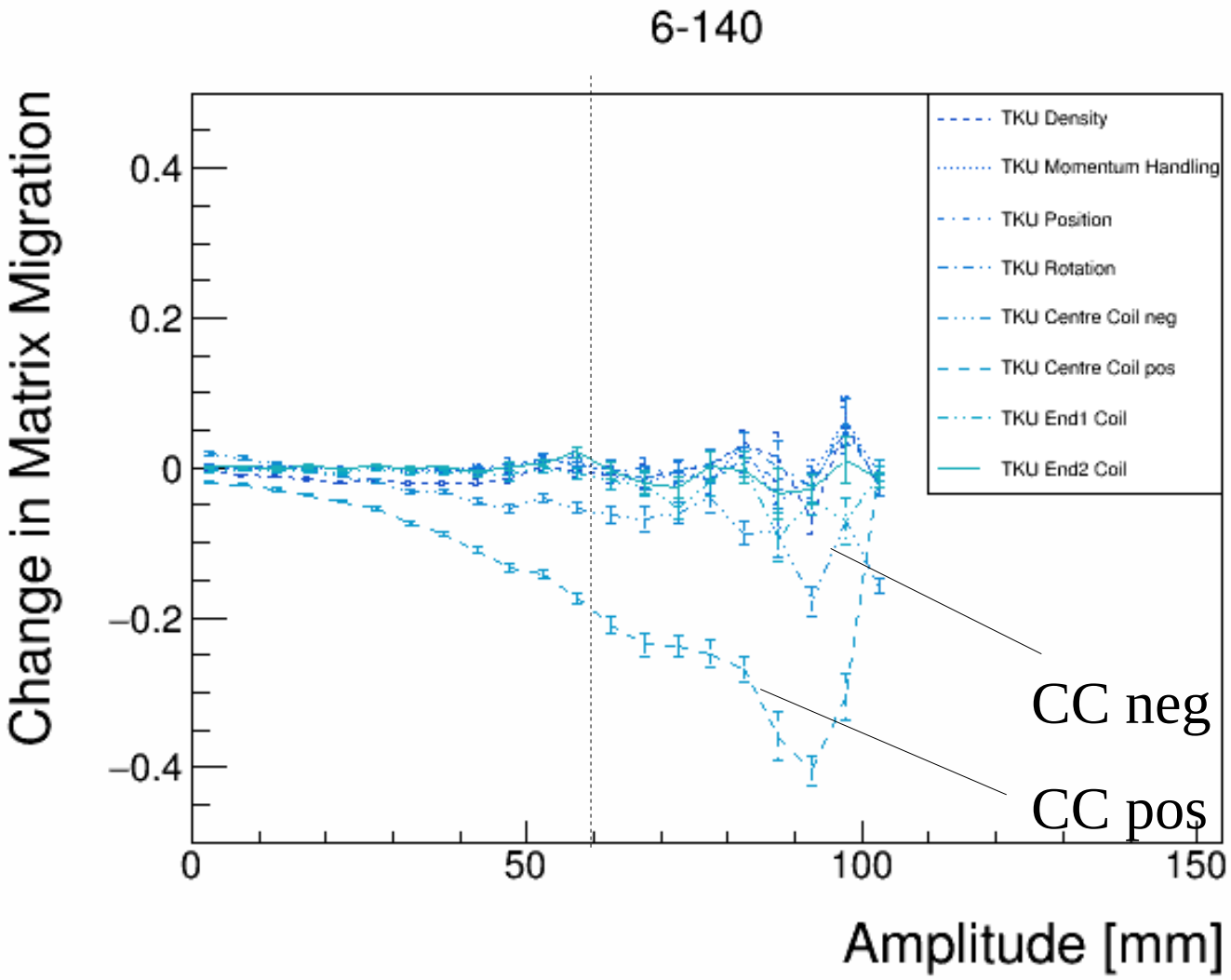
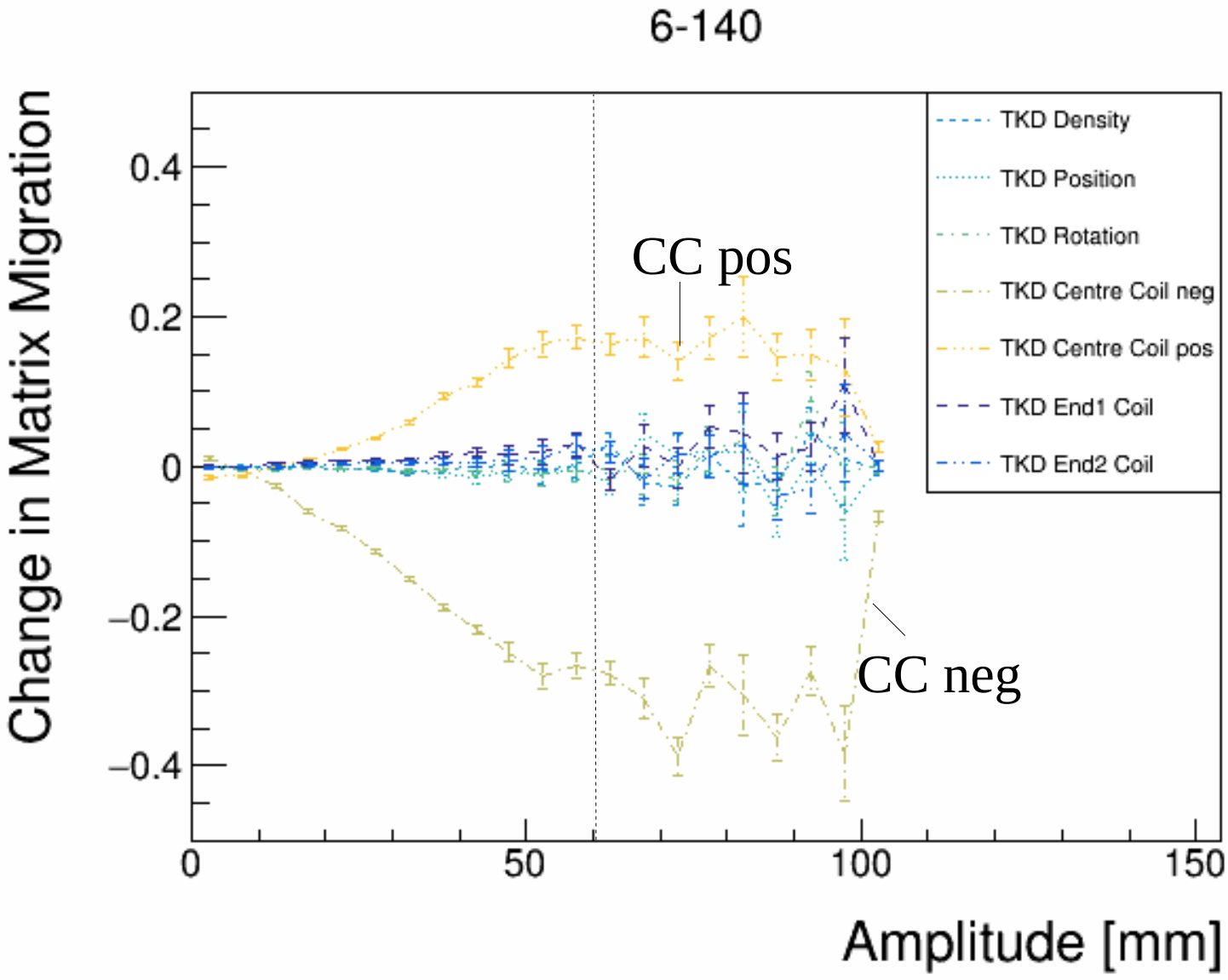
Systematic Uncertainties - Recon

