

# Solenoid Mode Analysis: Canonical Angular Momentum Growth



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03/12/2020 / Christmas VC 218

# Solenoid Mode Analysis Review

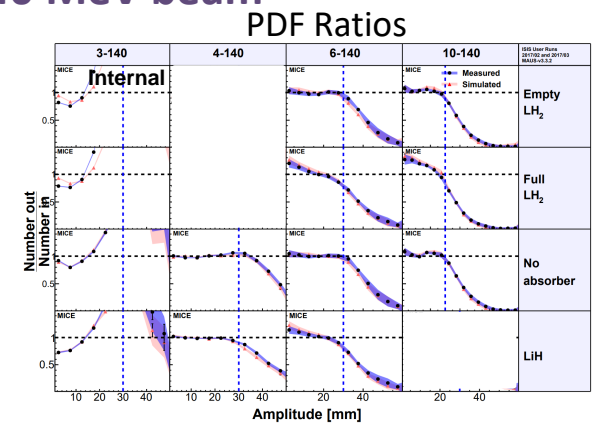
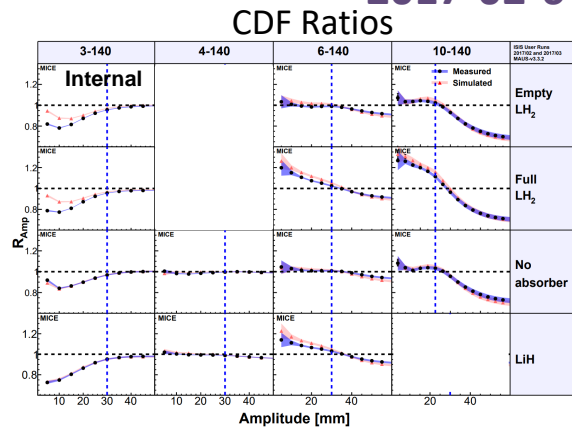
- Analysis of 2017-02-6 solenoid mode data in good shape (ish)
  - Need recommissioning of this MC, expect better matching of Px, Py distributions after redoing dipole beam tuning
  - Amplitude analysis with systematics for 3,4,6,10-140 & 3-170,200,240 beams
  - Canonical angular momentum measurement introduced

Systematics :

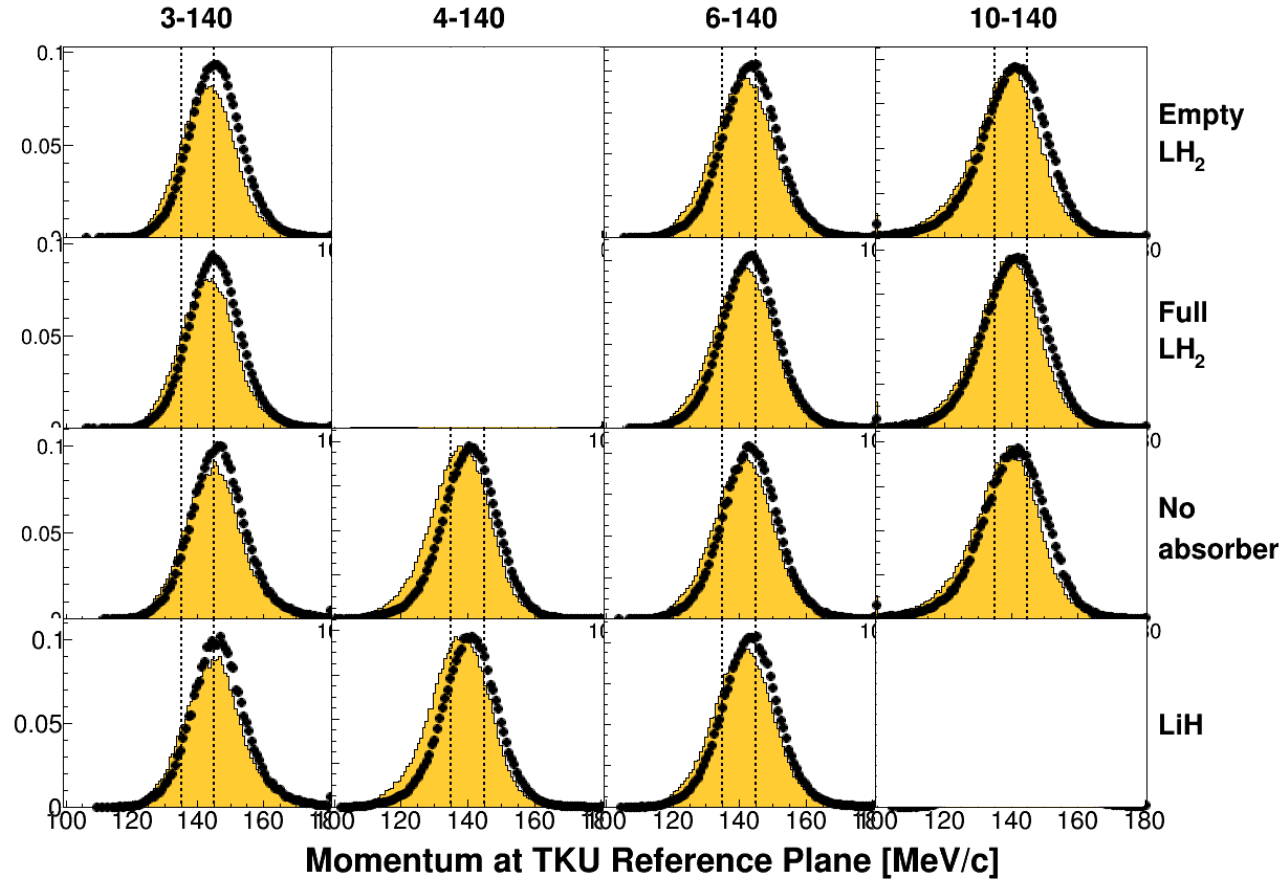
- +3mrad tku/tkd rotation in x
- +3mm tku/tkd position in x
- +3% in SSU/SSD Centre
- +5% in SSU/SSD E1/E2
- +50% (2->3g/cm<sup>3</sup>) tracker glue density

## 2017-02-6 140 MeV beam

- Event selection with plots etc. for all solenoid mode data, no amplitude analysis yet as this requires MC corrections
- Official MC commissioning for other CC tags underway



# Momentum Cut - Data vs MC Reco



Differences in momentum distribution noted, updated MC tune commission coming soon..

# Solenoid Mode – Canonical Angular Momentum Growth

$$L_{\text{canon}} = L_{\text{kin}} + L_{\text{field}}$$

$$L_{\text{kin}} = xP_y - yP_x$$

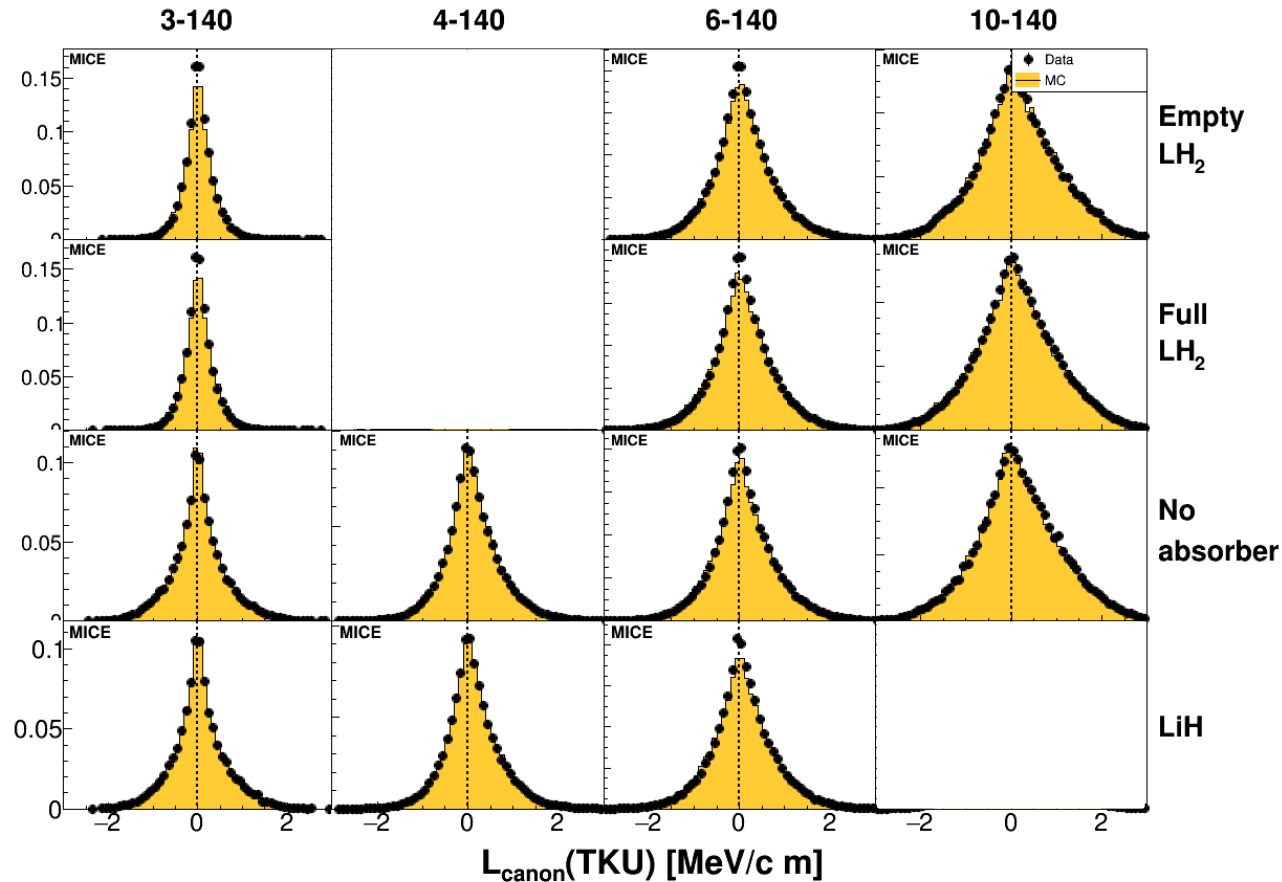
$$L_{\text{field}} = qrA_\phi \approx \frac{qr^2B_z}{2} \text{ by paraxial approximation (first order)}$$

Load particle  $B_z$  at reconstructed trackpoint  $(x,y,z)$  position from MAUS field geometry

