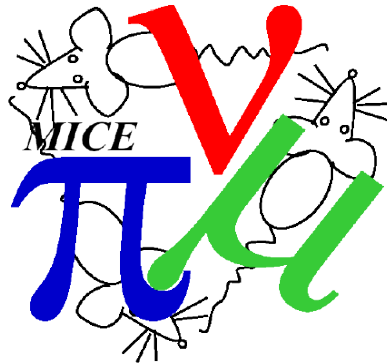


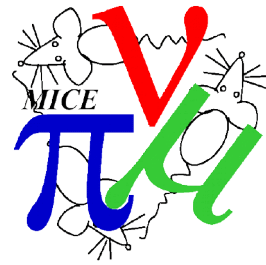


Emittance Evolution



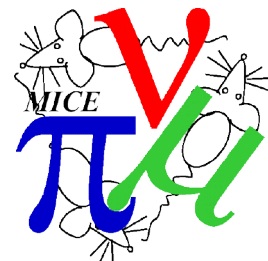
C. Rogers, ISIS Intense Beams Group
Rutherford Appleton Laboratory

Overview



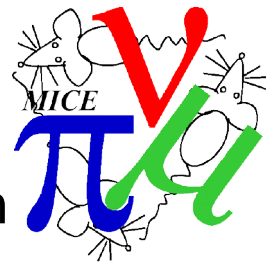
- Aim of the paper is to demonstrate decrease in beam emittance
 - Phrase this in terms of “amplitude”
- Present the current status of the full analysis
 - Sampling
 - Validation of correct operation of equipment
 - Amplitude distributions
 - Correction factors
- Highlight issues that still need cleaning up
 - Nb: still battling with plotting library to make the plots look pretty
- No systematic errors

Data



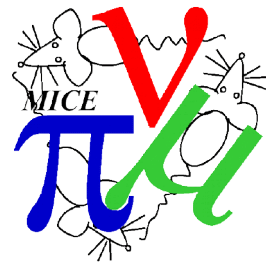
- All data is taken from 2017-02-7 setting
 - Flip mode with nominal $\beta_{\text{perp}} \sim 500$ mm
 - Consider all cylindrical configurations:
 - No absorber at all (None)
 - Empty IH2
 - Full IH2
 - LiH
- All data is 140 MeV/c
- Nominal emittances 3 mm, 6 mm, 10 mm
- Analysis goes like:
 - Choose data sample
 - Cross-checks to demonstrate self-consistency of data and detectors
 - Calculate amplitude
 - Including correction for resolution and efficiency
- Including simulation with full MAUS model from target

Upstream Sample



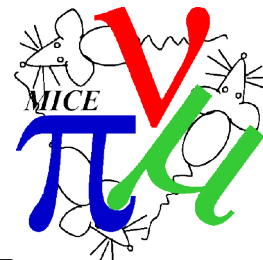
- Aim to show change in amplitude distribution between upstream and downstream samples
- Choose an upstream sample
- Upstream sample – data quality selection
 - Require exactly 1 TOF1 space point
 - Require exactly 1 TOF0 space point
 - Require exactly 1 TKU track
 - $\text{TKU Chi2/dof} < 5$
 - $\text{TKU track radius} < 150 \text{ mm}$
- Upstream sample – physics selection
 - TOF01 consistent with muon peak
 - TOF01 – (extrapolated TOF01) consistent with muon hypothesis
 - $135 < \text{Total momentum} < 145 \text{ MeV/c}$
 - Successfully extrapolate track from TKU to TOF0
 - Track falls within diffuser aperture ($< 100 \text{ mm}$)
- Show plots of “cut variable” with all cuts except the cut of interest applied

Upstream Sample



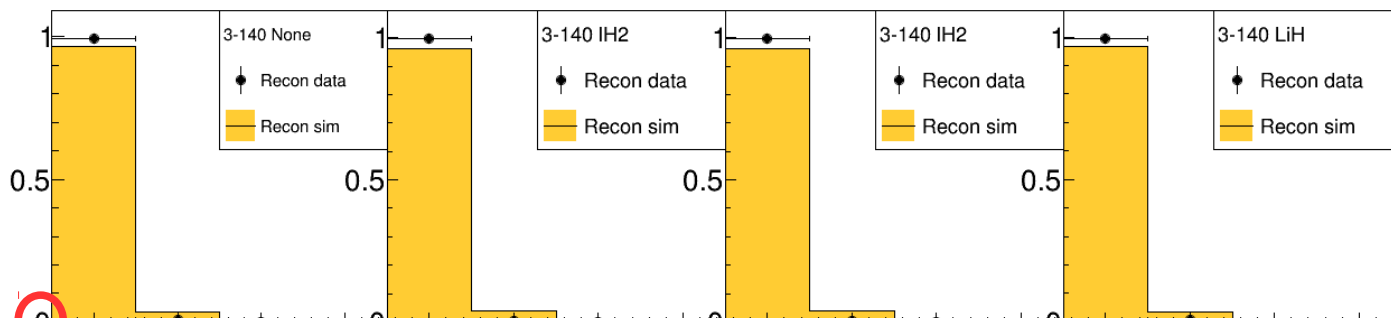
- Choose an upstream sample
- Aim to show change in amplitude distribution in downstream sample
- Upstream sample – data quality:
 - Require exactly 1 TOF1 space point
 - Require exactly 1 TOF0 space point
 - Require exactly 1 TKU track
 - TKU $\text{Chi}^2/\text{dof} < 5$
 - TKU track radius < 150 mm
- Upstream sample – physics
 - TOF01 consistent with muon peak
 - TOF01 – extrapolated TOF01 consistent with muon hypothesis
 - $135 < \text{Total momentum} < 145$ MeV/c
 - Successfully extrapolate track from TKU to TOF0
 - Track falls within diffuser aperture (< 100 mm)
- Show plots of “cut variable” with all cuts except the cut of interest applied