- Systematic uncertainties in recon due to
  - Rotation of Sss +3 mrad
  - Offset of Sss +3 mm
  - Field magnitude uncertainty (centre coil) +/-3 %
  - Field uniformity uncertainty (end coil) +5 %
  - TK density 50 %
- Leads to uncertainty in correction matrix (TKU and TKD) and efficiency (TKD)

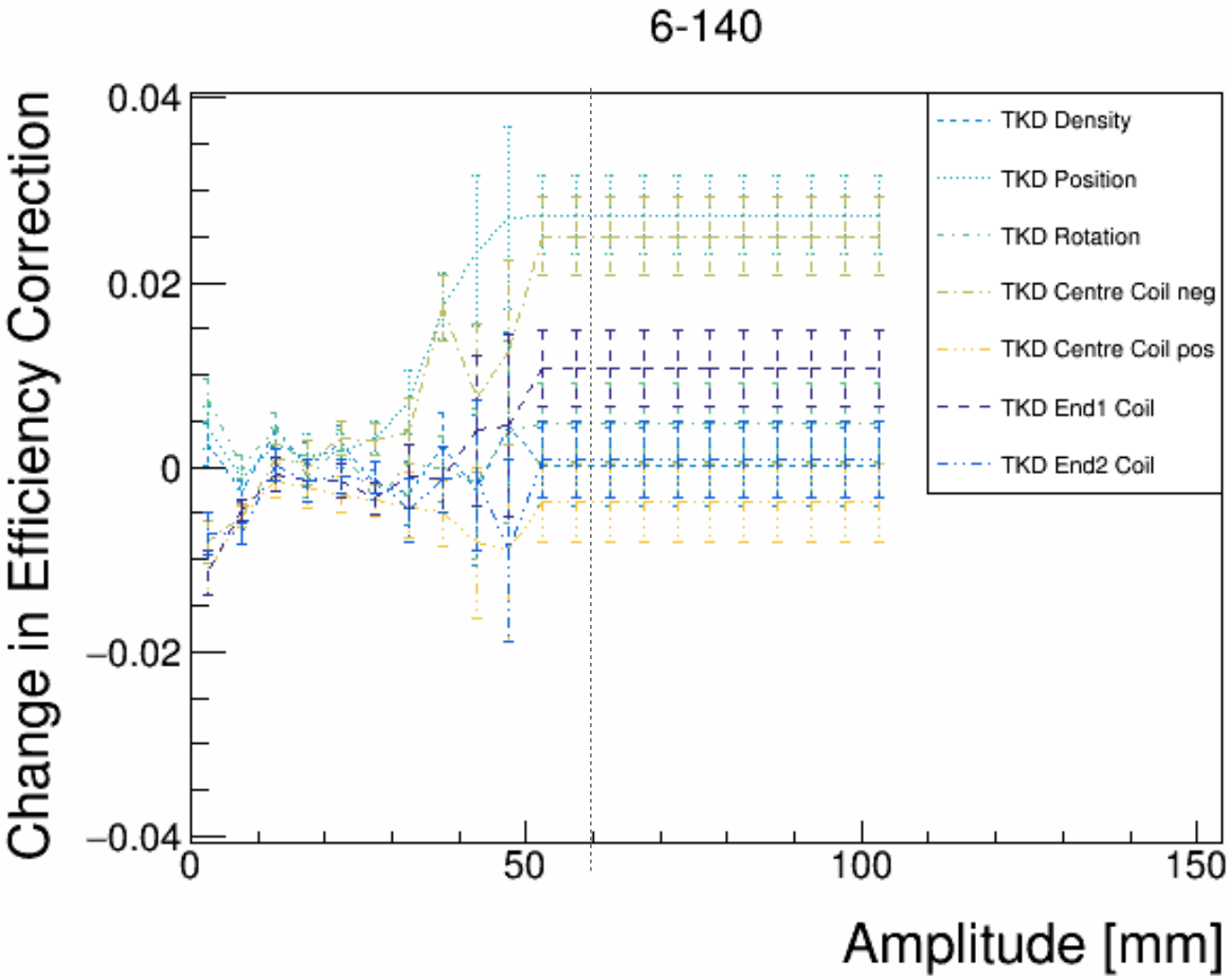
Systematic uncertainty – TKU resolution



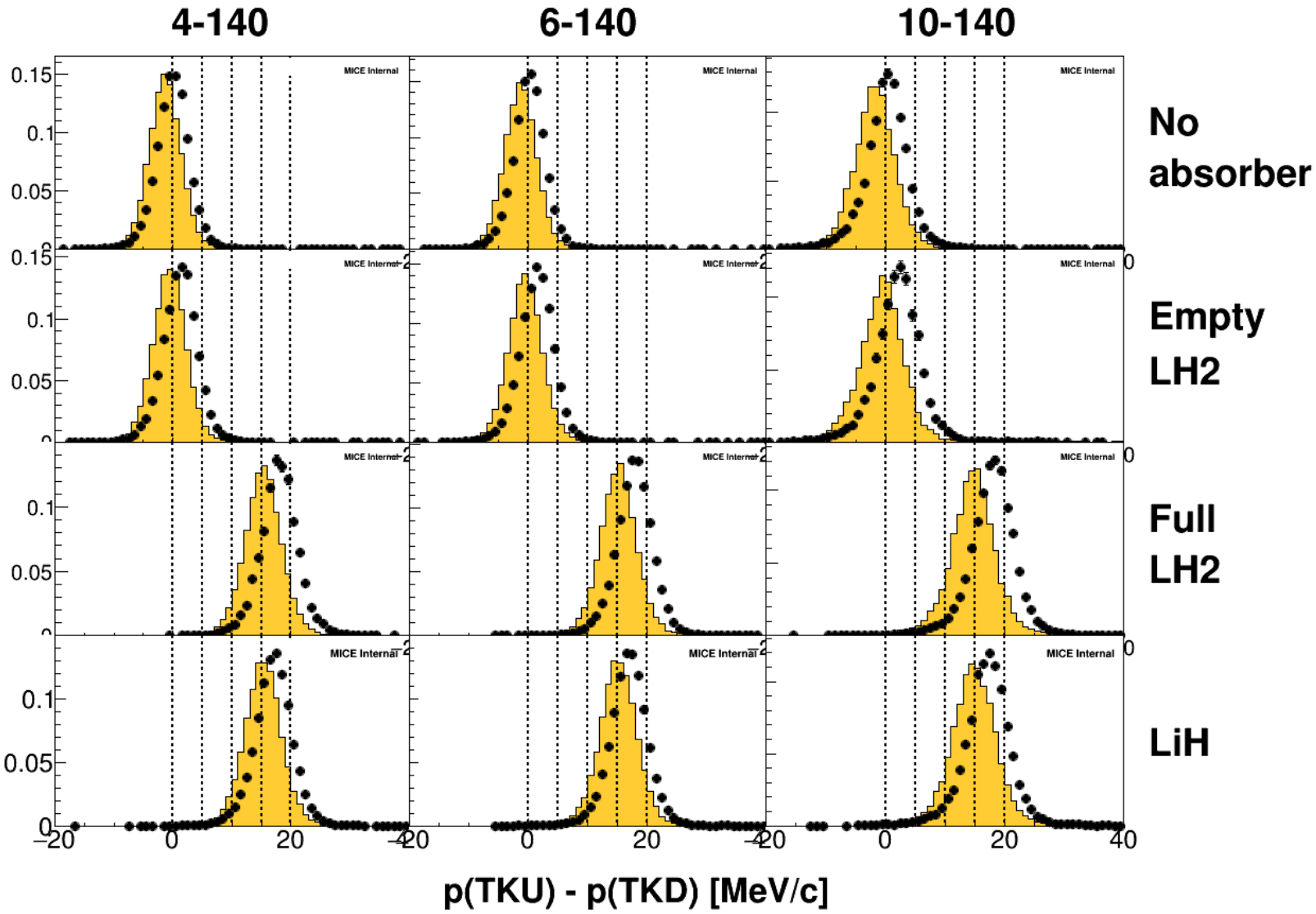
Systematic uncertainty – TKD resolution



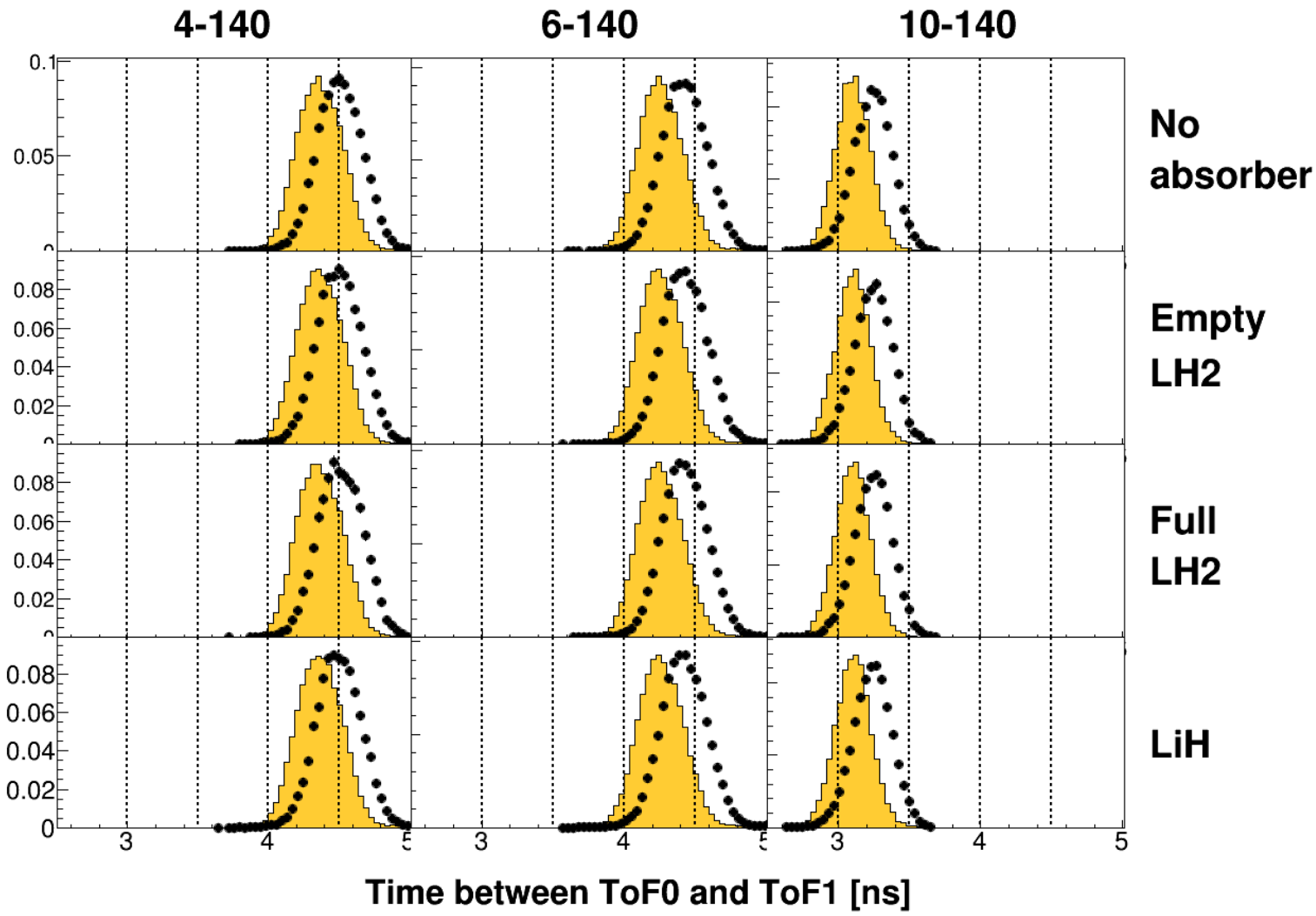
Systematic uncertainty – TKD inefficiency