# 1D Distributions

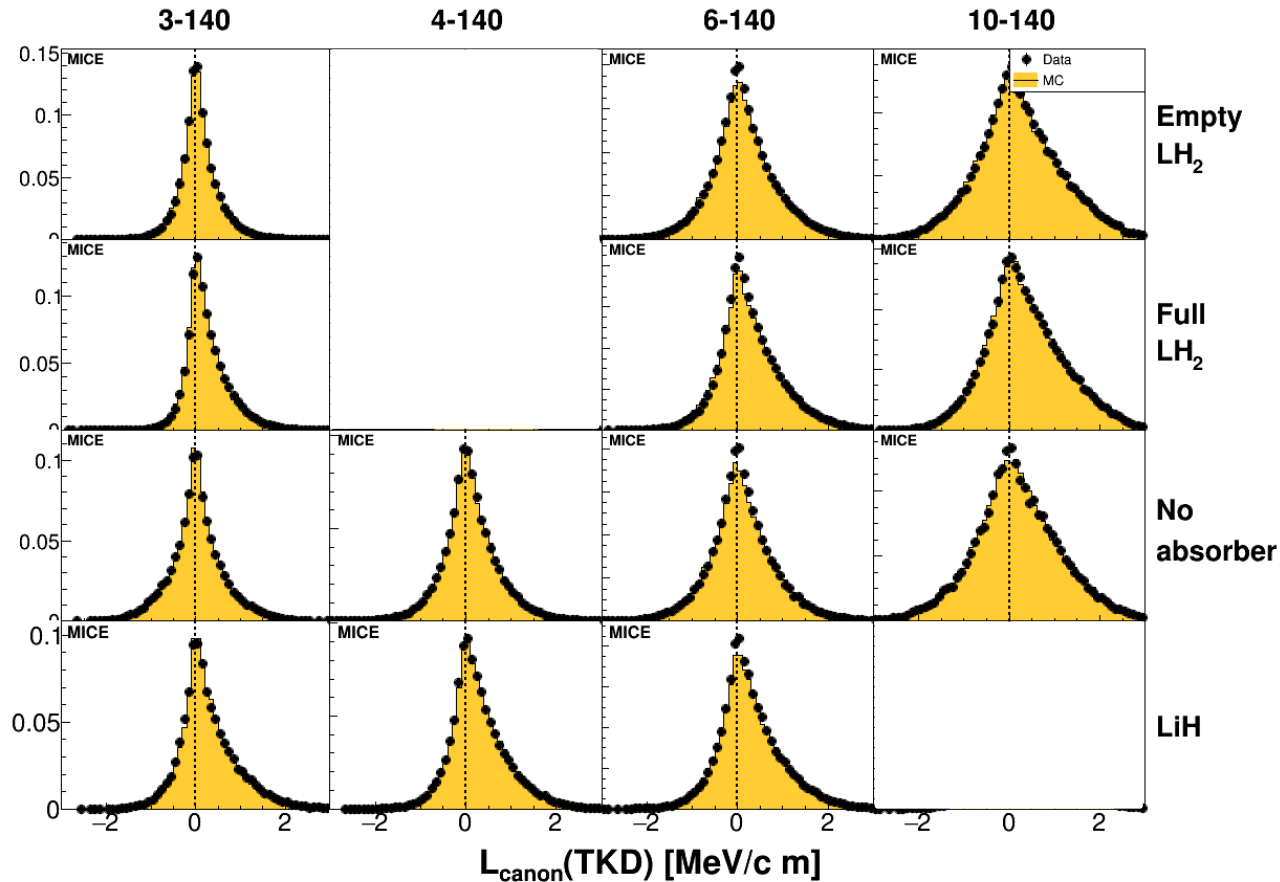
# L canon - Data vs MC Reco

Data vs MC reco  
at TKU S1



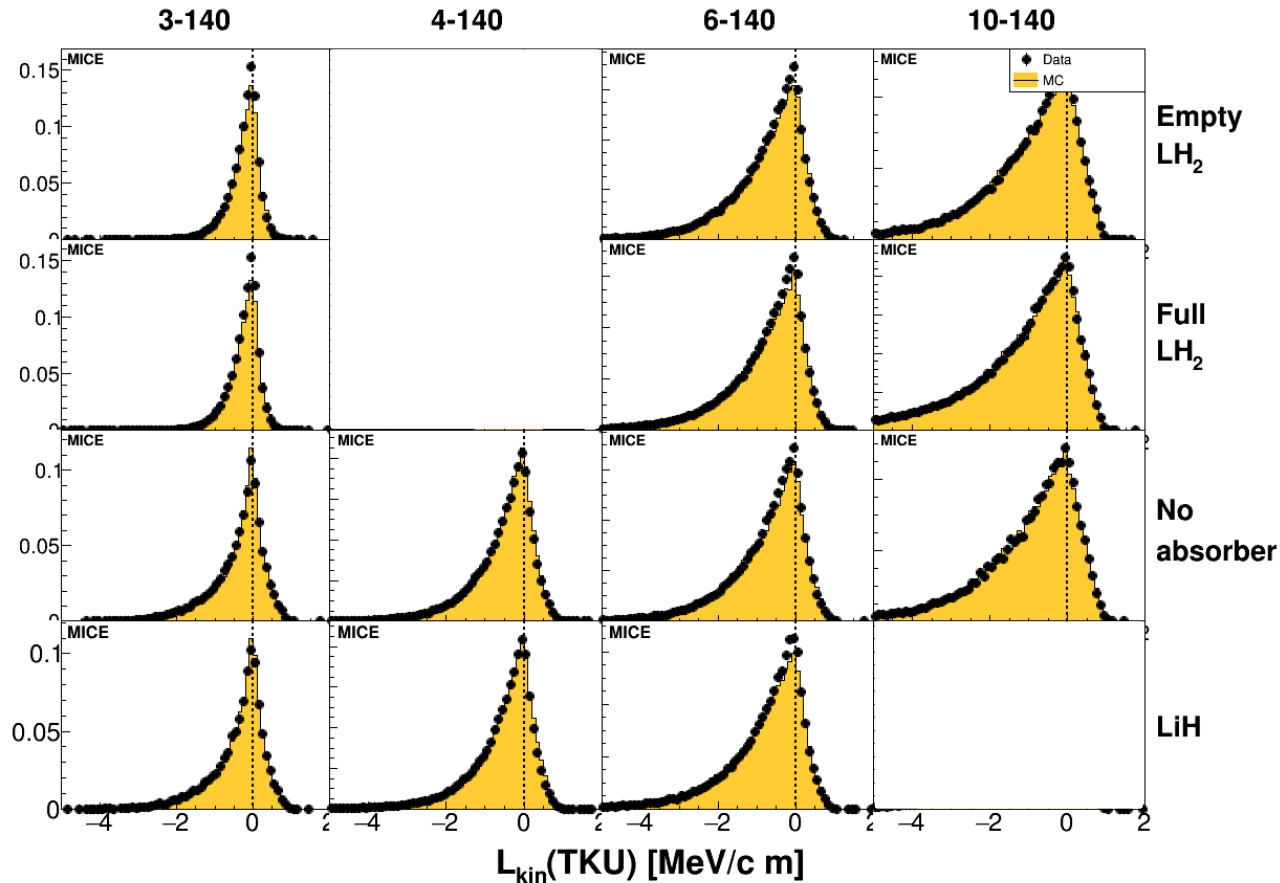
# L canon - Data vs MC Reco

Data vs MC reco  
at TKD S1



# L kin - Data vs MC Reco

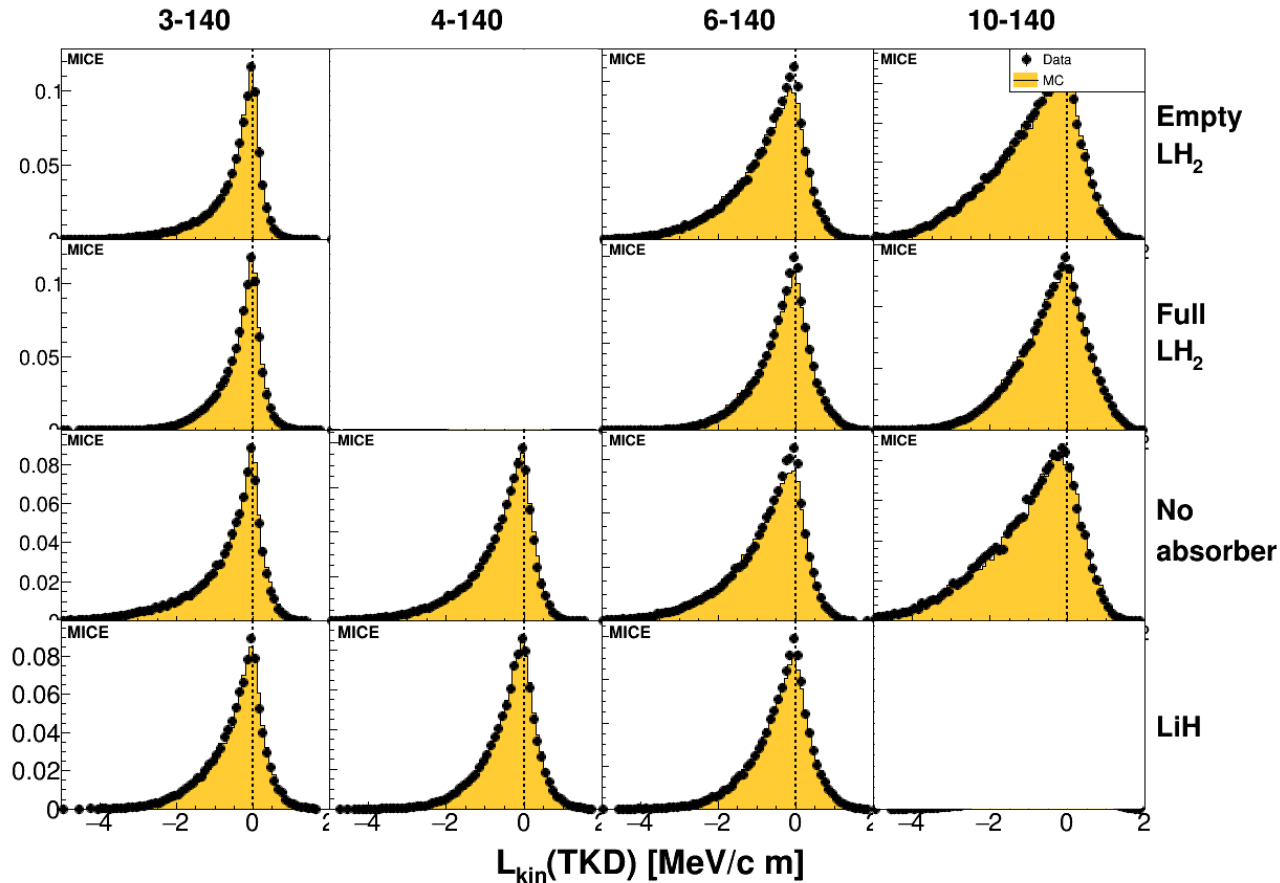
Data vs MC reco  
at TKU S1





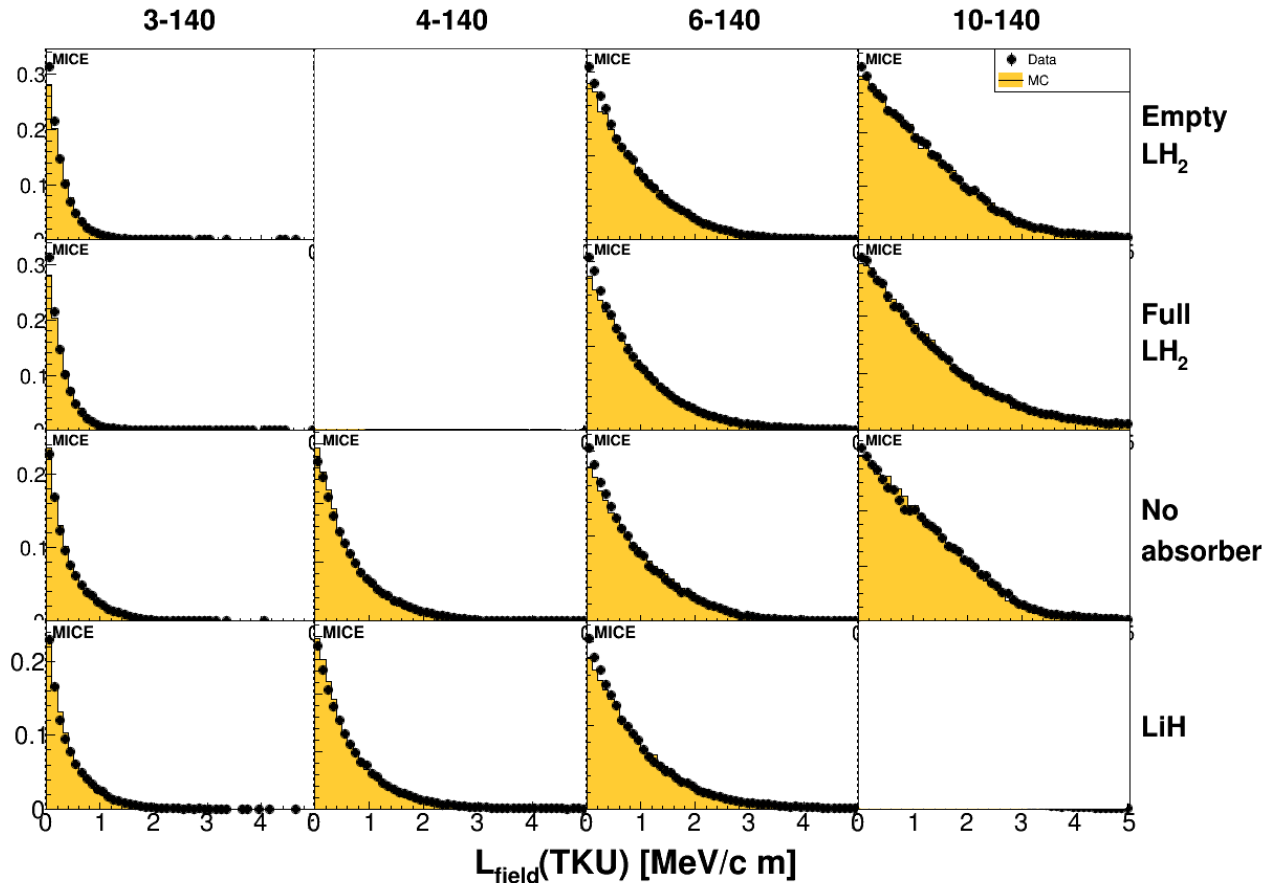
# L kin - Data vs MC Reco

Data vs MC reco  
at TKD S1



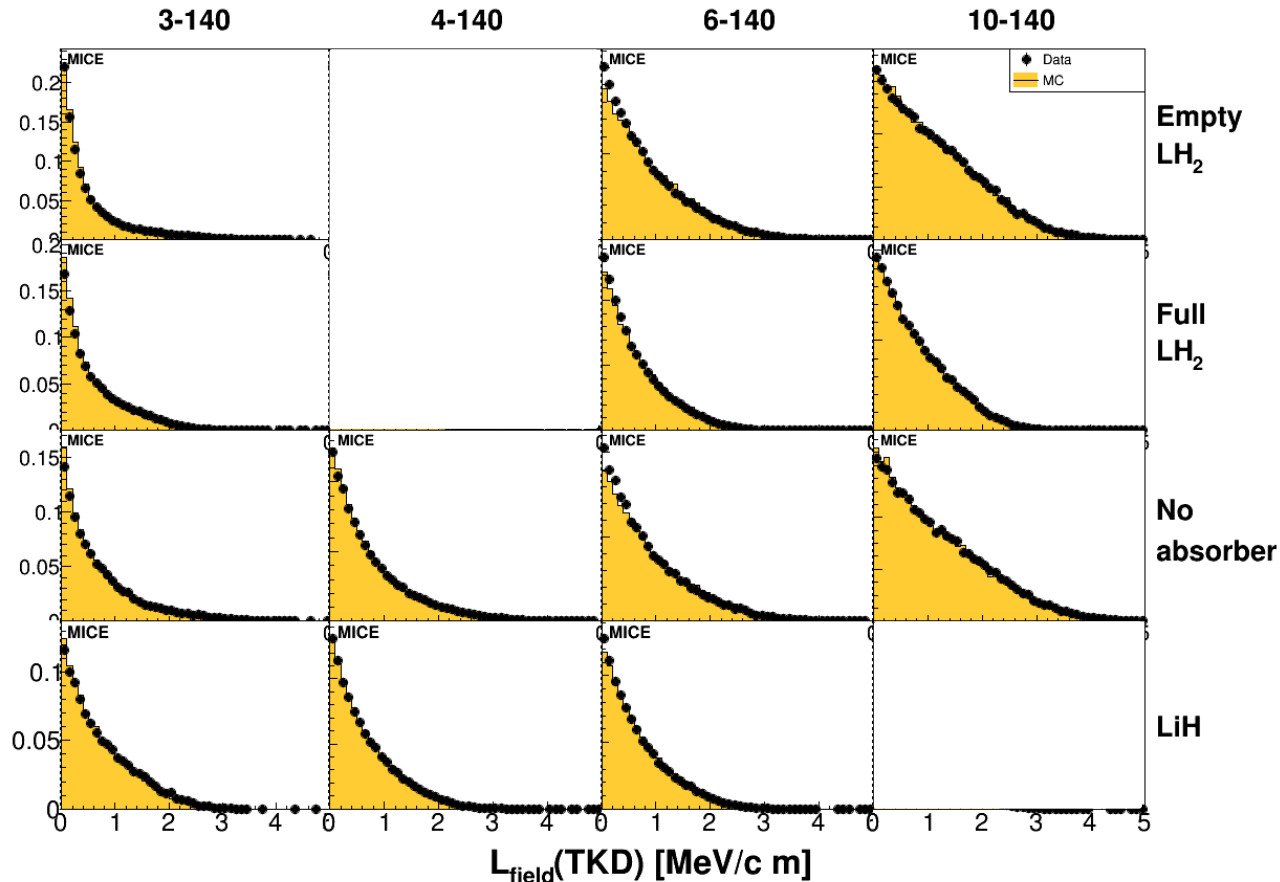
# L field - Data vs MC Reco

Data vs MC reco  
at TKU S1



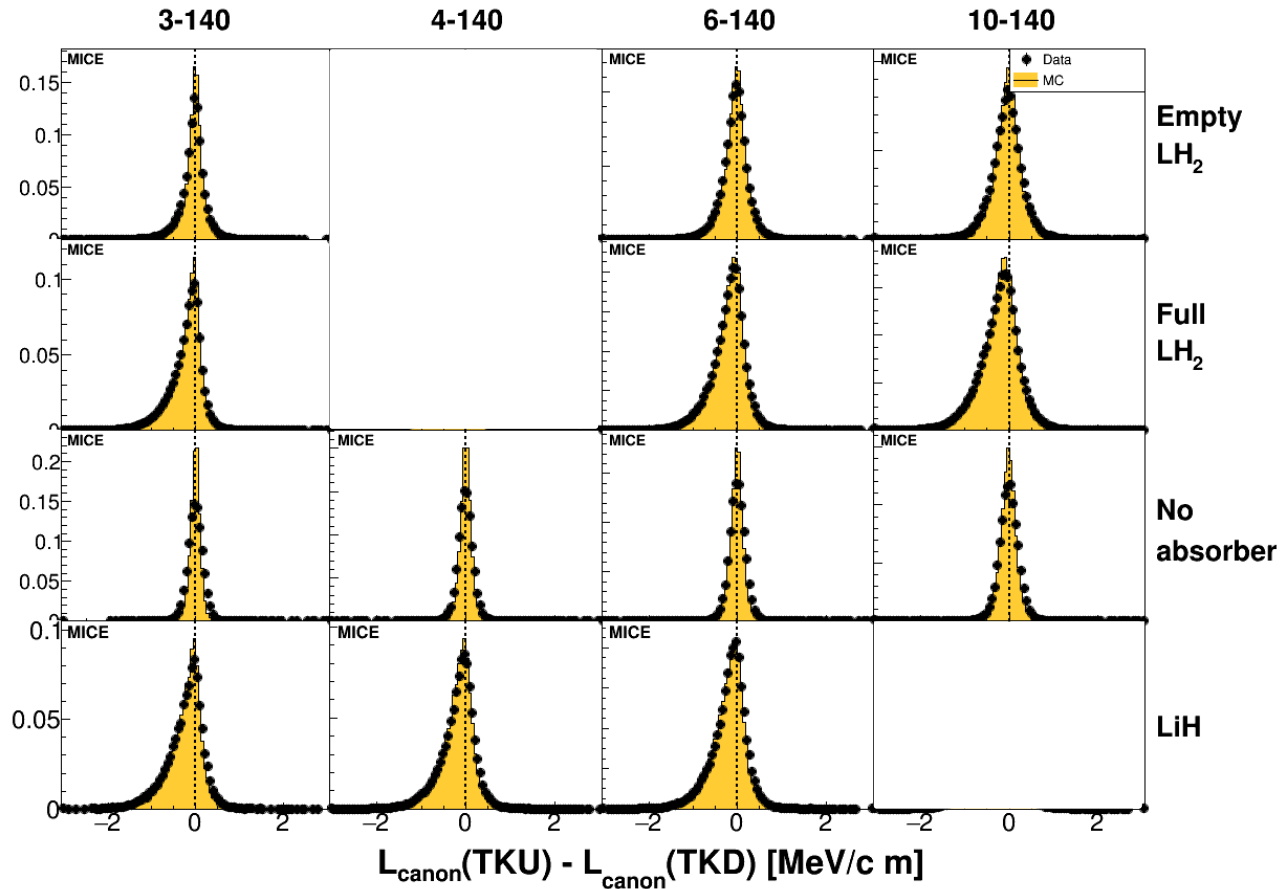
# L field - Data vs MC Reco

Data vs MC reco  
at TKD S1



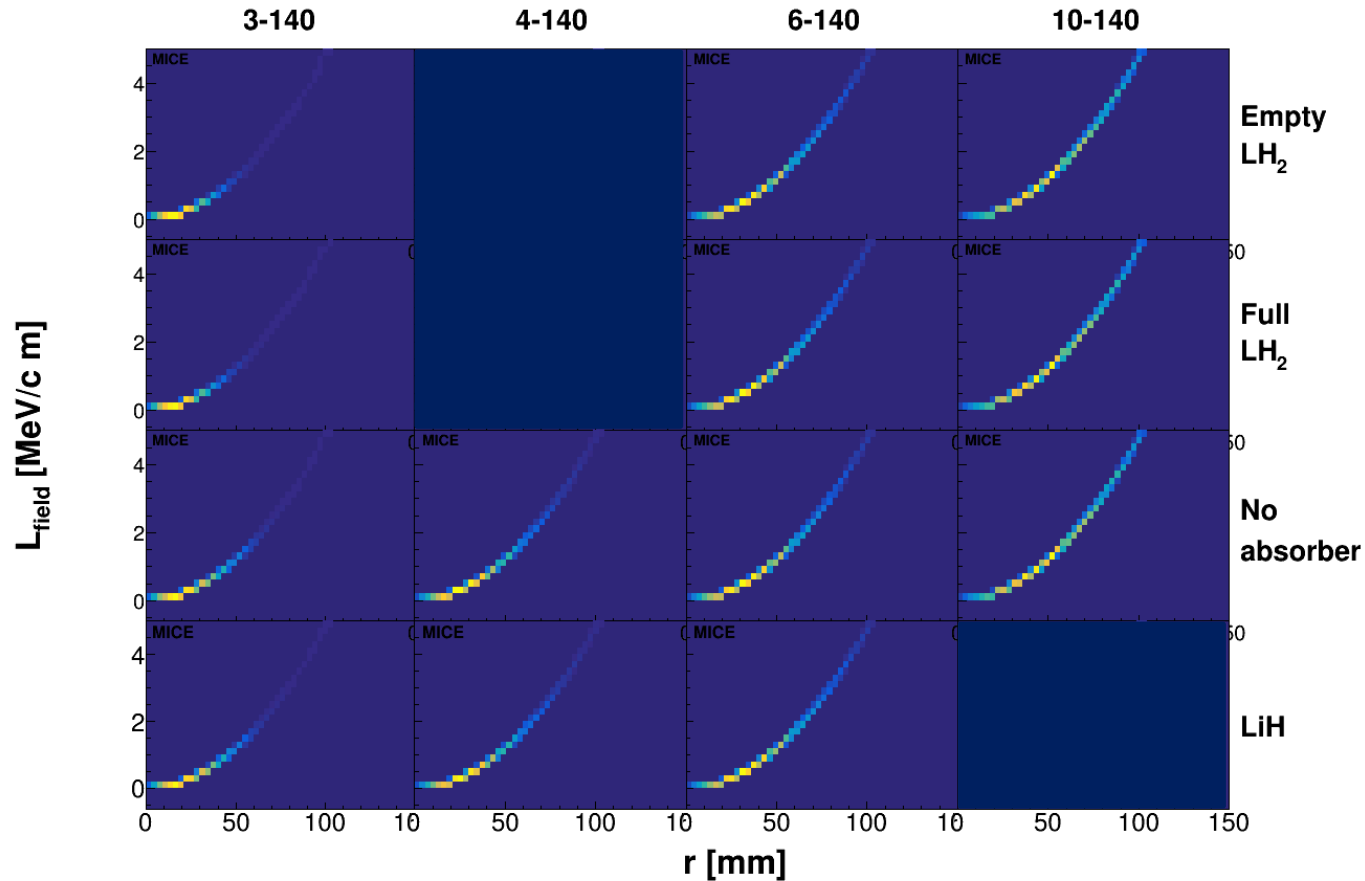
# L canon - Change Across Absorber – Data vs MC Reco

