Flip mode emittance analysis

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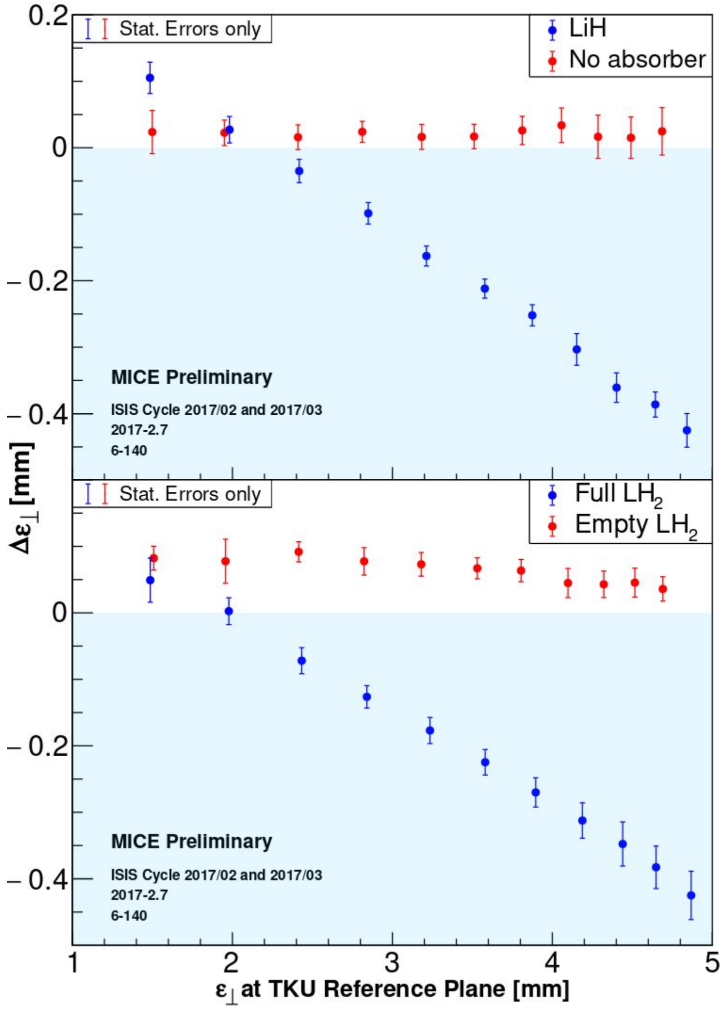
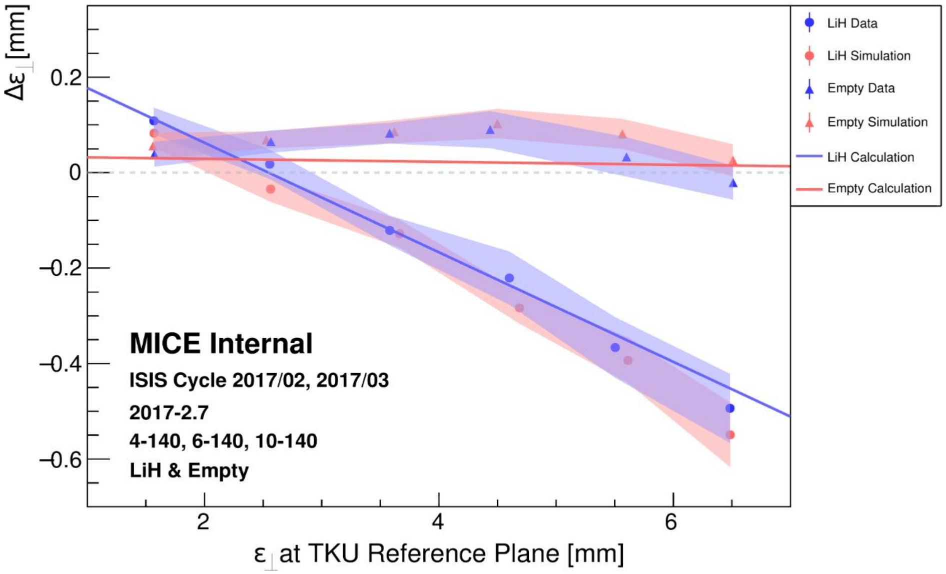
MICE Special VC

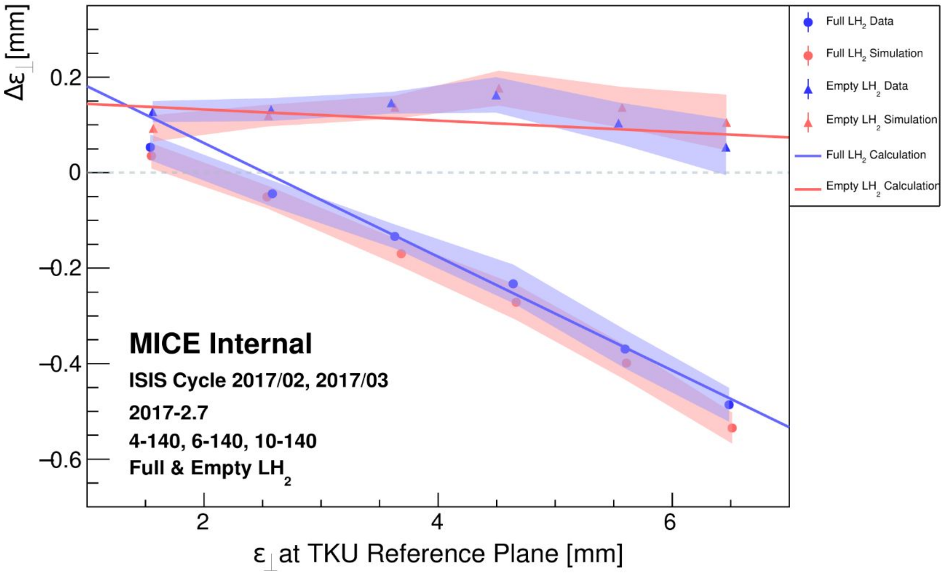
Emittance change: 2020 plots

- presented at Neutrino and ICHEP
- contain only data, namely 6-140 dataset
- no systematics
- beams are correlated i.e. they share events



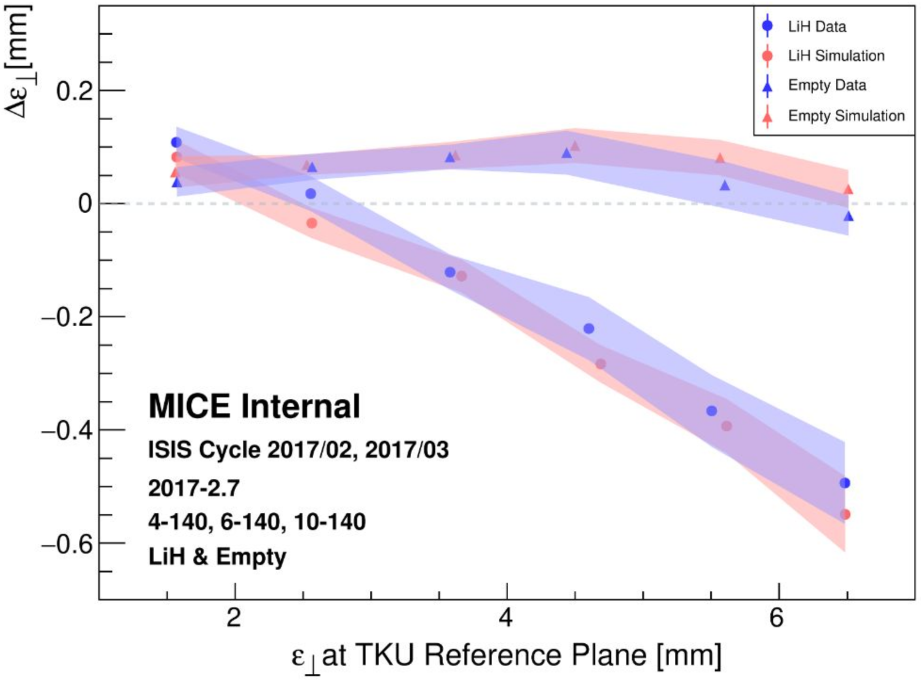
Emittance change: updated plots

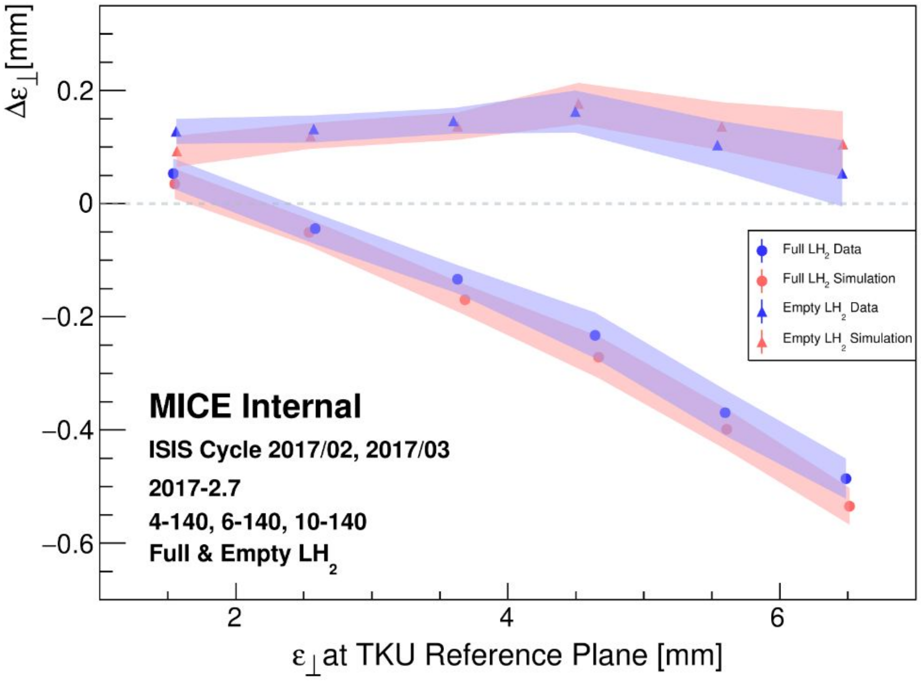




- include 4,6,10 - 140 dataset and the corresponding MC
- beams are not correlated, don't share any muons
- systematic uncertainties included
- transmission bias corrected

Emittance change: updated plots (2)