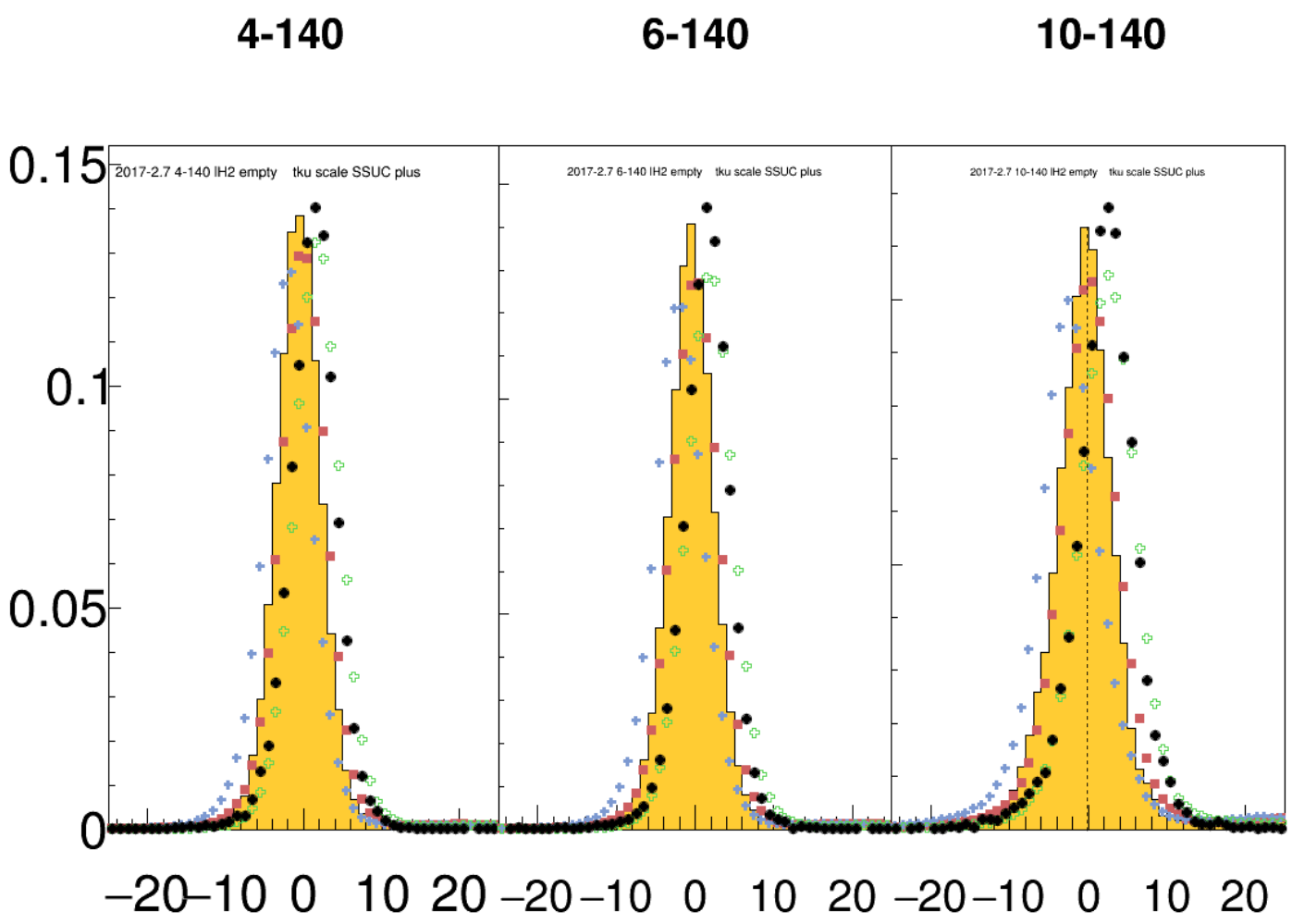
Why 3 % CC offset? - delta p



Why 3 % CC offset? - tof01



Why 3 % CC offset? - delta p



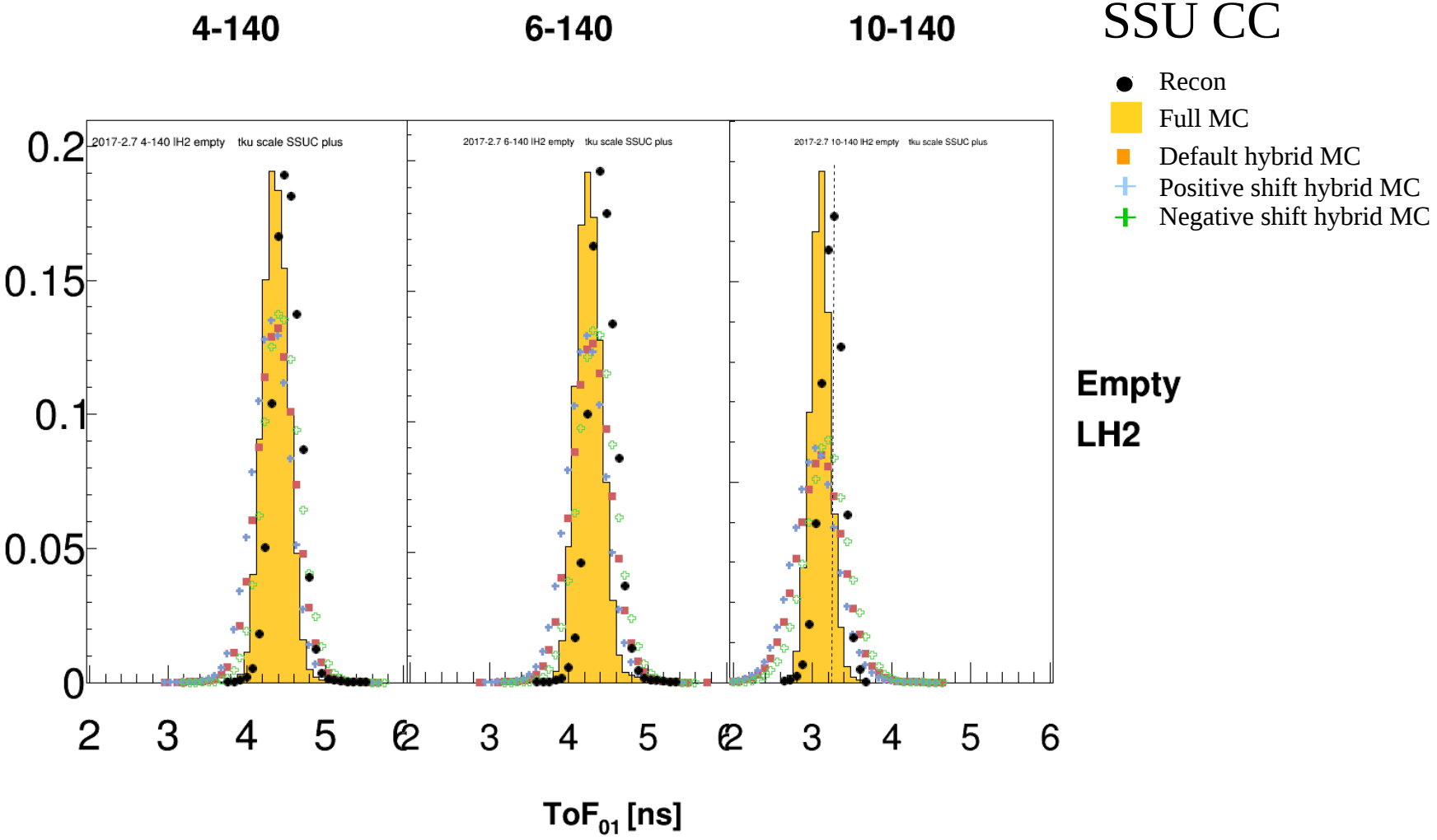
SSU CC

- Recon
- Full MC
- Default hybrid MC
- Positive shift hybrid MC
- Negative shift hybrid MC