Data vs MC reco



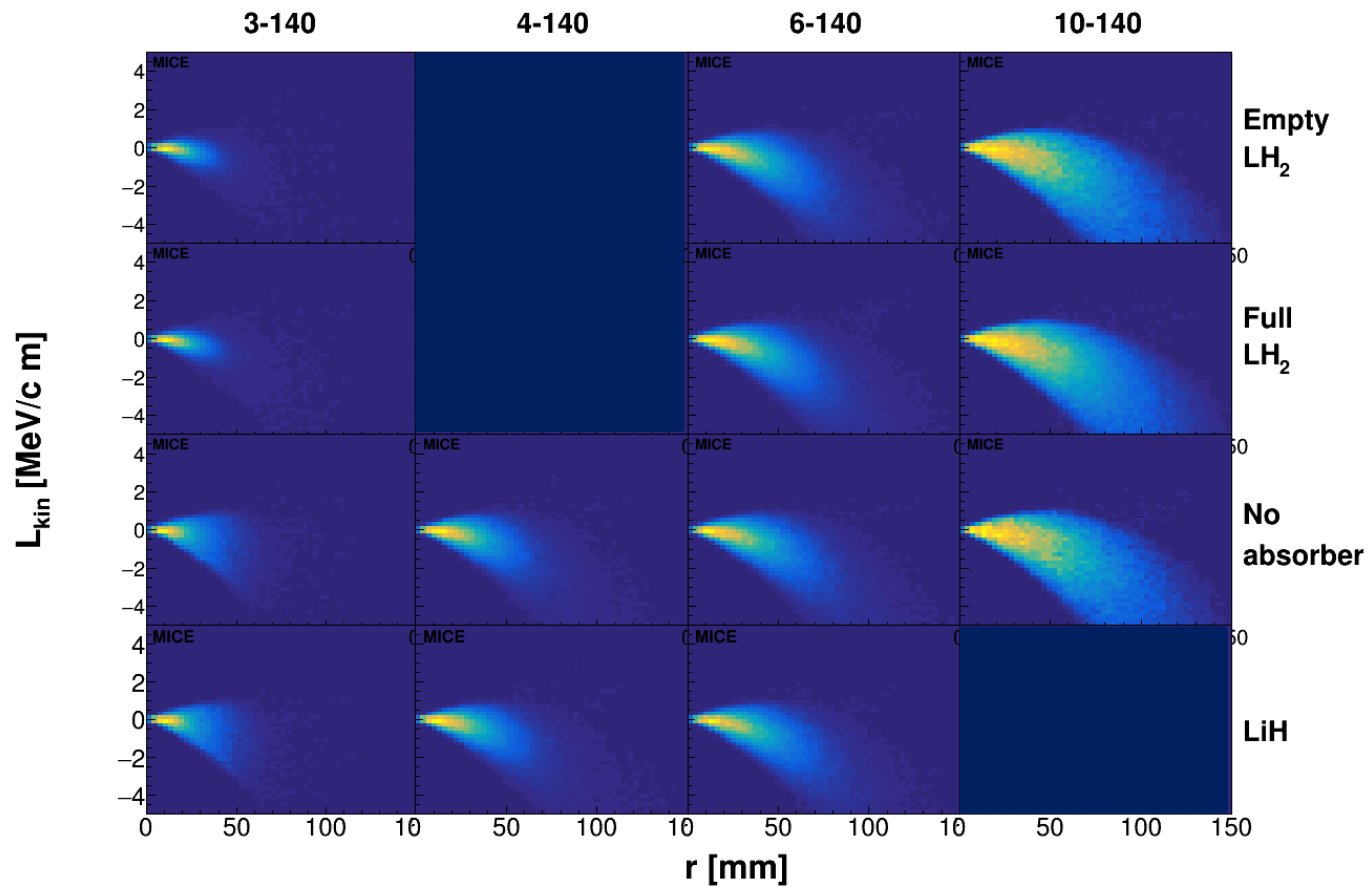
# 2D Distributions

# L field vs r plots – Data, US cut

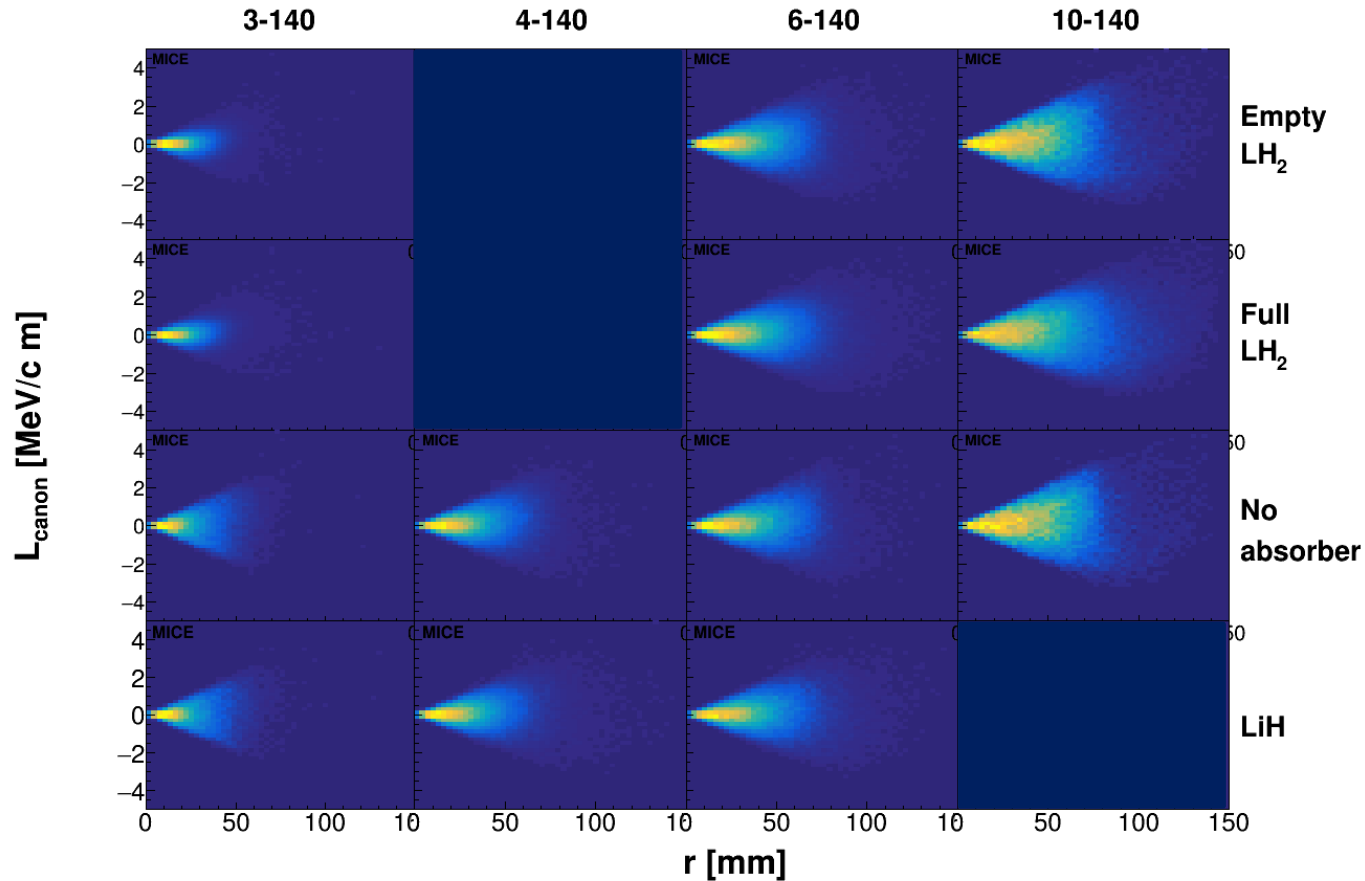


L field follows field maps for x,y,z position of trackpoints

# L kin vs r plots – Data, US cut

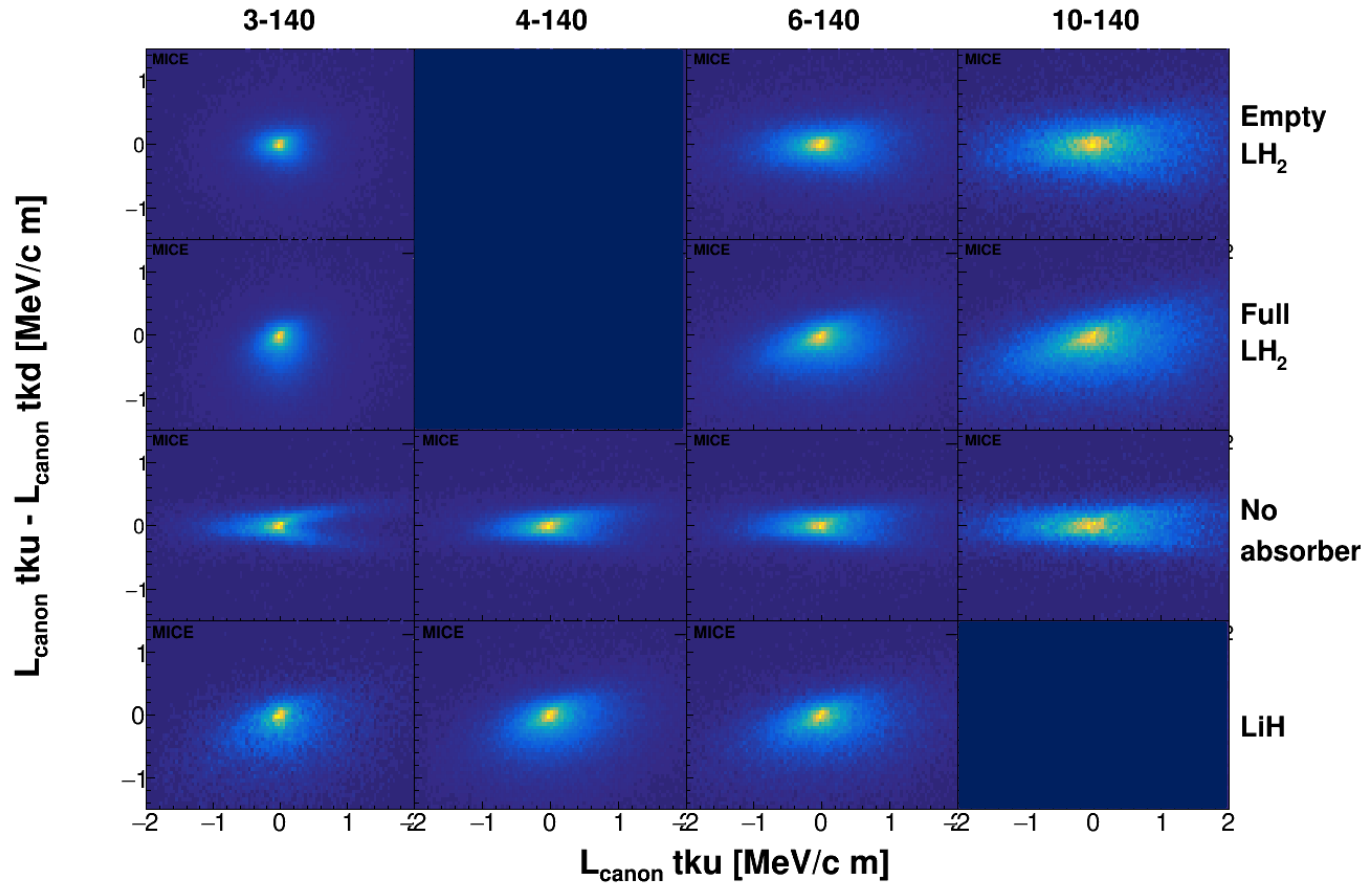


# L canon vs r plots – Data, US cut

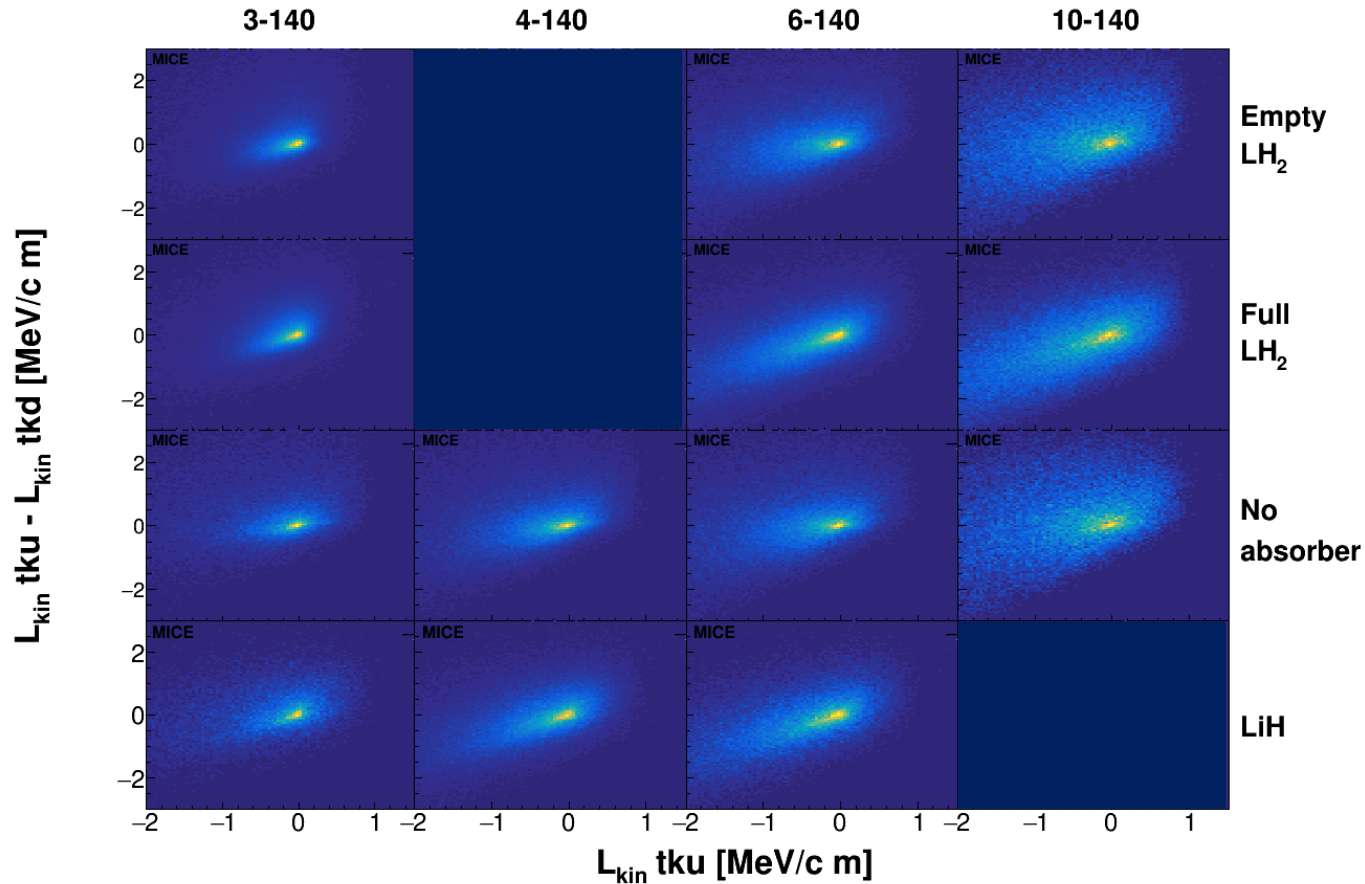




# L canon tku vs L canon tku change across absorber – Data, US cut

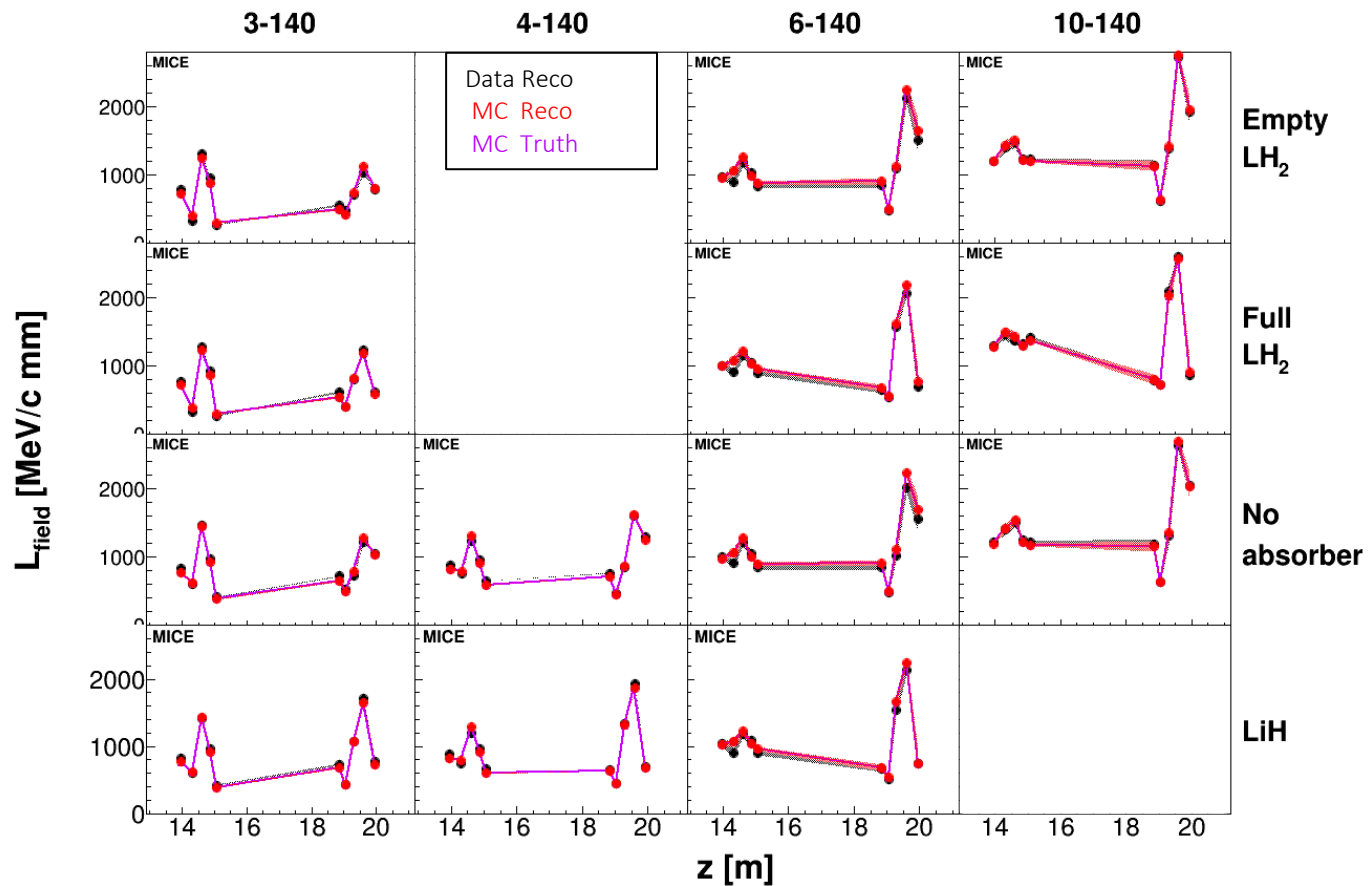


# L kin tku vs L kin change across absorber – Data, US cut



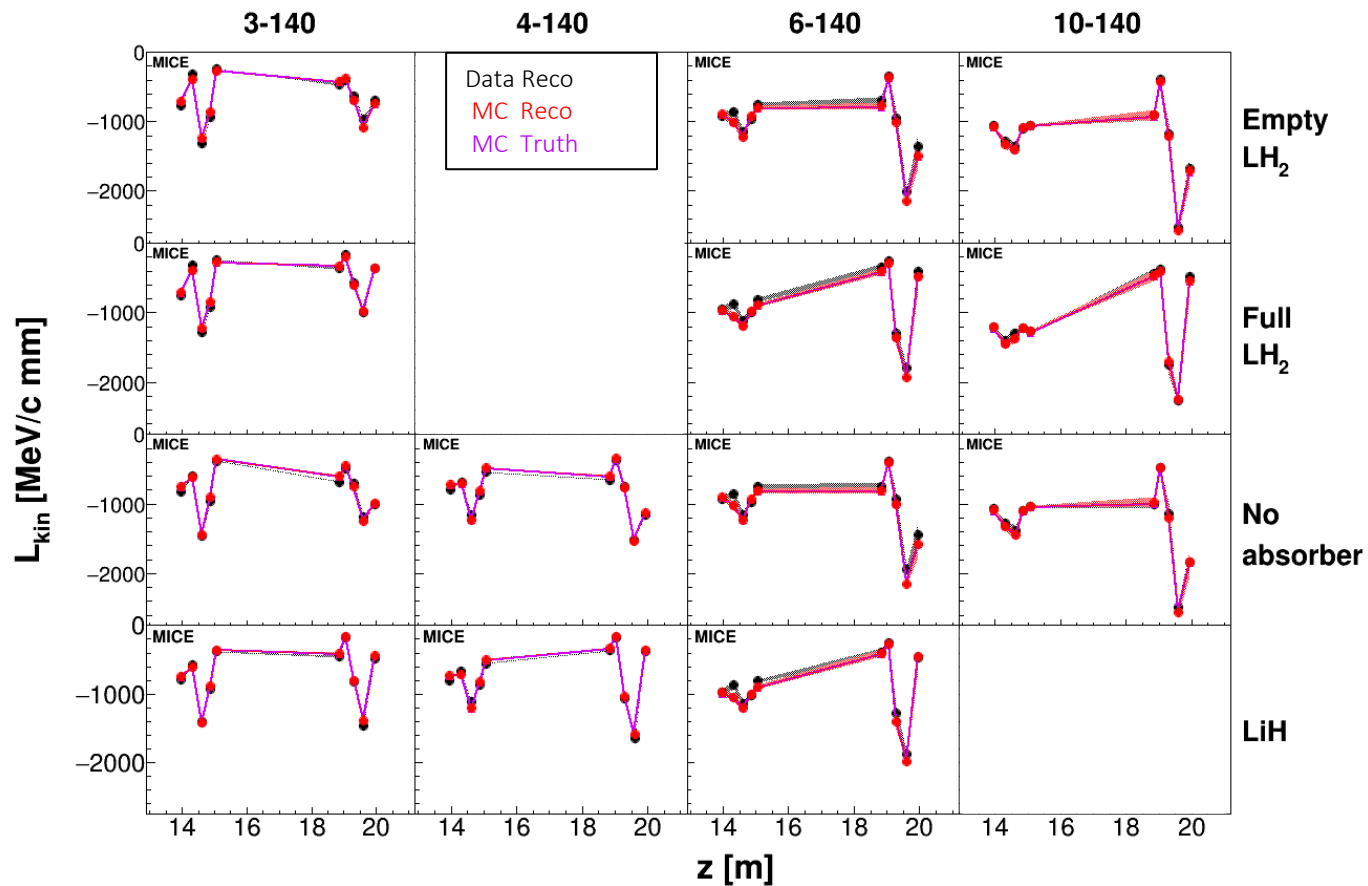
# Tracker Evolution

# Canonical Angular Momentum – Field Term



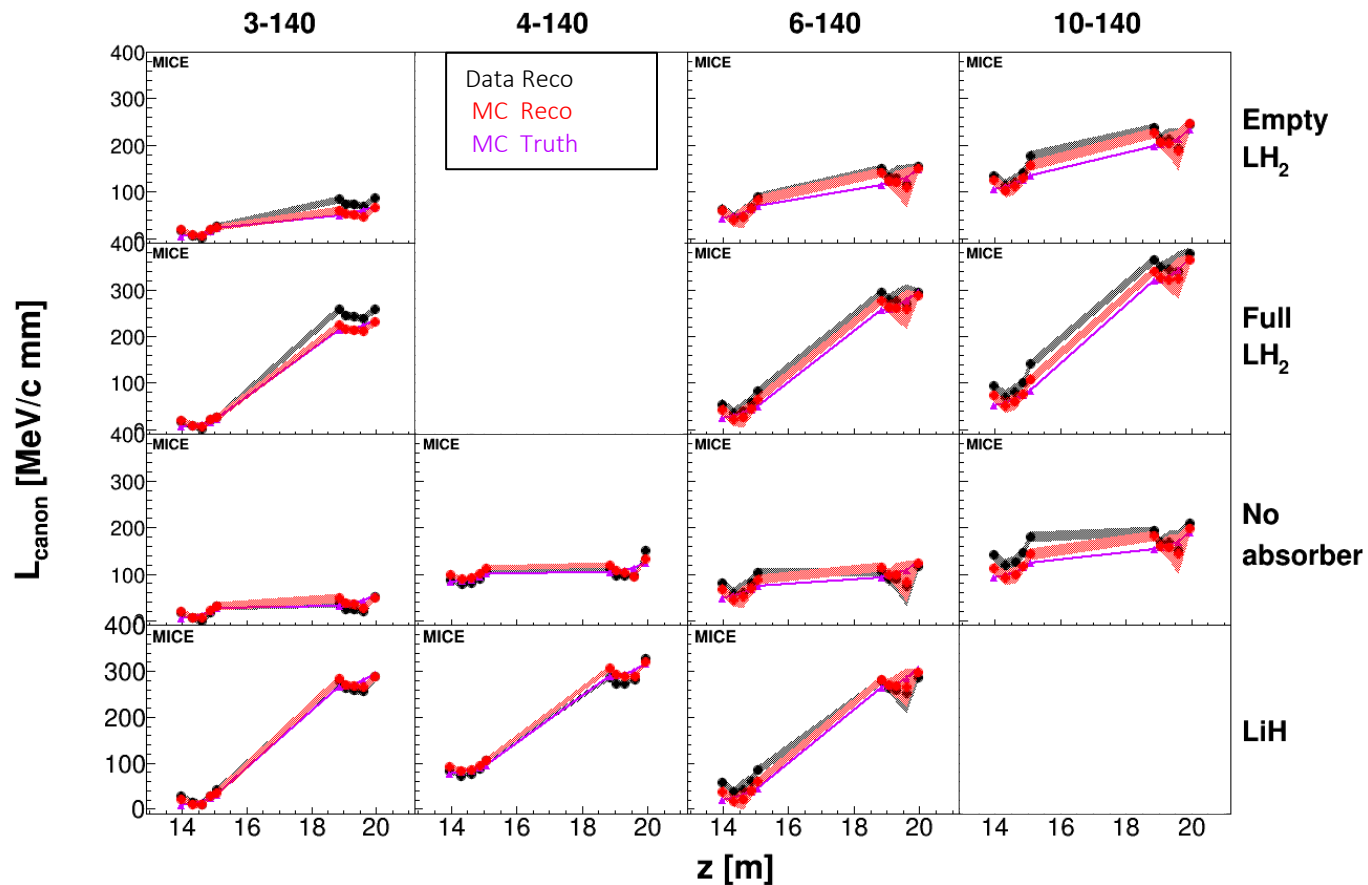
Band shows  
Sys + Stat Error

# Canonical Angular Momentum – Kinetic Term

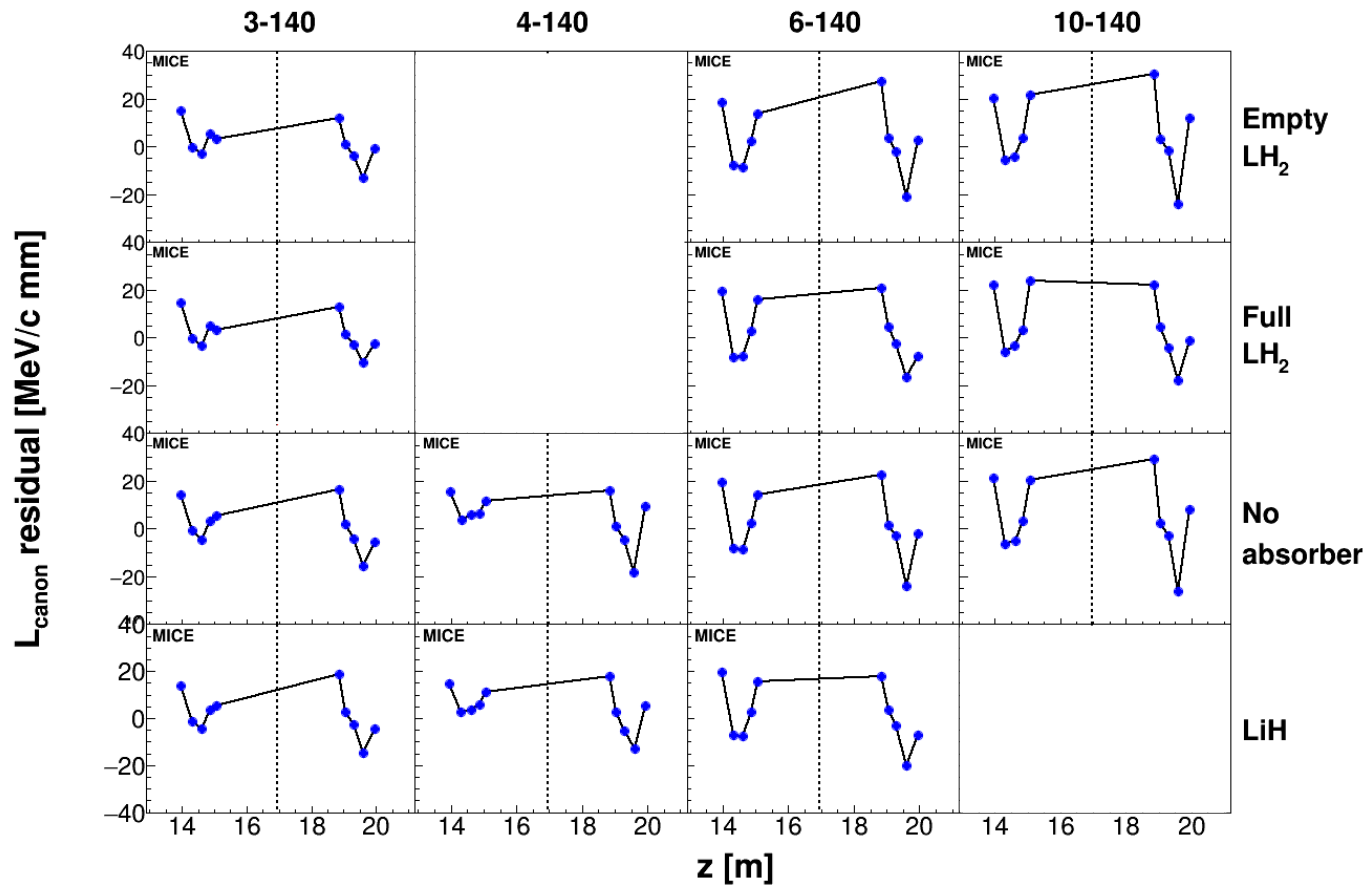


Band shows  
Sys + Stat Error

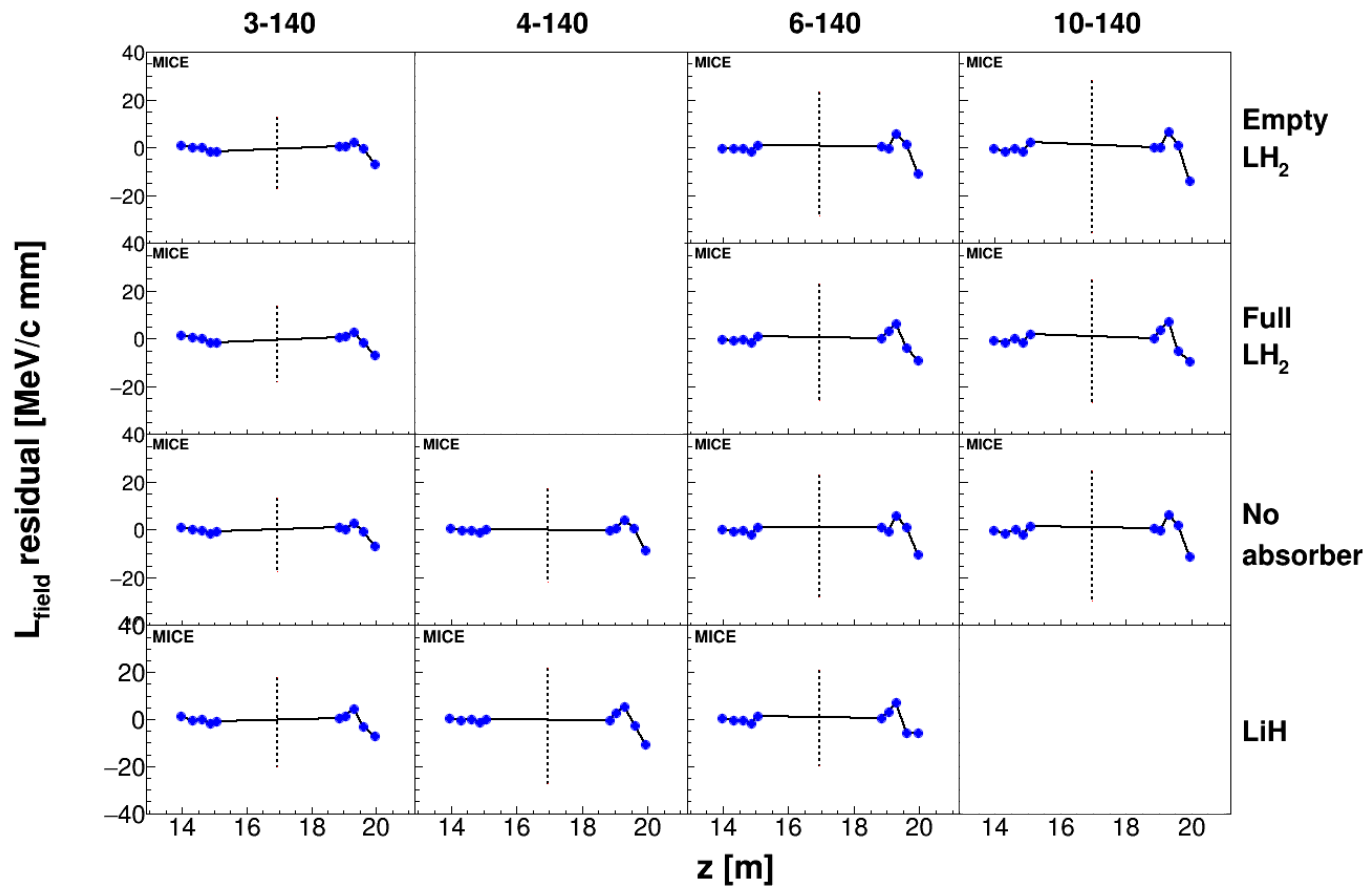
# Canonical Angular Momentum – Kinetic + Field Term



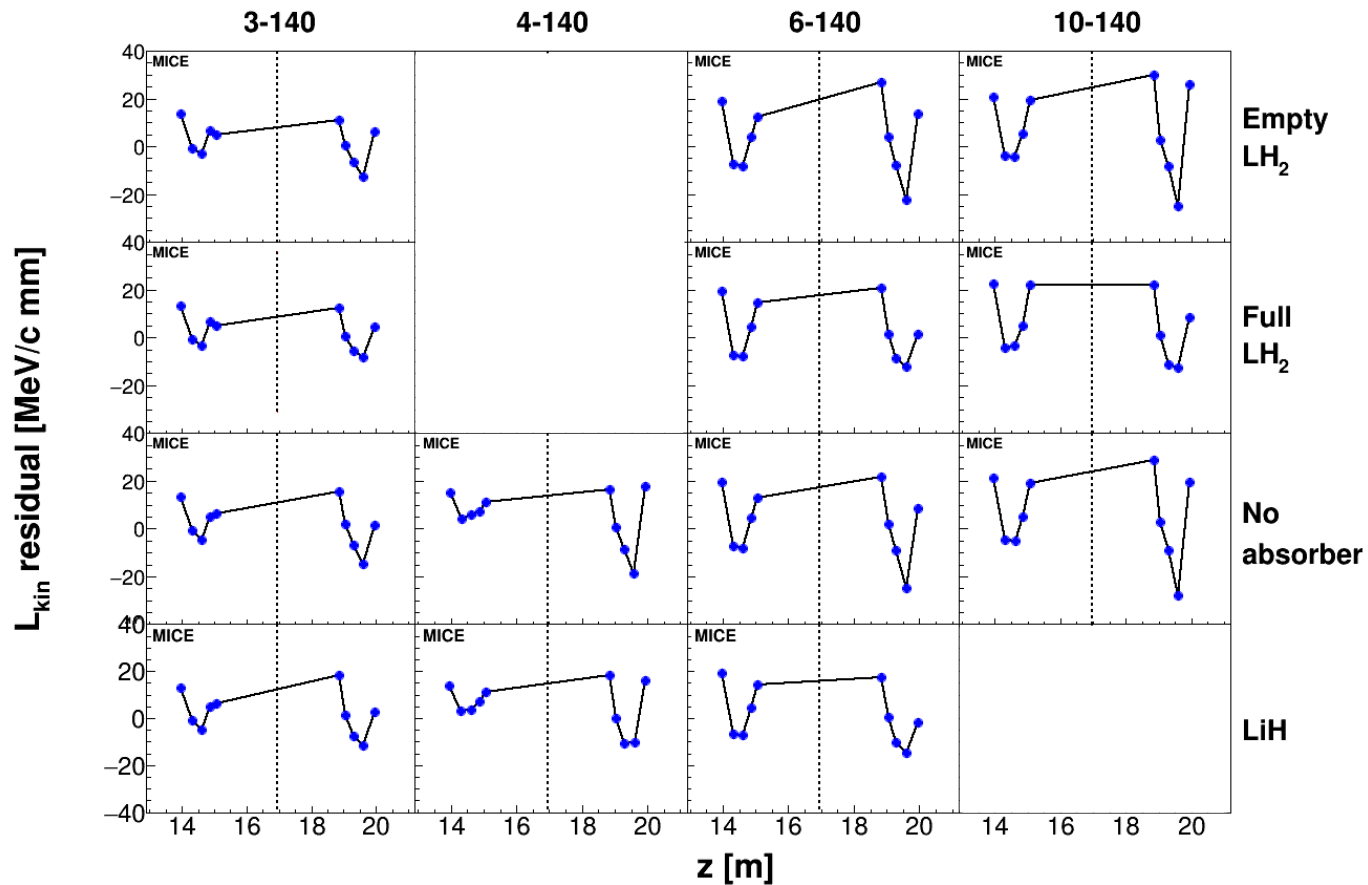
Band shows  
Sys + Stat Error

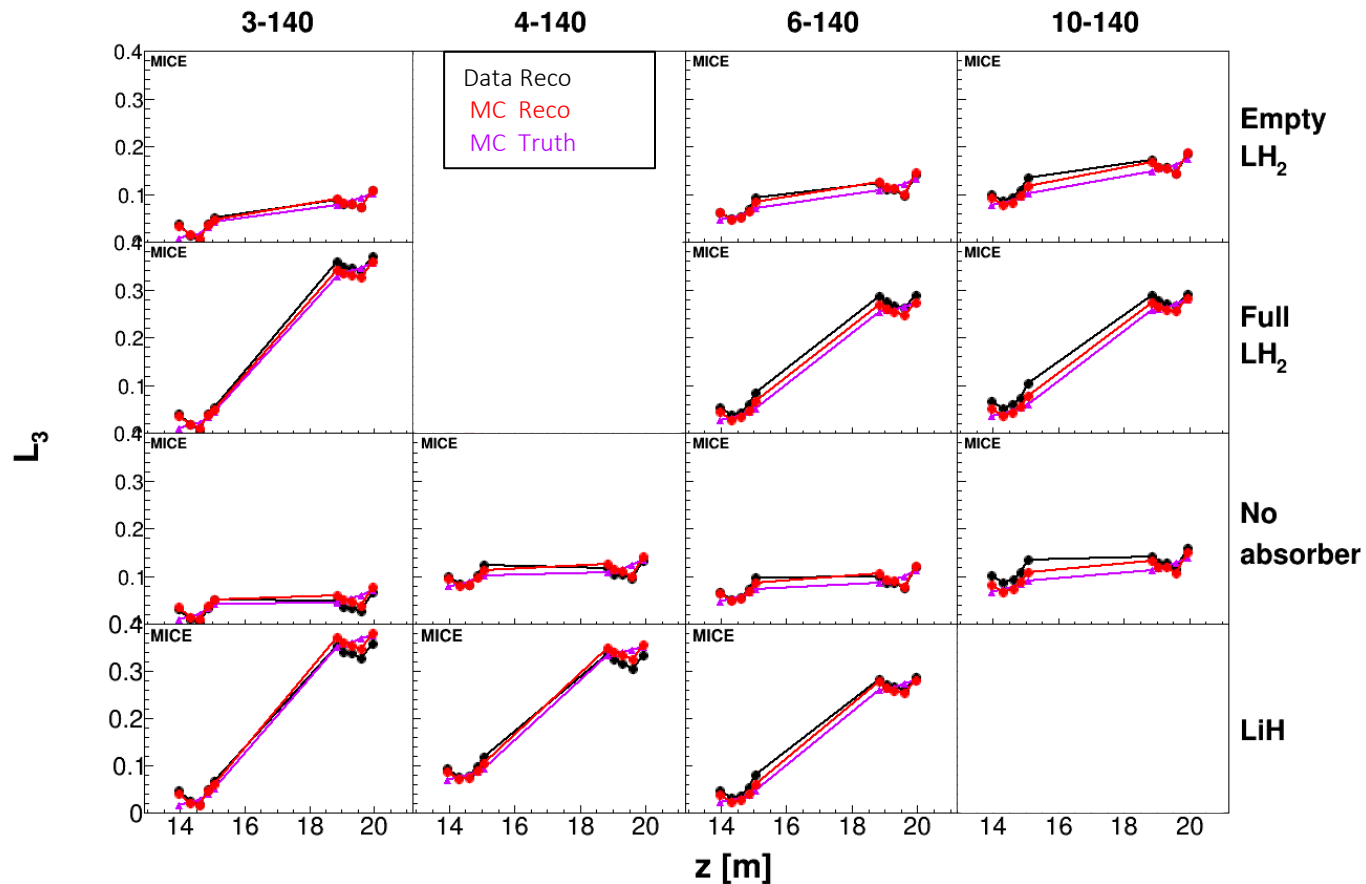


# L field residual









Dimensionless net canonical angular momentum of the beam, derived from covariance matrix

$$\begin{aligned} \langle xP_y - yP_x \rangle \\ = -2mc\epsilon_N(\beta_{\perp}\kappa - L) \end{aligned}$$

Production of MC for additional cooling channel tag datasets underway, analysis coming shortly after. 2017-02-5 & 2017-02-2 maybe next.

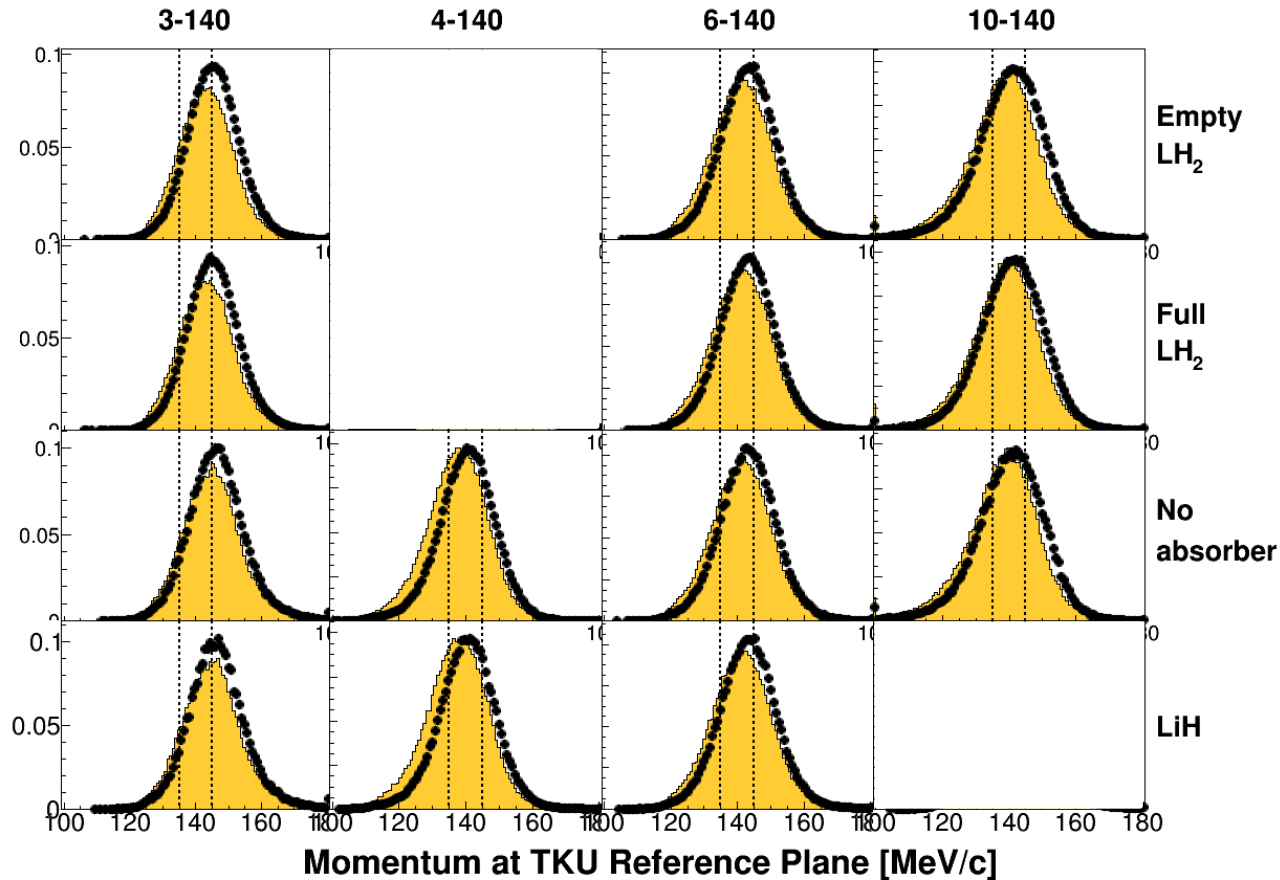
Current amplitude analysis needs updated MC for 2017-02-6 CC tag, expect improvements to data/MC agreement from next round

Canonical angular momentum growth across the absorber and through tracker stations looks reasonable in truth for 140 MeV beam, reconstruction effects are evident although systematics error on same scale as reco error – expect larger systematics error with mc beam offset

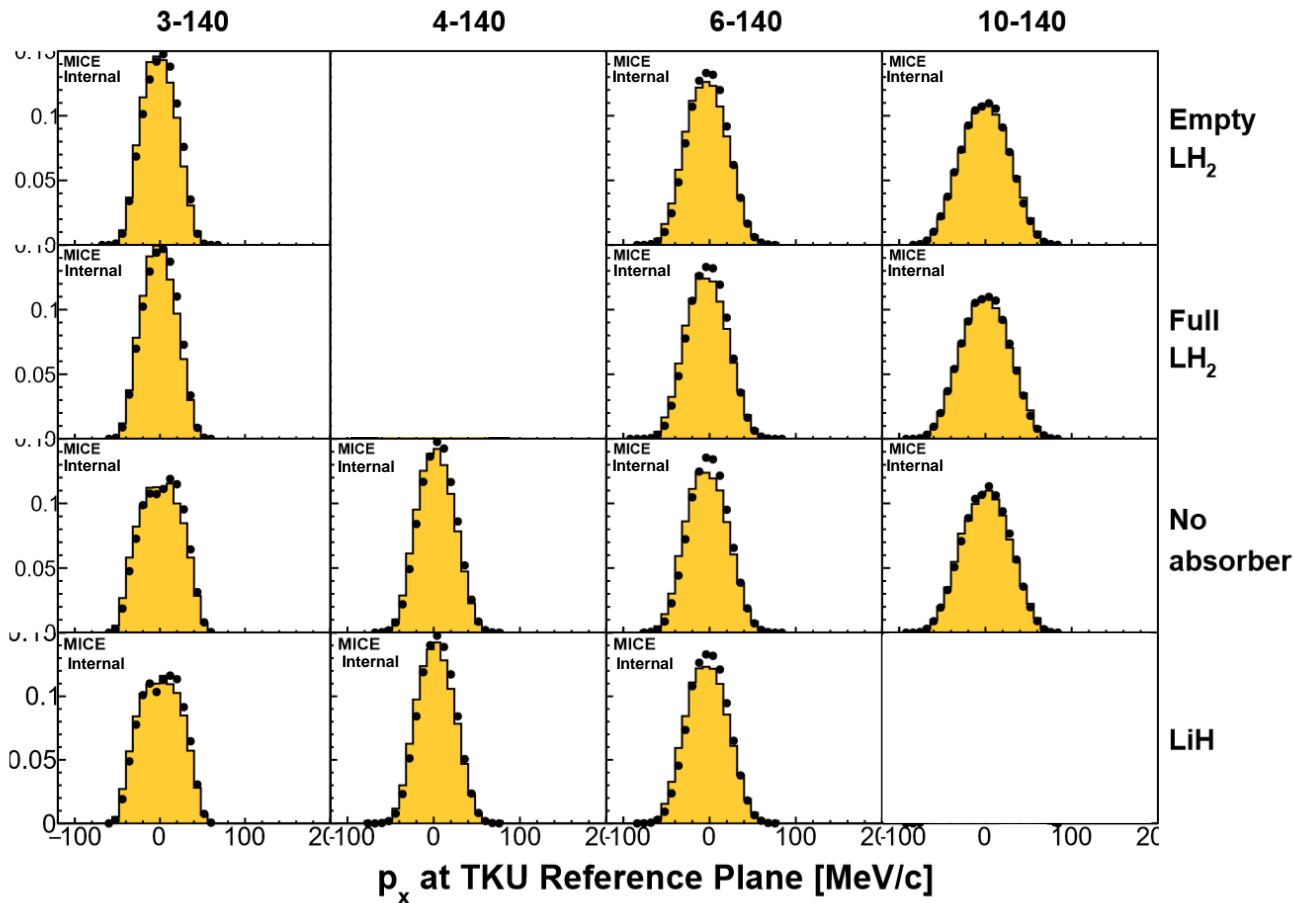
Some work into a reco correction has been done, but not applied here.