Canonical angular momentum

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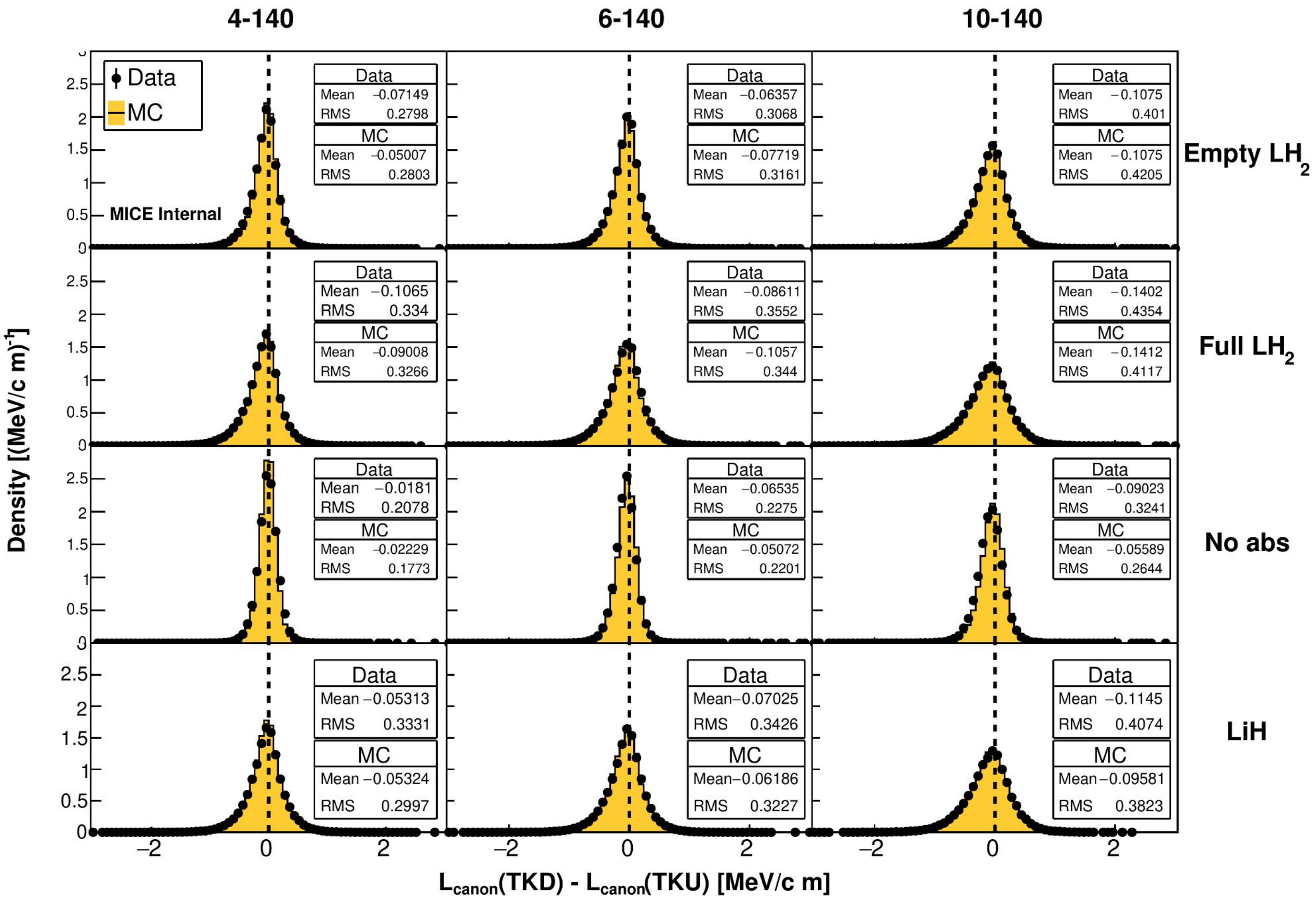
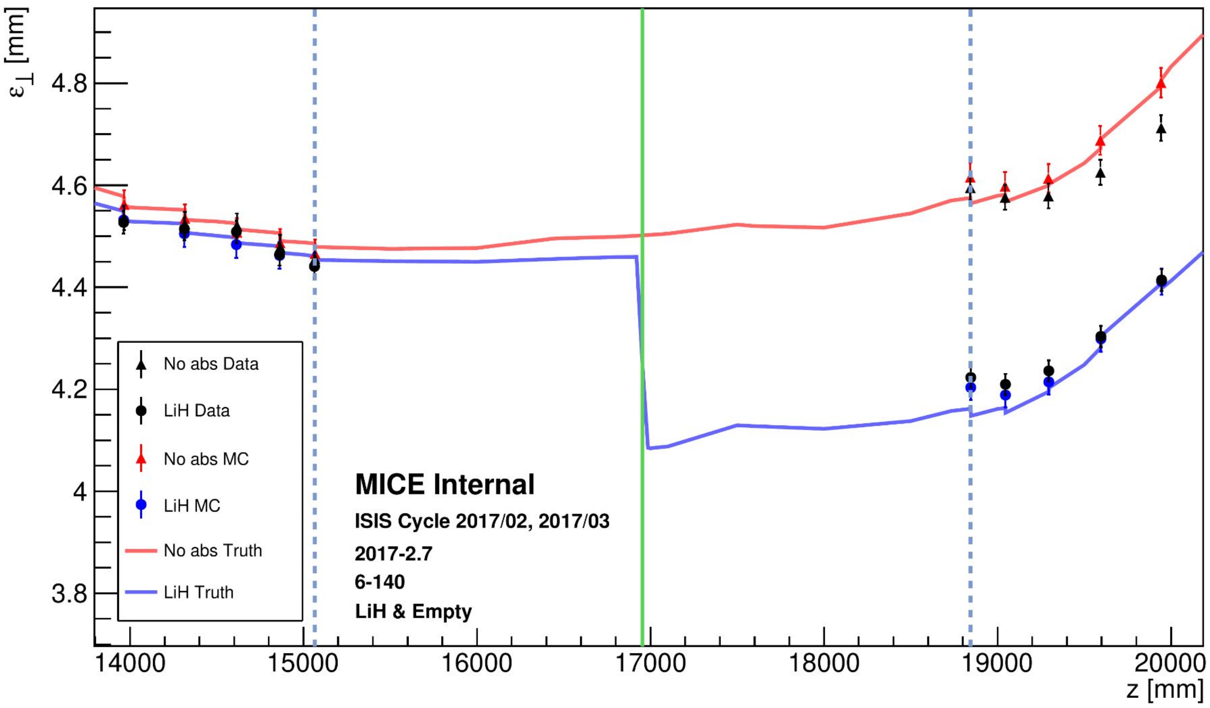


Emittance evolution vs z

Aim is to provide a comparison of emittance evolution through the cooling channel - empty vs absorber

Note: no corrections applied at this stage

~ 4.5 mm beam, LiH and No absorber



IPAC21

Paul Bogdan Jurj

Normalized Transverse Emittance Reduction via Ionization Cooling in MICE 'Flip' Mode

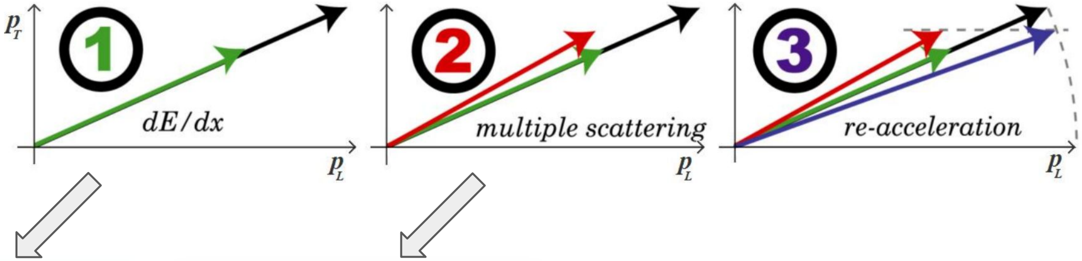
Paul Bogdan Jurj
Imperial College London
On behalf of the MICE collaboration

2x/05/2021 IPACPoster Session

Ionization cooling

- High brightness muon beams essential for development of facilities such as Neutrino Factory and Muon Collider
- Muons typically produced via pion decay ➞ diffuse beam; difficult to characterize and manipulate
- IONIZATION COOLING: proposed technique to reduce muon beam phase-space volume (emittance)

- Beam momentum spread reduced via energy loss in an absorber material



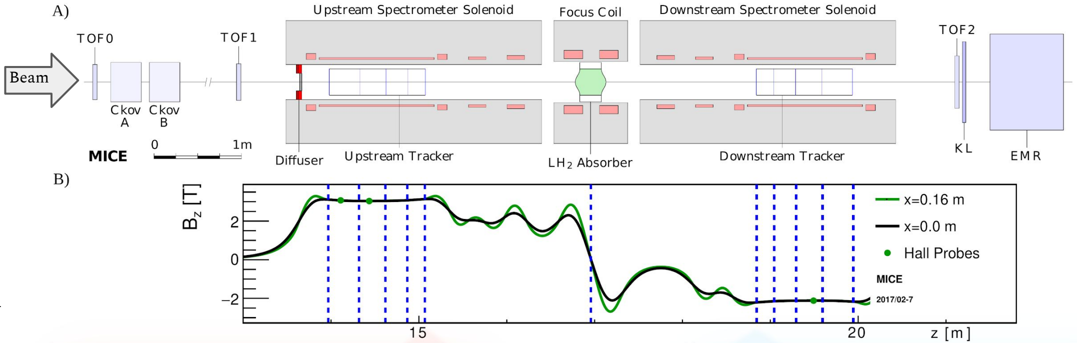
- Emittance evolution described by the cooling equation:

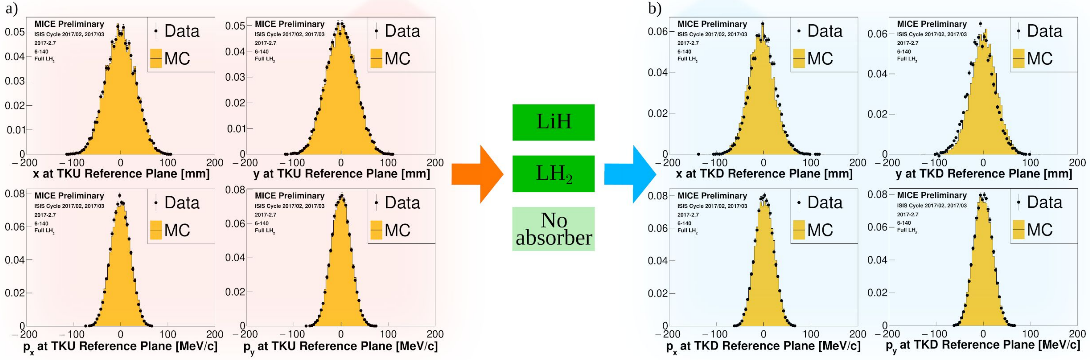
$$\frac{d\varepsilon_\perp}{dz} \simeq -\frac{1}{\beta^2}\frac{\varepsilon_\perp}{E_\mu}\left|\frac{dE_\mu}{dz}\right| + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{1}{X_0}. \quad (1)$$

- Cooling performance increased by using low Z, high radiation length materials and tightly focusing the beam at the absorber (low $\beta_\perp$)

MICE Cooling Apparatus

- A transfer line delivered the muon beam to the cooling apparatus
- Beam tightly focused using 12 superconducting solenoids
- Field flipped polarity at absorber to prevent canonical angular momentum build-up
- Individual muon position and momentum measured before and after passing through an absorber by scintillating fiber trackers immersed in 3 T and -2 T uniform fields
- Muon beams crossed liquid hydrogen (LH_2) and lithium hydride (LiH) absorbers

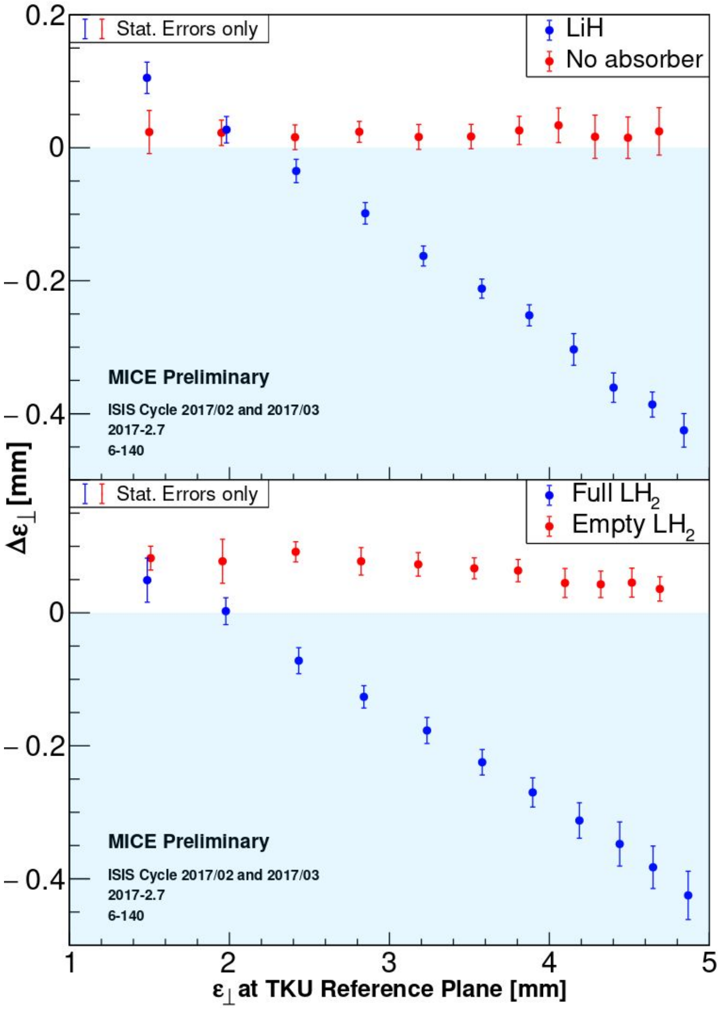




First demonstration of cooling published in Nature **578** (2020) 53,
doi: 10.1038/s41586-020-1958-9

Emittance reduction

- Emittance change: $\Delta\varepsilon_\perp = \varepsilon_{\perp downstream} - \varepsilon_{\perp upstream}$
- $\Delta\varepsilon_\perp < 0$ ➡ **COOLING**
- Data presented here taken using beams with 140 MeV/c nominal input momentum and 6 mm input normalized transverse emittance
- Rejection sampling used to obtain beams with optimized optics, reducing the heating
- ‘No absorber’ - no significant emittance change
- ‘Empty LH_2’ - slight heating due to muon scattering in the vessel windows
- ‘Full LH_2’ and ‘LiH’ demonstrate emittance reduction, clear signal of ionization cooling