Cuts summary – TOF1 SP = 1

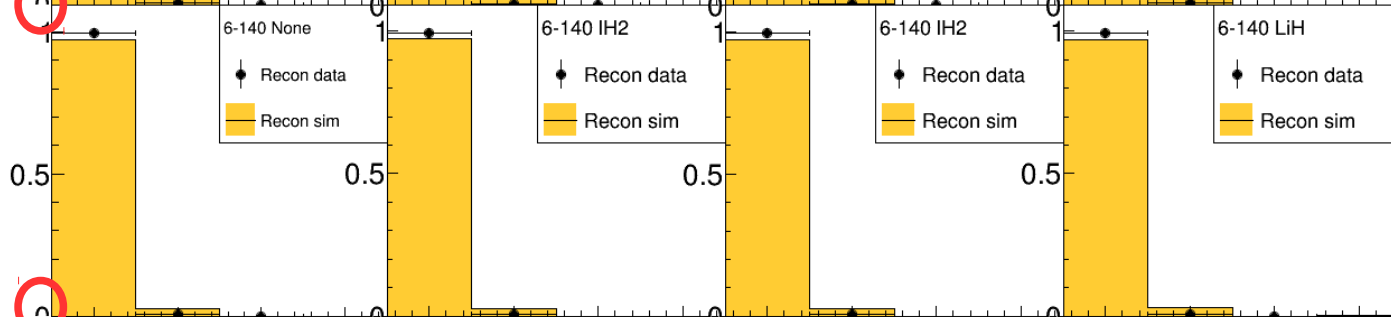


None LH2 Empty LH2 Full LiH

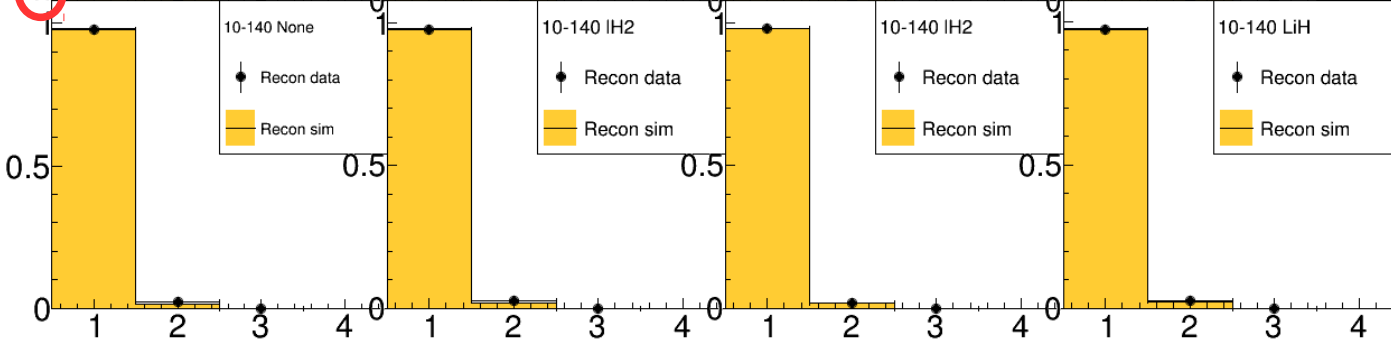
3 mm



6 mm

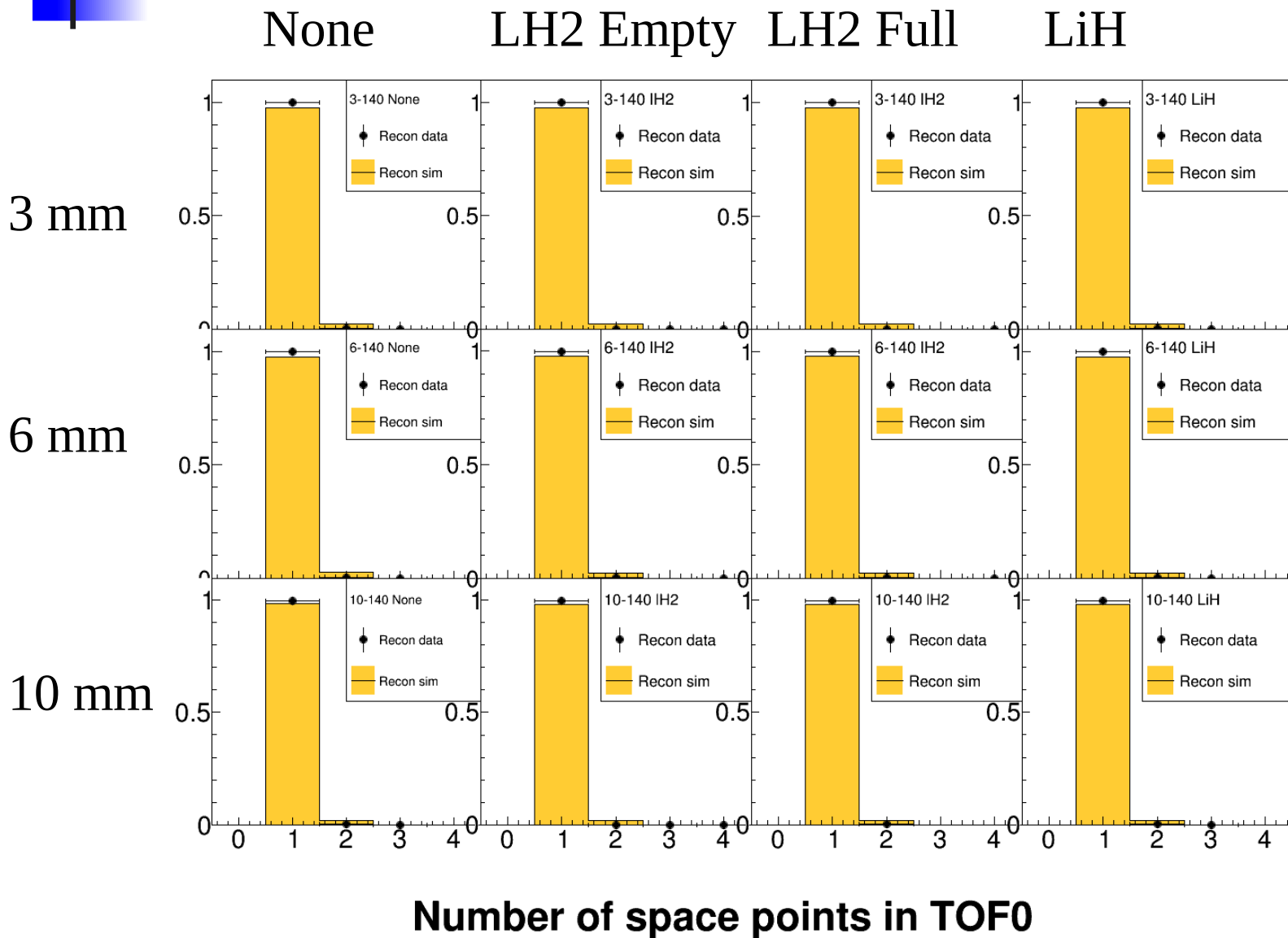
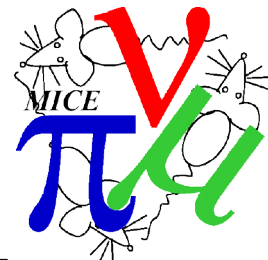