# Backup

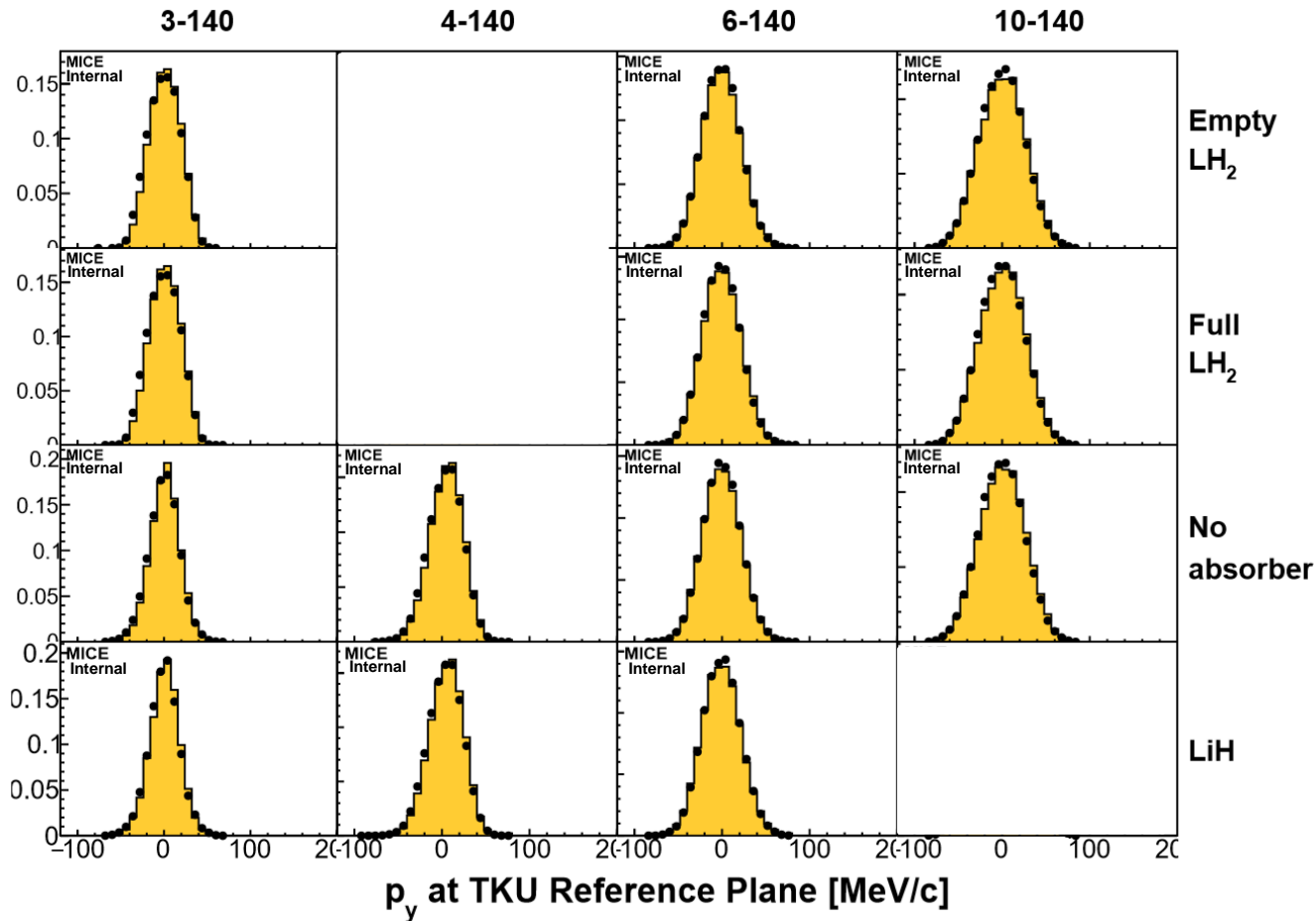
# Momentum Cut - Data vs MC Reco



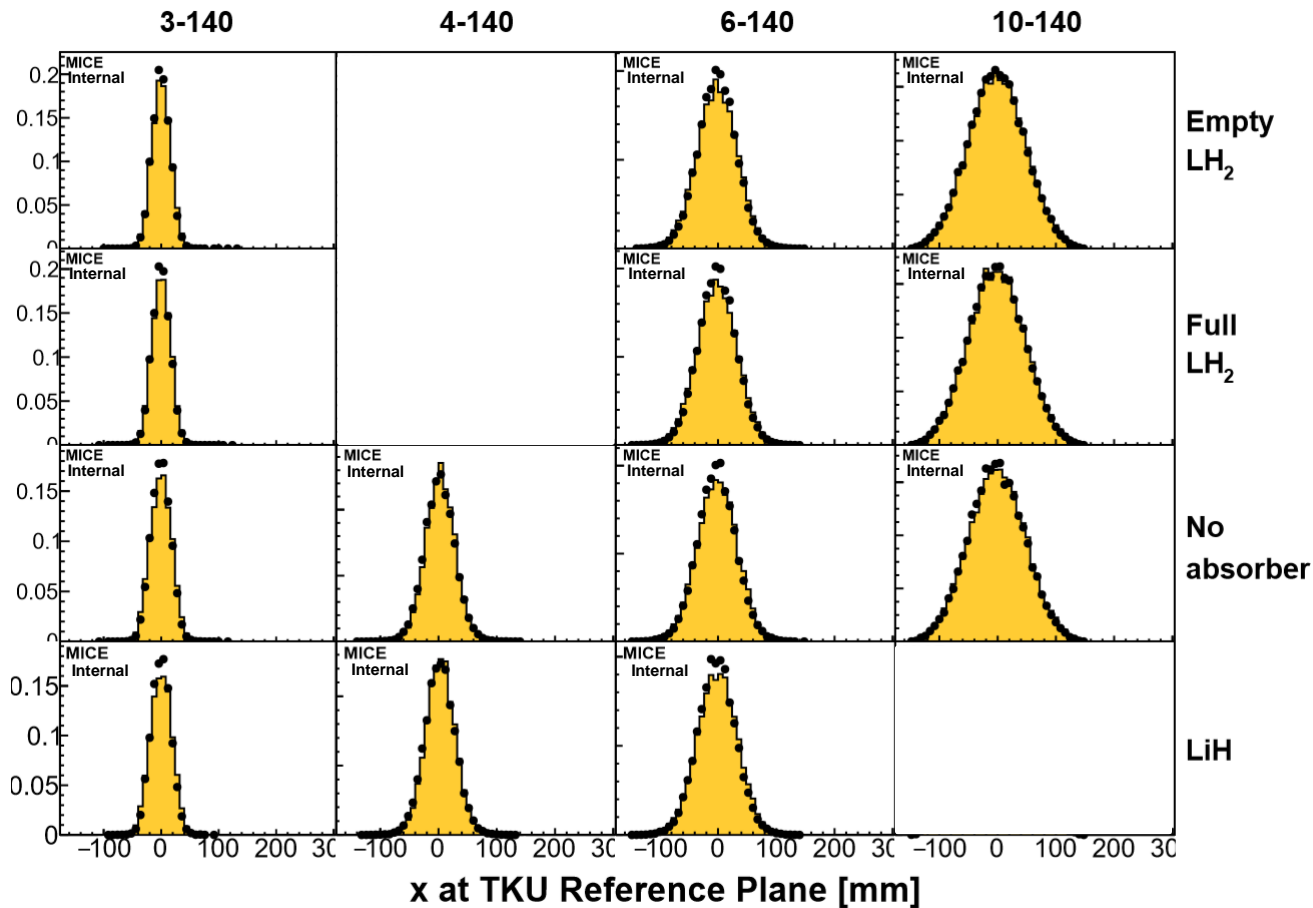
# TKU Px – Data vs MC Reco



# TKU Py – Data vs MC Reco

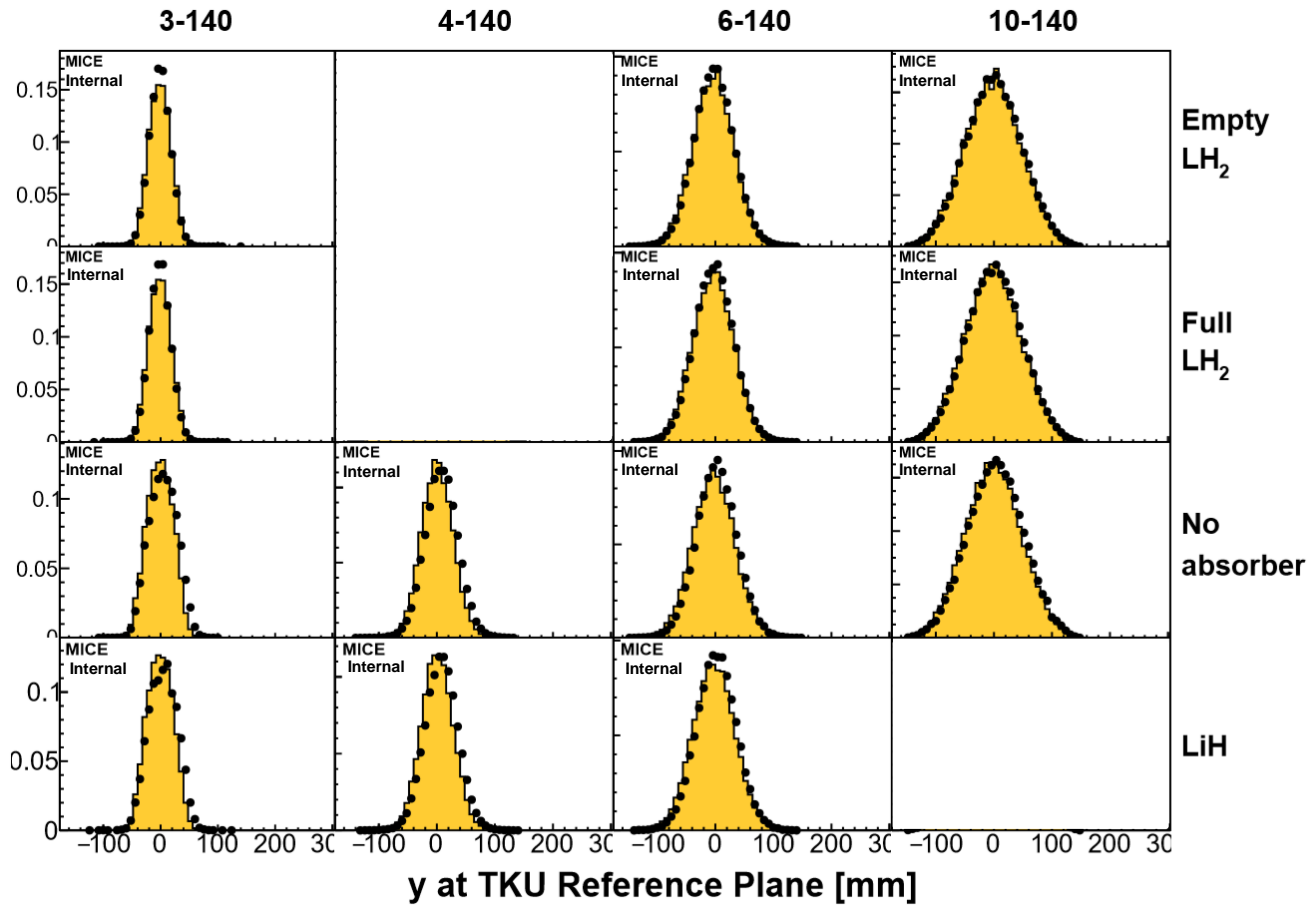


# TKU x – Data vs MC Reco

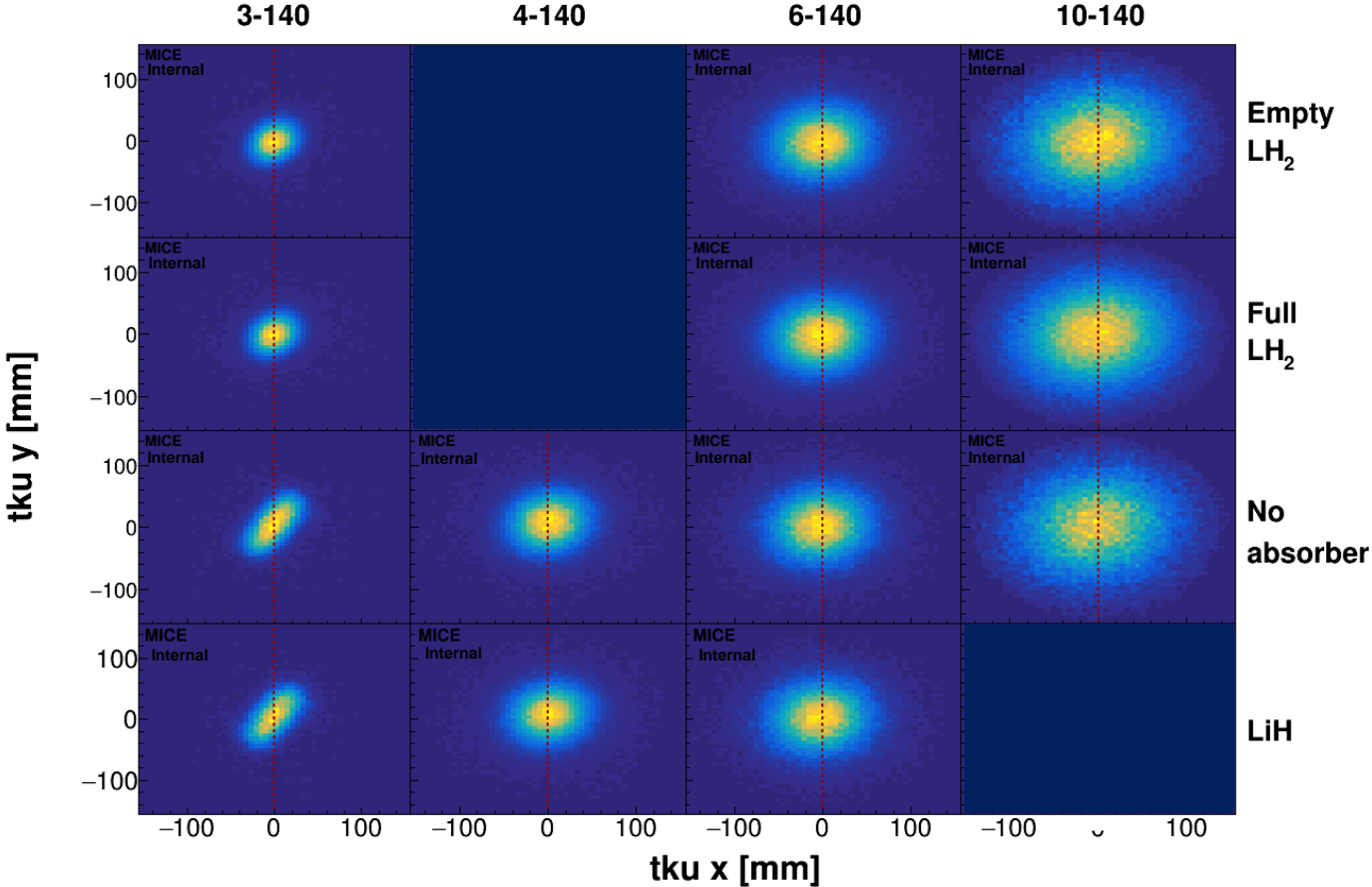




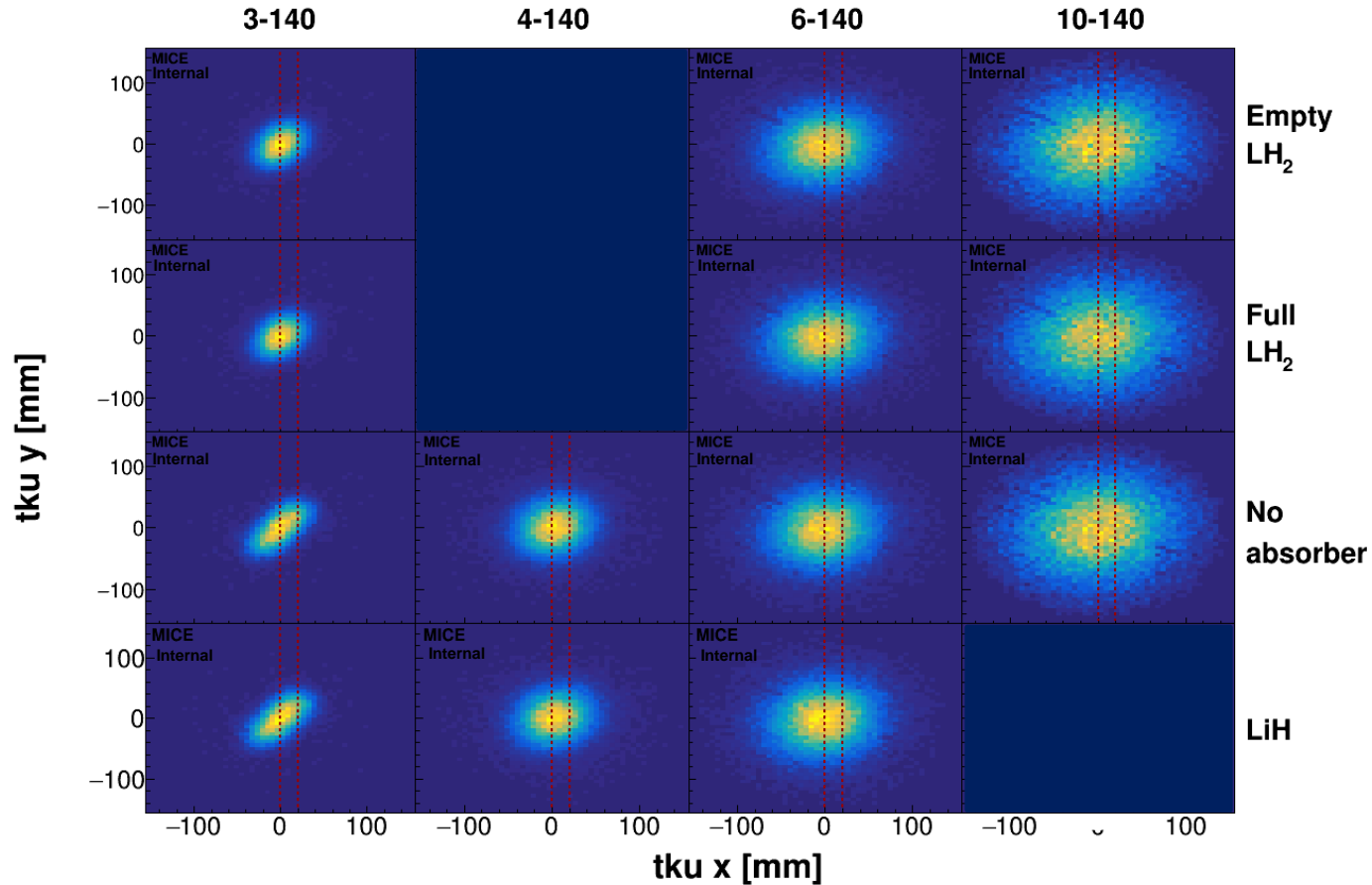
# TKU $\gamma$ – Data vs MC Reco



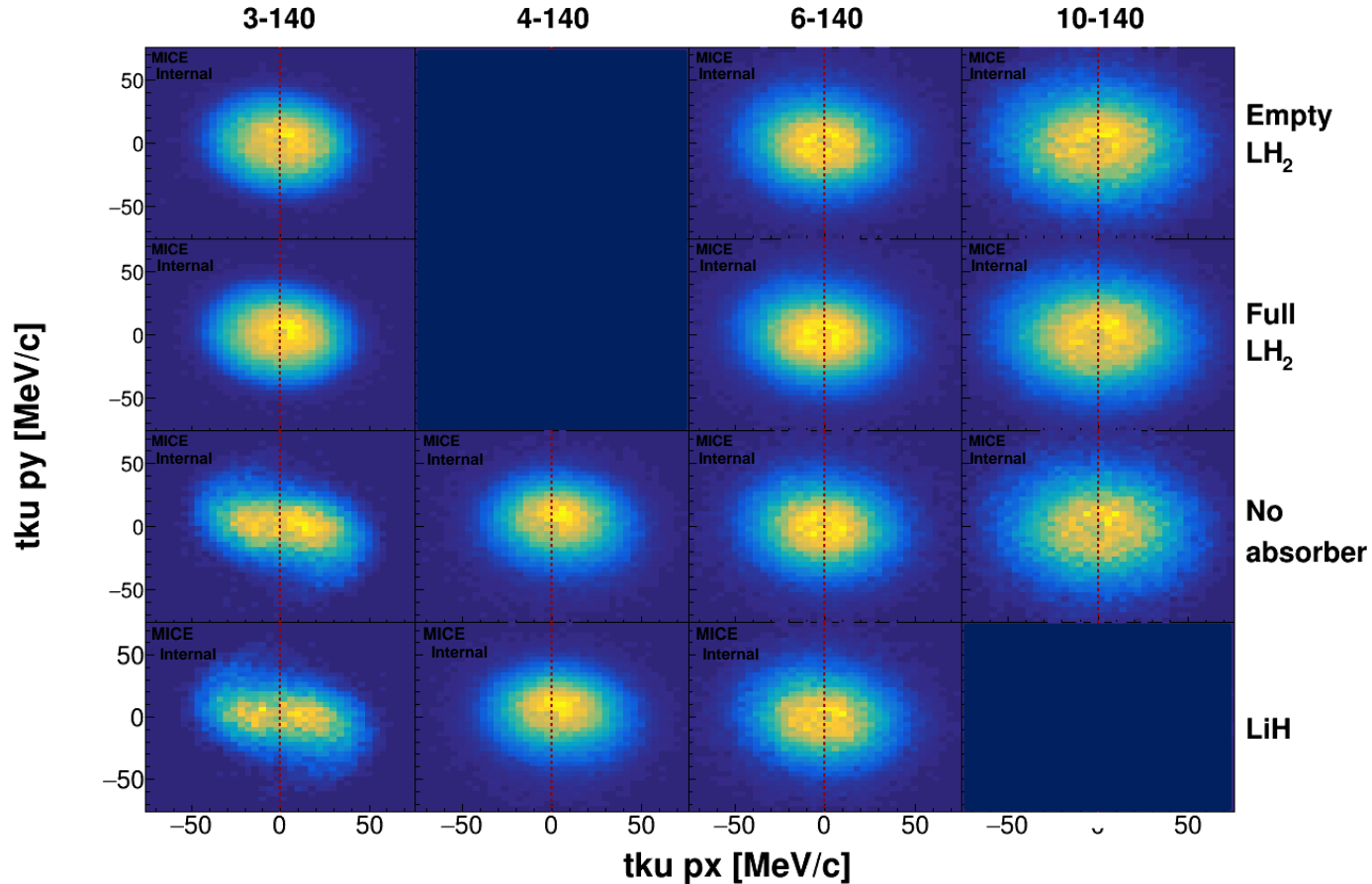
# TKU x vs y - Data



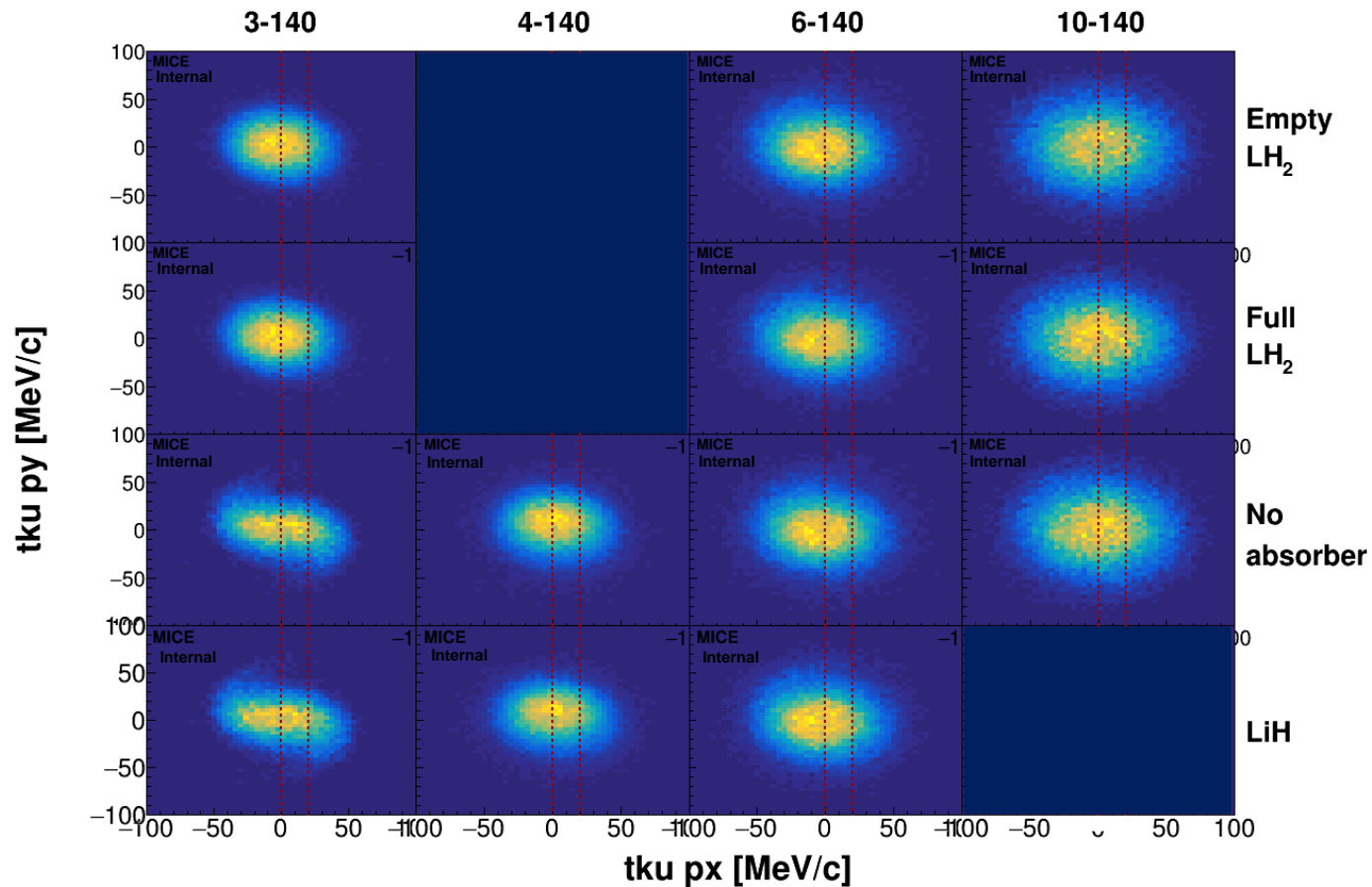
# TKU x vs y - MC Reco



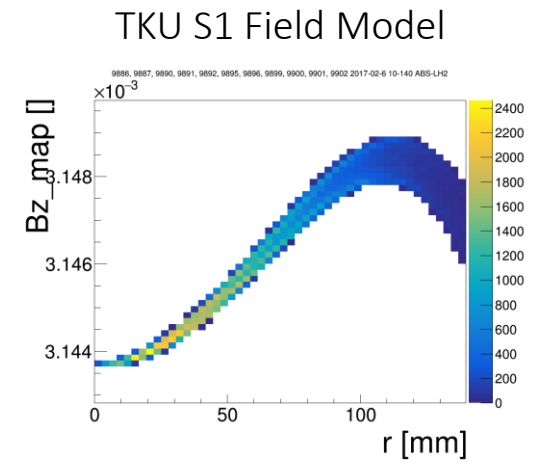
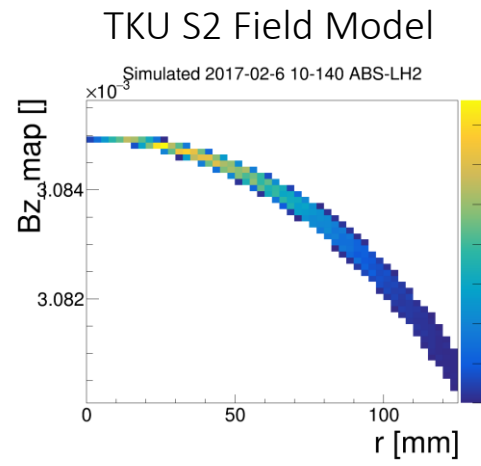
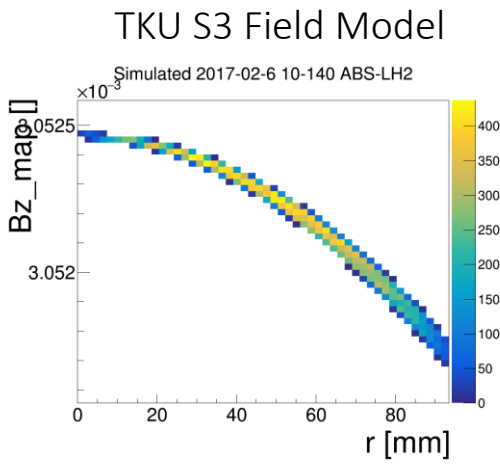
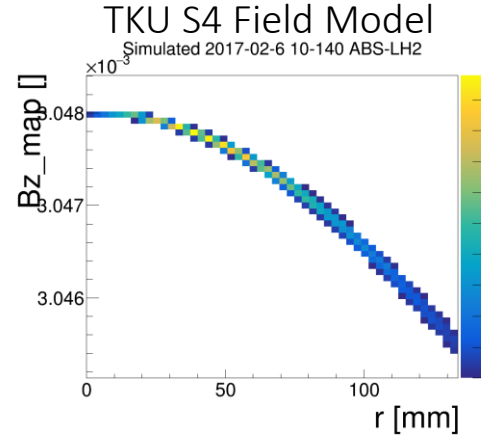
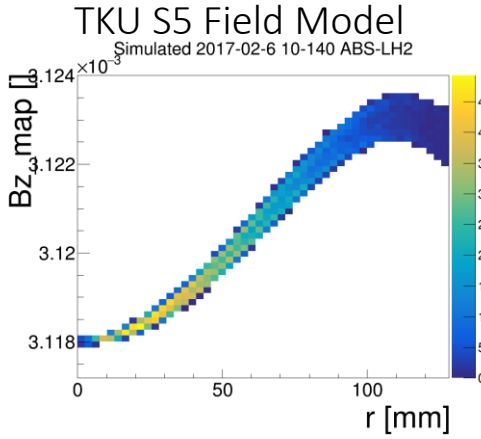
# TKU Px vs Py - Data



# TKU Px vs Py – MC Reco



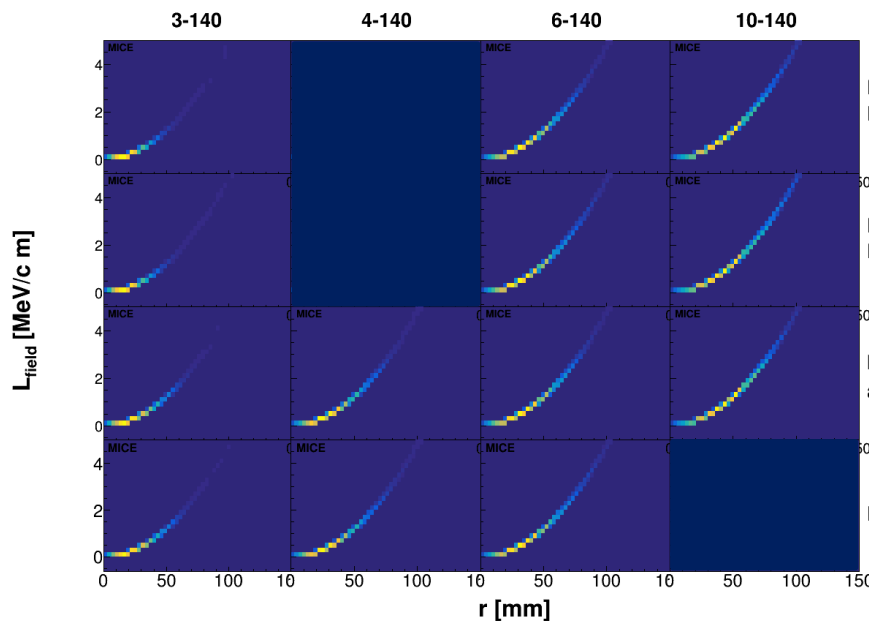
# B<sub>z</sub> vs r plots – Bz Field Map