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Canonical angular momentum evolution

$$\frac{d\langle L_{canon}\rangle}{dz} = \frac{1}{\beta^2 E_\mu}\left|\frac{dE}{dz}\right|(m_\mu c\epsilon_\perp \beta_\perp qB_z / < p_z > - < L_{canon} >)$$

Canonical Angular Momentum

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

$$L_{kin} = xp_y - yp_x$$

$$L_{field} = qrA \approx \frac{qr^2 B_z}{2}$$

For each particle, B_z at particle position is loaded from MAUS field map

1D Distributions

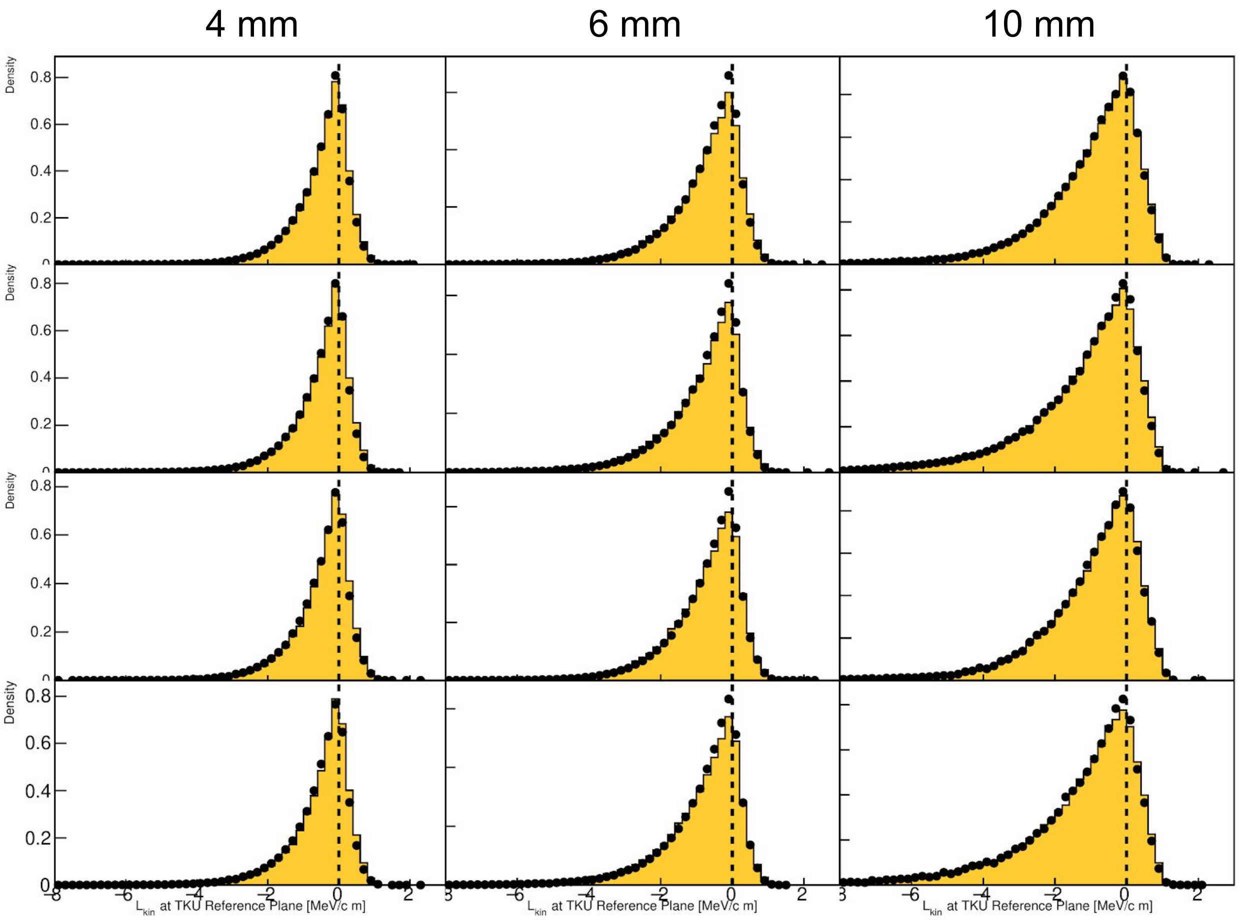
L_{kin} TKU

Empty LH2

LH2

No absorber

LiH



L_{kin} TKD

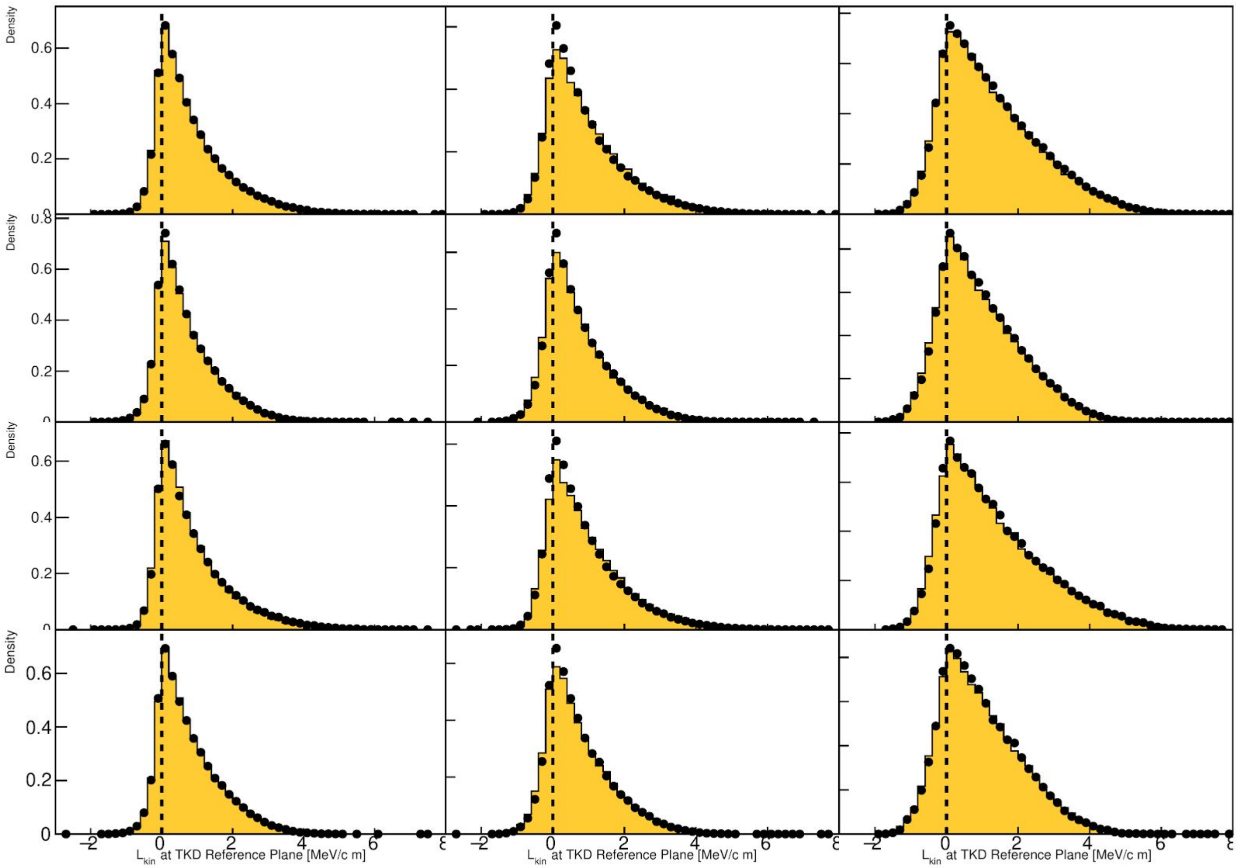
4 mm | 6 mm | 10 mm

Empty LH2

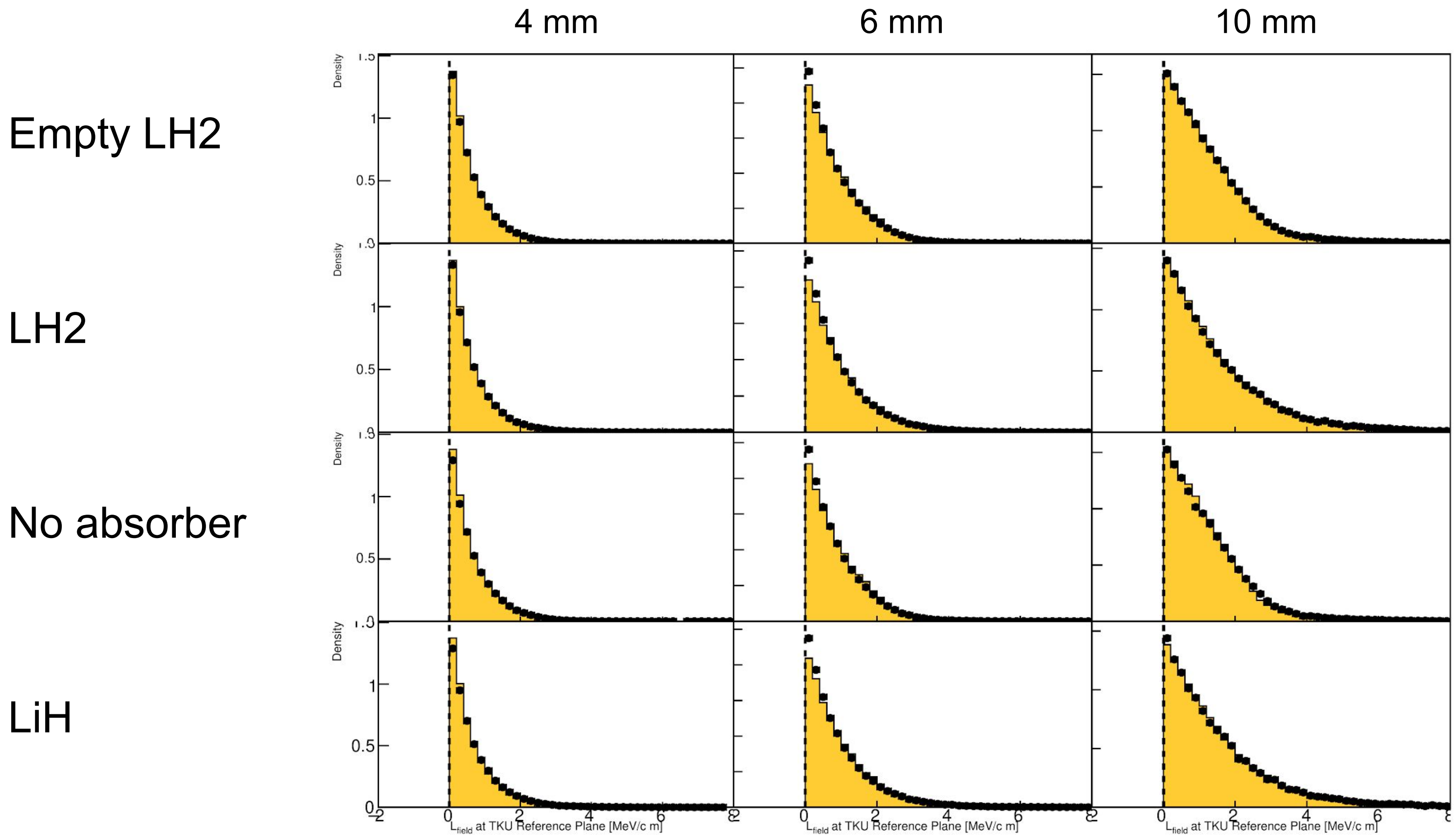
LH2

No absorber

LiH



L_{field} TKU



4 mm
6 mm
10 mm
Empty LH2
LH2
No absorber
LiH
Density
L_{field} at TKU Reference Plane [MeV/c m]