10 mm

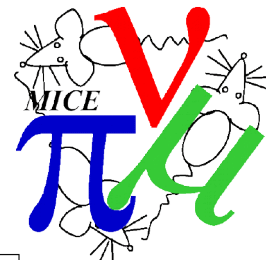


Number of space points in TOF1

Cuts summary – TOF0 SP = 1



Cuts summary tracks = 1



None

LH2 Empty

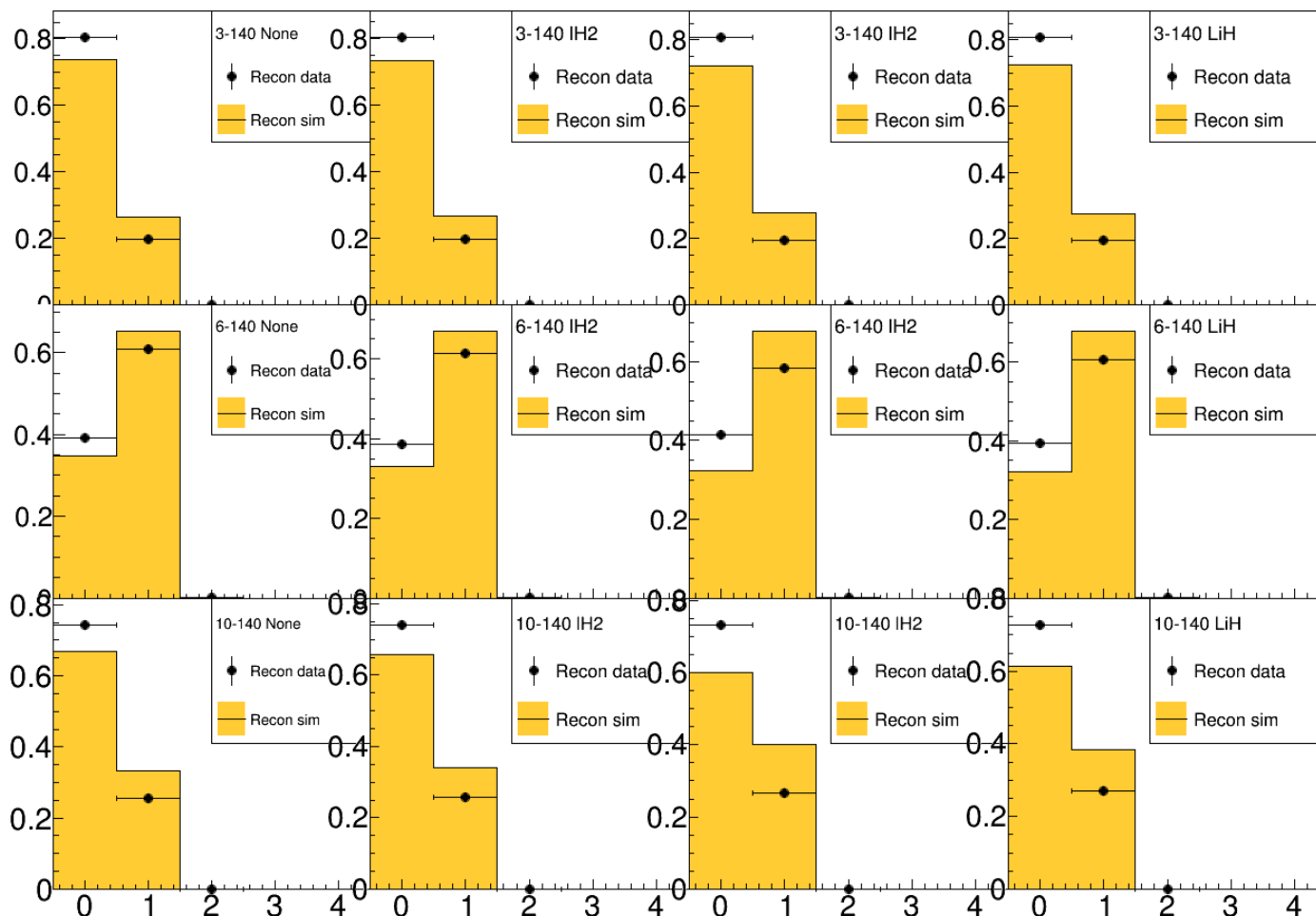
LH2 Full

LiH

3 mm

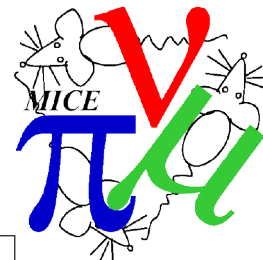
6 mm

10 mm



Number of tracks in TKU

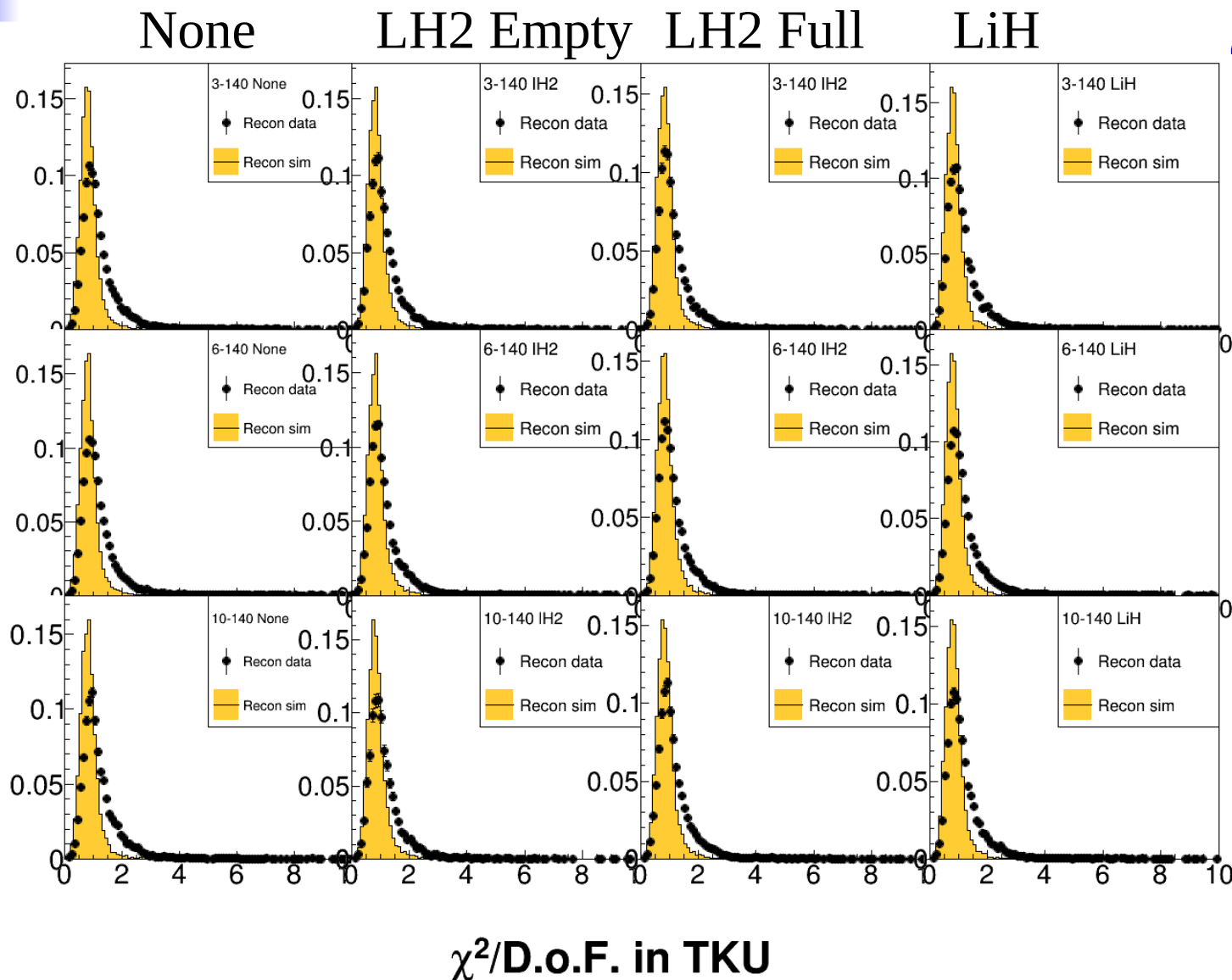
Cuts summary $\chi^2/\text{dof} < 5$



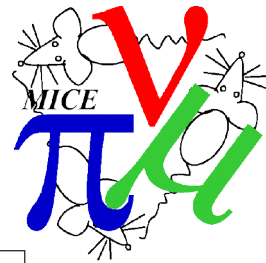
3 mm

6 mm

10 mm



Cuts summary $r < 150$ mm



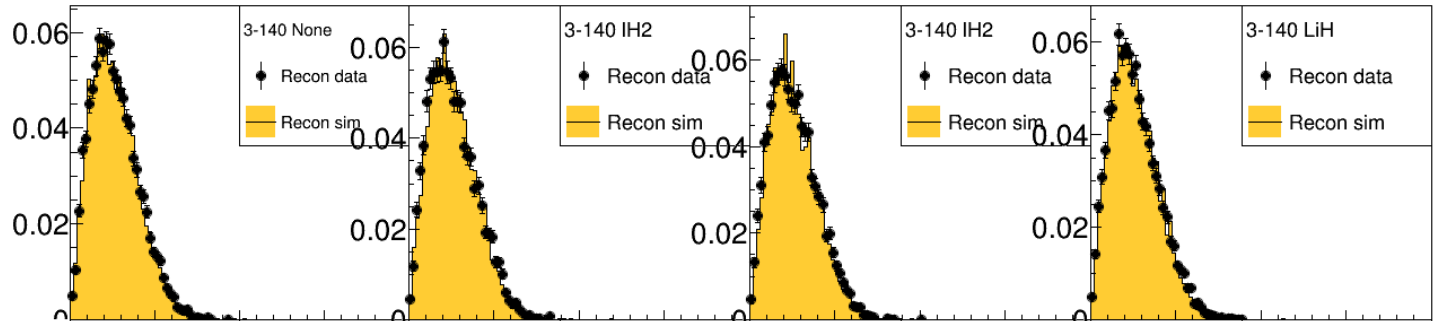
None

LH2 Empty

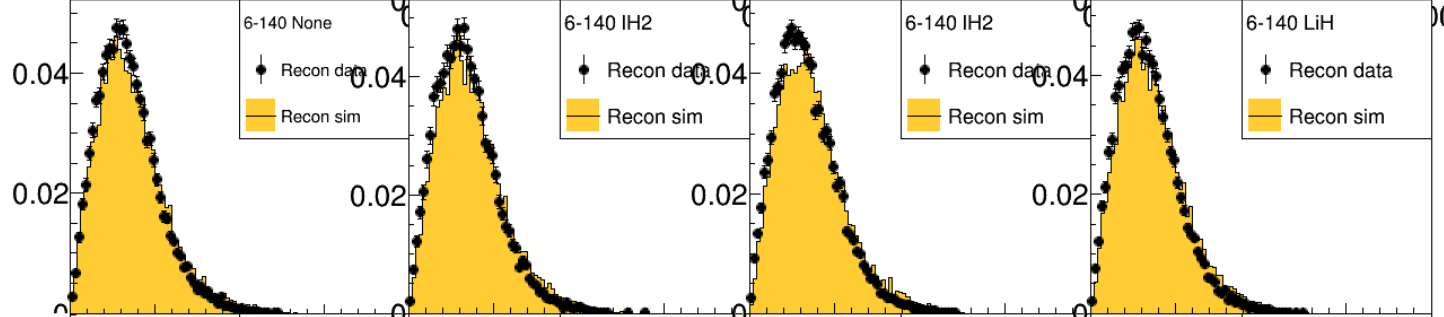
LH2 Full

LiH

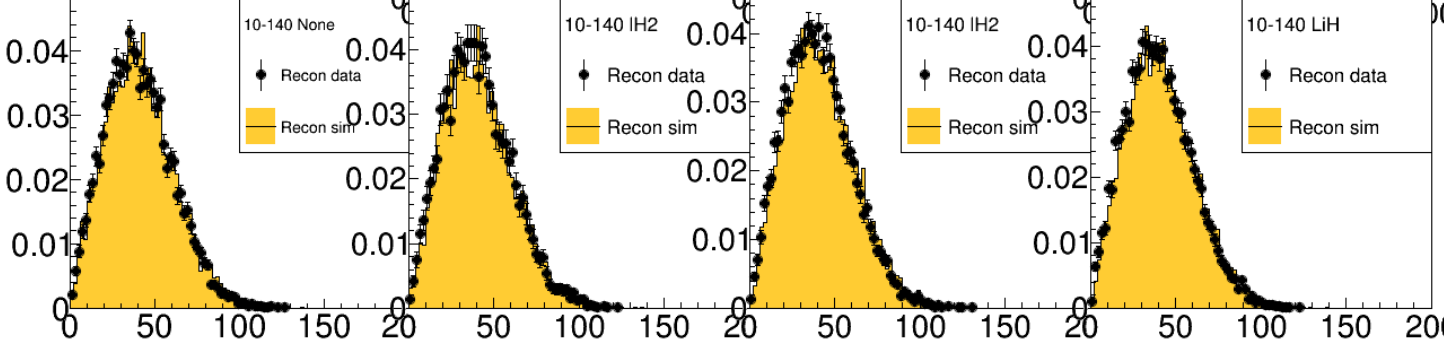
3 mm



6 mm

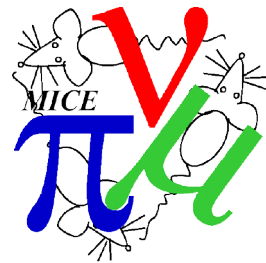


10 mm



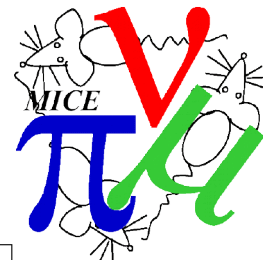
Maximum radius in TKU [mm]

Upstream Sample



- Choose an upstream sample
- Aim to show change in amplitude distribution in downstream sample
- Upstream sample – data quality:
 - Require exactly 1 TOF1 space point
 - Require exactly 1 TOF0 space point
 - Require exactly 1 TKU track
 - TKU Chi2/dof < 5
 - TKU track radius < 150 mm
- Upstream sample – physics
 - TOF01 consistent with muon peak
 - TOF01 – extrapolated TOF01 consistent with muon hypothesis
 - $135 < \text{Total momentum} < 145 \text{ MeV}/c$
 - Successfully extrapolate track from TKU to TOF0
 - Track falls within diffuser aperture (< 100 mm)
- Show plots of “cut variable” with all cuts except the cut of interest applied

Cuts summary

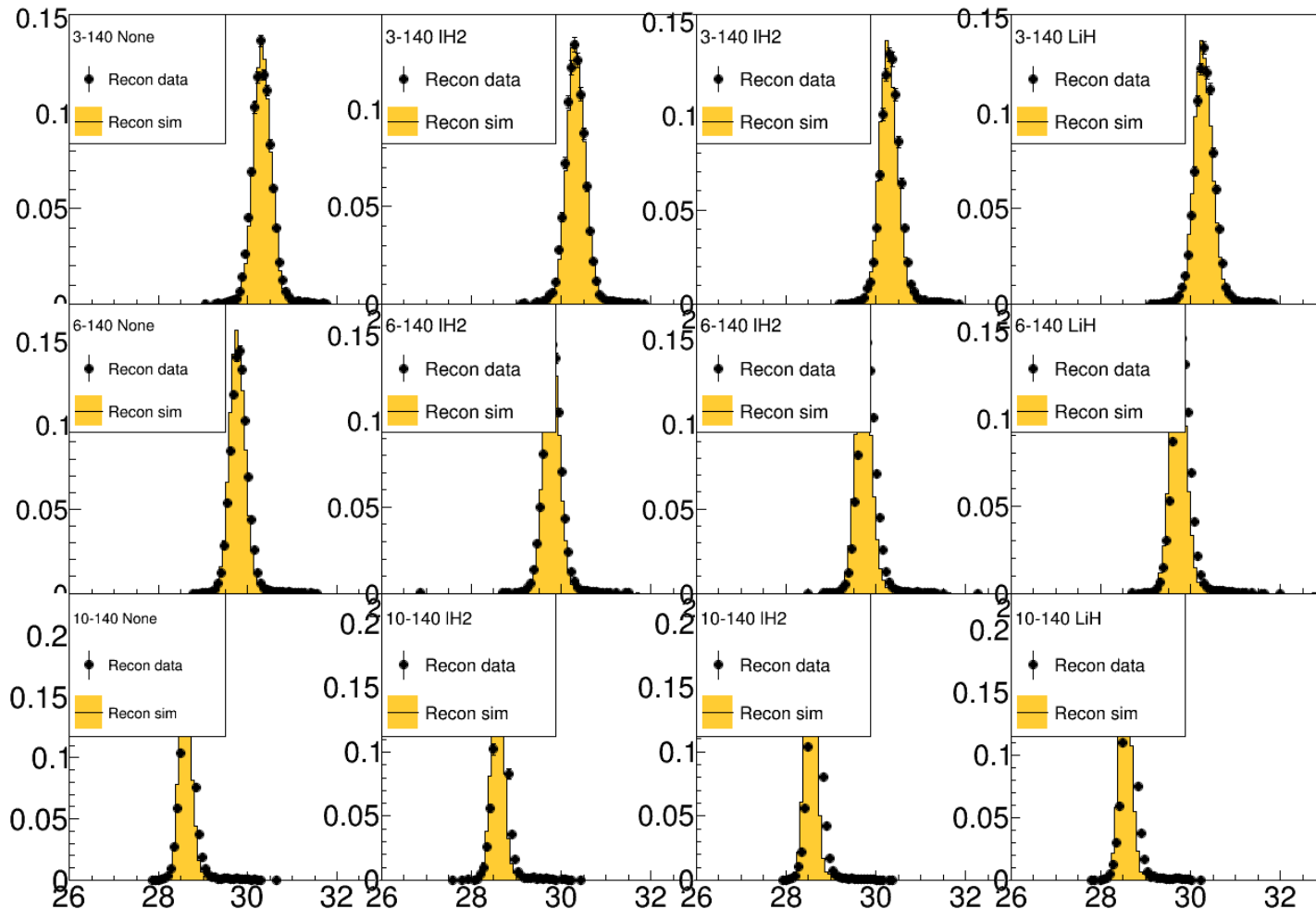


None LH2 Empty LH2 Full LiH

3 mm

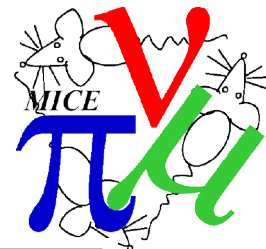
6 mm

10 mm



Time between TOF0 and TOF1 [ns]