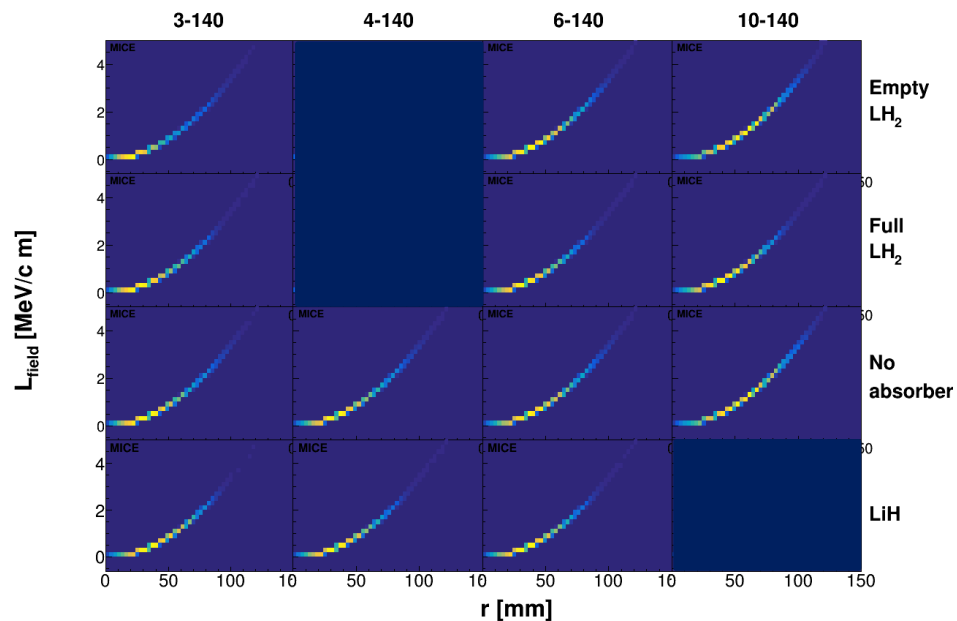
# L field vs r plots – Data

L field follows field maps for x,y,z position of trackpoints

TKU, DS Sample

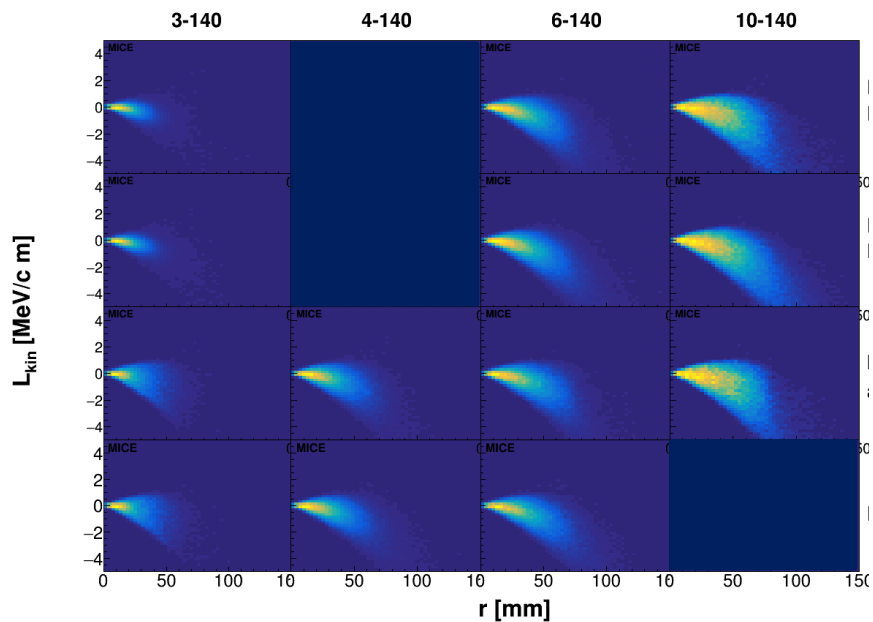


TKD, DS Sample

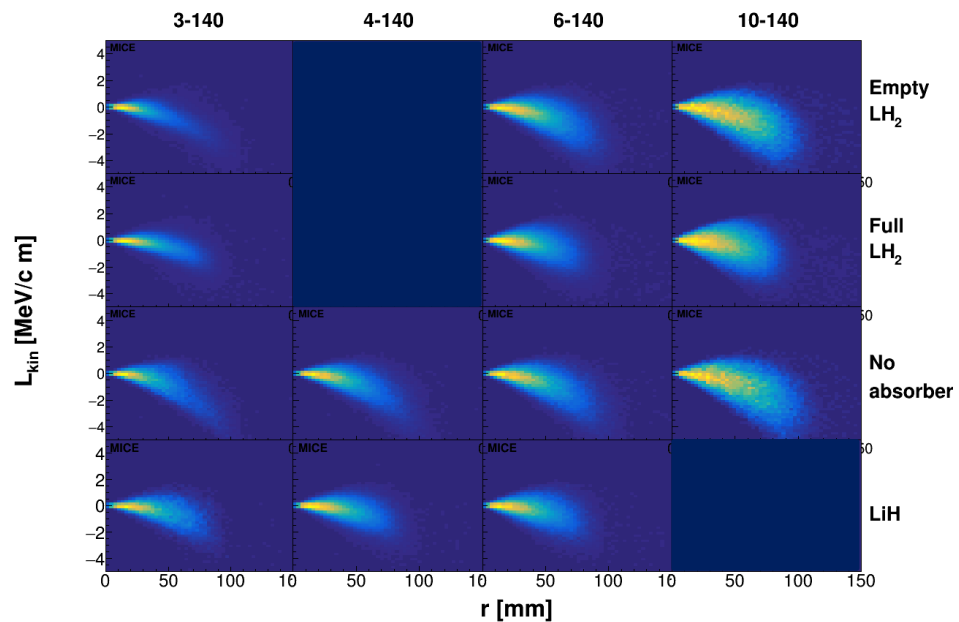


# L kin vs r plots – Data

TKU, DS Sample



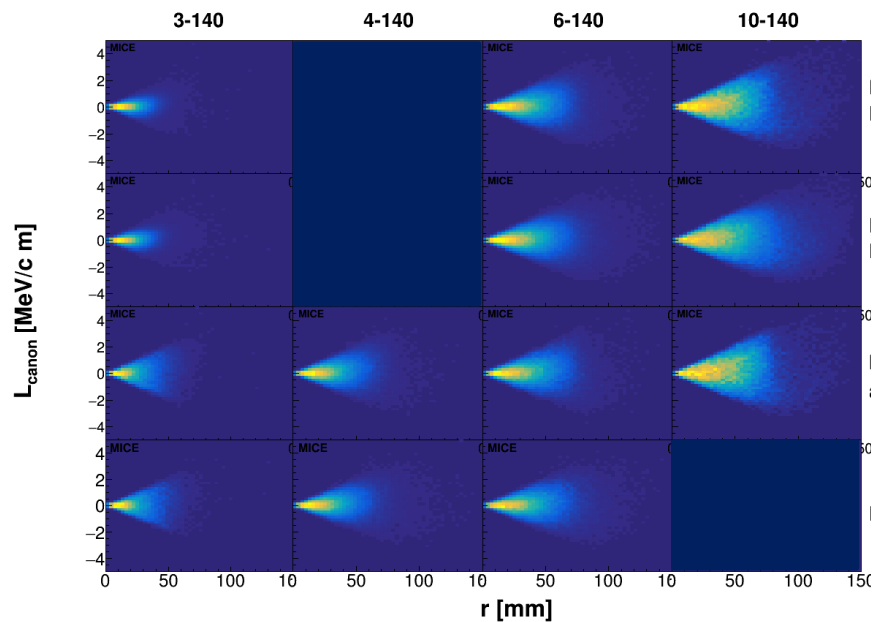
TKD, DS Sample



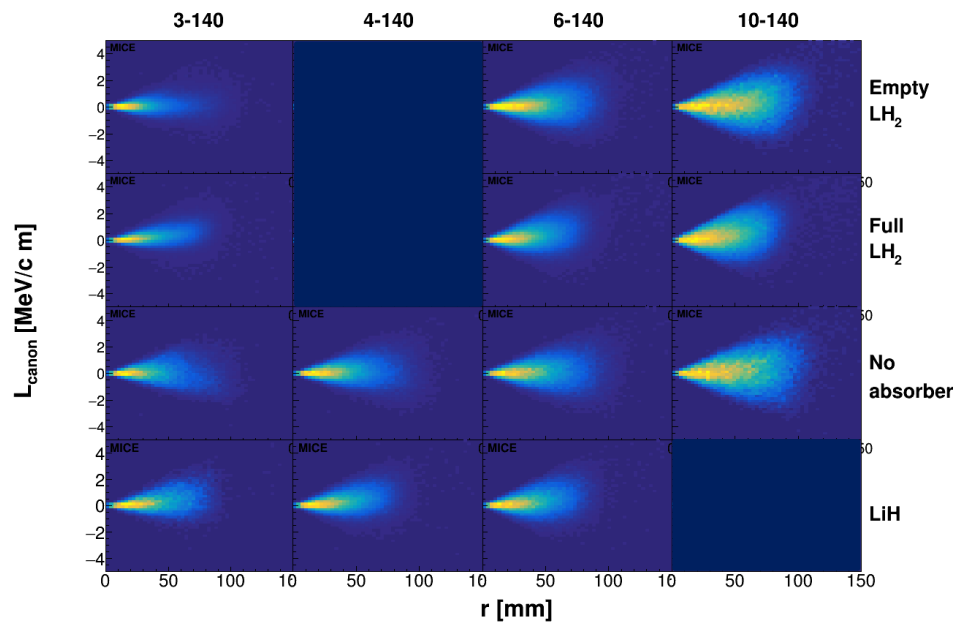


# L canon vs r plots – Data

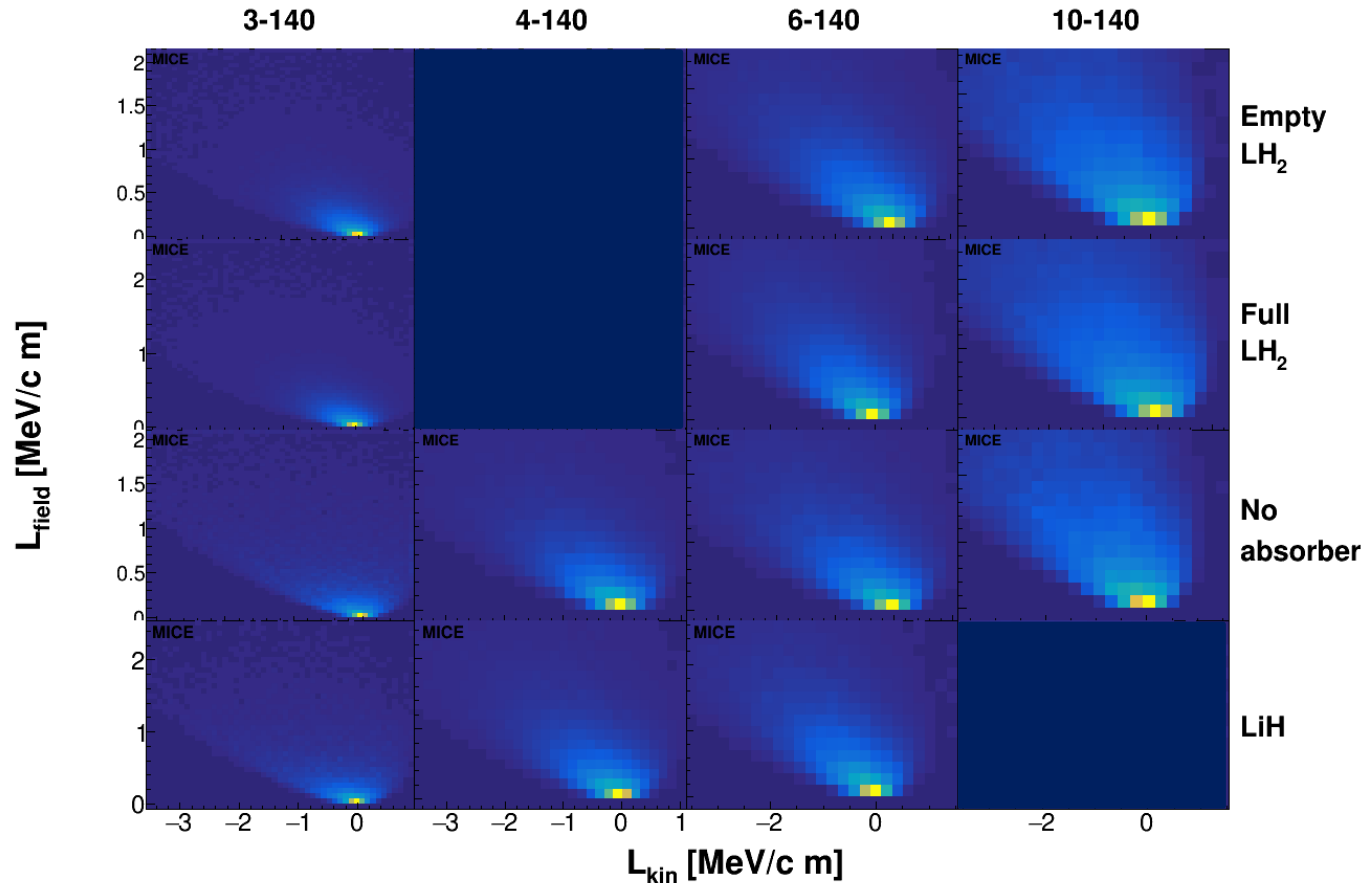
TKU, DS Sample



TKD, DS Sample



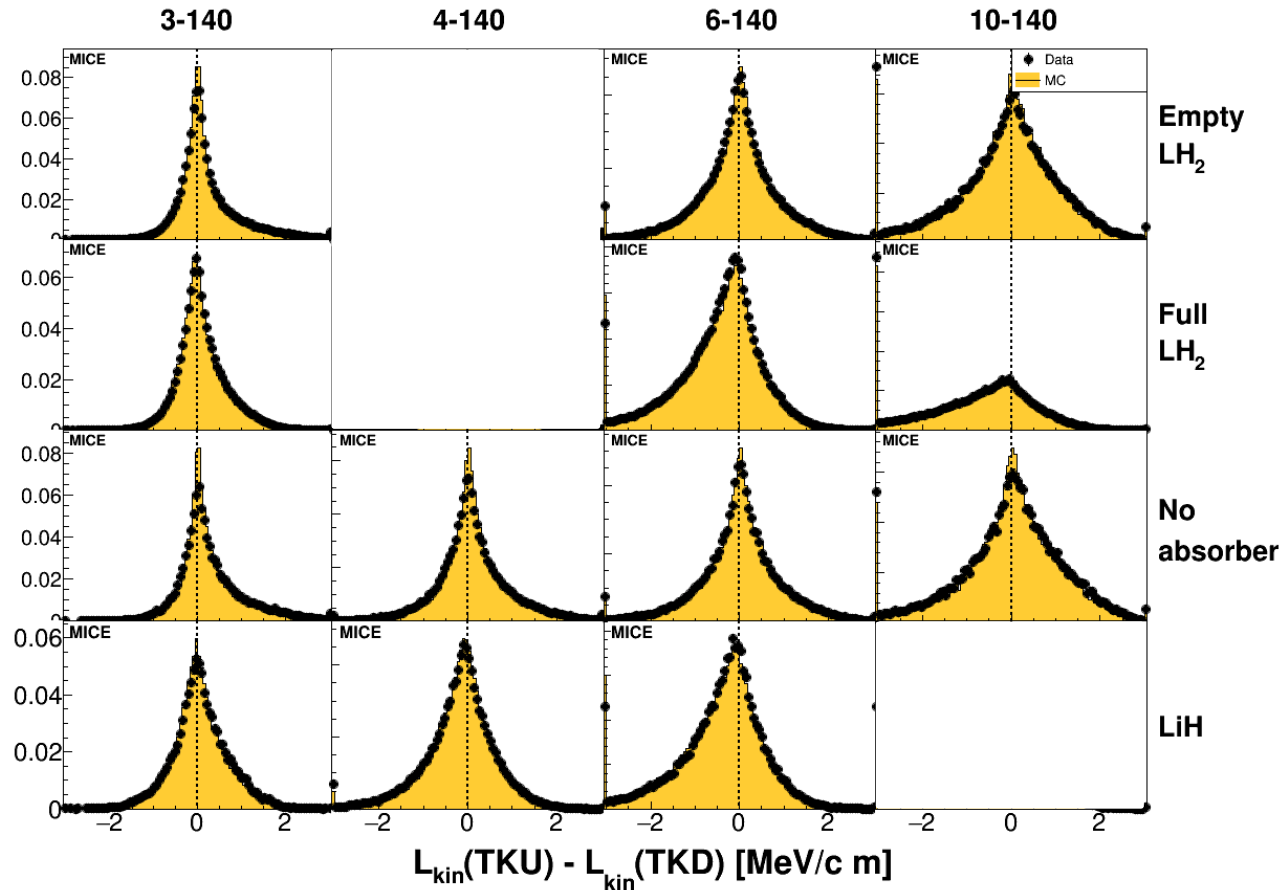
# L kin vs L field – Data, US cut



# L kin - Change Across Absorber

## Data vs MC Reco

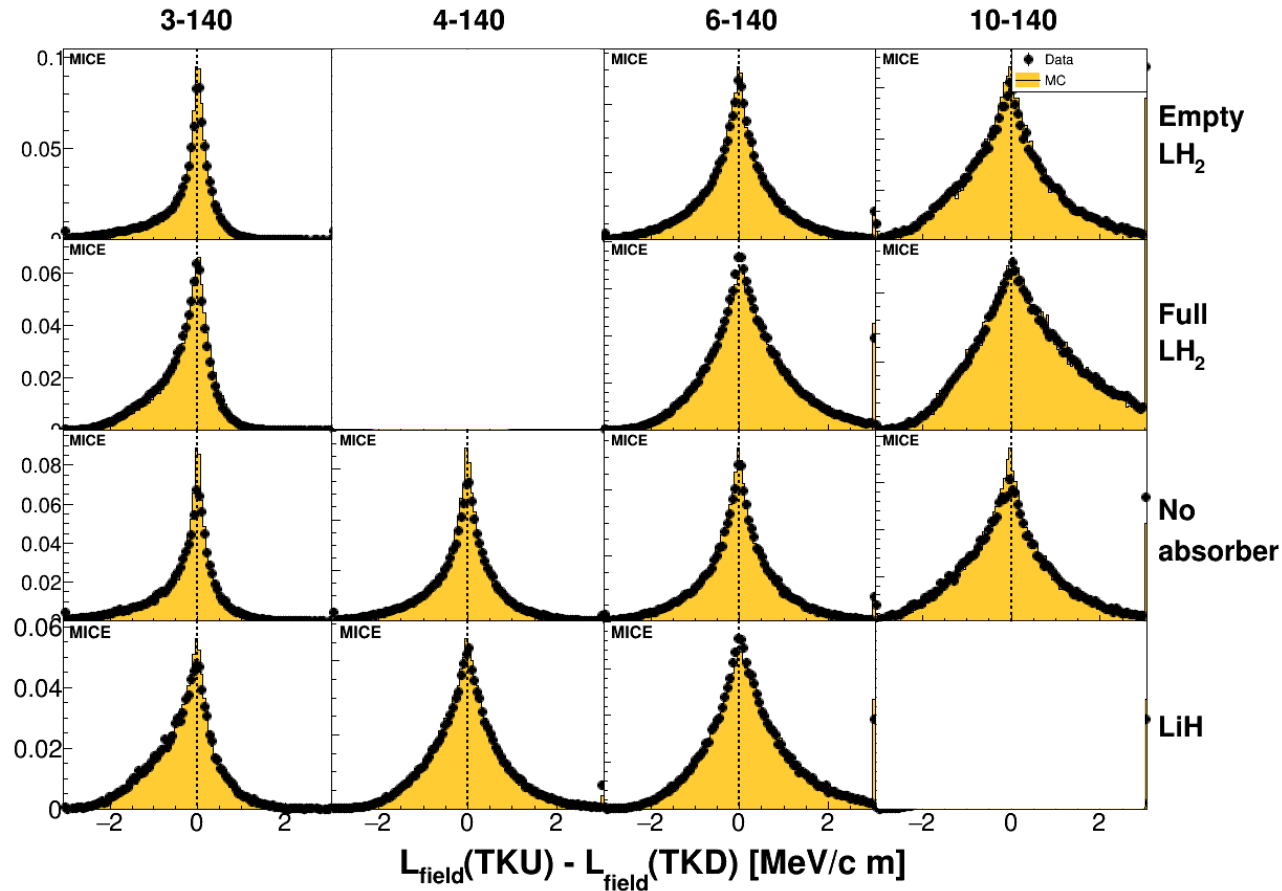
Data vs MC reco



# L field - Change Across Absorber

## Data vs MC Reco

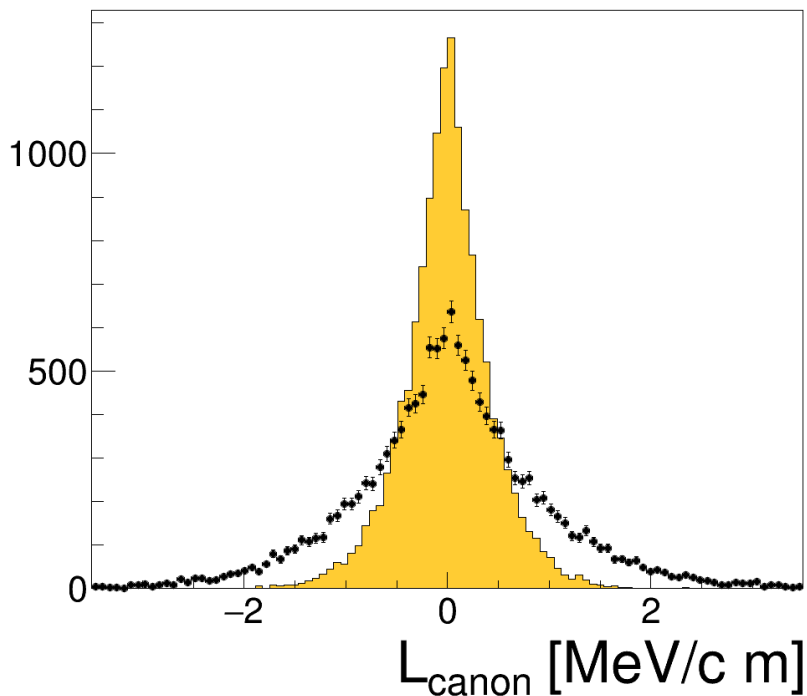
Data vs MC reco



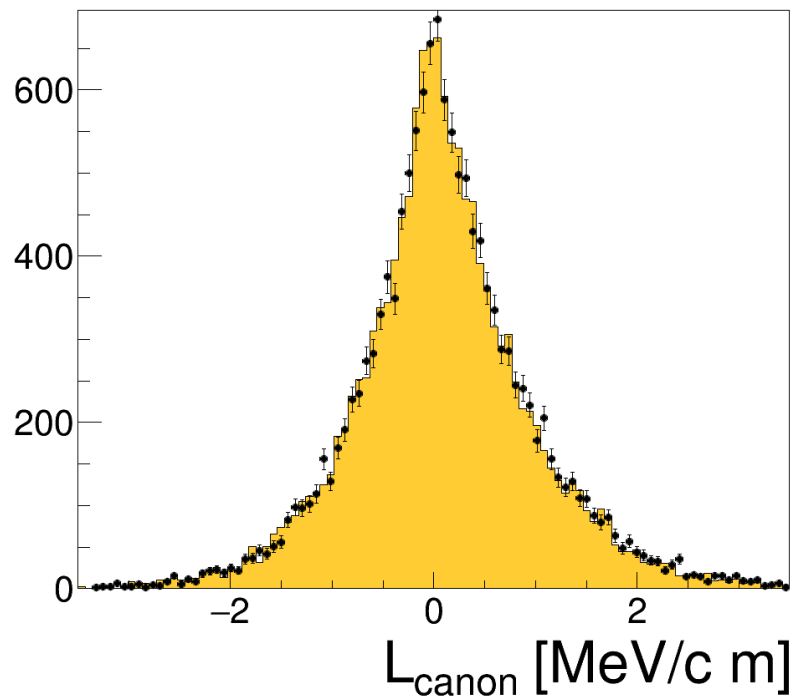
# L canon MC Reco vs MC Truth

MC Reco in black, MC Truth in yellow

Global through  
virtual diffuser us  
Simulated 2017-02-6 6-140 ABS-LH2



Global through  
virtual diffuser ds  
Simulated 2017-02-6 6-140 ABS-LH2

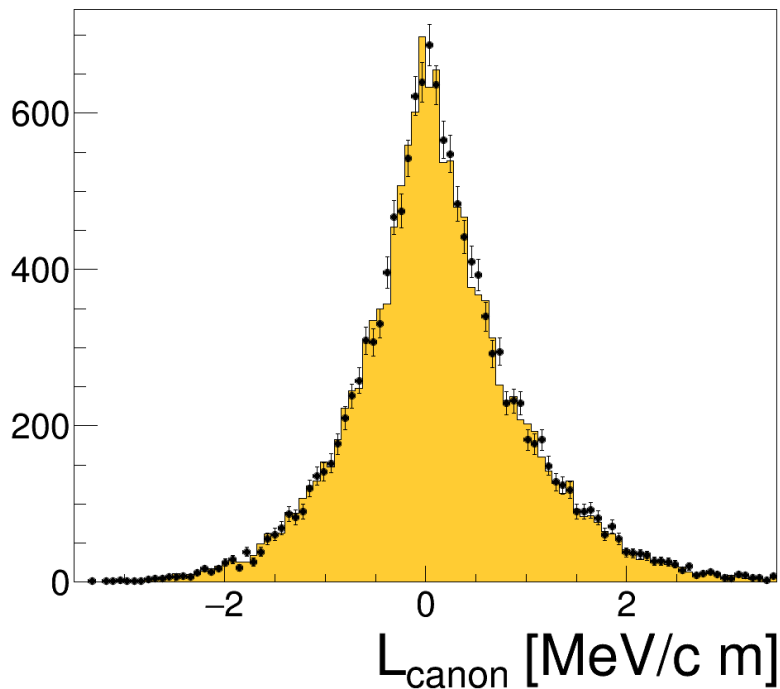


# L canon MC Reco vs MC Truth

MC Reco in black, MC Truth in yellow

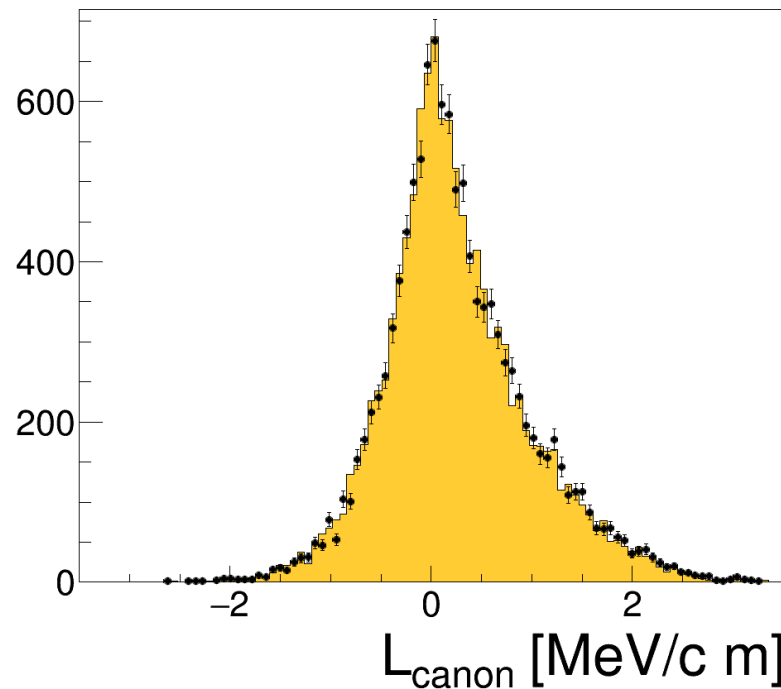
Tku 1

Simulated 2017-02-6 6-140 ABS-LH2

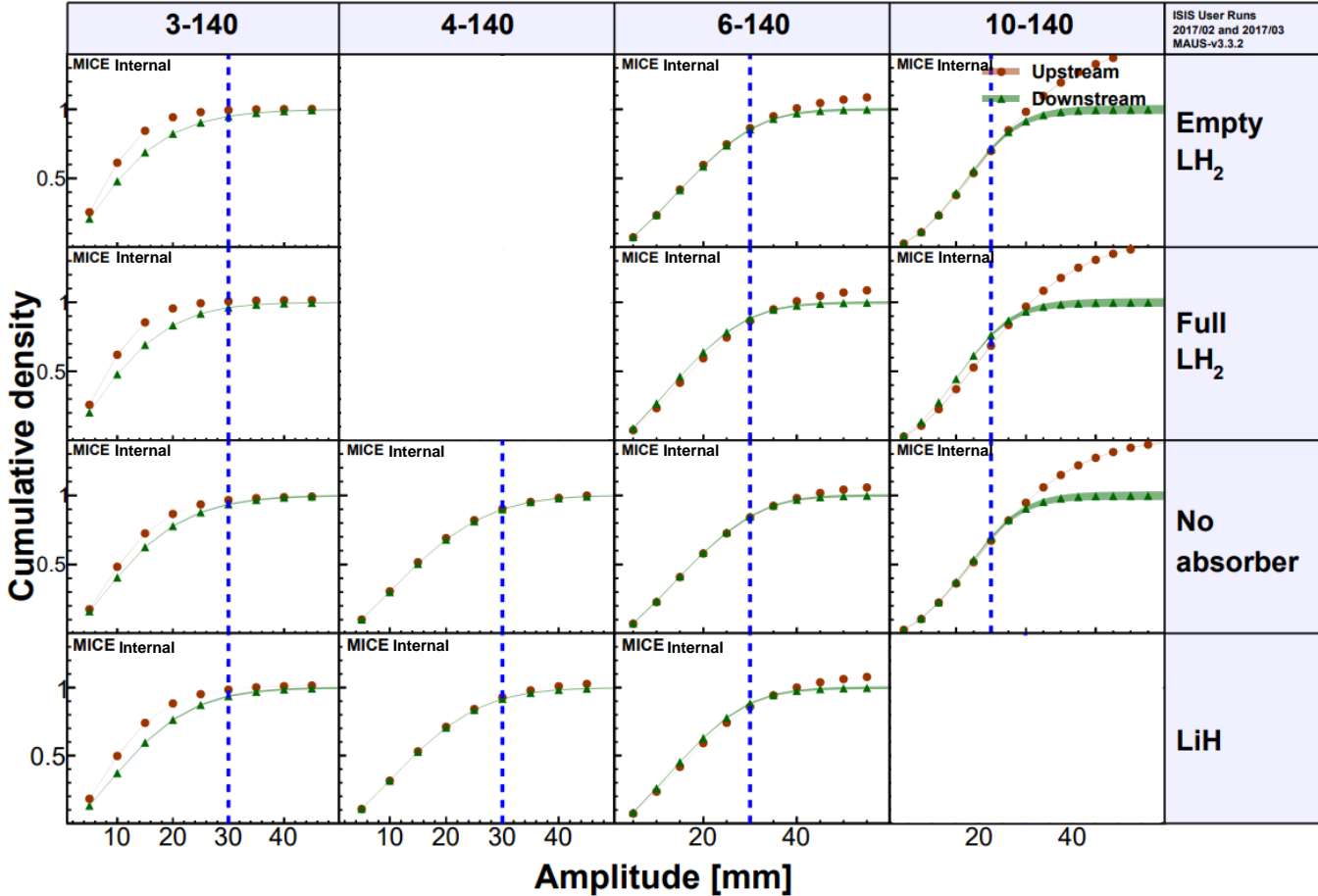


Tkd 1

Simulated 2017-02-6 6-140 ABS-LH2

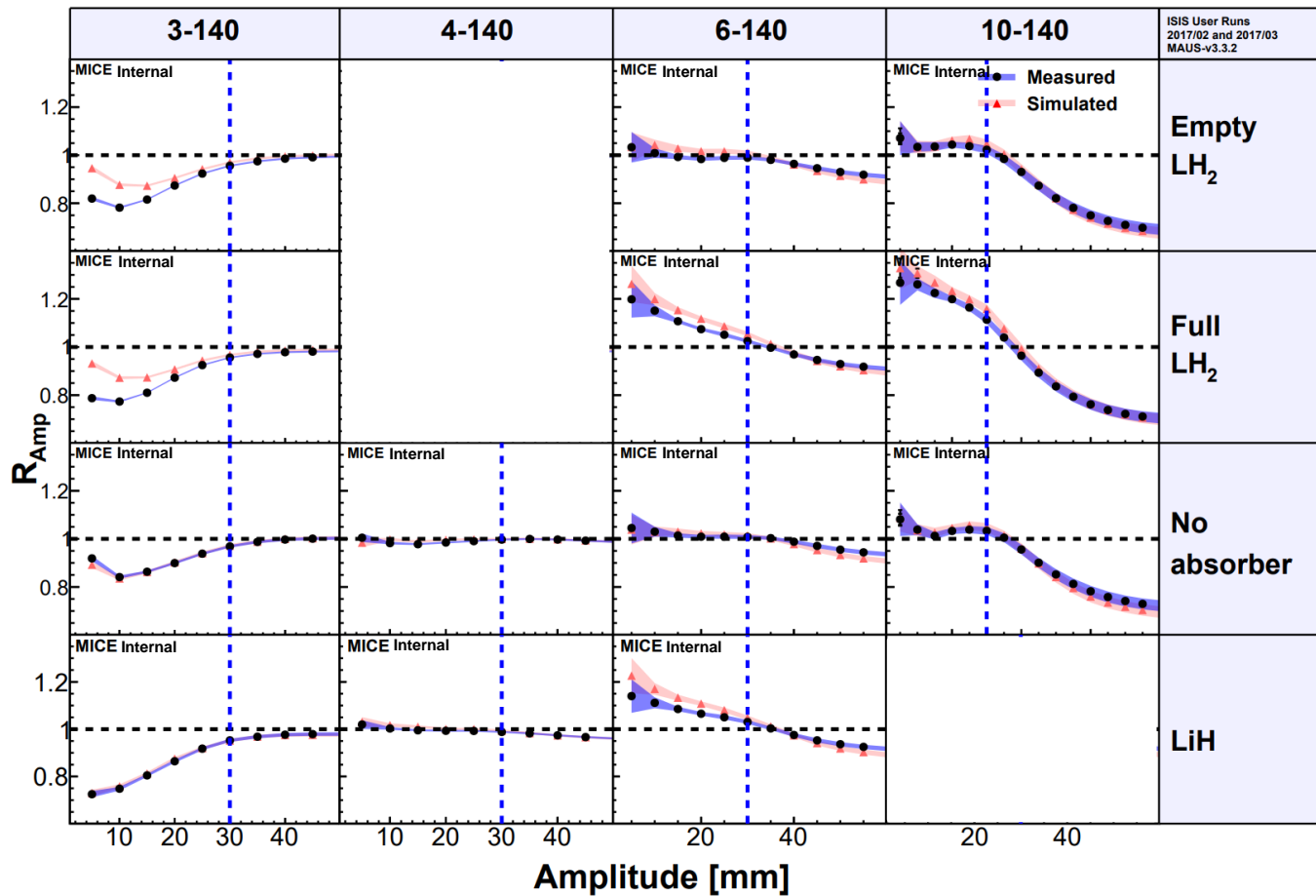


# CDFs - Data



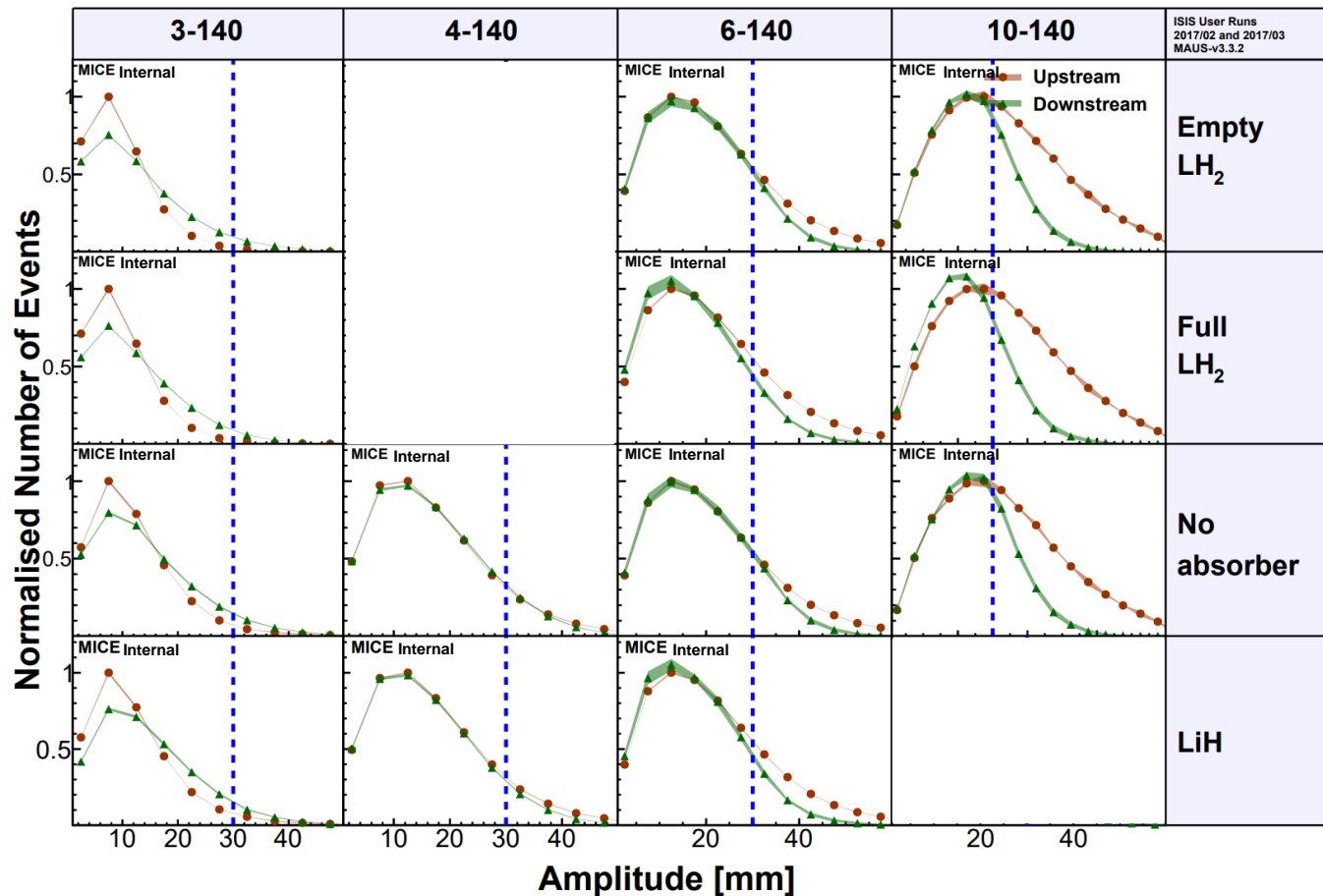
ISIS User Runs  
2017/02 and 2017/03  
MAUS-v3.3.2

# CDF Ratios

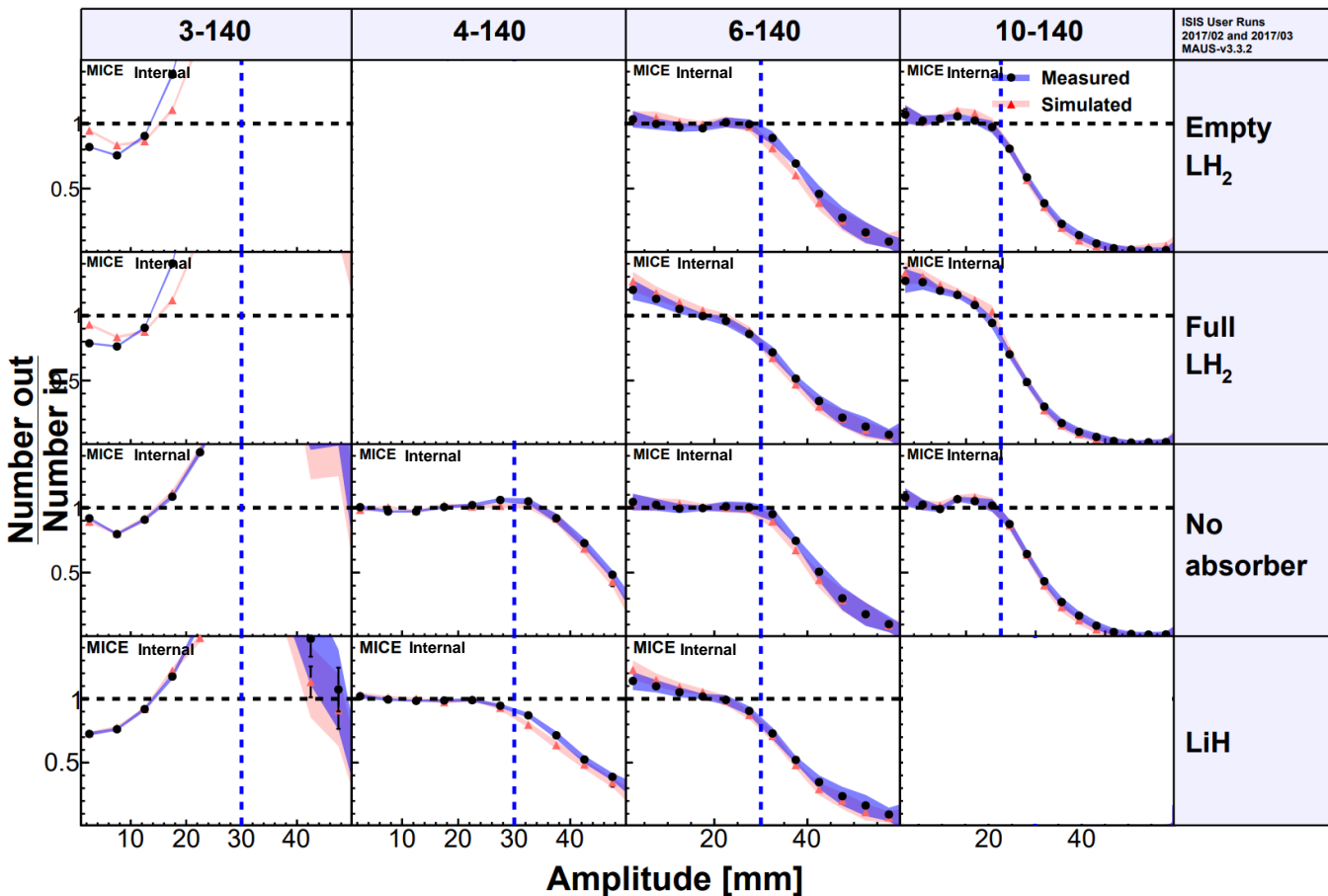




# PDFs - Data



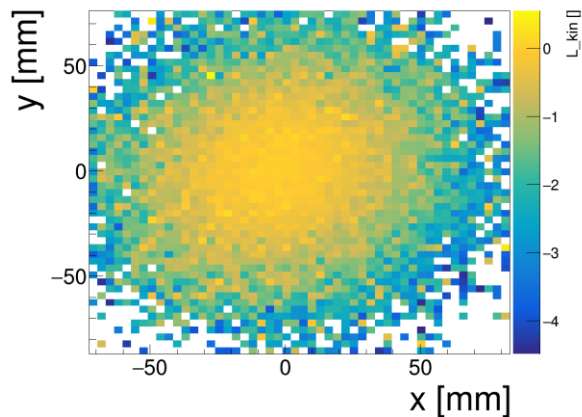
# PDF Ratios



# L kin vs x-y plots

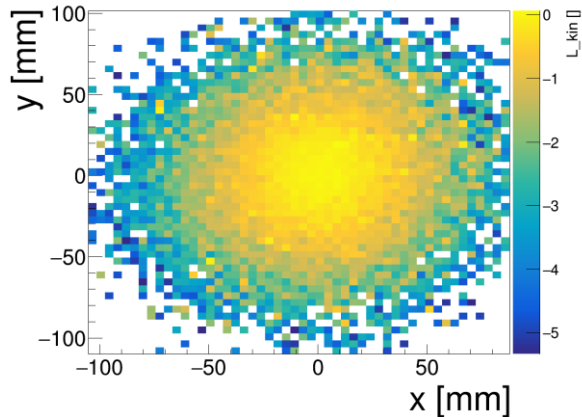
Tku 5

Simulated 2017-02-6 6-140 ABS-LH2



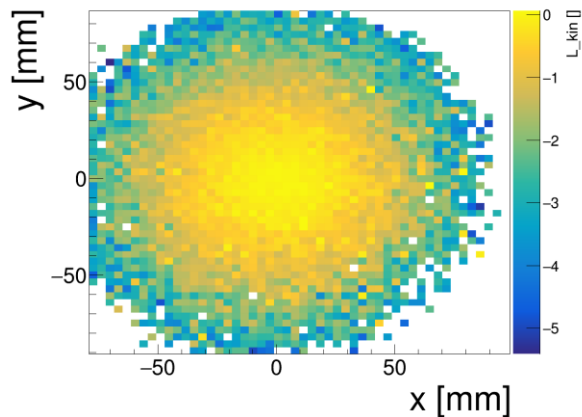
Tku 4

Simulated 2017-02-6 6-140 ABS-LH2



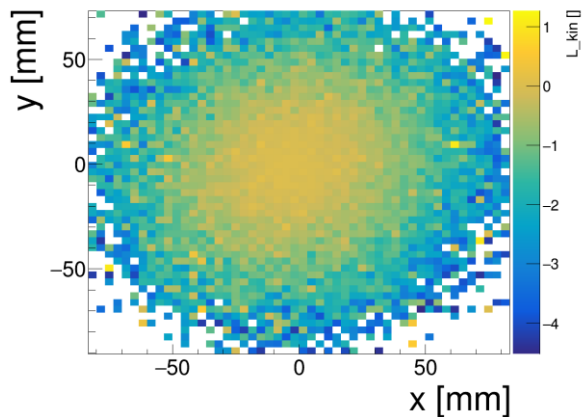
Tku 3

Simulated 2017-02-6 6-140 ABS-LH2



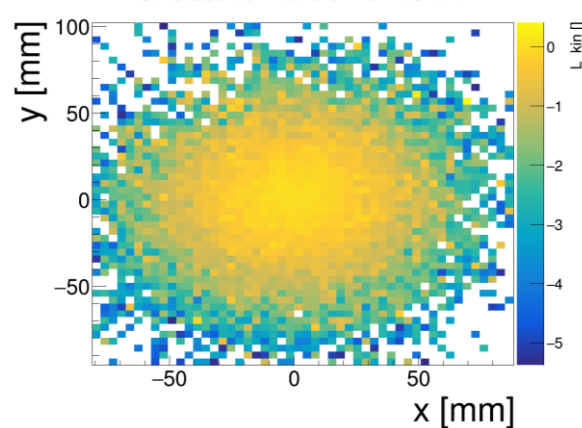
Tku 2

Simulated 2017-02-6 6-140 ABS-LH2



Tku 1

Simulated 2017-02-6 6-140 ABS-LH2

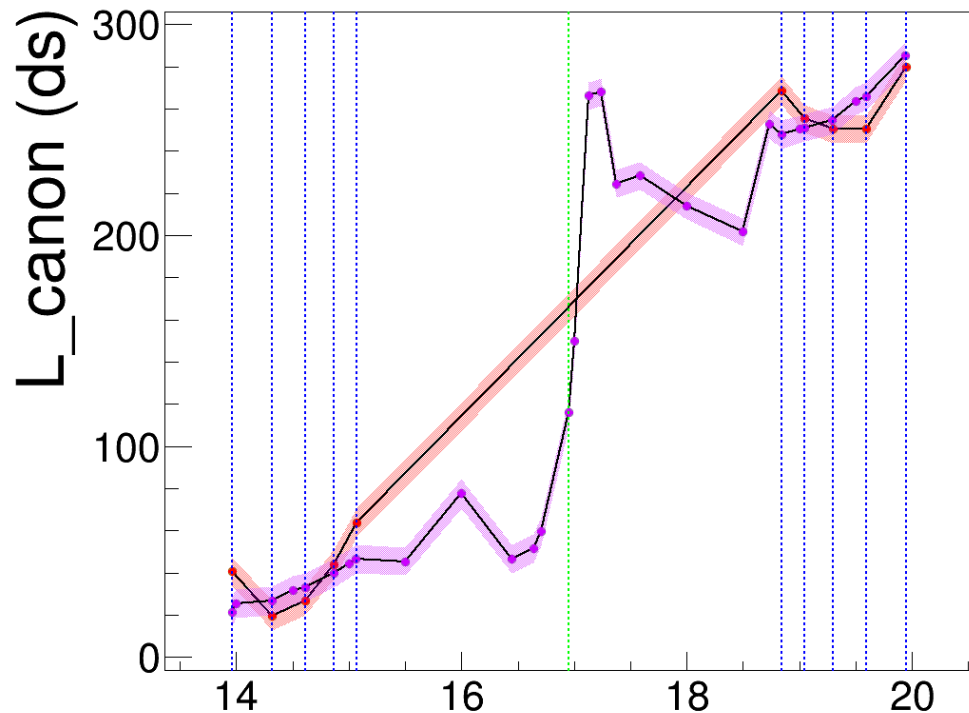


WARWICK  
THE UNIVERSITY OF WARWICK

Different z scales, can combine if interest

# L canon mean with more virtual planes

Simulated 2017-02-6 6-140 ABS-LH2

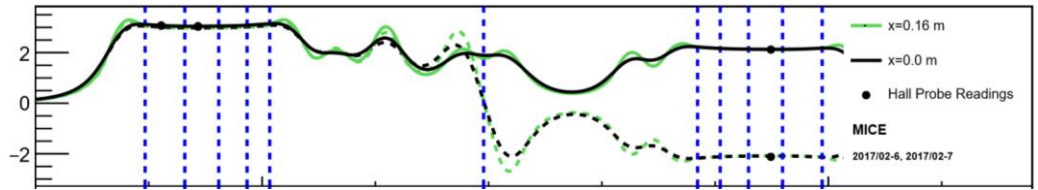


Reco in red  
TRUTH in violet



Higher order terms in  $L_{field}$  term probably contributing here

$$L_{field} = qrA_{\phi}$$
$$= qr \left( \frac{rB_z}{2} - \frac{r^3}{16} B_z'' + O(r^5) \dots \right)$$



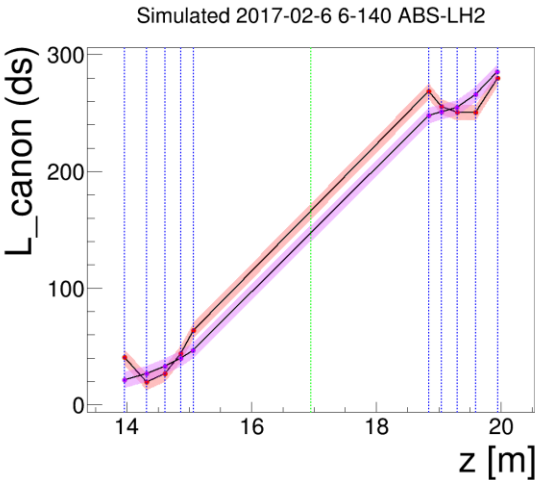
# Corrections

# Track Reconstruction in MAUS

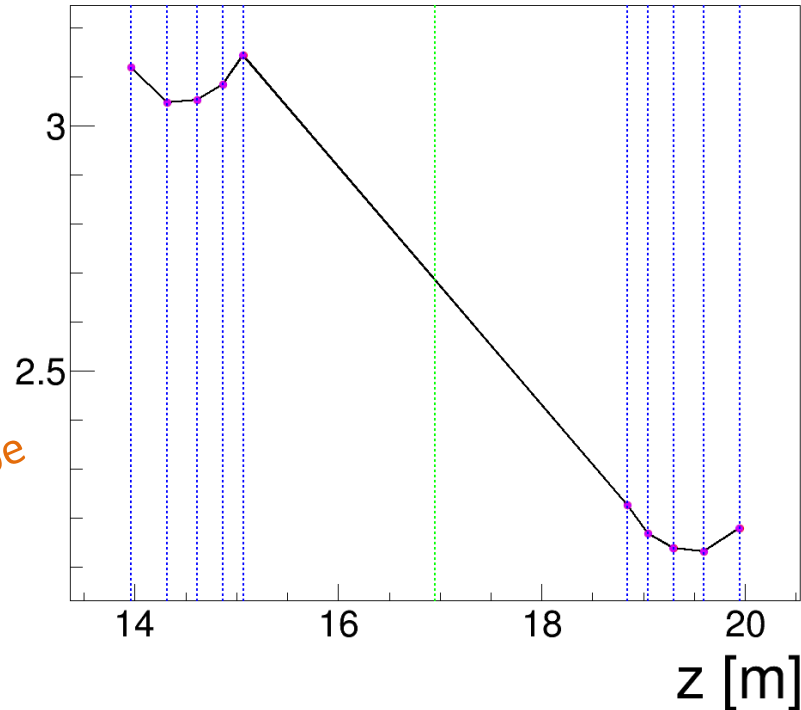
MAUS Kalman only sees single value for  $B_z$  in track propagation through each tracker