L_{field} TKD

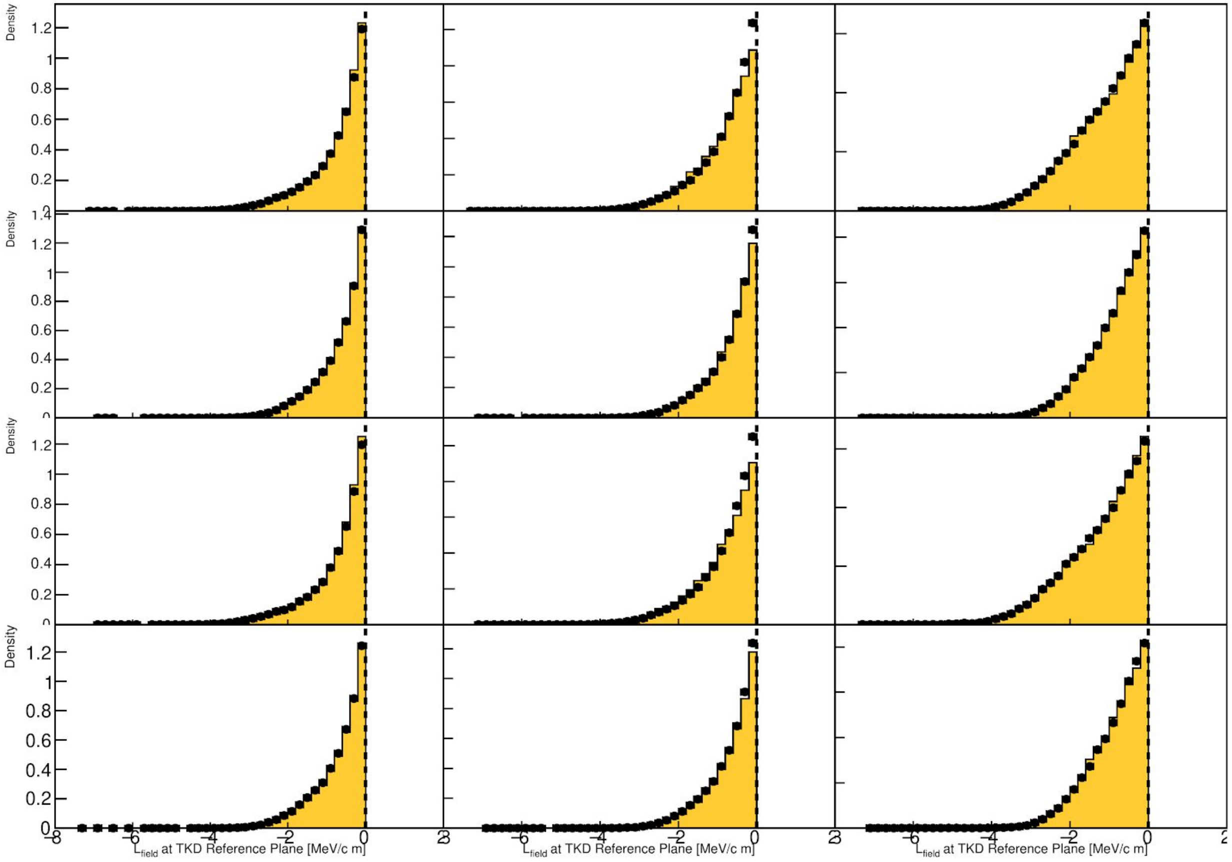
4 mm | 6 mm | 10 mm

Empty LH2

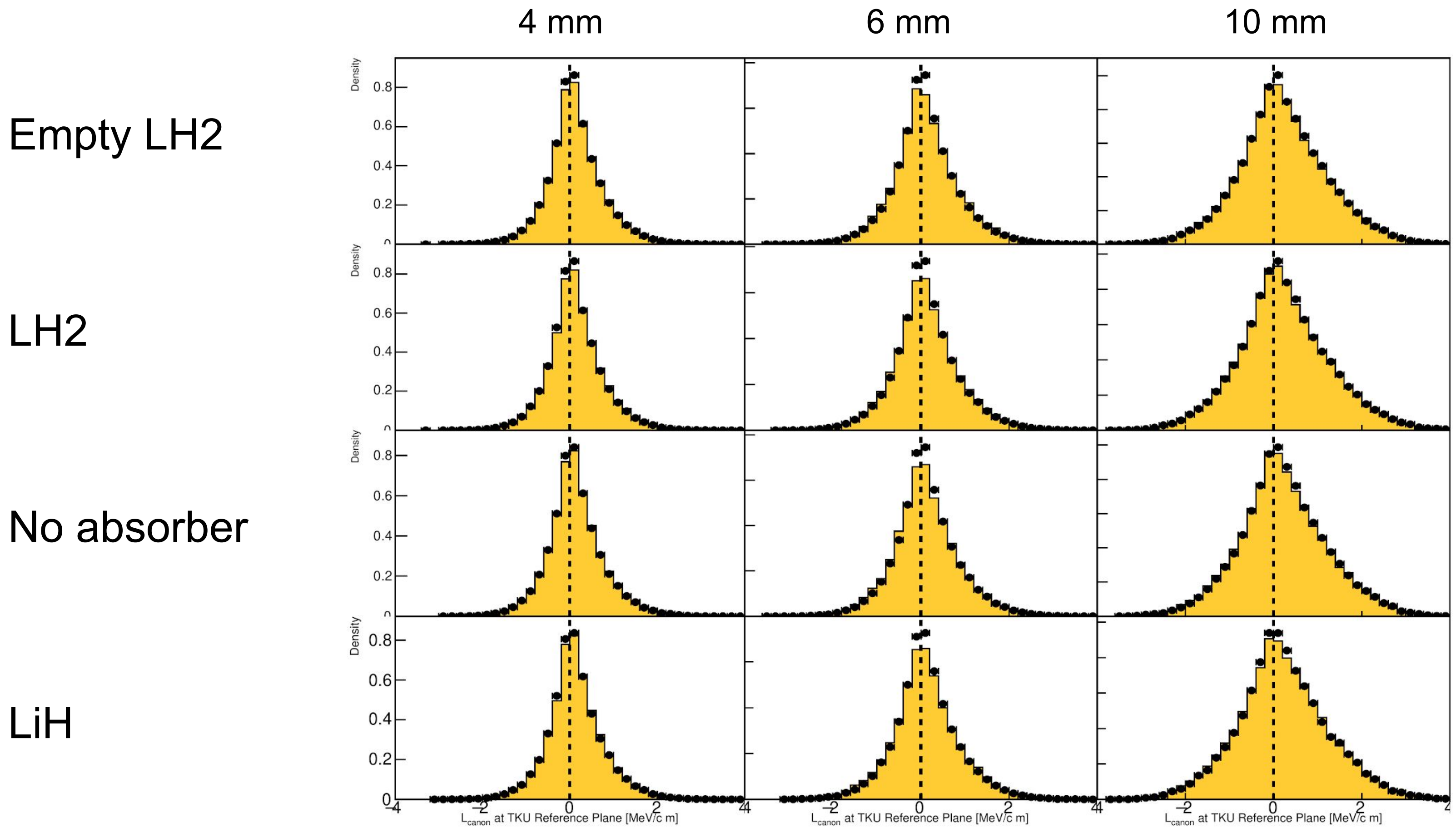
LH2

No absorber

LiH



L_{canon} TKU



4 mm
6 mm
10 mm
Empty LH2
LH2
No absorber
LiH
Density
0.8
0.6
0.4
0.2
0
−4
−2
0
2
4
L_{canon} at TKU Reference Plane [MeV/c m]

L_{canon} TKD

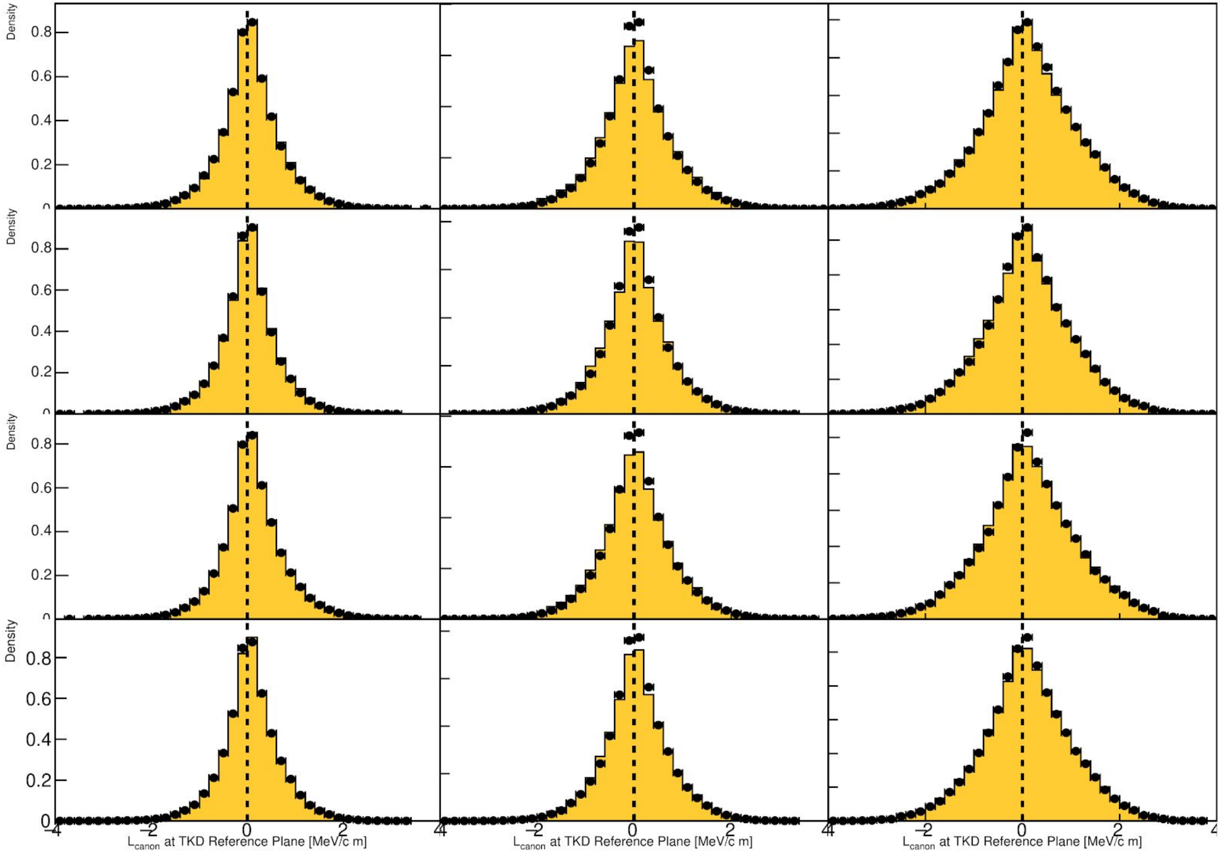
4 mm | 6 mm | 10 mm

Empty LH2

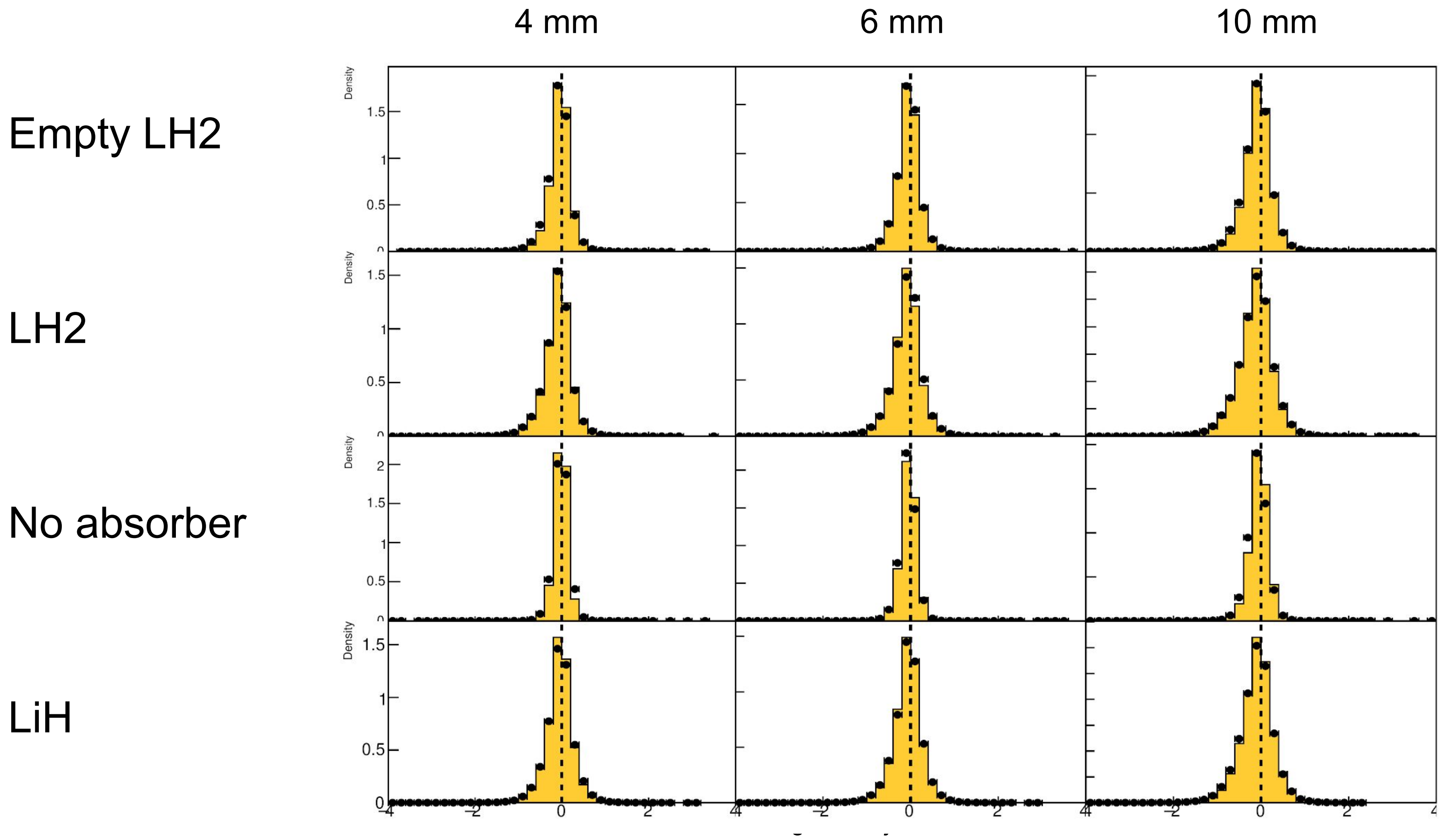
LH2

No absorber

LiH



L_{canon} (TKD) - L_{canon} (TKU)