Cuts summary $-1 < \text{TOF01} < 1.5$



None

LH2 Empty

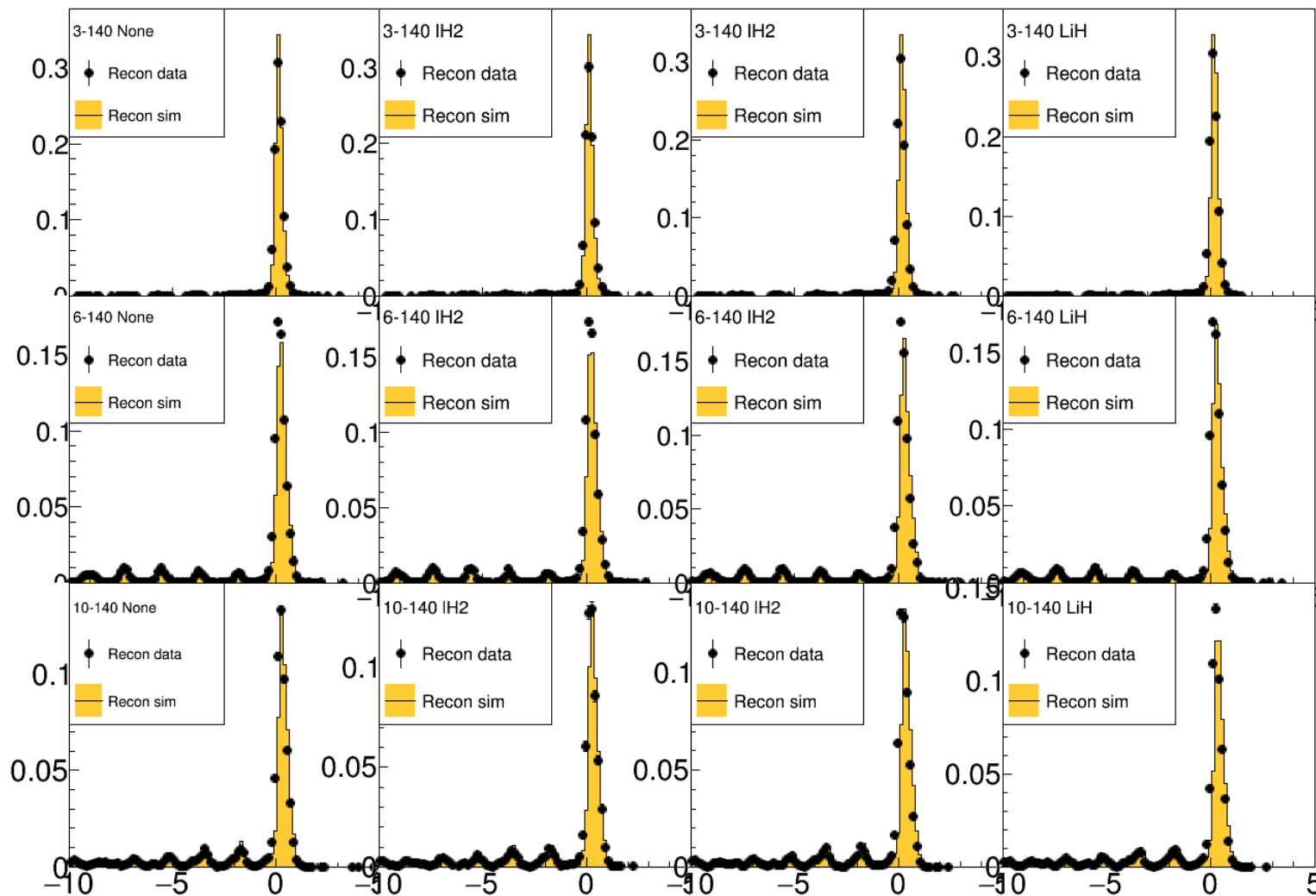
LH2 Full

LiH

3 mm

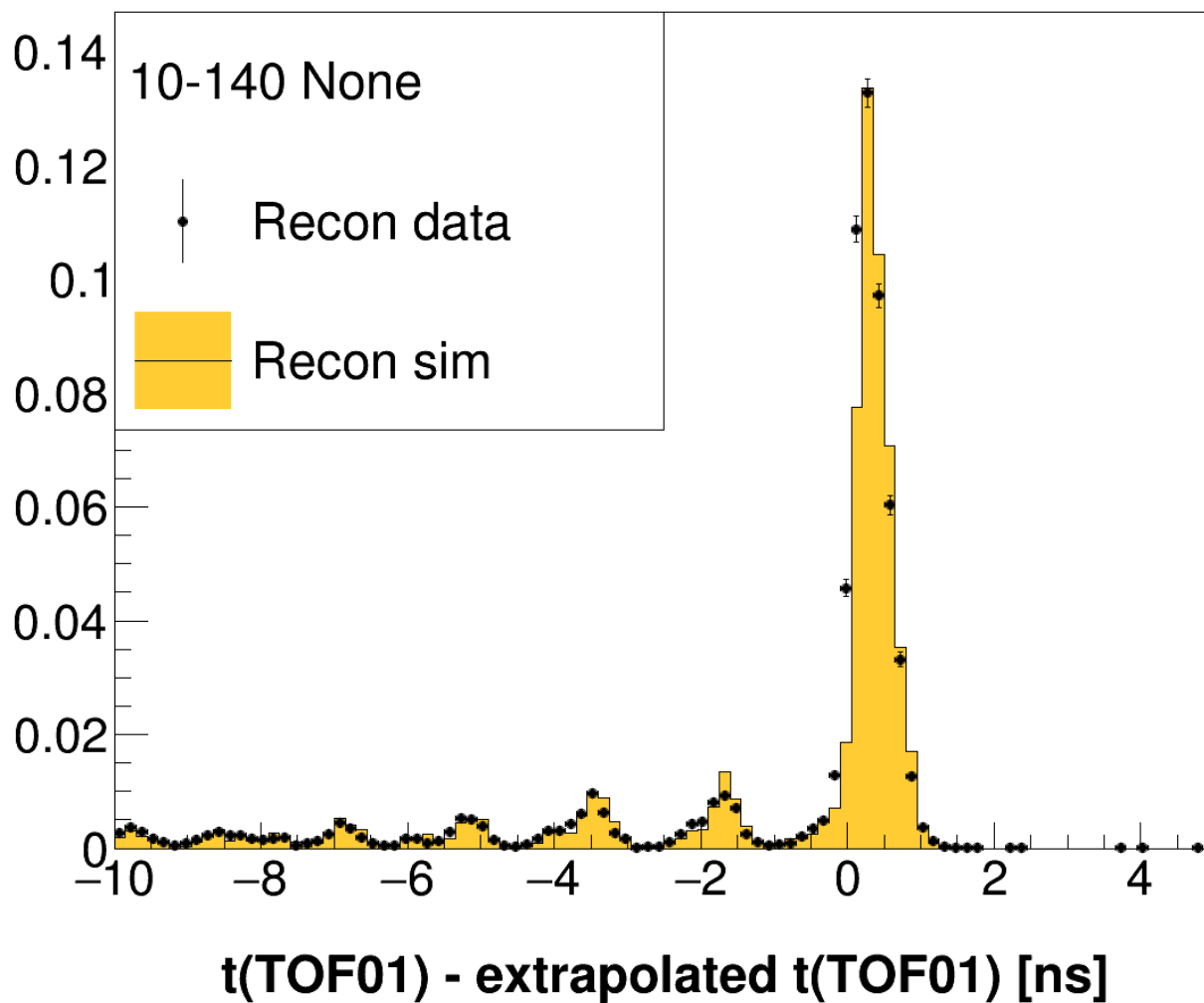
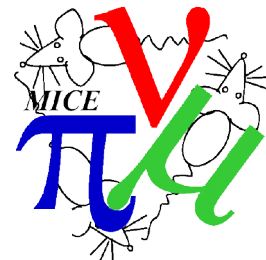
6 mm