Actual field varies through the tracker  $O(0.1\text{ T})$

Simulated 2017-02-6 6-140 ABS-LH2



mean\_  $B_z$  (ds)



Suspicious shape similarity

# Equations for Track Propagation

$$x' = x + \frac{p_x}{p_t} R \sin \Delta\theta - \frac{p_y}{p_t} R (1 - \cos \Delta\theta)$$

$$y' = y + \frac{p_y}{p_t} R \sin \Delta\theta + \frac{p_x}{p_t} R (1 - \cos \Delta\theta)$$

$$z' = z + \Delta z$$

$$p'_x = p_x \cos \Delta\theta - p_y \sin \Delta\theta$$

$$p'_y = p_y \cos \Delta\theta + p_x \sin \Delta\theta$$

$$p'_z = p_z;$$

$$R = \frac{p_t}{qB_z}$$

$$\Delta\theta = \frac{cB_z Q \Delta z}{p_z}$$

$$c \approx \frac{0.299 \text{ MeV}}{cT^{-1} \text{ mm}^{-1}}$$

# Rescaling Correction

Rescaling correction:

Assume helix remains the same so  $x, x', y, y', R, \Delta\theta$  fixed

→ direction of Pt ( $\frac{p_x}{p_t}$  &  $\frac{p_y}{p_t}$ ) remain the same

$p_x$  and  $p_y$  scaled equally:

$$p'_x = \frac{B'_z}{B_z} p_x, \quad p'_y = \frac{B'_z}{B_z} p_y$$

$$\Delta\theta = \frac{cB_z Q \Delta z}{p_z} \rightarrow p'_z = \frac{B'_z}{B_z} p_z$$

New  $p_z$  looks U-shaped through the trackers,  
so we leave  $p_z$  as is

$$R = \frac{p_t}{qB_z}$$
$$\Delta\theta = \frac{cB_z Q \Delta z}{p_z}$$
$$c \approx \frac{0.299 \text{ MeV}}{cT^{-1} \text{ mm}^{-1}}$$

$$x' = x + \frac{p_x}{p_t} R \sin \Delta\theta - \frac{p_y}{p_t} R (1 - \cos \Delta\theta)$$

$$y' = y + \frac{p_y}{p_t} R \sin \Delta\theta + \frac{p_x}{p_t} R (1 - \cos \Delta\theta)$$

$$z' = z + \Delta z$$

$$p'_x = p_x \cos \Delta\theta - p_y \sin \Delta\theta$$

$$p'_y = p_y \cos \Delta\theta + p_x \sin \Delta\theta$$

$$p'_z = p_z;$$



# Recalculating Correction

Simultaneous eqn correction: Recalculating  $p_x$ ,  $p_y$  with new  $B_z$   
Residuals on  $x, x', y, y'$  order of magnitude lower, keep fixed  
Keep  $p_z$  fixed to calc  $\Delta\theta$

$$\text{Use } R = \frac{p_t}{qB_z}, \quad \Delta\theta = \frac{cB_z Q \Delta z}{p_z}$$

Solve simultaneous equations for  $p_x$ ,  $p_y$ :

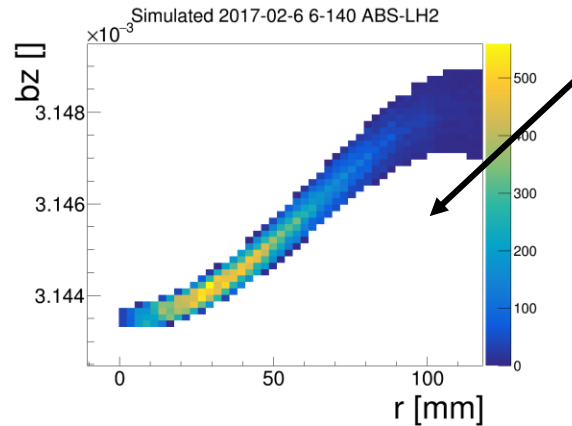
$$x' - x = \frac{p_x}{qB_z} \sin\Delta\theta - \frac{p_y}{qB_z} (1 - \cos\Delta\theta),$$
$$y' - y = \frac{p_y}{qB_z} \sin\Delta\theta + \frac{p_x}{qB_z} (1 - \cos\Delta\theta),$$

- Recalculating with old  $B_z$  under/overestimates slightly,
- Recalculating with new  $B_z$  gives close to MAUS reco  $p_x$ ,  $p_y$ ,  
Some values wildly off

# MAUS Correction

MAUS uses a single  $B_z$  value for track propagation in each tracker, replace with station-to-station average  $B_z$  values

Average  $B_z$  along central solenoid axis – other choices could be better, beam does not mostly populate  $r = 0$