2D Distributions

L_{kin} vs r (TKU, Data)

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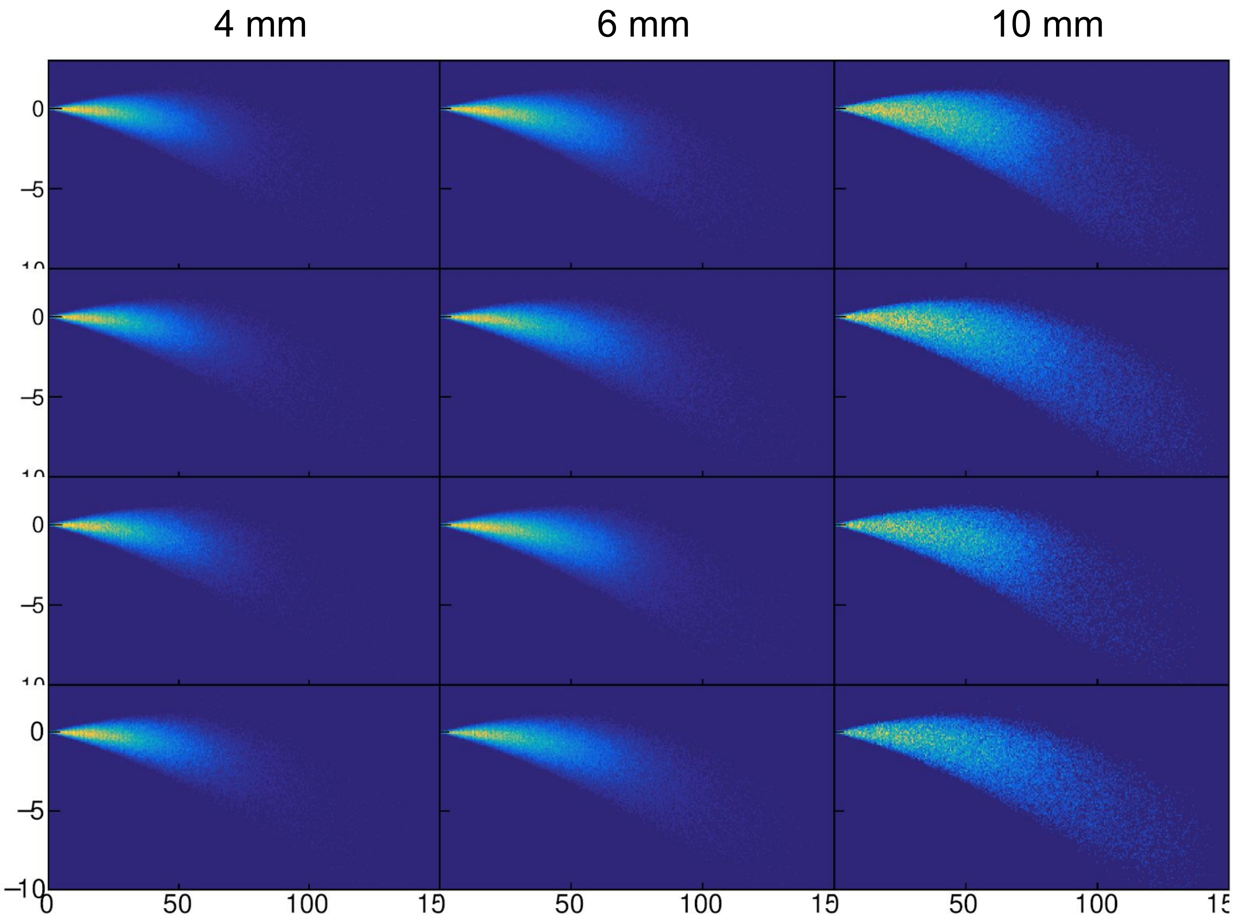

L_{kin} vs r (TKD, Data)

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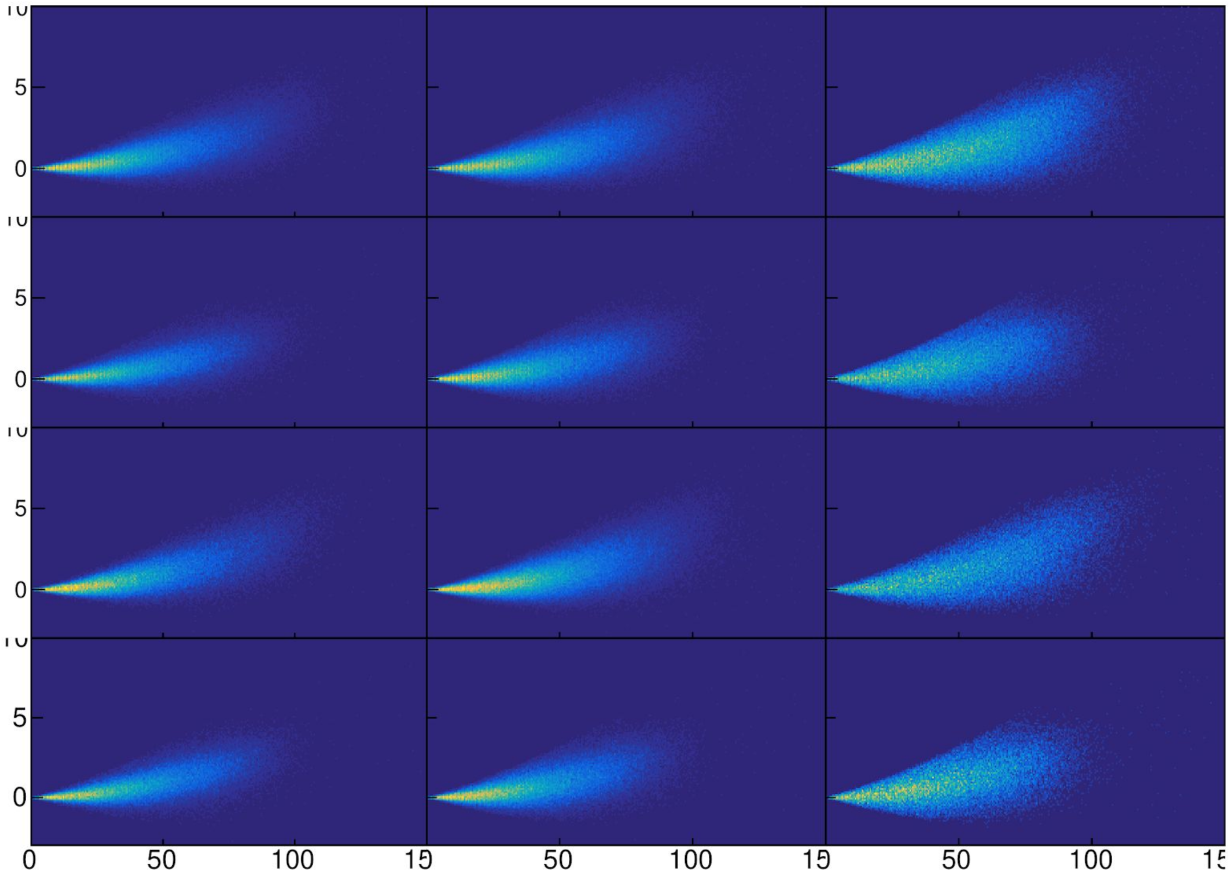
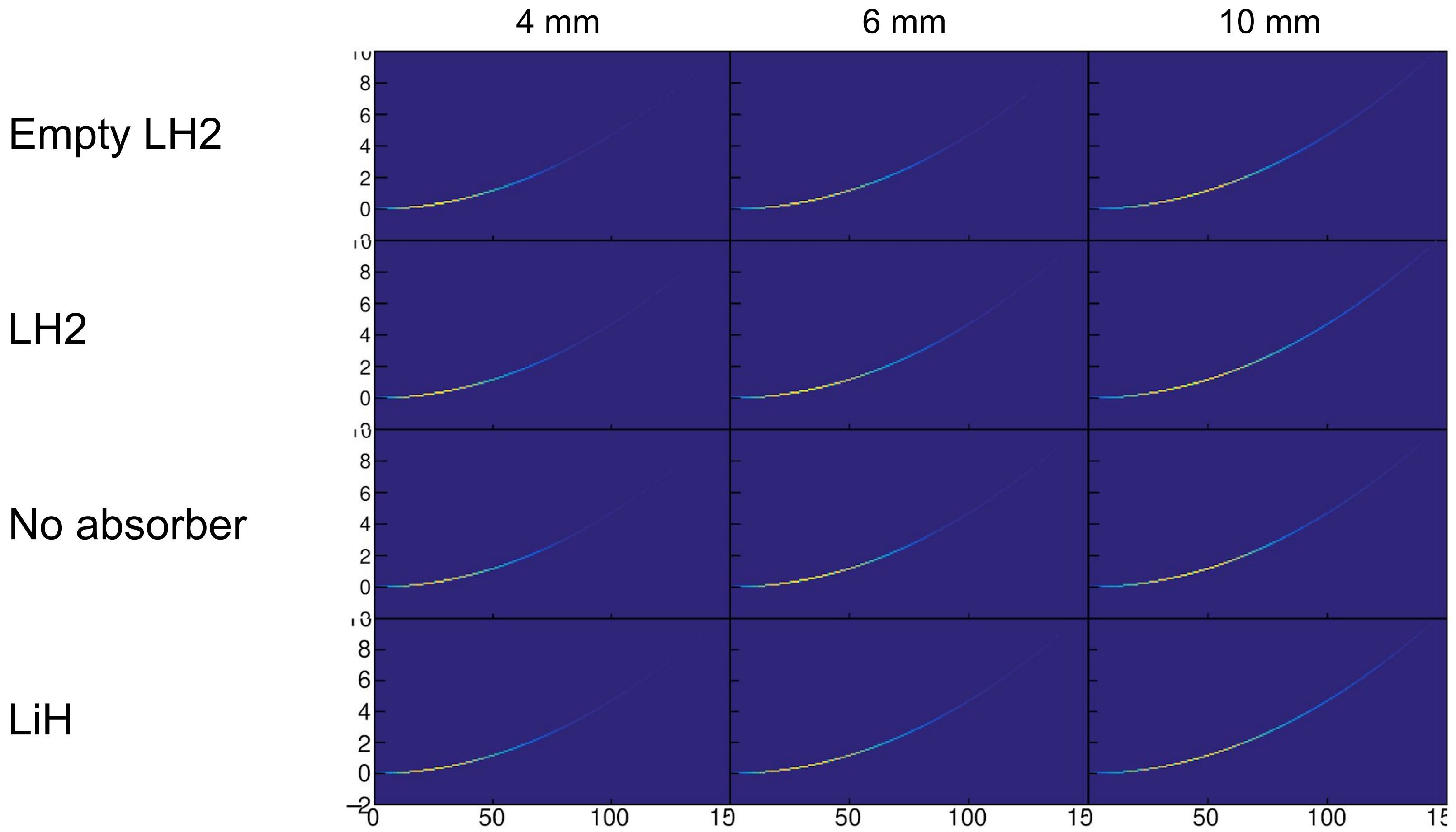
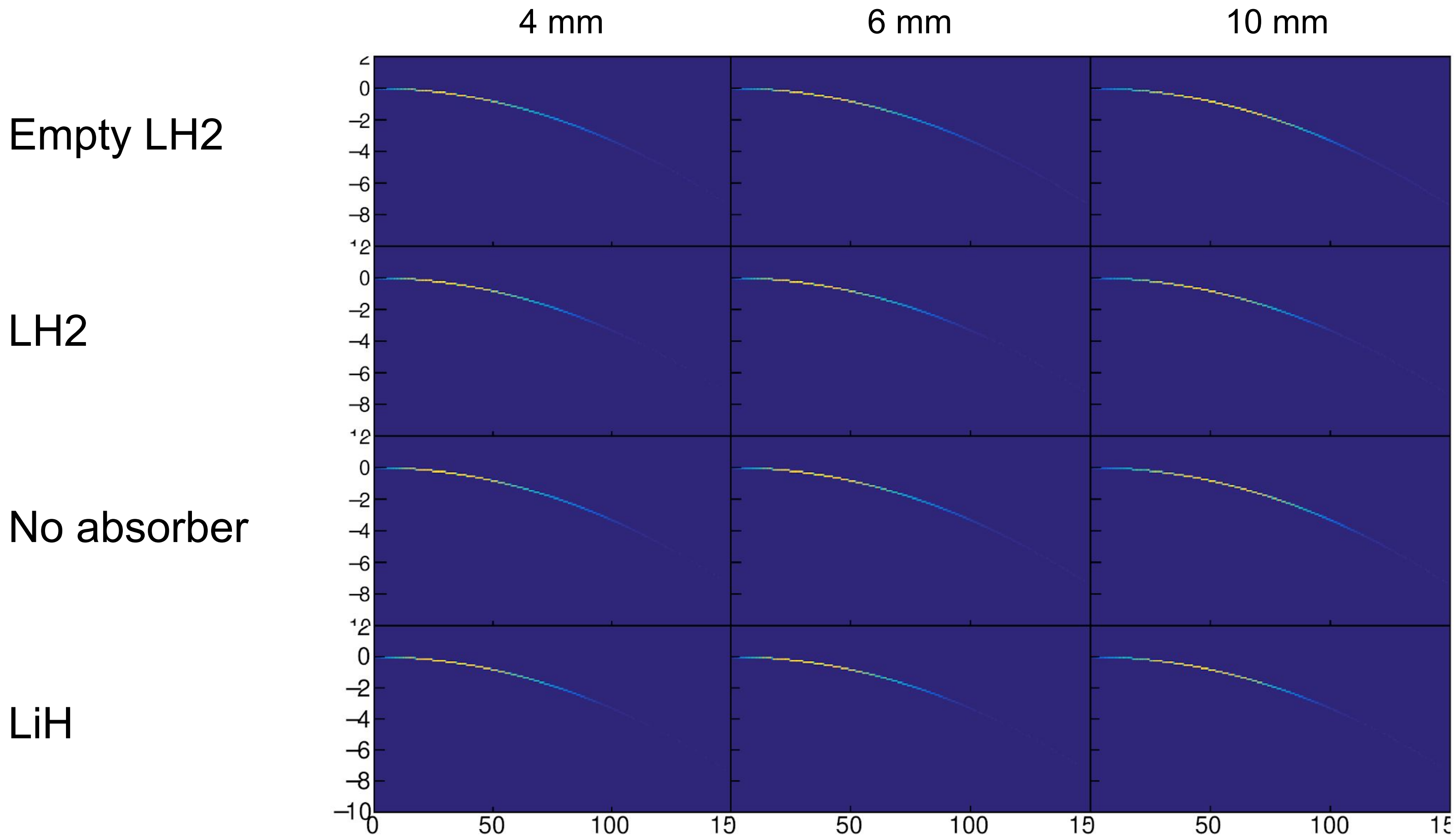
	4 mm	6 mm	10 mm
Empty LH2			
LH2			
No absorber			
LiH			