10 mm

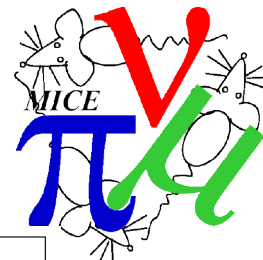


$t(\text{TOF01}) - \text{extrapolated } t(\text{TOF01}) [\text{ns}]$

Cuts summary



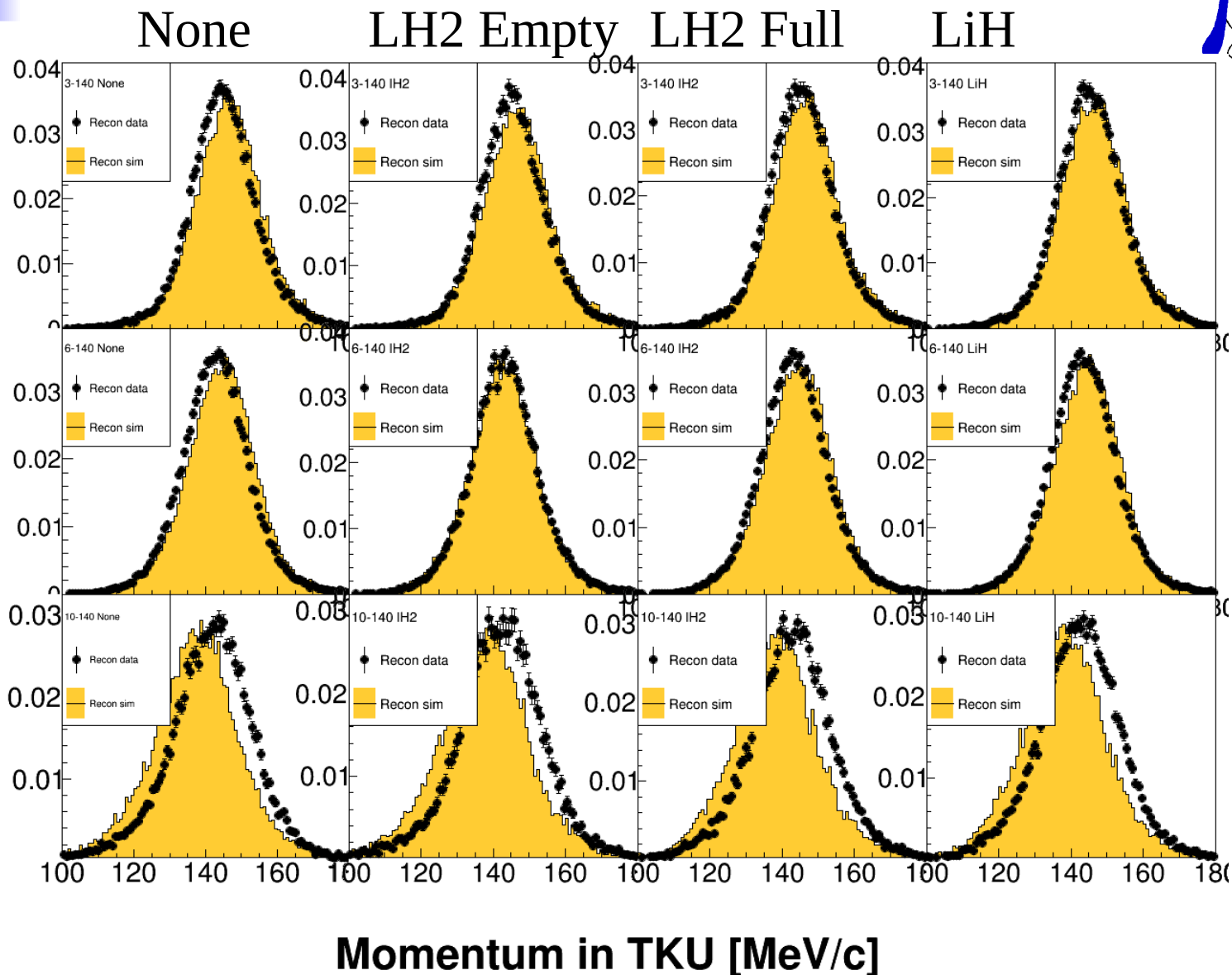
Cuts summary $135 < p < 145$



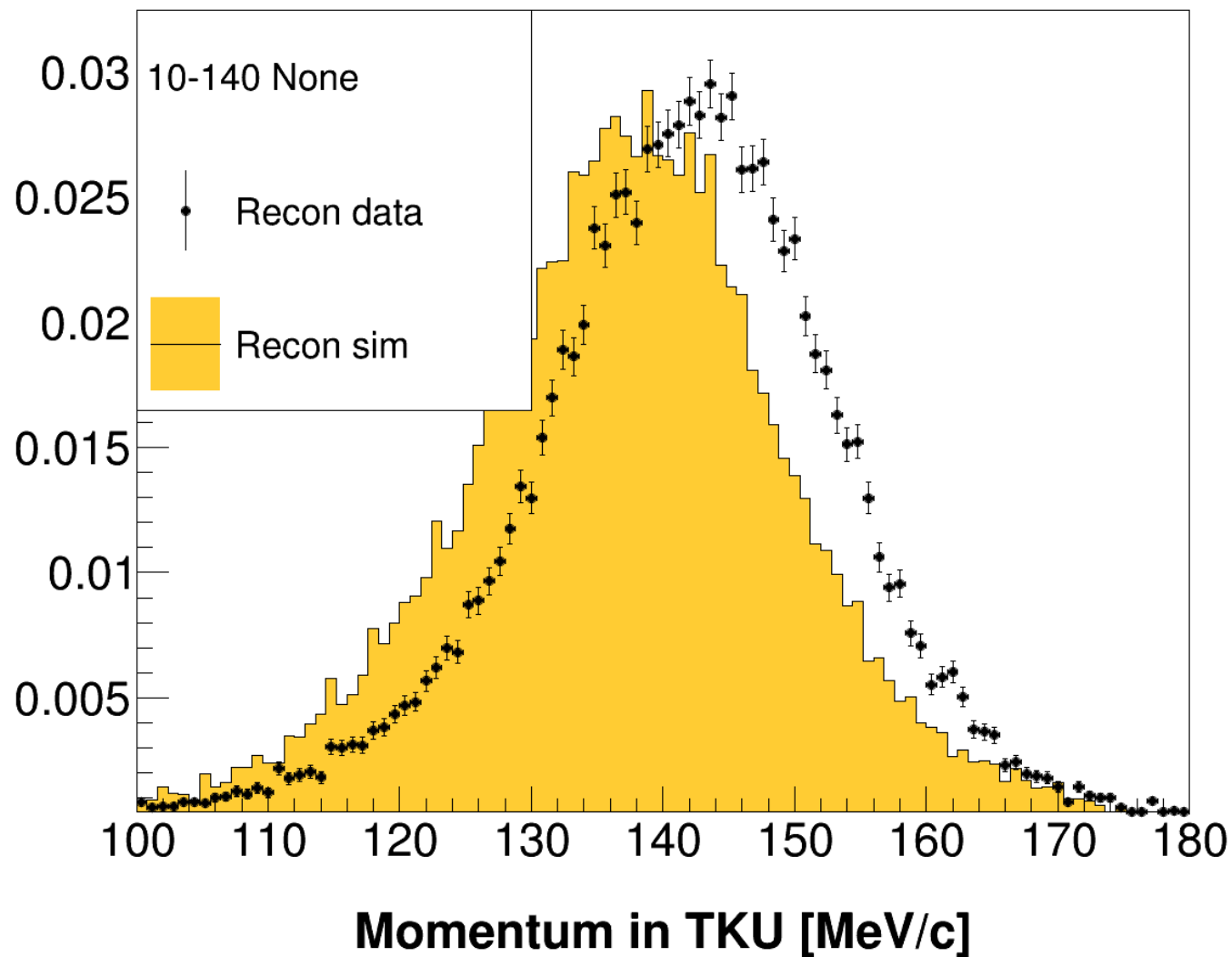
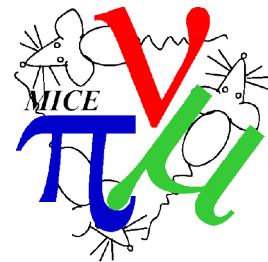
3 mm

6 mm

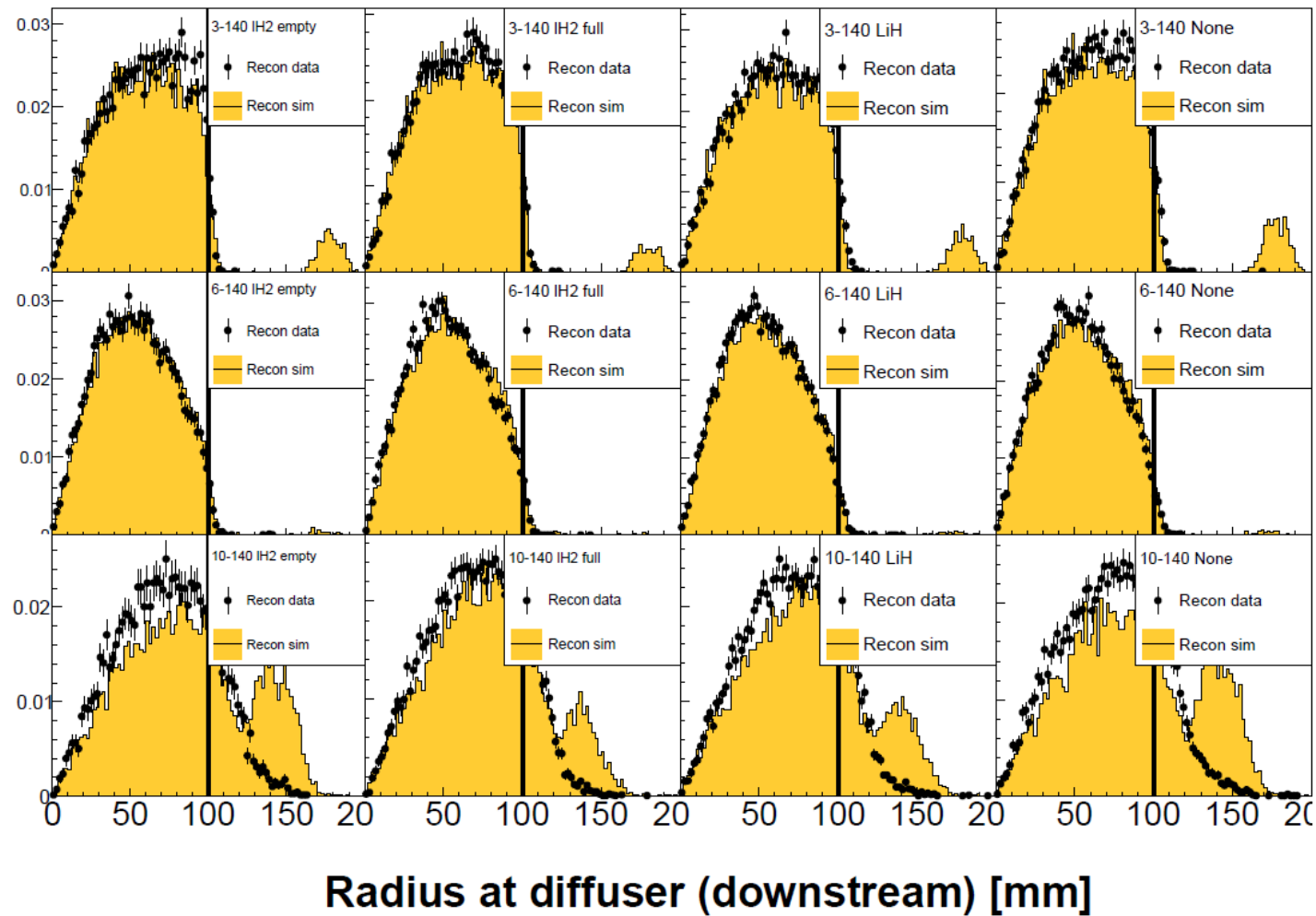
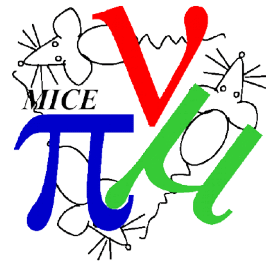
10 mm