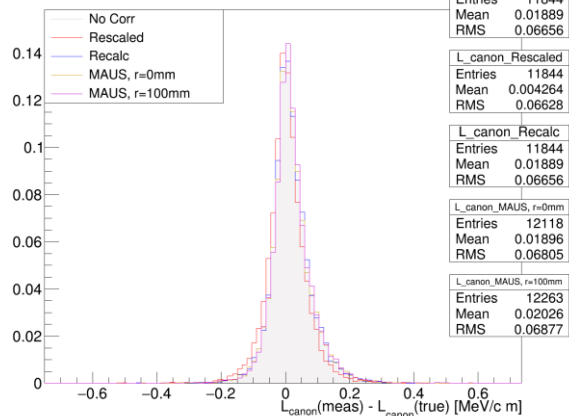


O(0.1%) field variation in  $r$ , so expect small effect

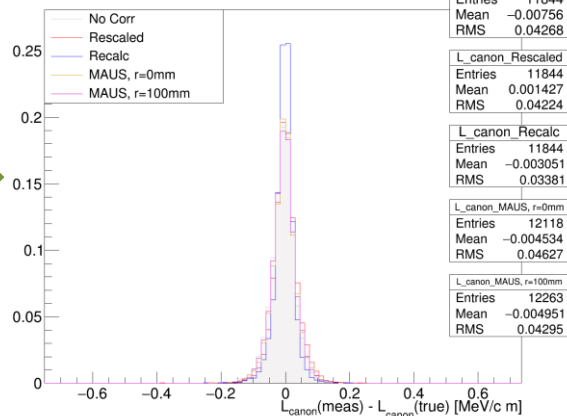
# Correction Residuals

# L\_canon Residuals, TKU

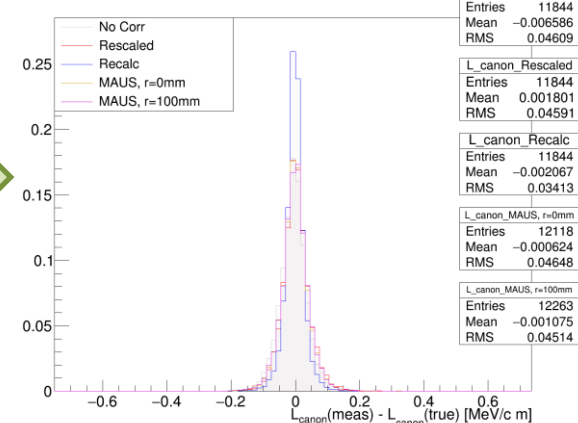
tku\_5



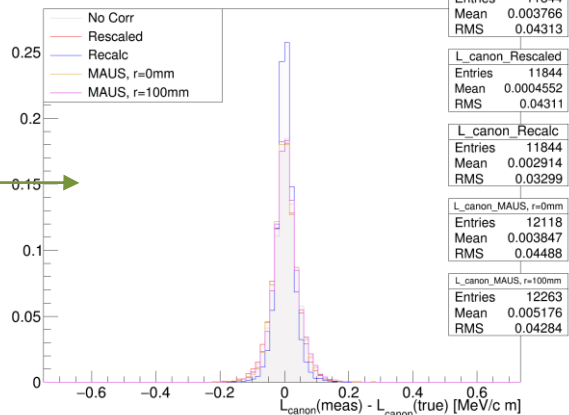
tku\_4



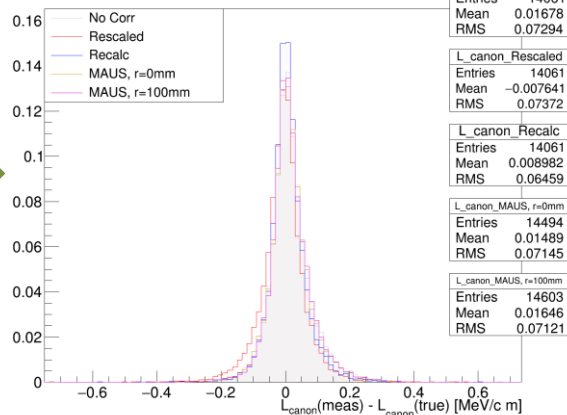
tku\_3



tku\_2

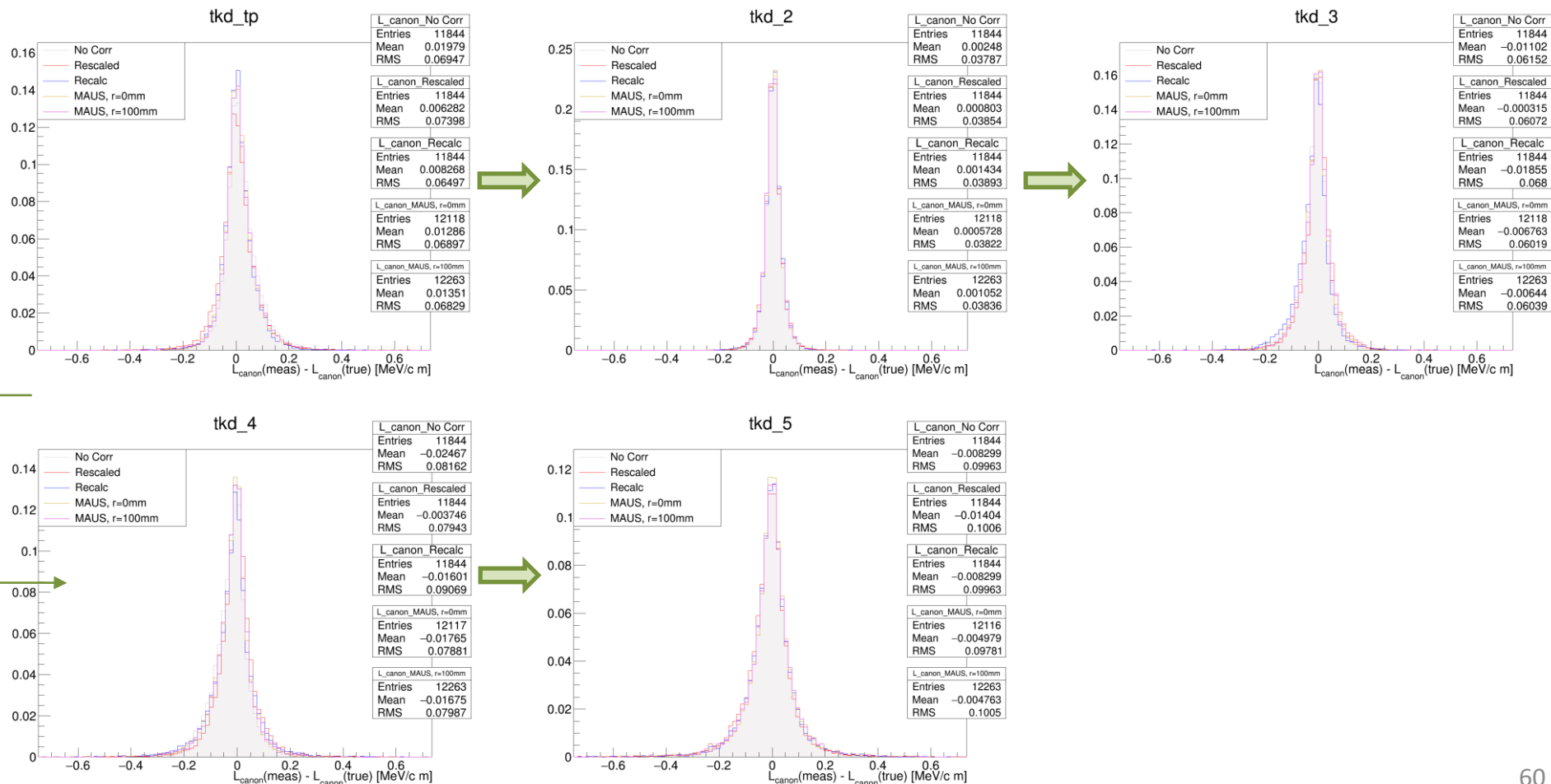


tku\_tp



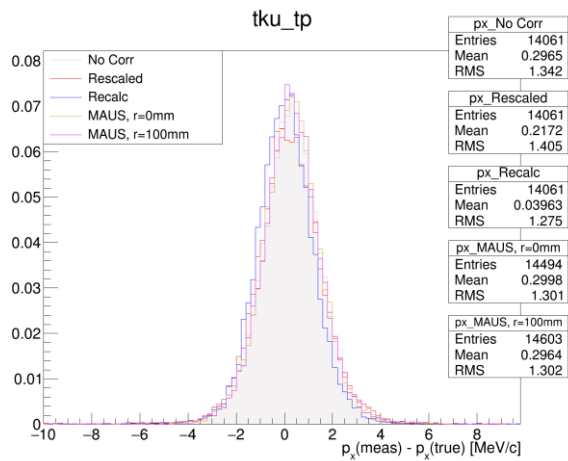
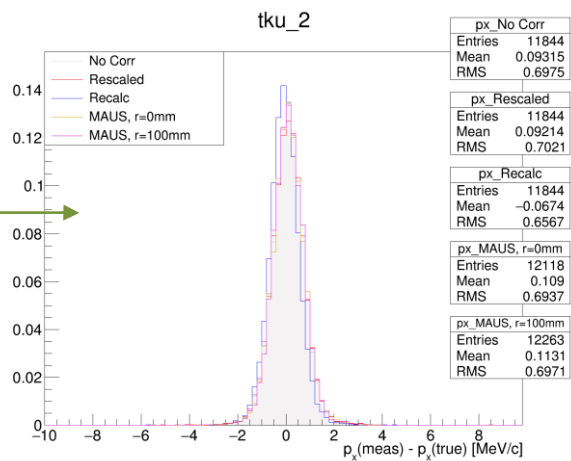
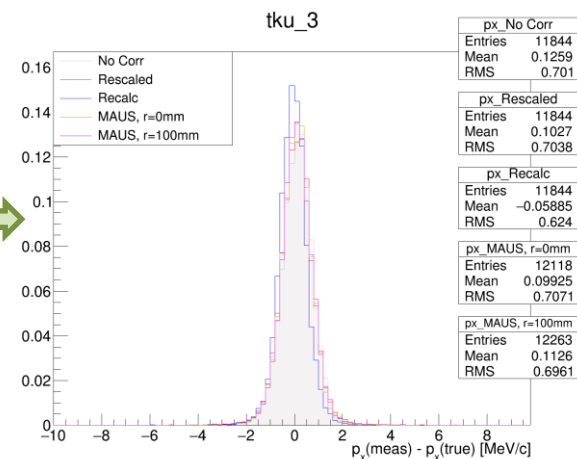
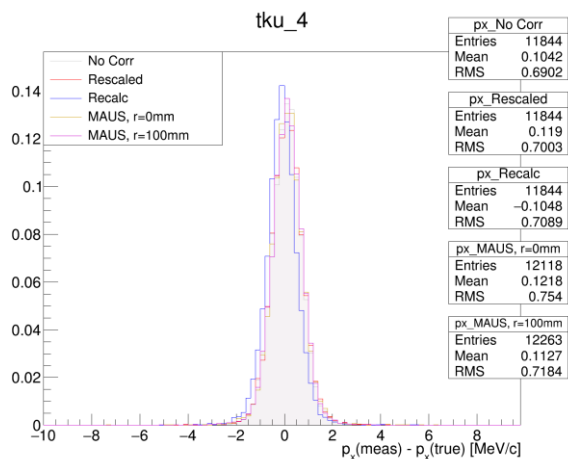
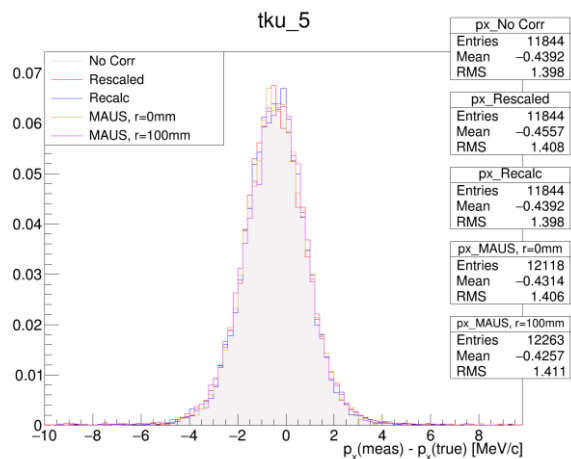
# Correction Residuals

# L\_canon Residuals, TKD



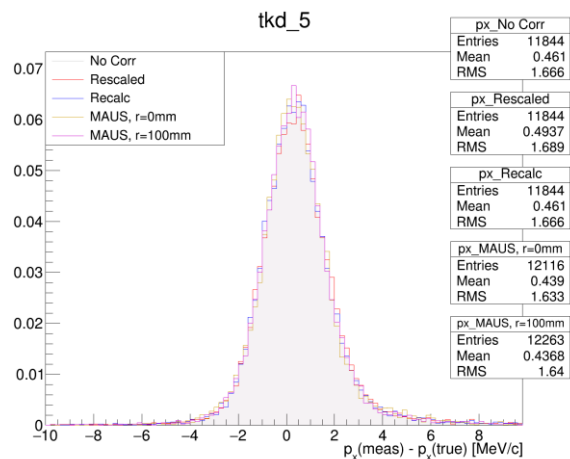
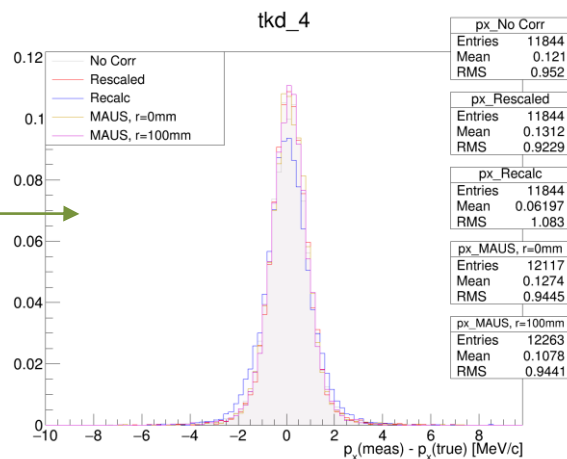
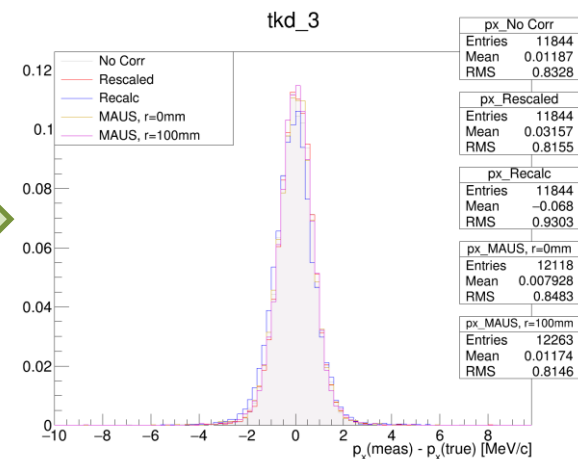
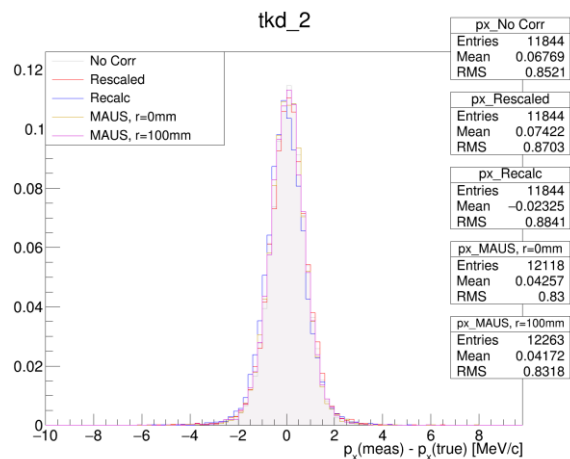
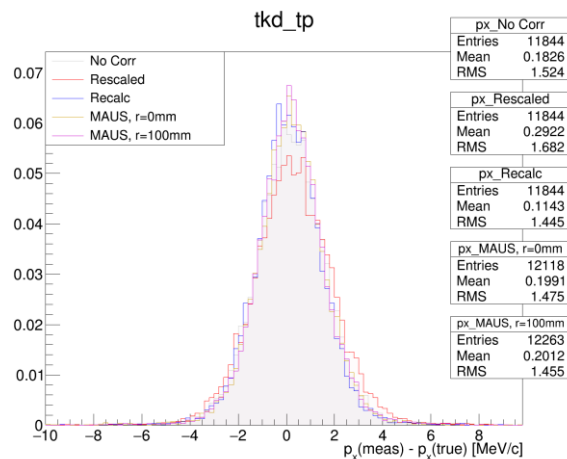
# Correction Residuals

# Px Residuals, TKU



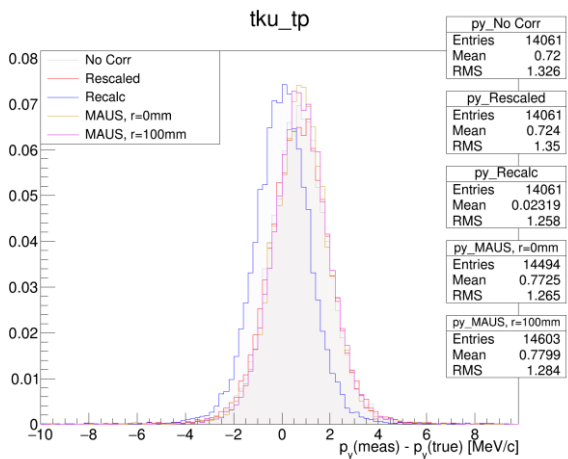
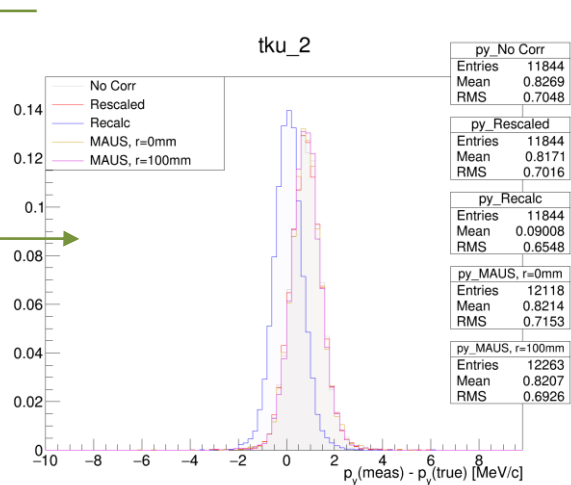
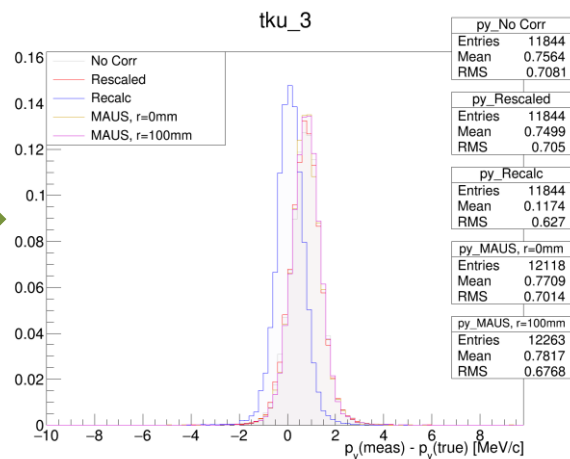
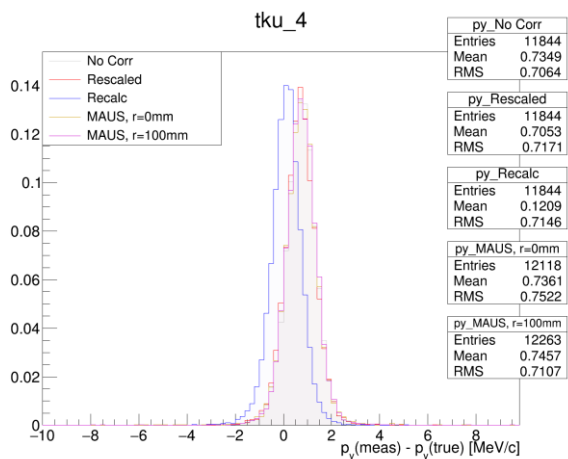
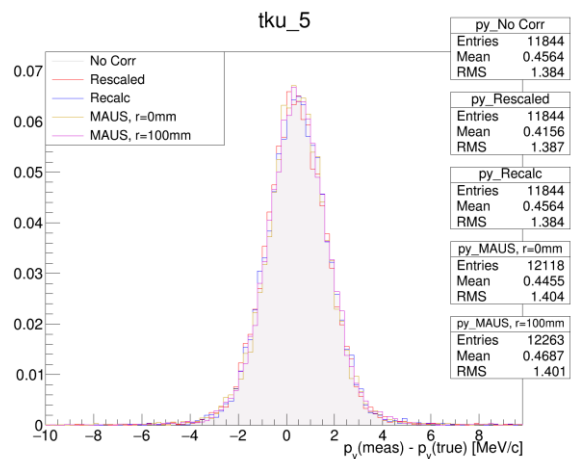
# Correction Residuals

# Px Residuals, TKD



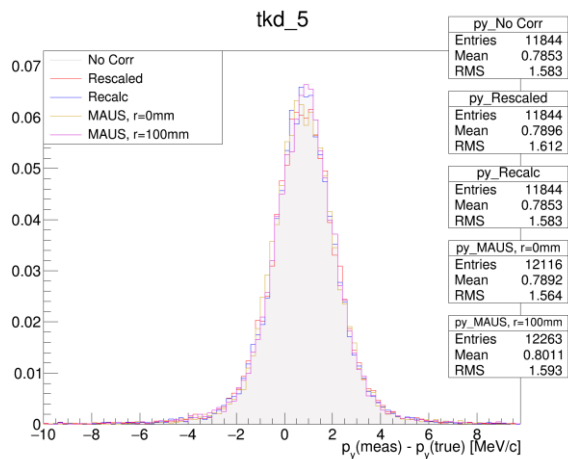
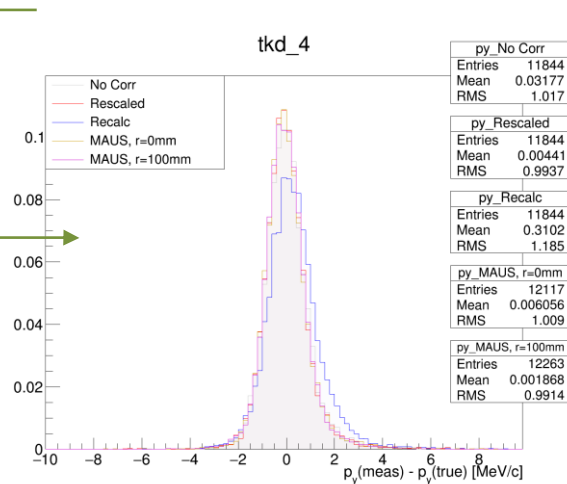
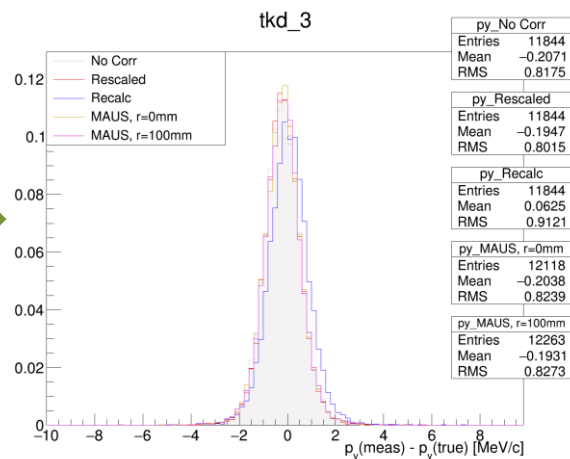
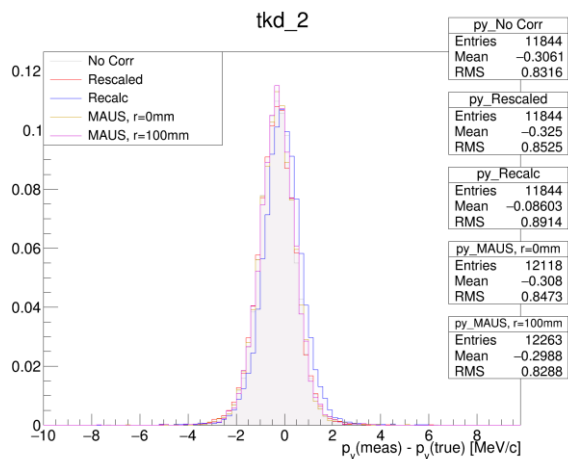
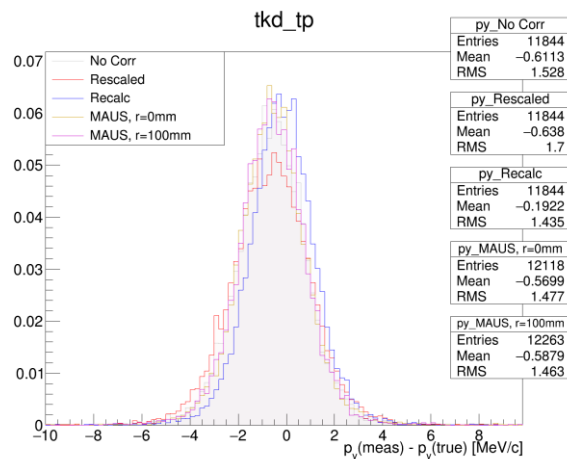
# Correction Residuals

# Py Residuals, TKU



# Correction Residuals

# Py Residuals, TKD

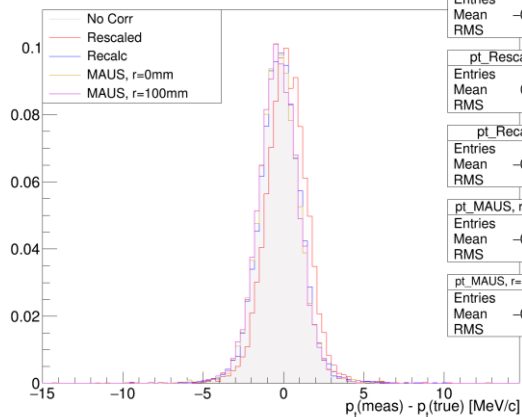




# Correction Residuals

# Pt Residuals, TKU

tku\_5



pt_No Corr	
Entries	11844
Mean	-0.2187
RMS	1.396

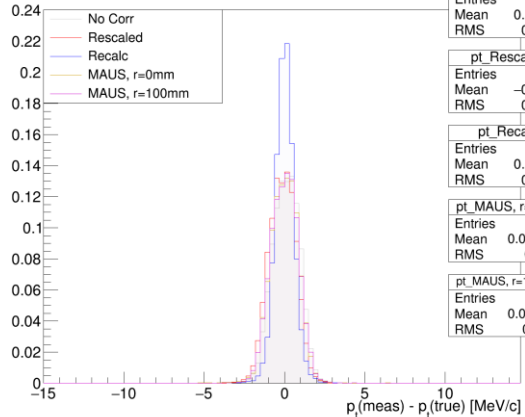
pt_Rescaled	
Entries	11844
Mean	0.2028
RMS	1.393

pt_Recalc	
Entries	11844
Mean	-0.2187
RMS	1.396

pt_MAUS, r=0mm	
Entries	12118
Mean	-0.2773
RMS	1.405

pt_MAUS, r=100mm	
Entries	12263
Mean	-0.2985
RMS	1.396

tku\_4



pt_No Corr	
Entries	11844
Mean	0.09885
RMS	0.8788

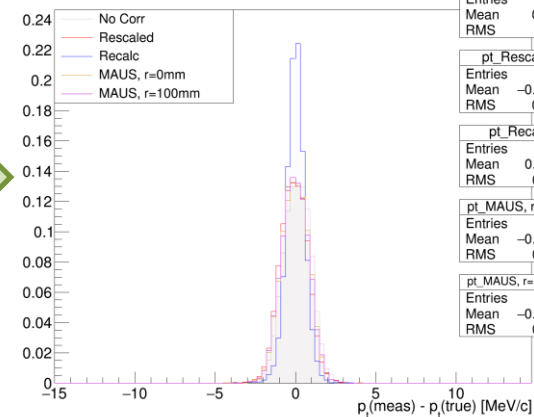
pt_Rescaled	
Entries	11844
Mean	-0.1409
RMS	0.8709

pt_Recalc	
Entries	11844
Mean	0.01259
RMS	0.6636

pt_MAUS, r=0mm	
Entries	12118
Mean	0.004813
RMS	0.9421

pt_MAUS, r=100mm	
Entries	12263
Mean	0.005003
RMS	0.8838

tku\_3



pt_No Corr	
Entries	11844
Mean	0.1094
RMS	0.8761

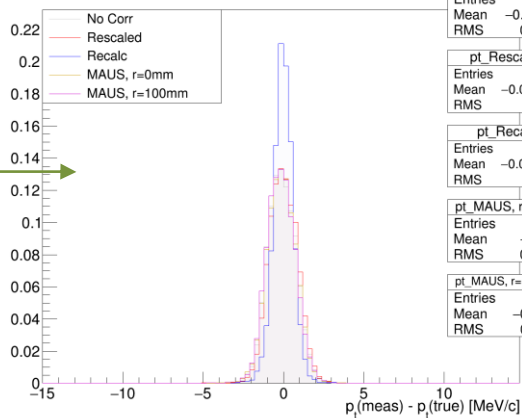
pt_Rescaled	
Entries	11844
Mean	-0.08742
RMS	0.8727

pt_Recalc	
Entries	11844
Mean	0.02149
RMS	0.6319

pt_MAUS, r=0mm	
Entries	12118
Mean	-0.01495
RMS	0.9023

pt_MAUS, r=100mm	
Entries	12263
Mean	-0.02398
RMS	0.8666

tku\_2



pt_No Corr	
Entries	11844
Mean	-0.09817
RMS	0.8924

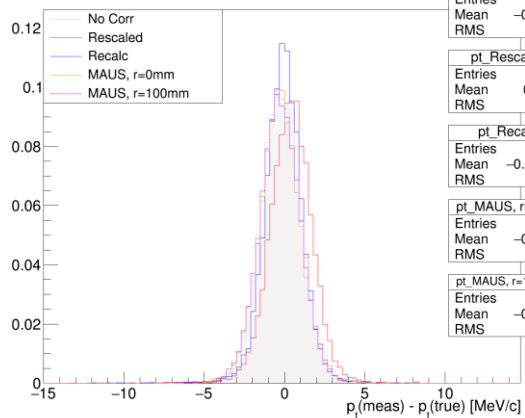
pt_Rescaled	
Entries	11844
Mean	-0.001569
RMS	0.8927

pt_Recalc	
Entries	11844
Mean	-0.009072
RMS	0.648

pt_MAUS, r=0mm	
Entries	12118
Mean	-0.108
RMS	0.9207

pt_MAUS, r=100mm	
Entries	12263
Mean	-0.1506
RMS	0.8888

tku\_tp



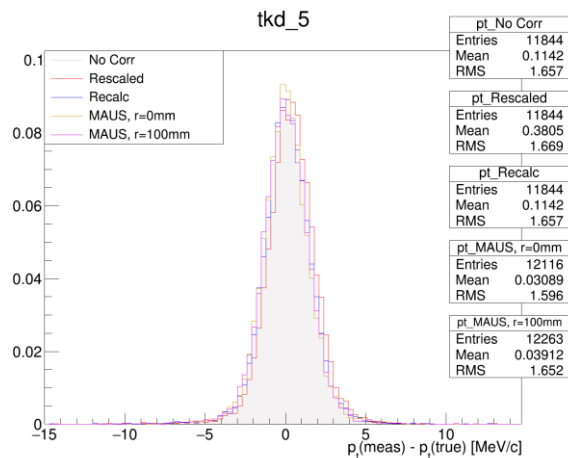
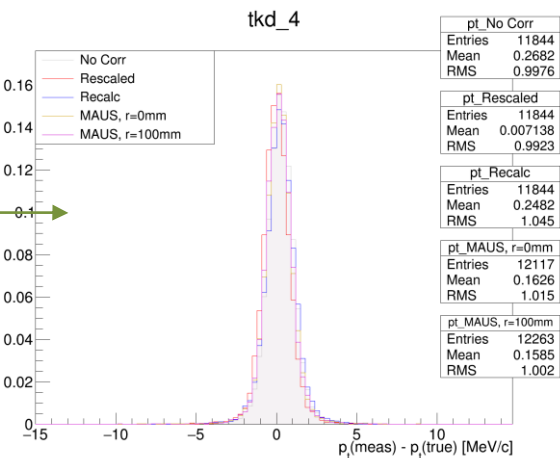
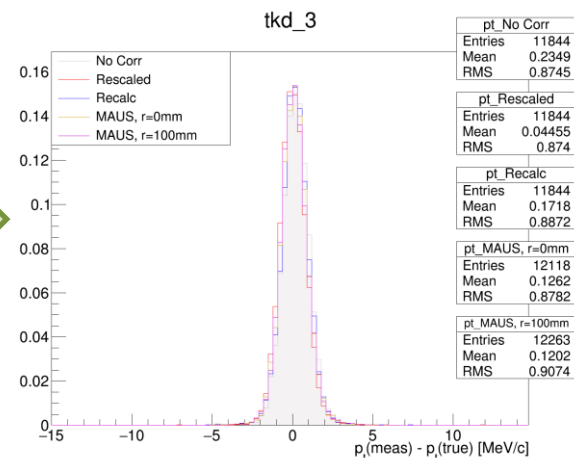
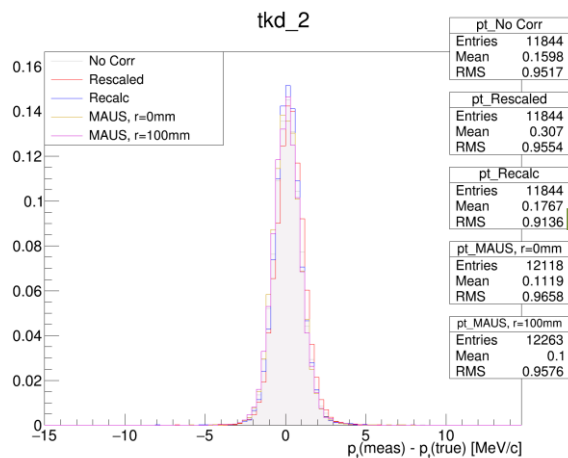
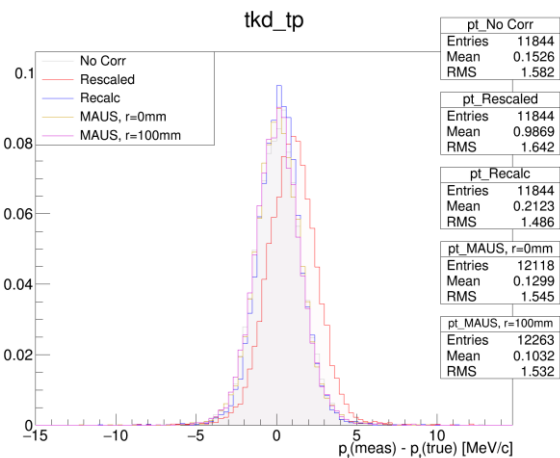
pt_No Corr	
Entries	14061
Mean	-0.2719
RMS	1.411