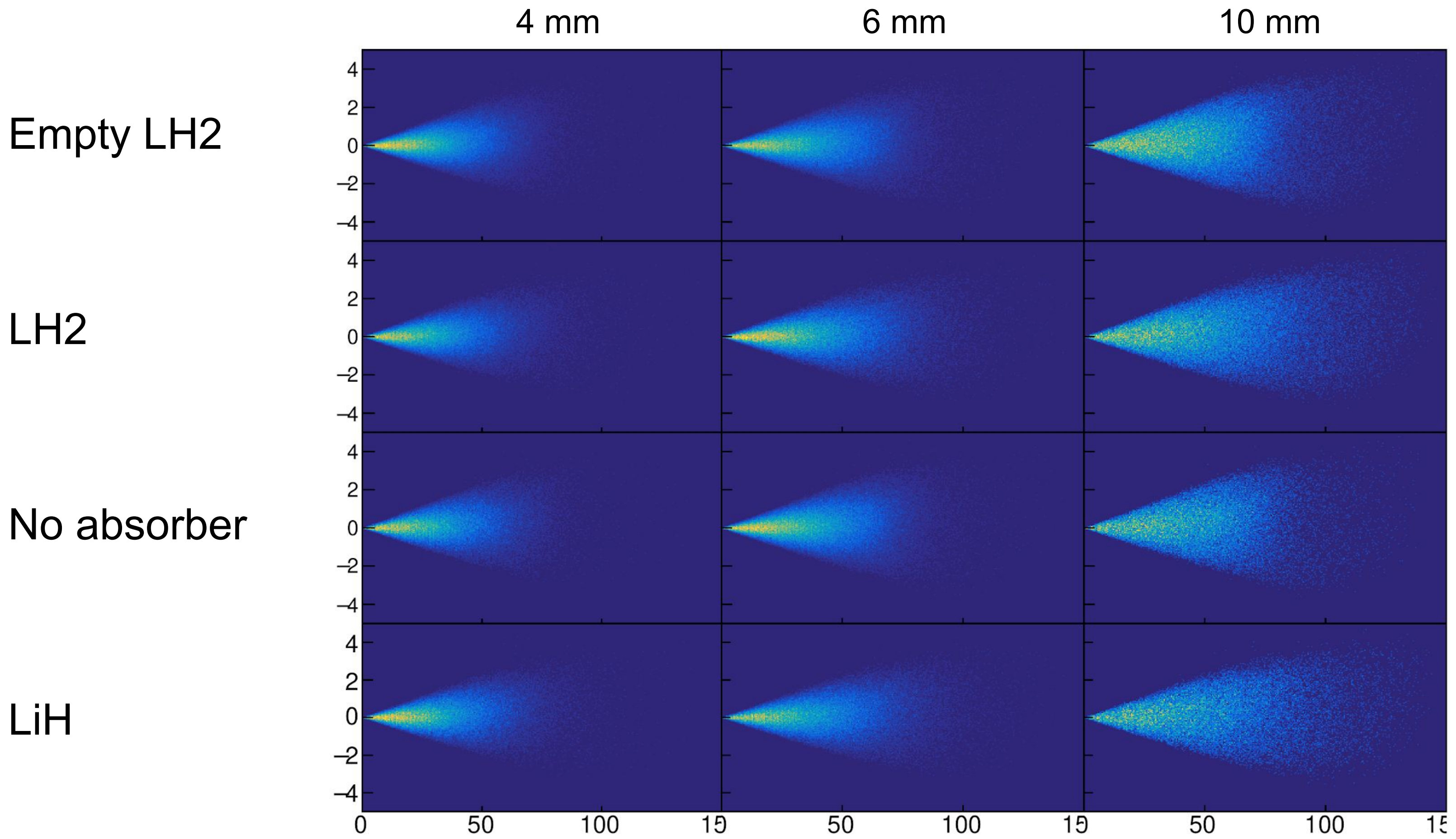
L_{field} vs r (TKU, Data)



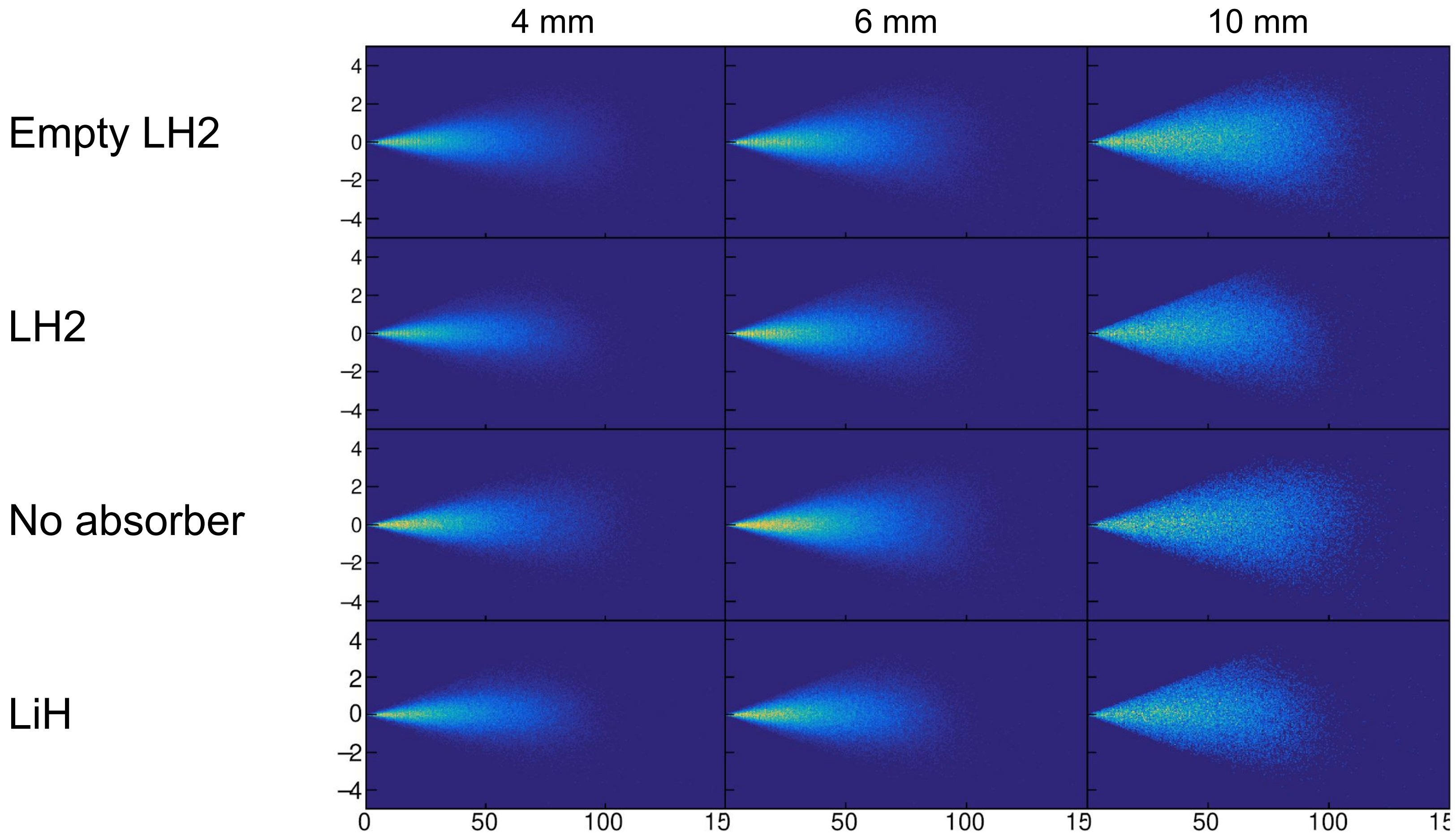
L_{field} vs r (TKD, Data)



L_{canon} vs r (TKU, Data)



L_{canon} vs r (TKD, Data)



L_{canon} (TKD) - L_{canon} (TKU) vs L_{canon} (TKU) (Data)