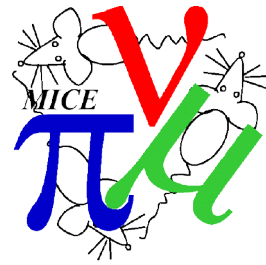
Cuts summary



Cuts summary: $r < 100$

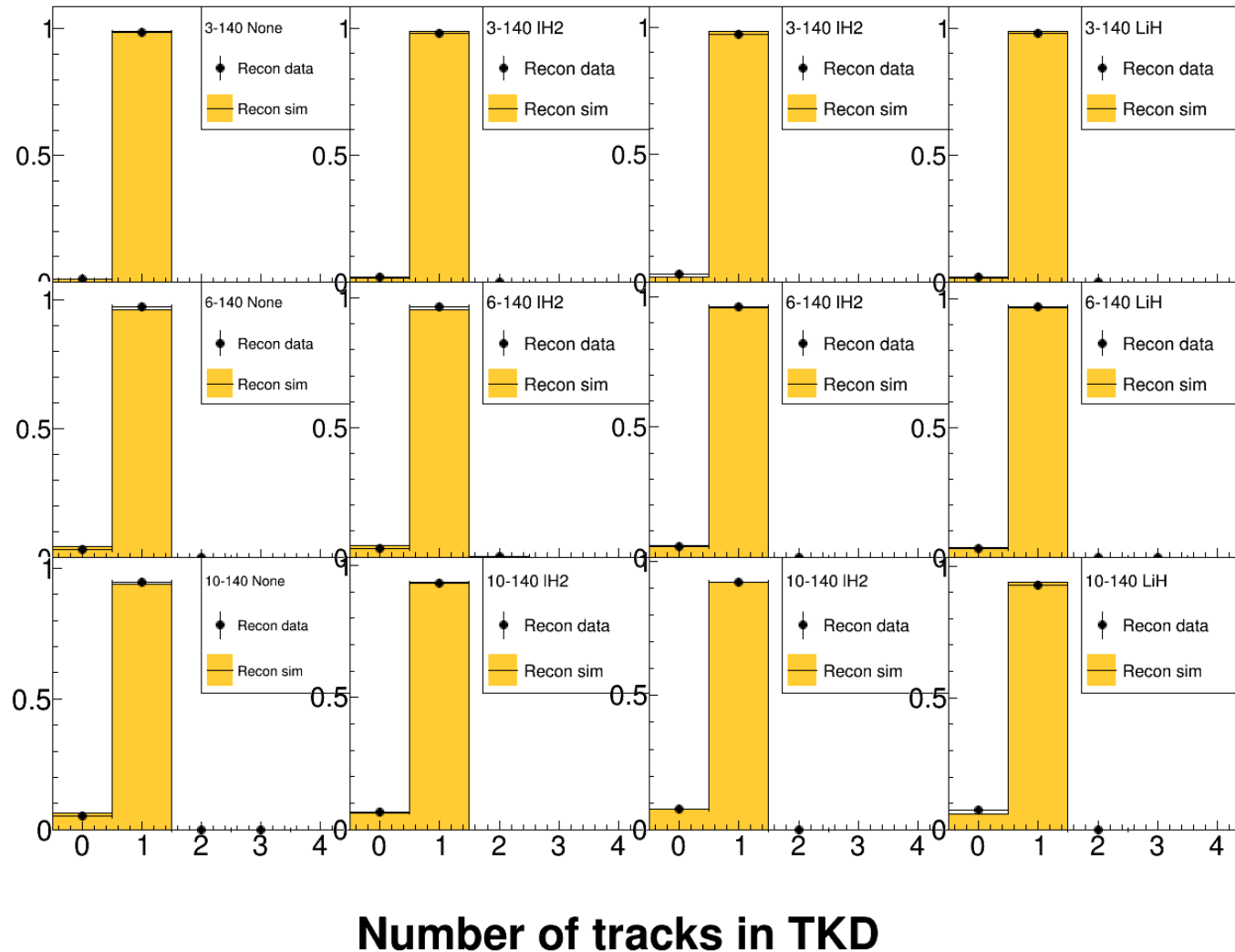
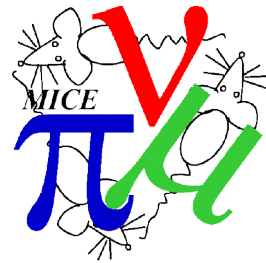


Downstream Sample

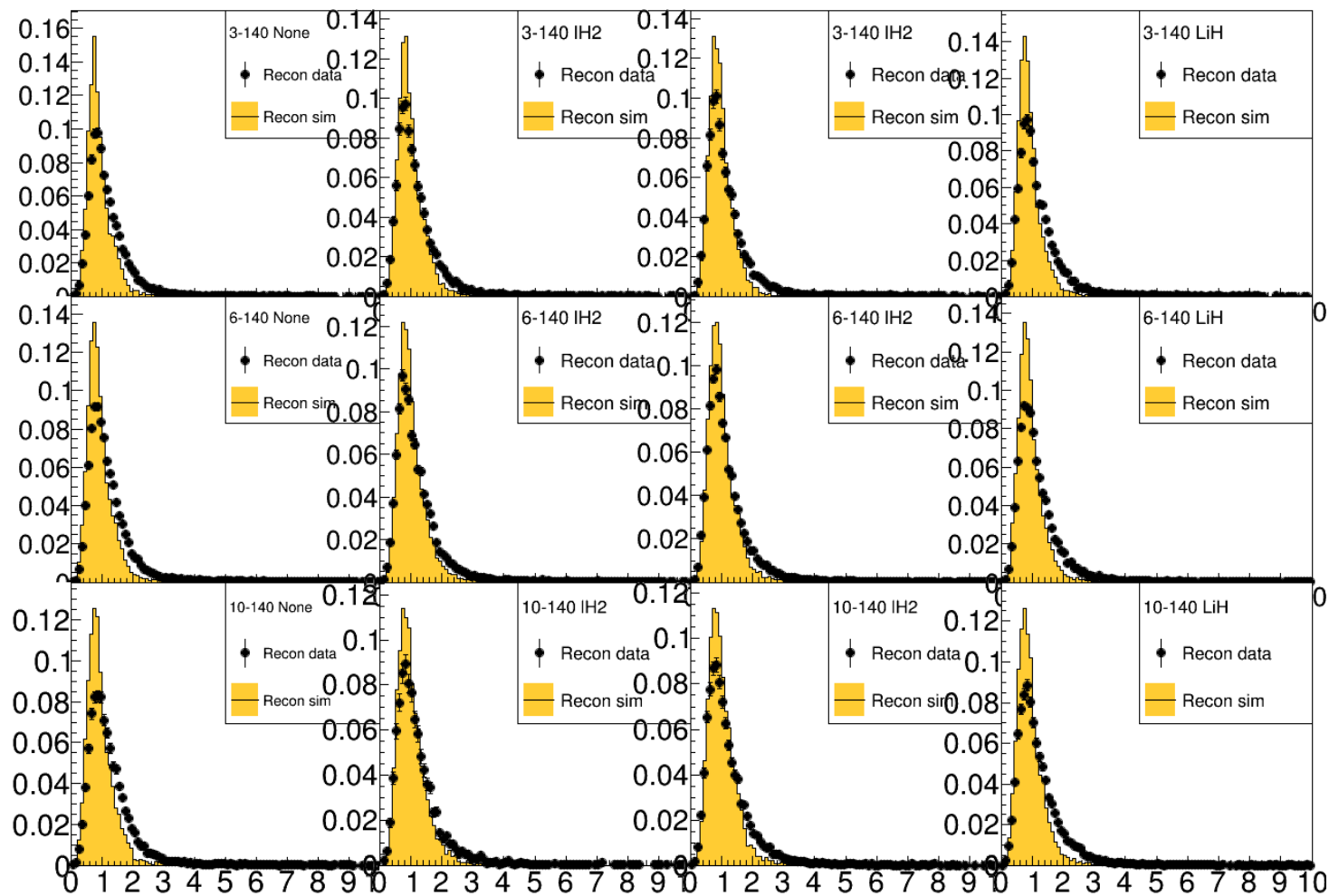
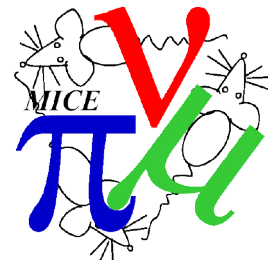


- Aim to show change in amplitude distribution in downstream sample
 - Keep downstream cuts as light as possible
 - Want to reject obviously bad tracks, but nothing else
- Downstream sample
 - Exactly one track in TKD
 - TKD $\text{Chi}^2/\text{dof} < 5$
 - TKD track radius < 150 mm
 - $100 < \text{Total momentum} < 200$ MeV/c
- Show plots of “cut variable” with all cuts except the cut of interest applied