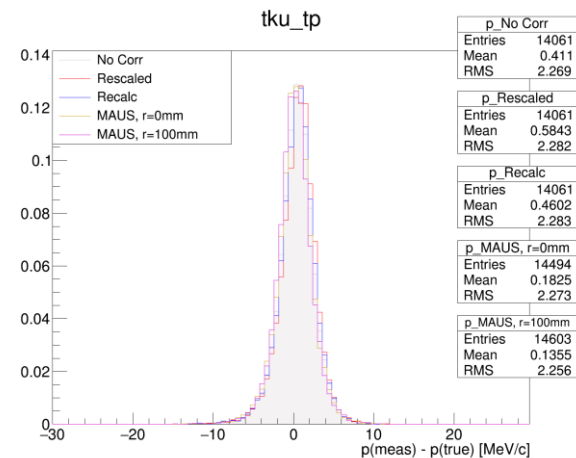
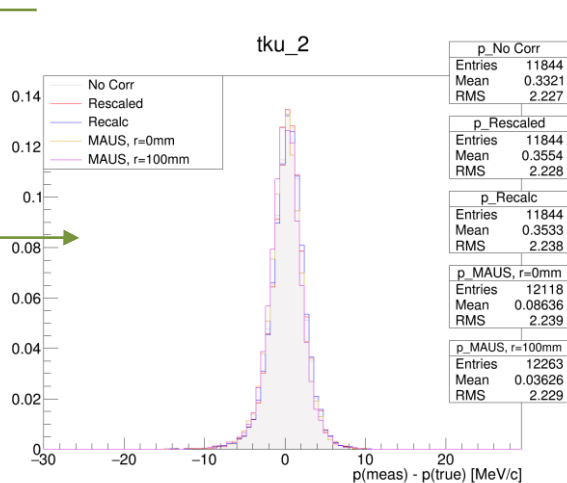
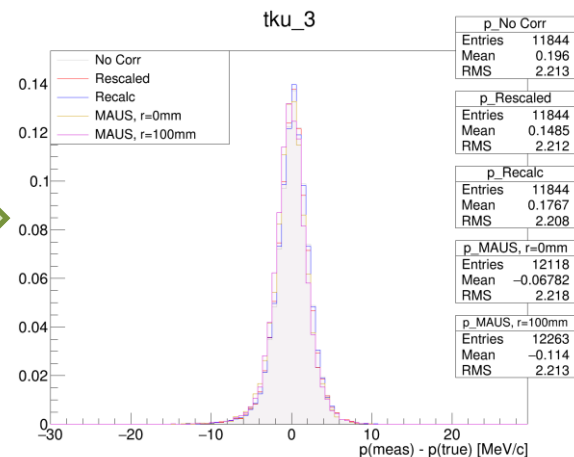
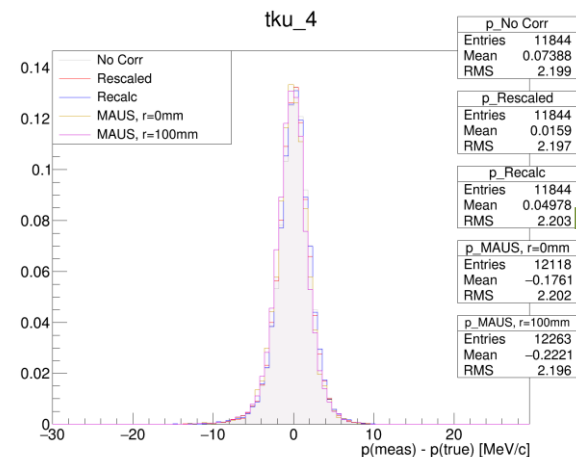
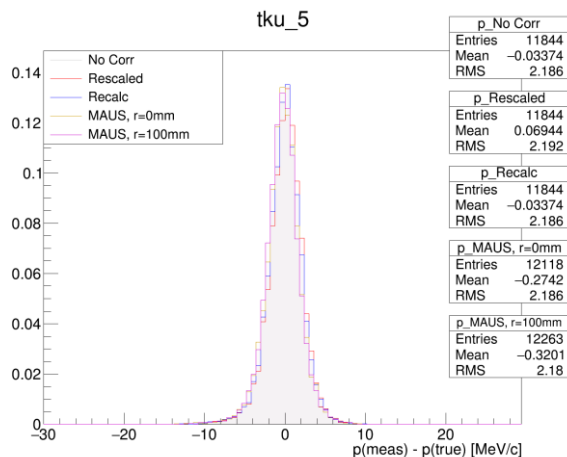
pt_Rescaled	
Entries	14061
Mean	0.4001
RMS	1.435

pt_Recalc	
Entries	14061
Mean	-0.07983
RMS	1.3

pt_MAUS, r=0mm	
Entries	14494
Mean	-0.2557
RMS	1.394

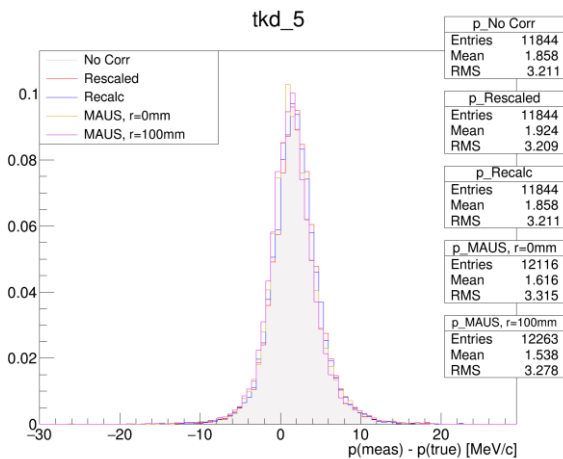
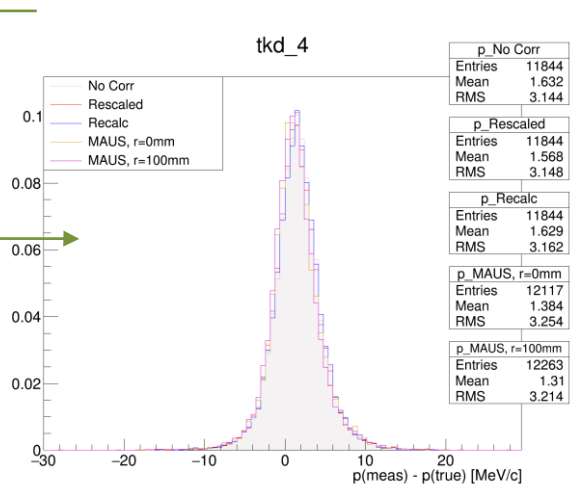
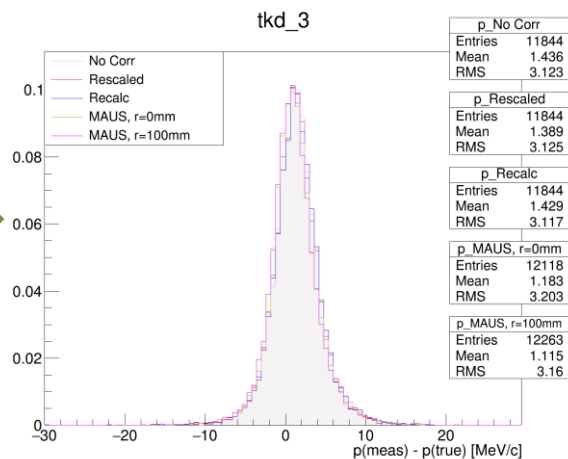
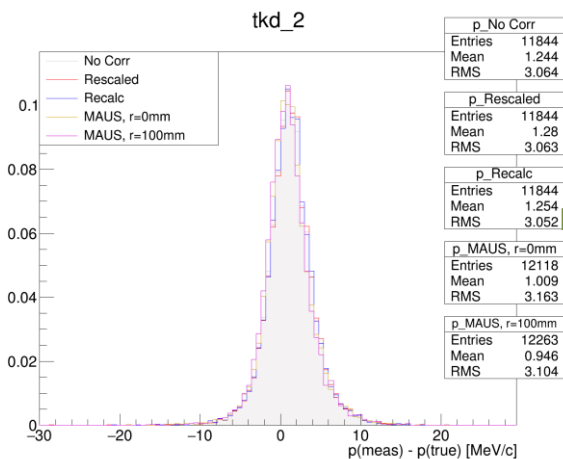
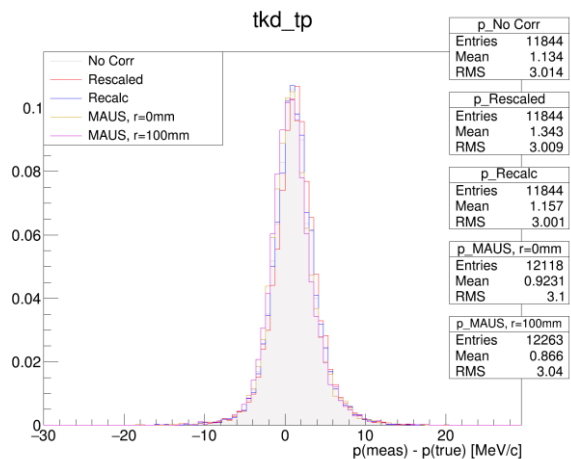
pt_MAUS, r=100mm	
Entries	14603
Mean	-0.2802
RMS	1.378





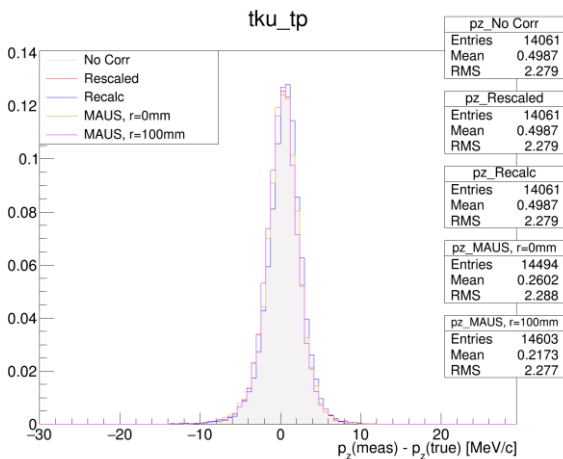
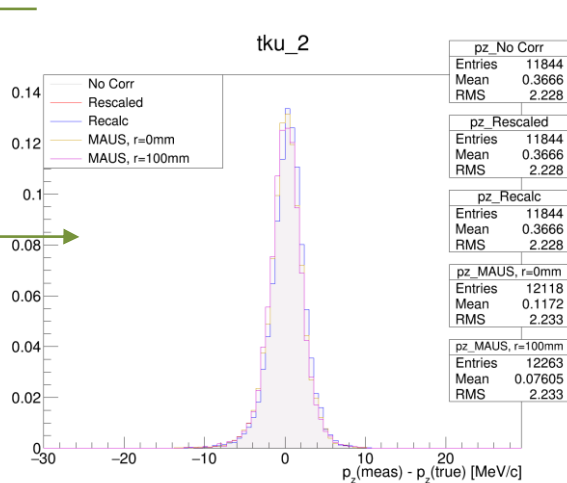
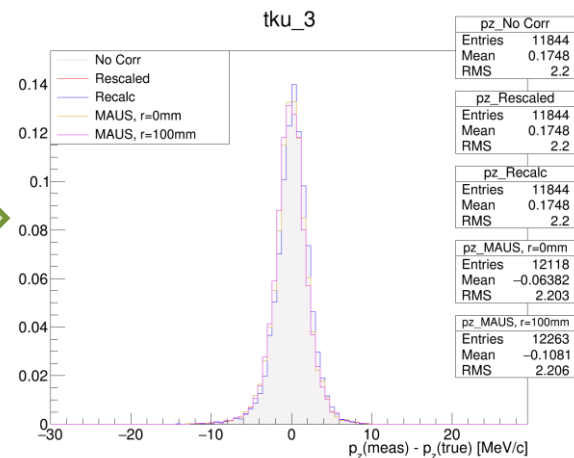
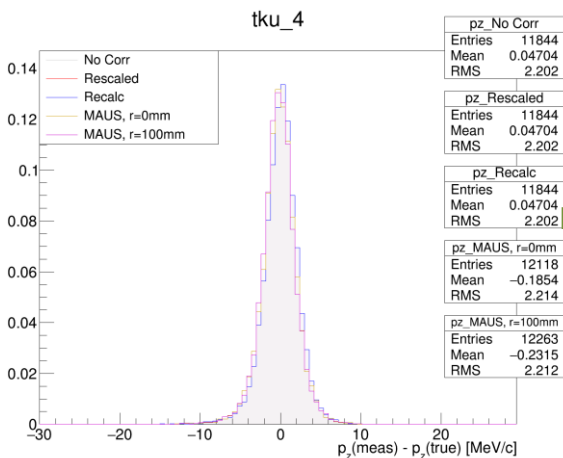
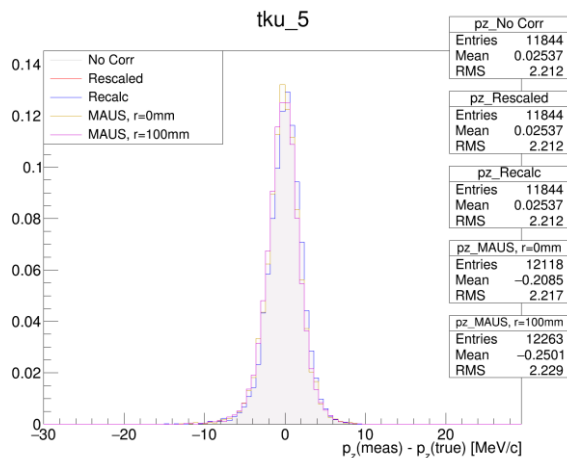
# Correction Residuals

# P Residuals, TKD



# Correction Residuals

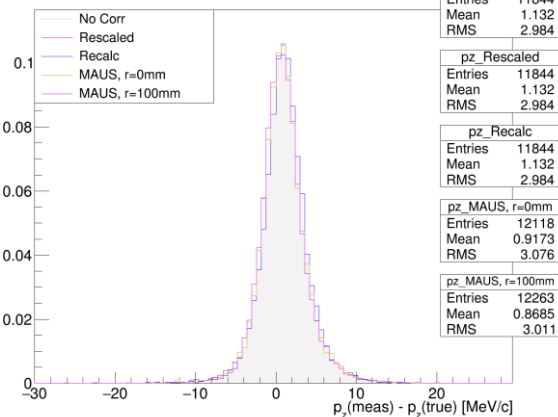
# Pz Residuals, TKU



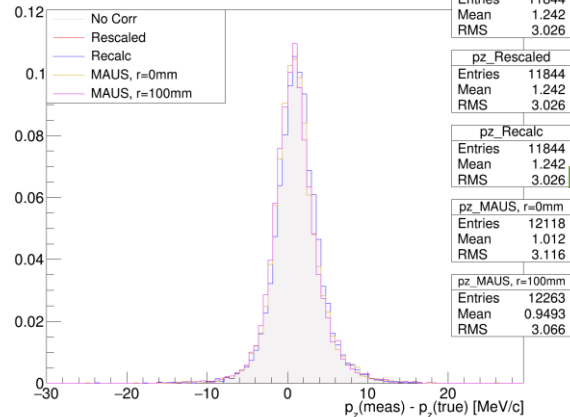
# Correction Residuals

# Pz Residuals, TKD

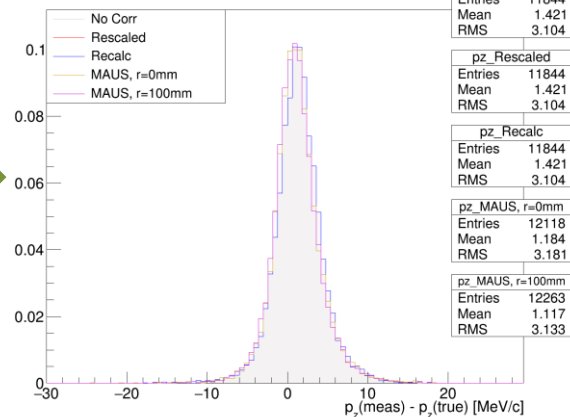
tkd\_tp



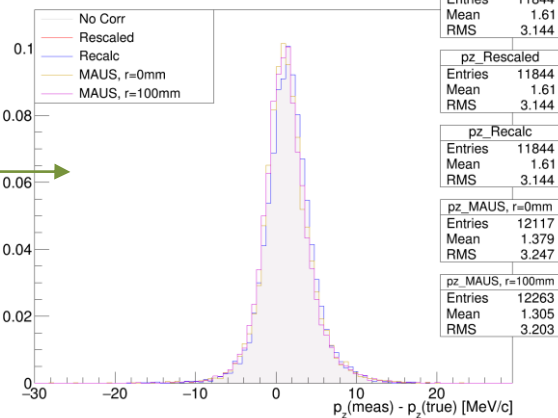
tkd\_2



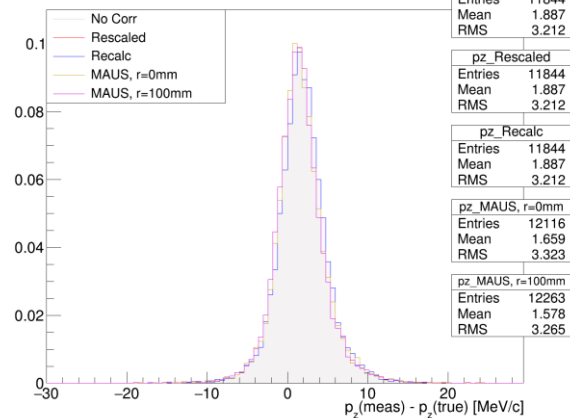
tkd\_3

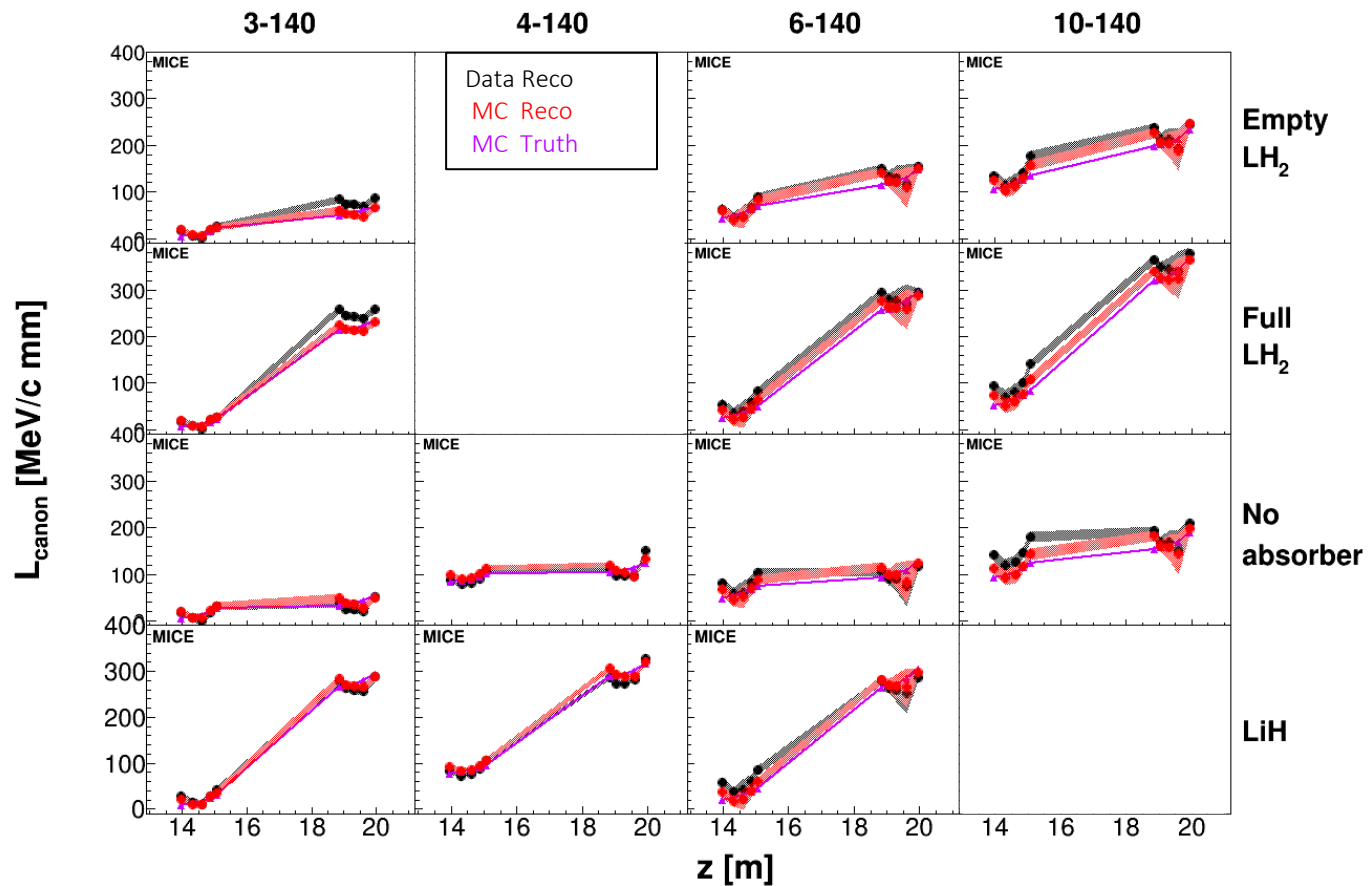


tkd\_4



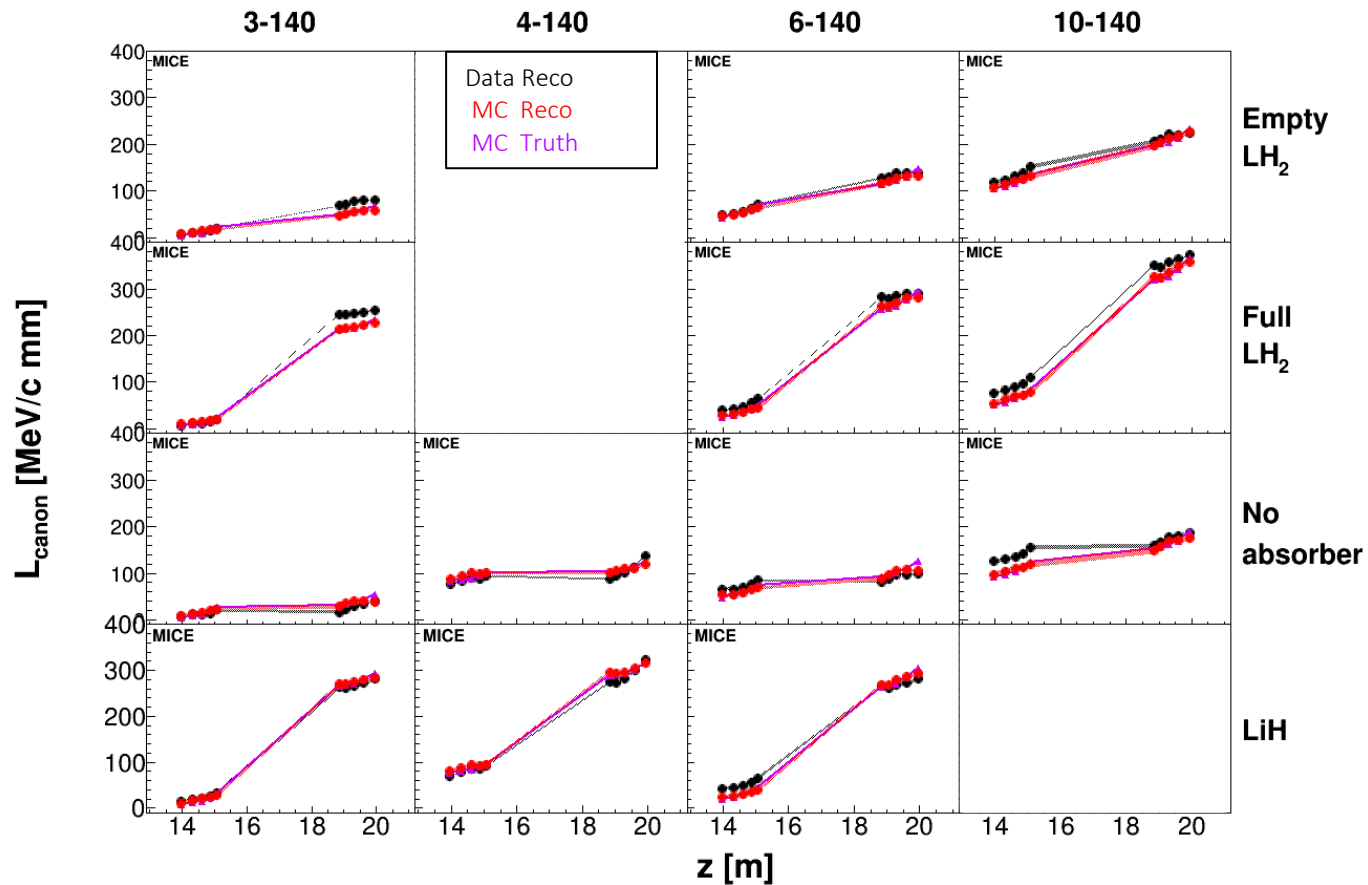
tkd\_5





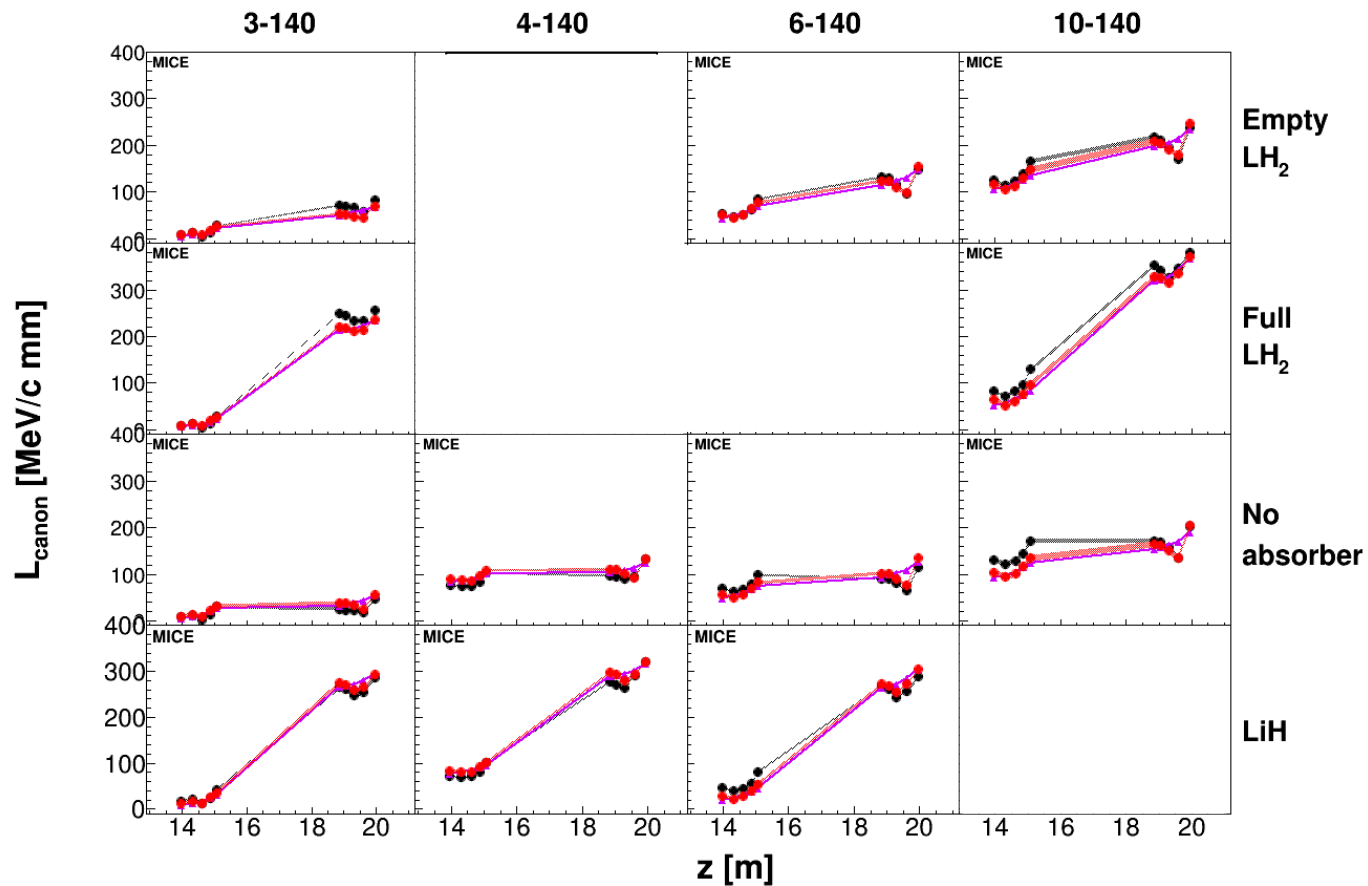
No Correction,  
Band shows  
Sys + Stat Error

# L canon Mean – Rescaled Corr



Rescaled Correction  
Stat Error Only

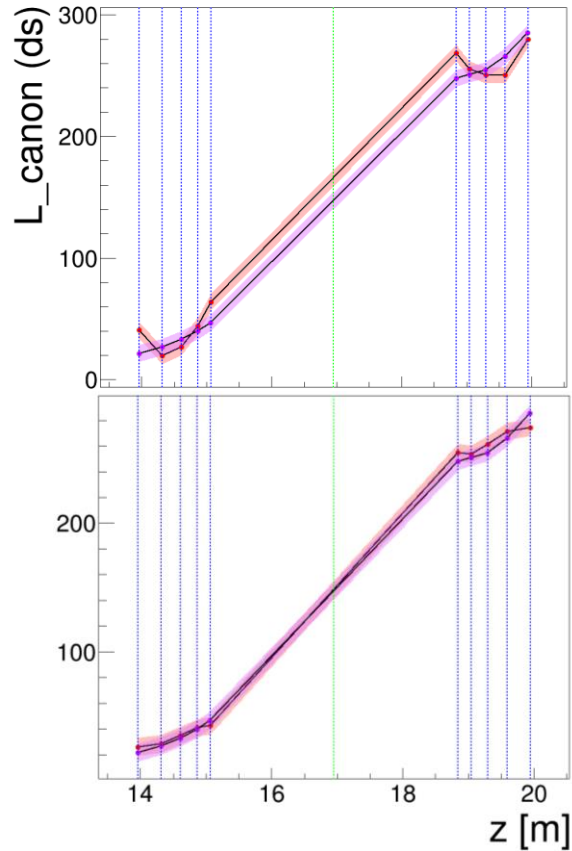




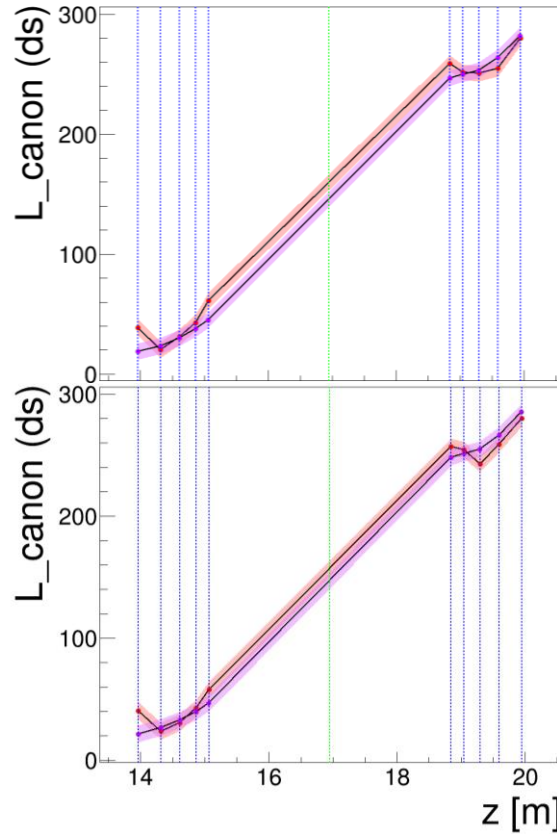
Recalc Correction  
Stat Error Only

# Corrections

MAUS 3.3.2 No Correction  
Simulated 2017-02-6 6-140 ABS-LH2



MAUS 3.3.5 Correction  
Simulated 2017-02-6 6-140 ABS-LH2



MAUS 3.3.2 Rescaling Correction

MAUS 3.3.2 Recalculated Correction