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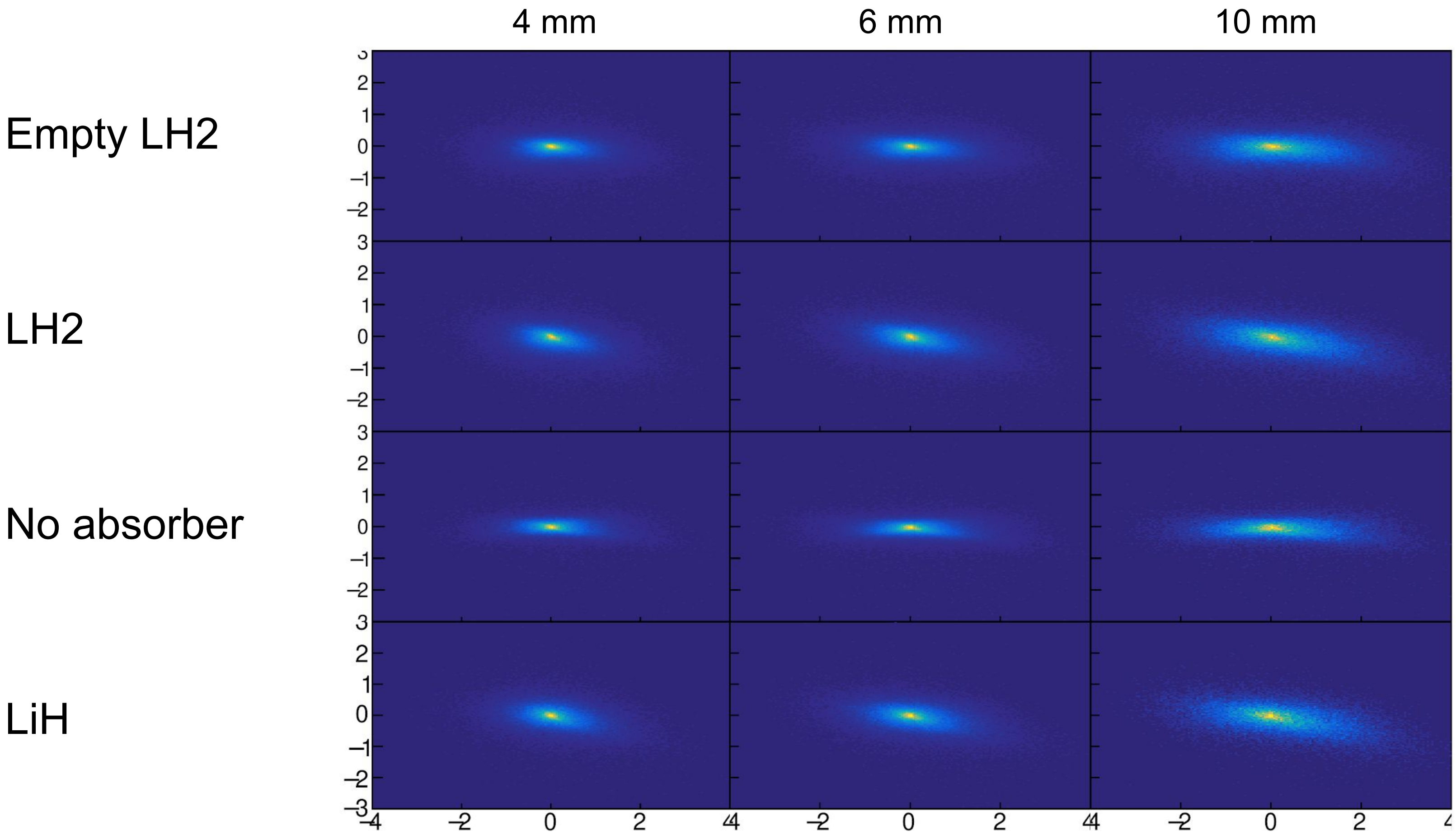
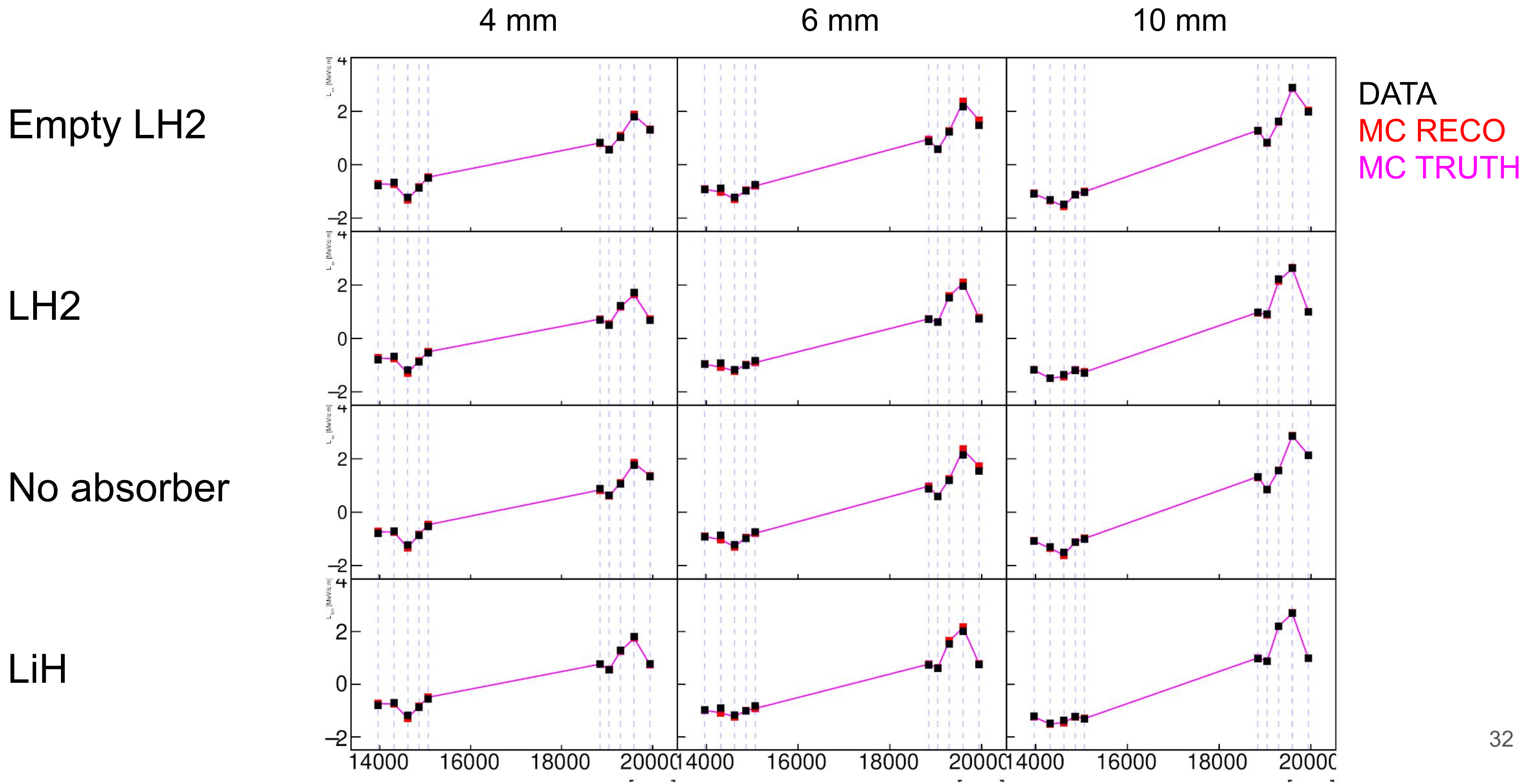


Means evolution through cooling channel

L_{kin} mean



4 mm
6 mm
10 mm
Empty LH2
LH2
No absorber
LiH
DATA
MC RECO
MC TRUTH
4
2
0
−2
14000
16000
18000
20000

L_{field} mean

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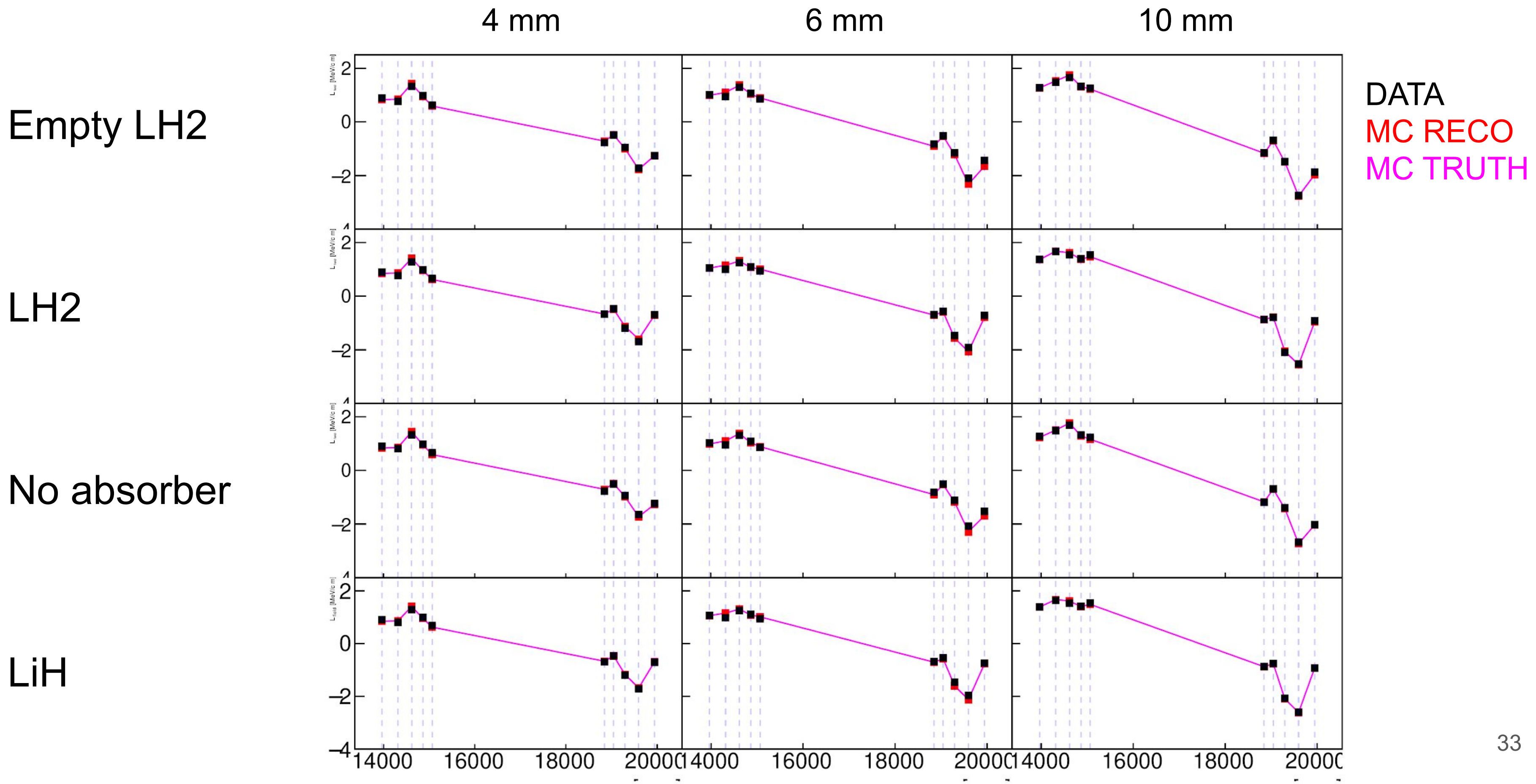
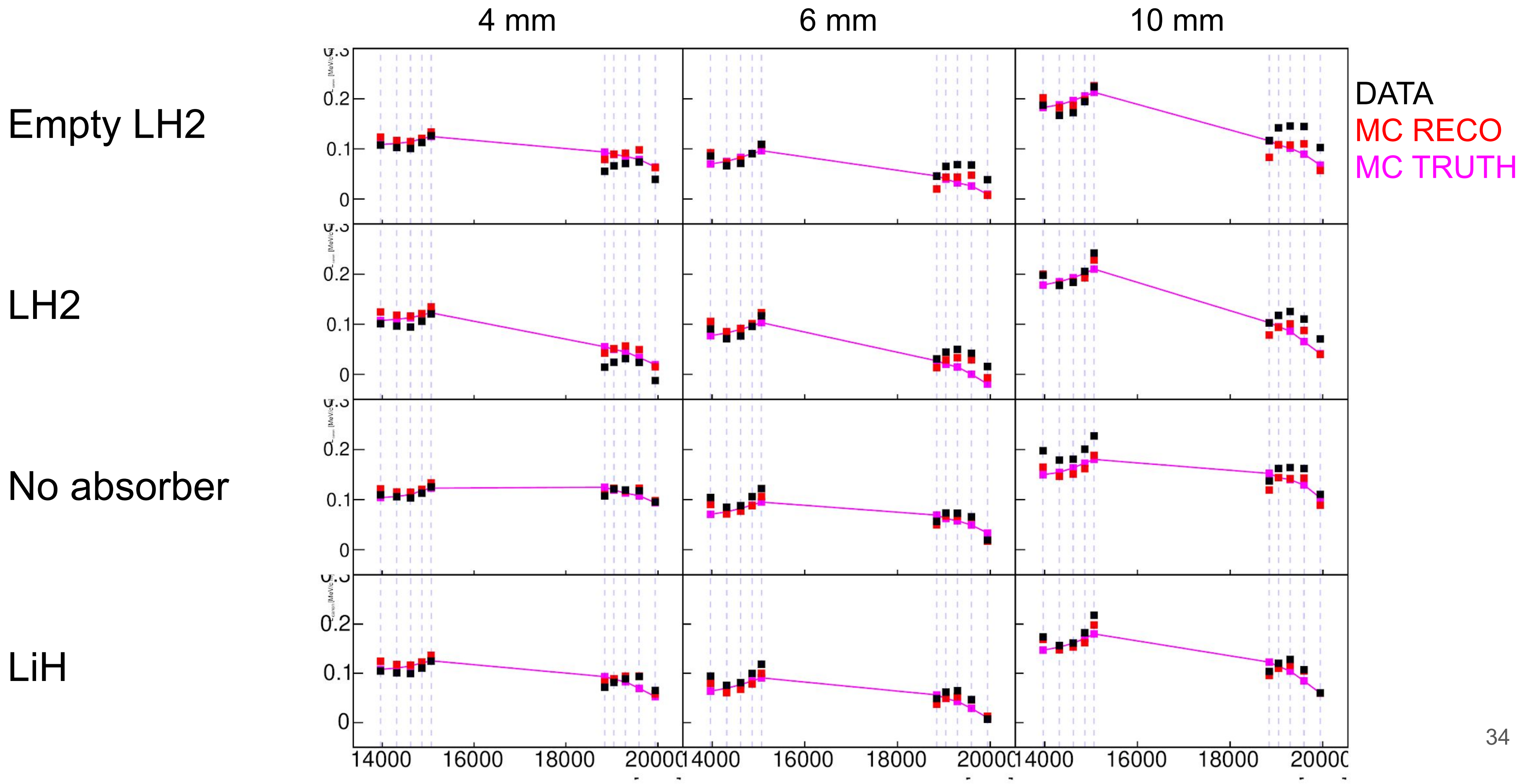