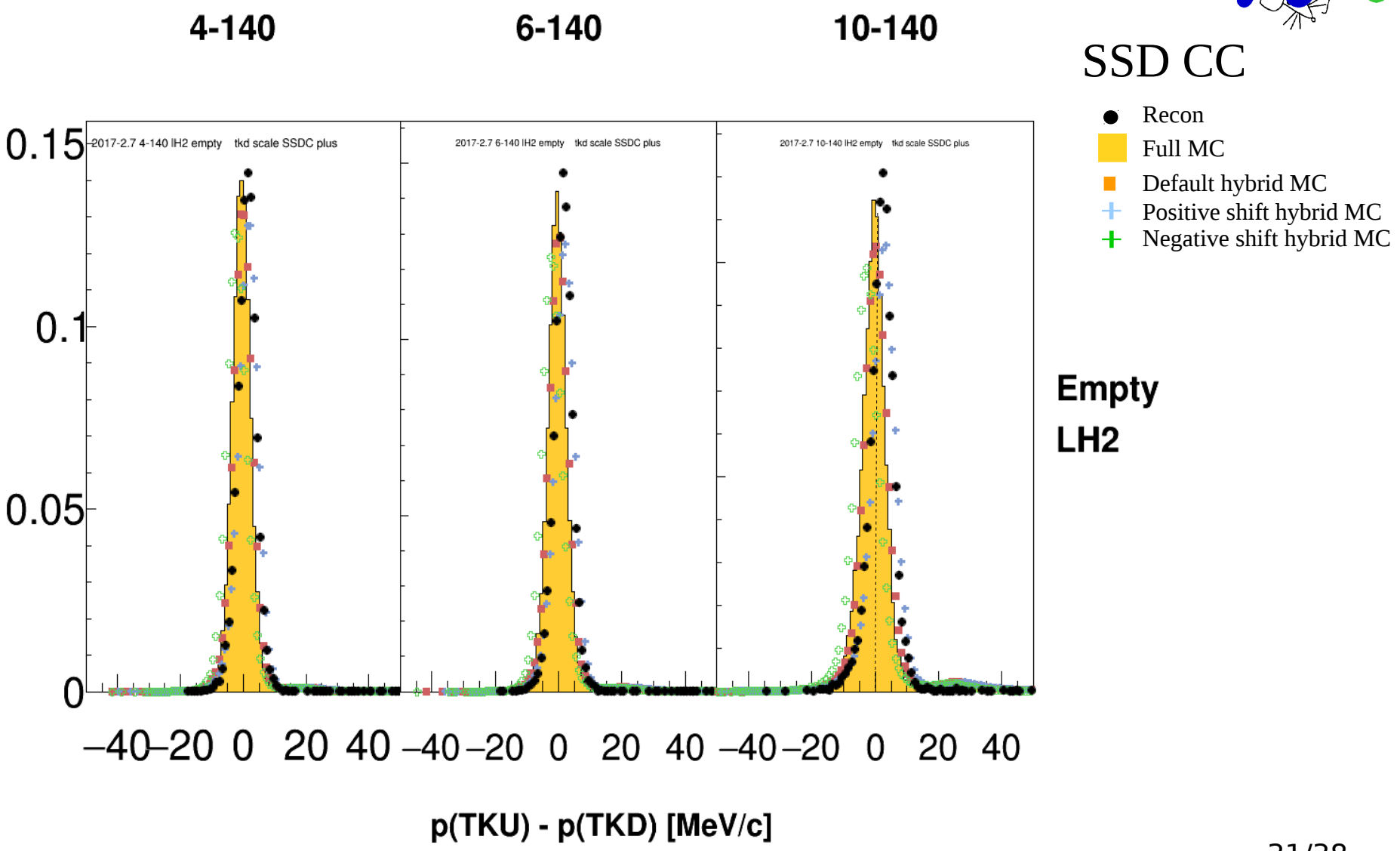
Empty

LH2

Why 3 % CC offset? - TOF01



Why 3 % CC offset? - delta p (SSD)



And another thing...

- D2 field is increased by 4 %, compared to measured field, to get good agreement between MC and data

Performance Systematics

- Systematic uncertainty on the performance of the cooling channel
  - e.g. if the beam alignment is worse than simulated, how does performance behave?
- Study
  - FCU/FCD mispowering by 1 %
  - M1U/M2U mispowering by 1 %
  - M2D mispowering by 1 %
  - Beam misalignment by x=3 mm, px=3 MeV/c, dp=3 MeV/c
  - Beam misalignment by x=-3 mm, px = -3 MeV/c, dp = -3 MeV/c
  - (Absorber density)