Cuts summary tracks = 1

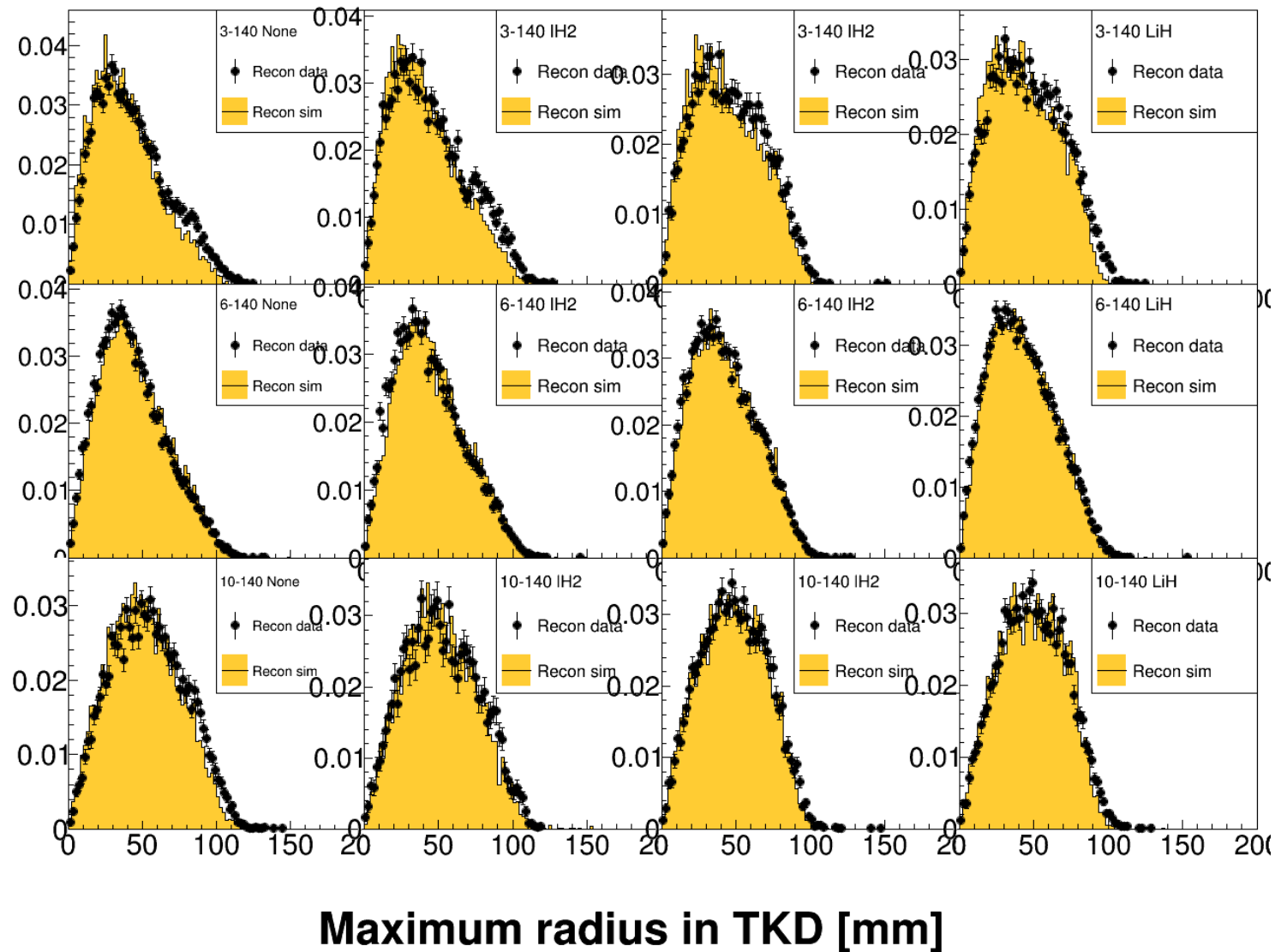
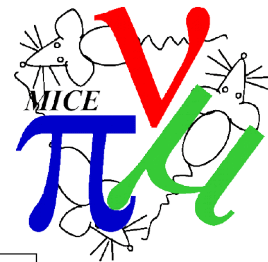


Cuts summary $\chi^2/\text{dof} < 5$

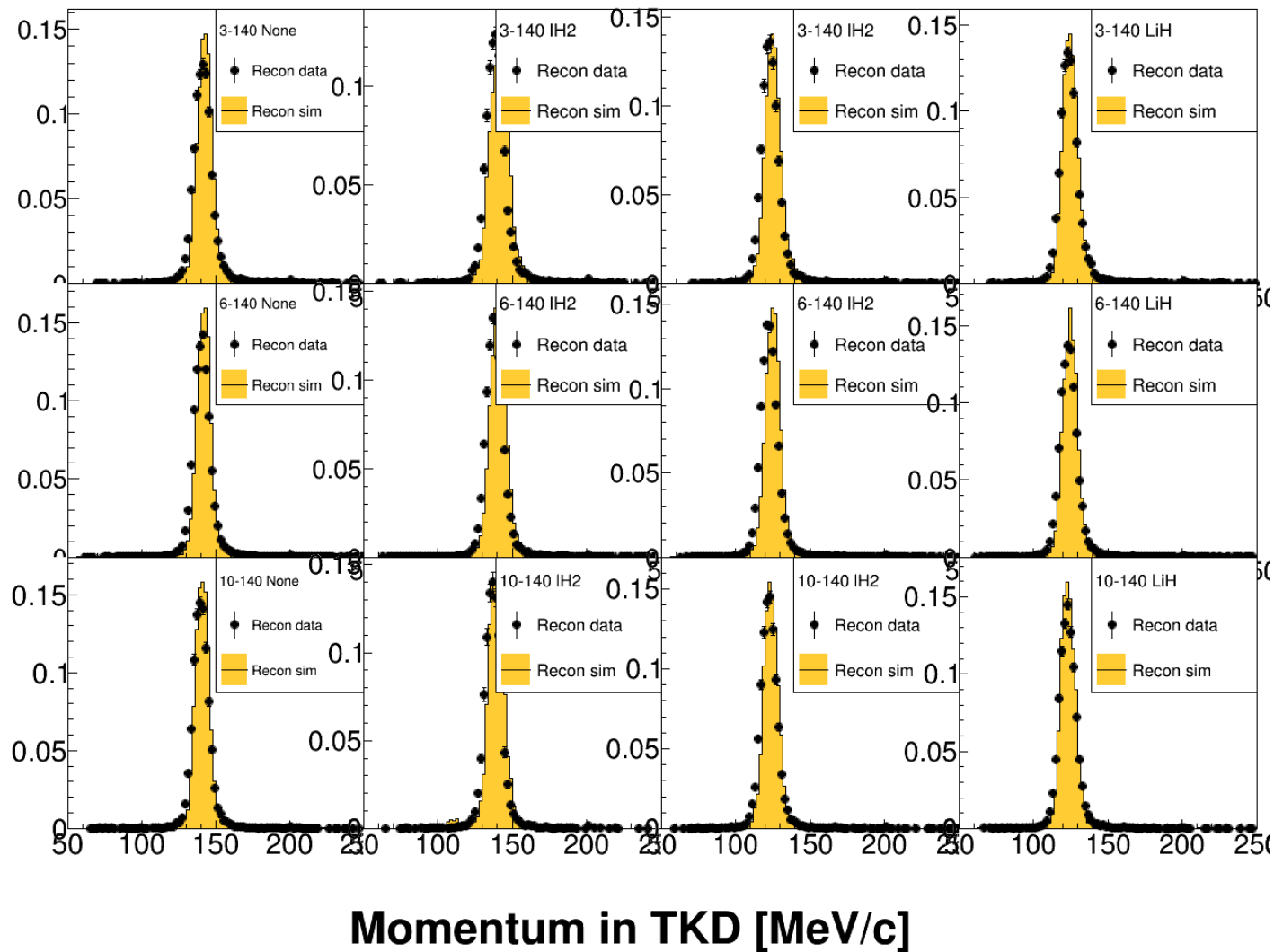
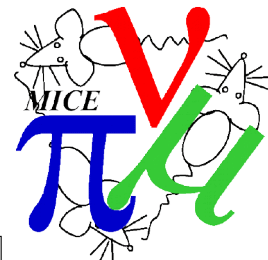


$\chi^2/\text{D.o.F. in TKD}$

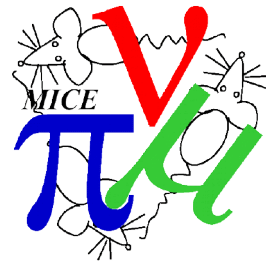
Cuts summary $r < 150$



Cuts summary $100 < p < 200$

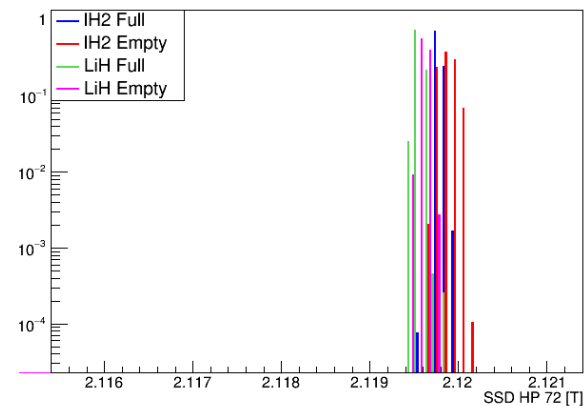
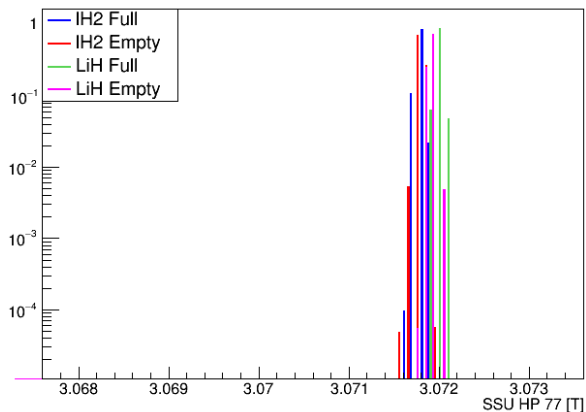
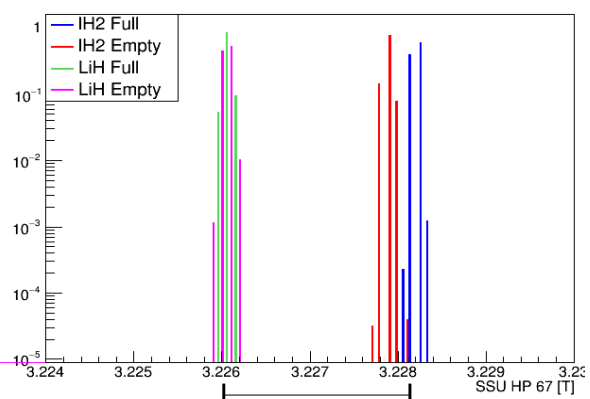
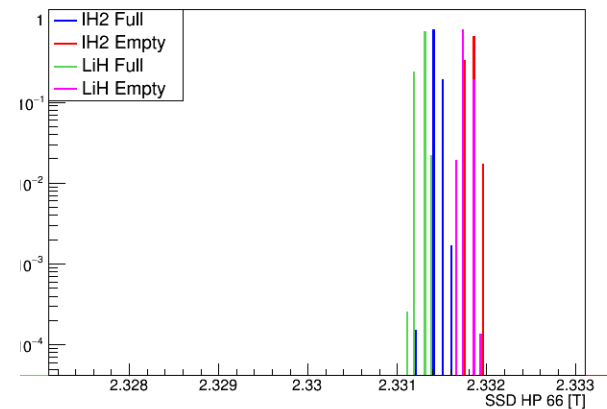
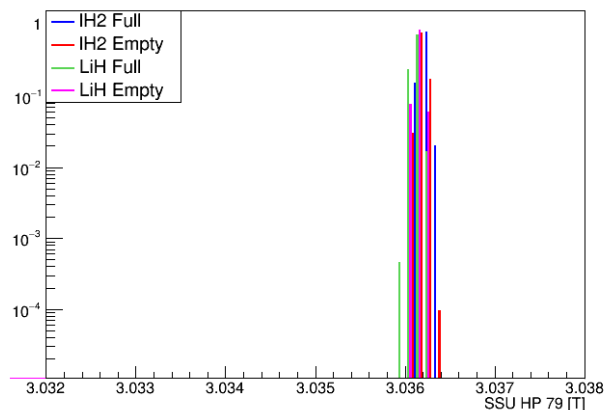
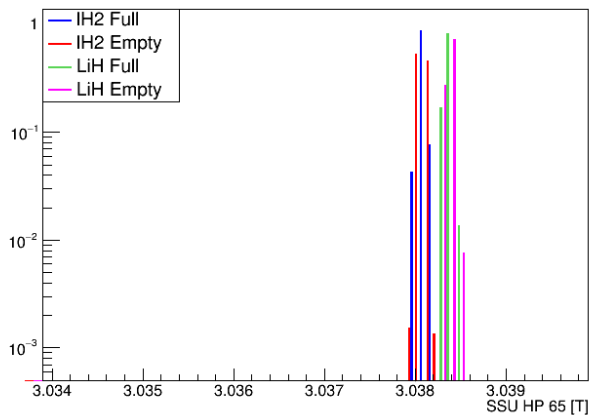
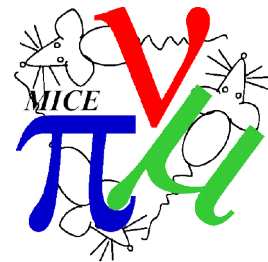