4 mm
6 mm
10 mm
Empty LH2
LH2
No absorber
LiH
DATA
MC RECO
MC TRUTH
2
0
−2
−4
14000
16000
18000
20000

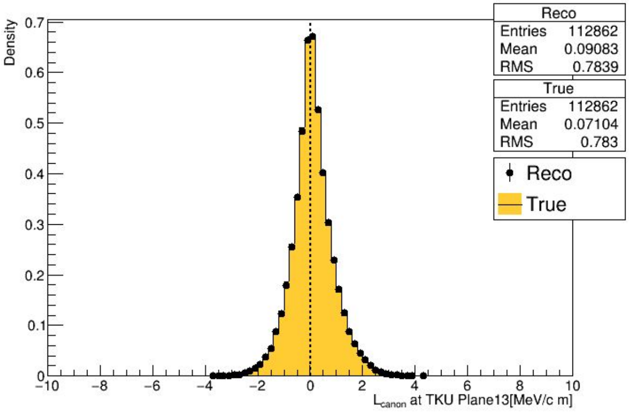
L_{canon} mean

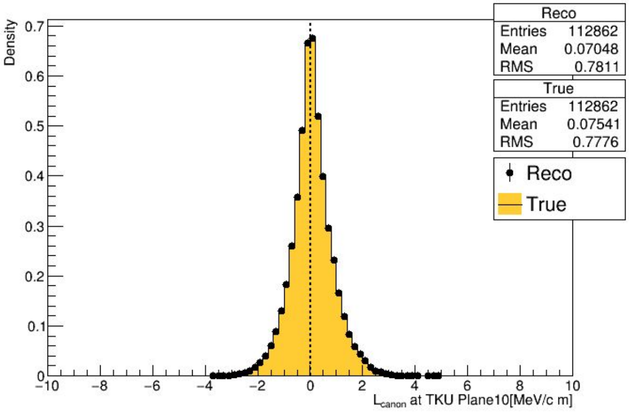

4 mm
6 mm
10 mm
Empty LH2
LH2
No absorber
LiH
0.3
0.2
0.1
0
14000
16000
18000
20000
DATA
MC RECO
MC TRUTH

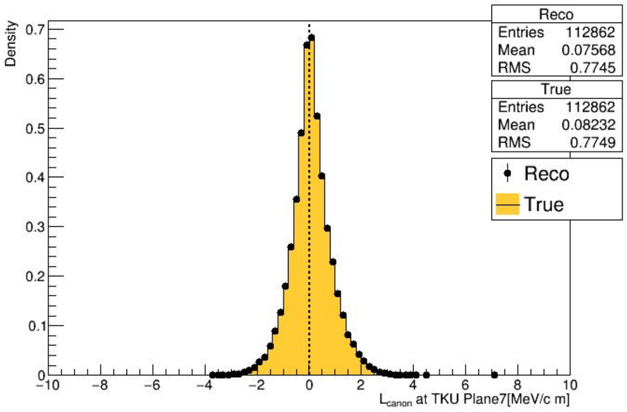
MC: RECO VS TRUE

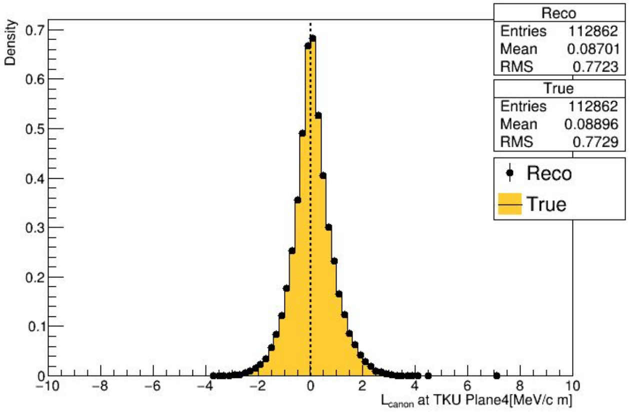
(No absorber 6-140)

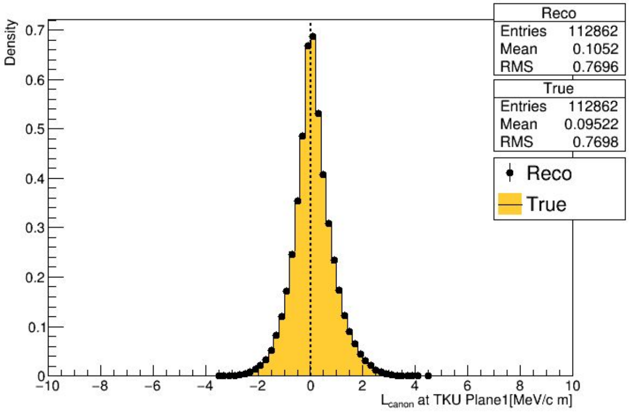
L_{canon} in TKU stations



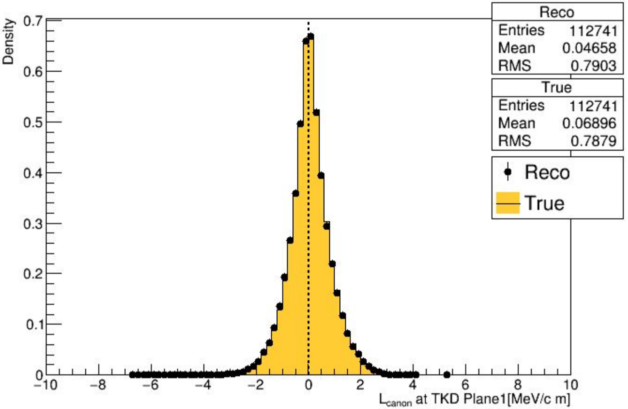


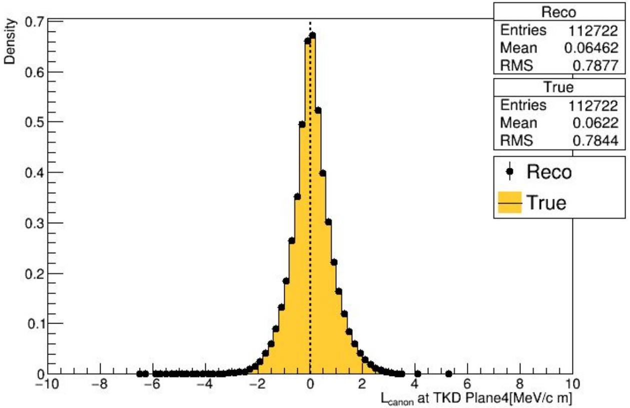


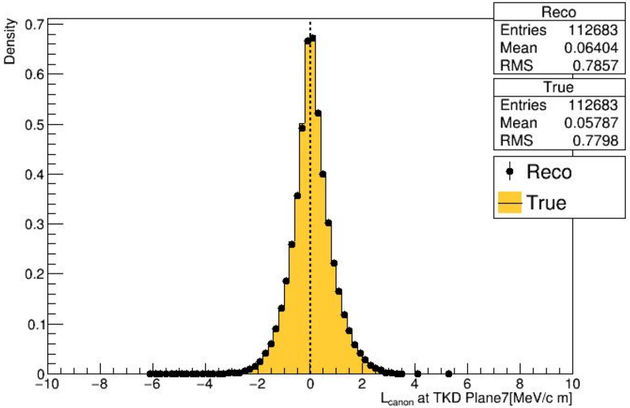


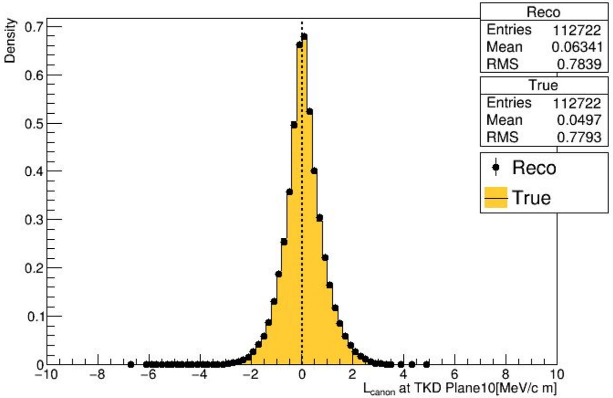


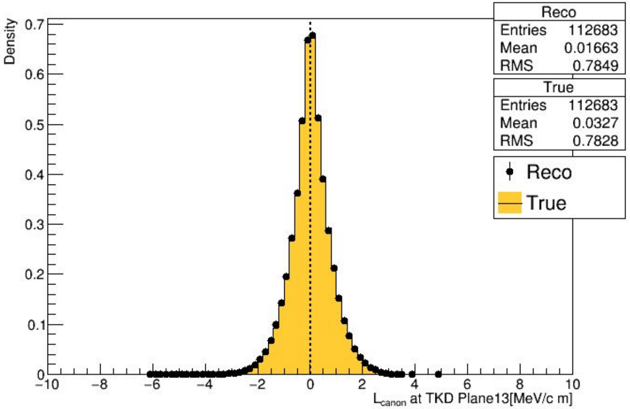
L_{canon} in TKD stations











BACKUP

Equilibrium emittance calculation

- used Bethe's mean stopping power formula to calculate dE/dz at 140 MeV/c
- parameters used for eqm. emittance:

$$
\begin{aligned}
&LiH\\
&p = 140\, MeV/c\\
&dE/dz = 1.925\, MeV/cm\\
&X_0 = 102.04\, cm\\
&\beta_\perp = 420\, mm
\end{aligned}
$$

$$
\begin{aligned}
&LH_2\\
&p = 140\, MeV/c\\
&dE/dz = 0.361\, MeV/cm\\
&X_0 = 890.4\, cm\\
&\beta_\perp = 420\, mm
\end{aligned}
$$

Paul Bogdan Jurj

Statistical errors on absolute emittance change

- Starting from John Cobb's derivation of statistical errors on relative emittance change in Note 268
- John has also worked on this derivation and came up with a result
- Currently our results are not identical, will take some time to revise

$$\sigma^2_{\Delta\epsilon} = \frac{1}{2n}\left[(\epsilon_d - \epsilon_u)^2 + \epsilon_u\epsilon_d - \alpha^2\frac{\epsilon_u^3}{\epsilon_d}\right]$$

Paul Bogdan Jurj