Migration matrix

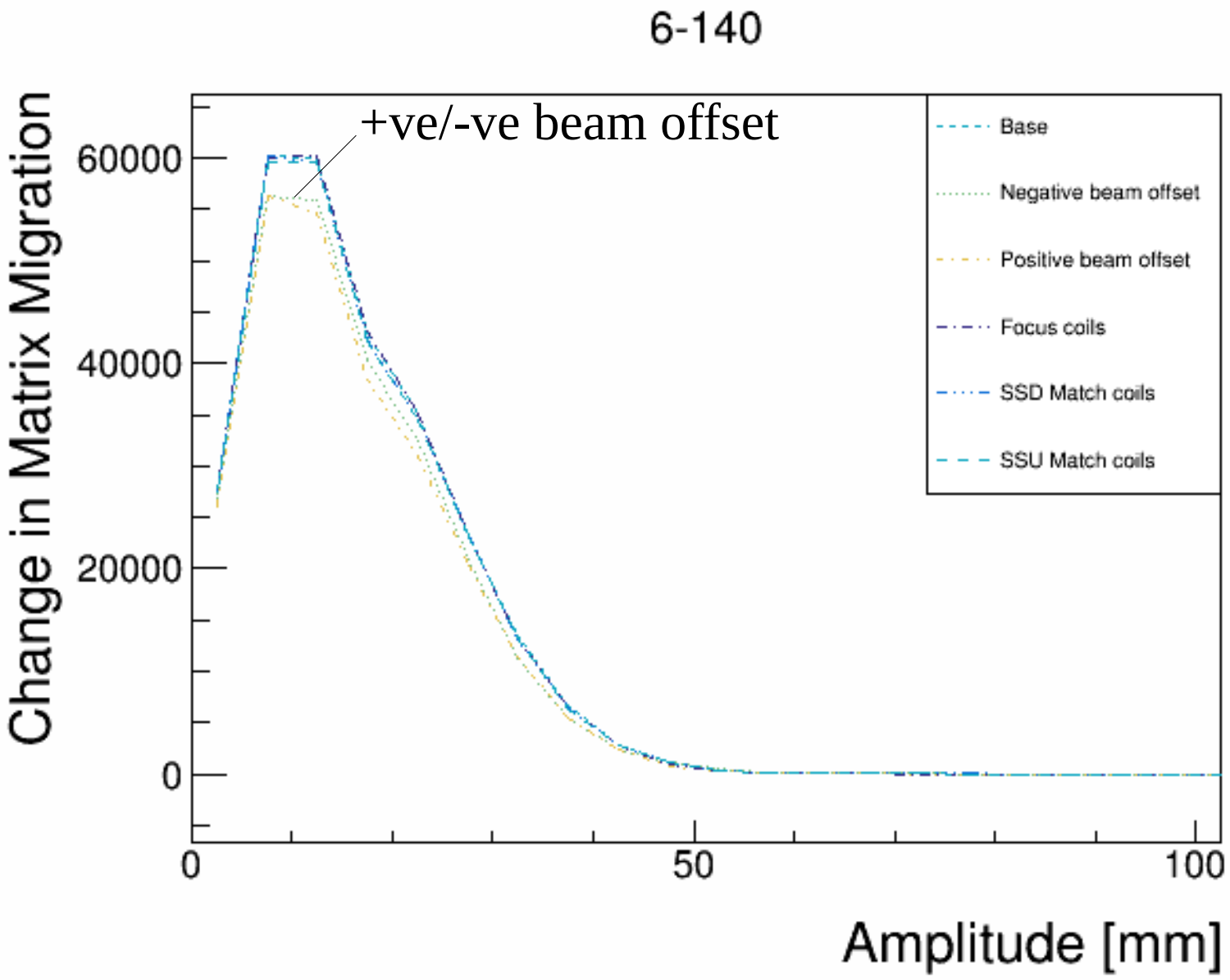
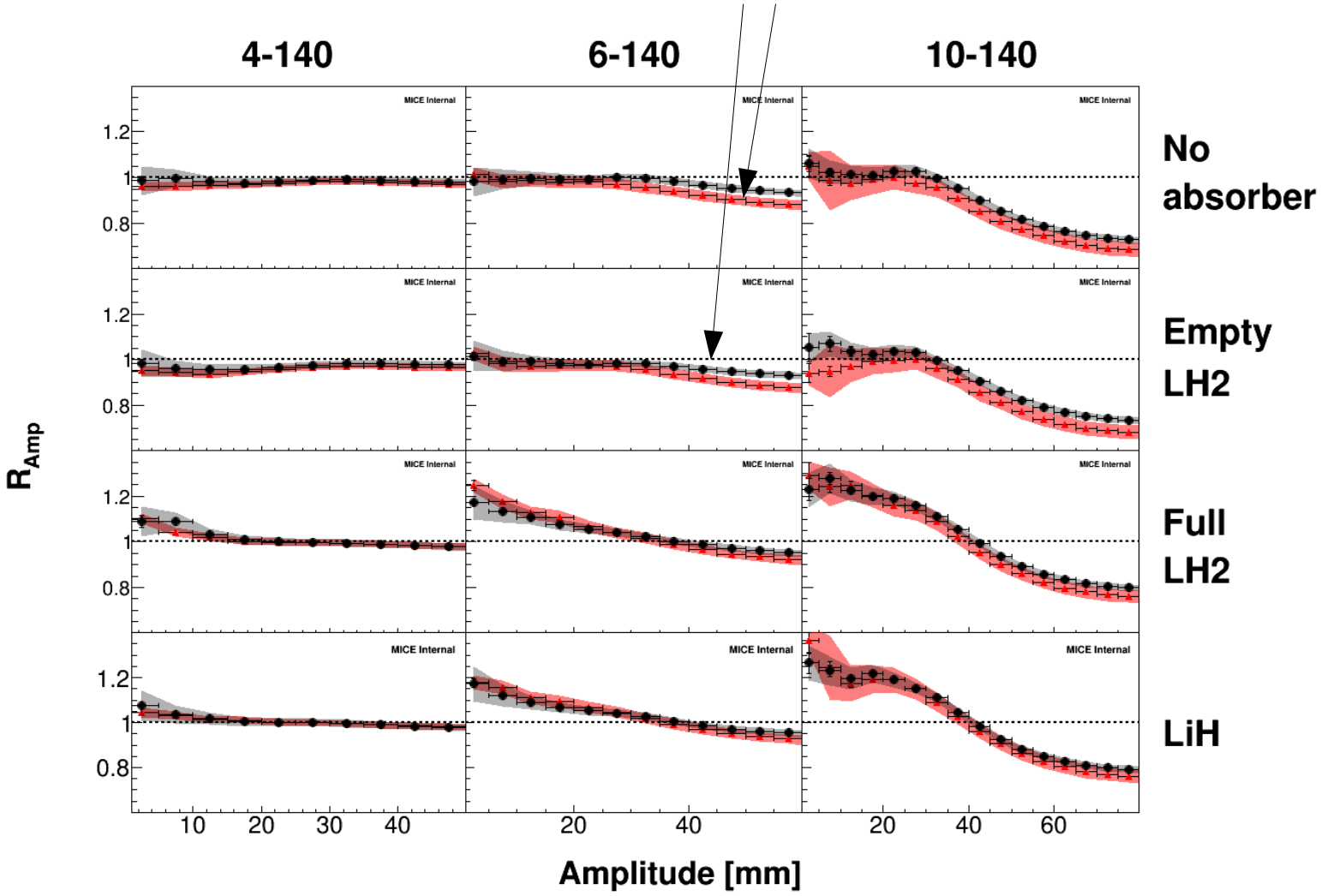


Fig. 5 (a)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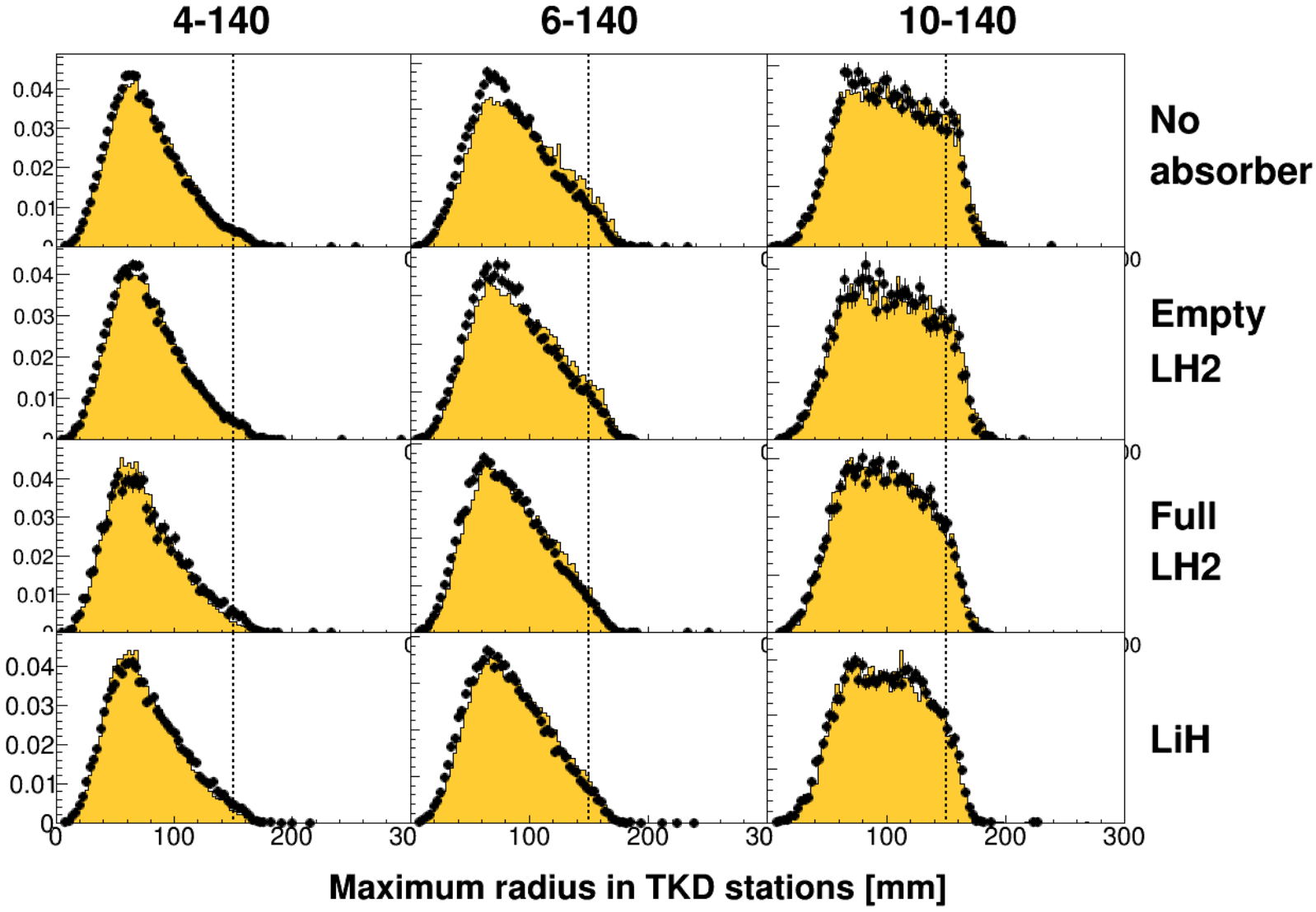
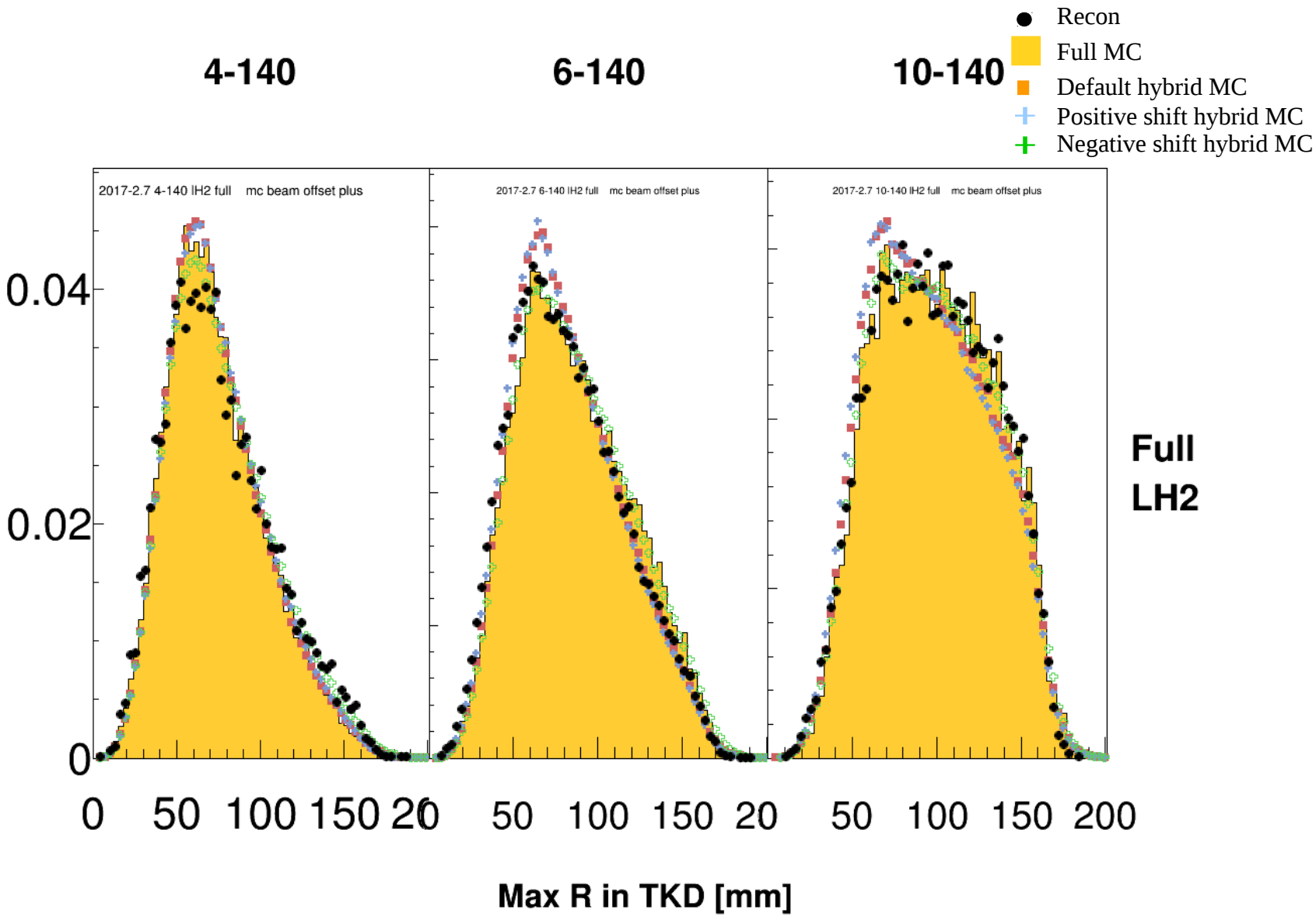
Amplitude [mm]
No absorber
Empty LH2
Full LH2
LiH

Note about beam radius



Note about beam radius



Conclusions

- Amplitude analysis is mature
  - Density (and fractional emittance) analysis catching up
- Details of systematic uncertainty show interesting features
  - BUT still record 5 sigma effect and agreement between MC and data
  - And this is not the Higgs discovery