Data validation



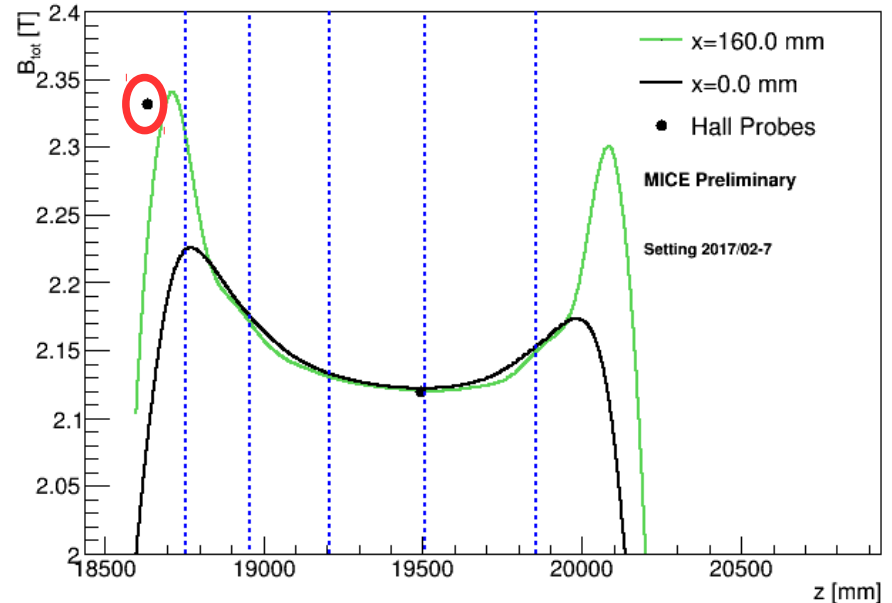
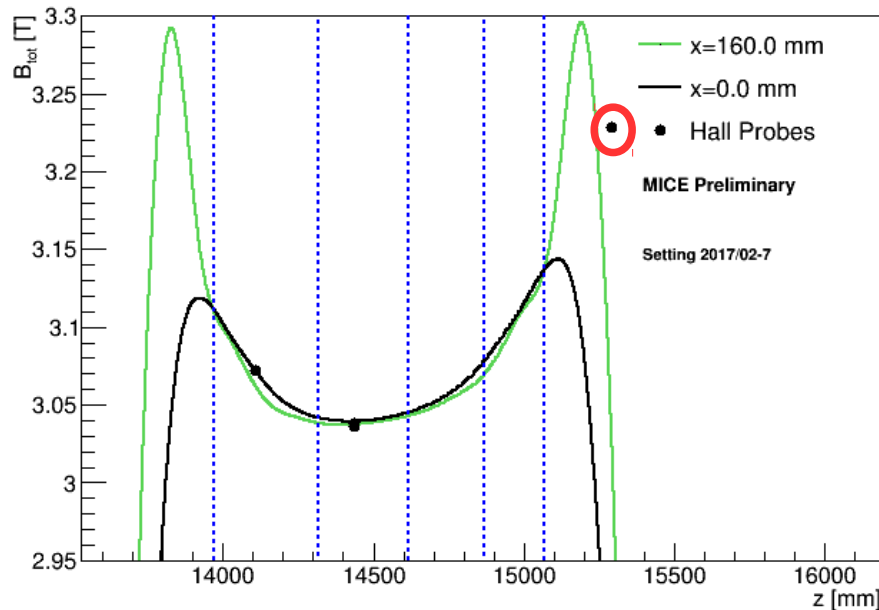
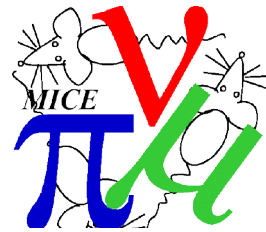
- Some cross-checks to understand the data better
 - Check the field is good
 - Chi2/dof in tracker – shown above
 - Do I reconstruct okay?
 - Check the tracker reconstruction at cluster level
 - Is noise and inefficiency handled okay in MC?
 - Check TOF slab dt
 - Is TOF calibration self-consistent?
 - Check energy loss in absorber
 - Any obvious issues?

Hall probes



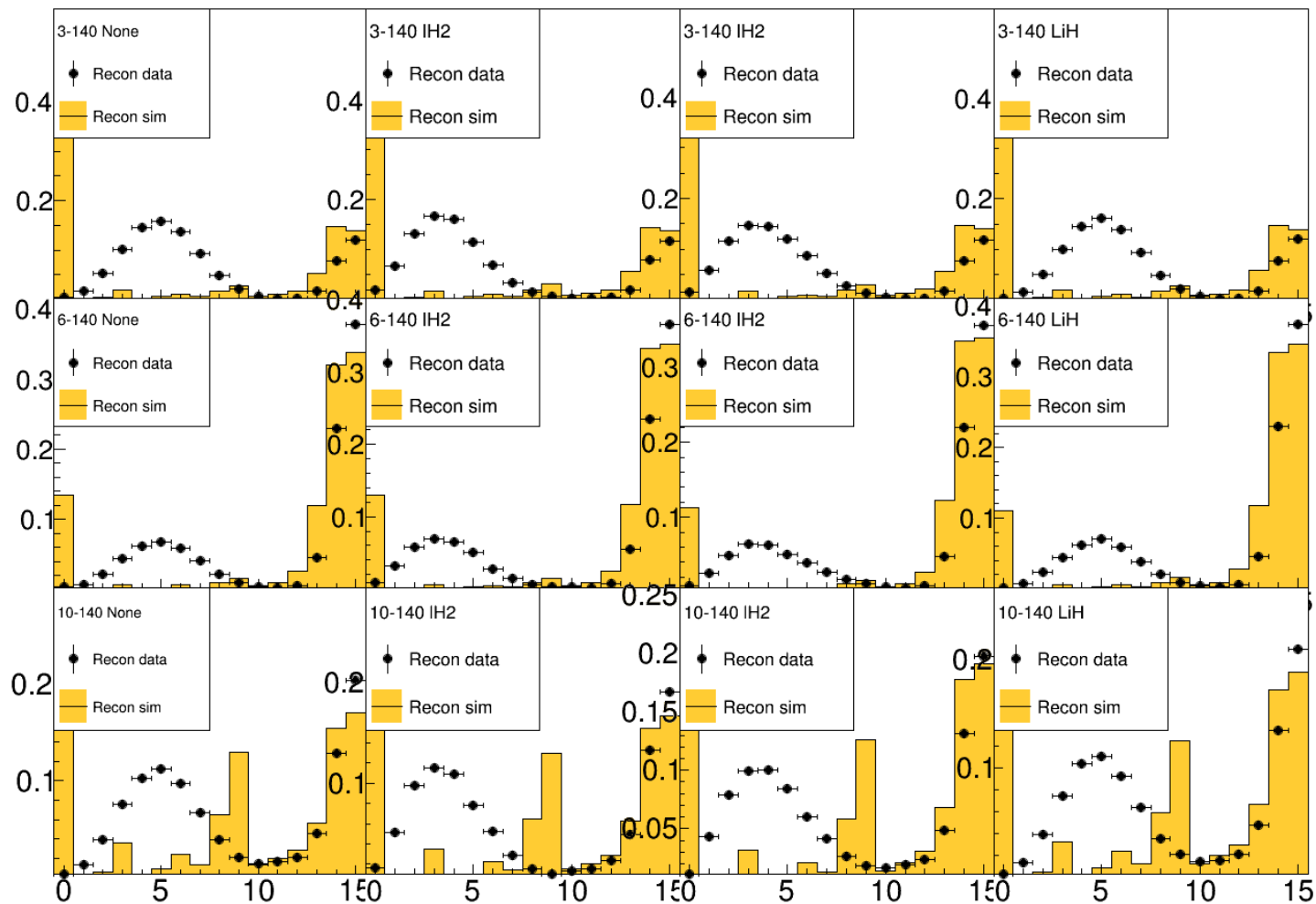
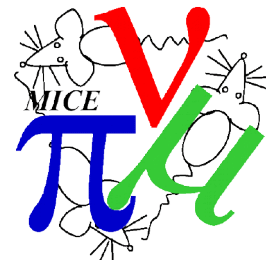
2 mT

Hall probes



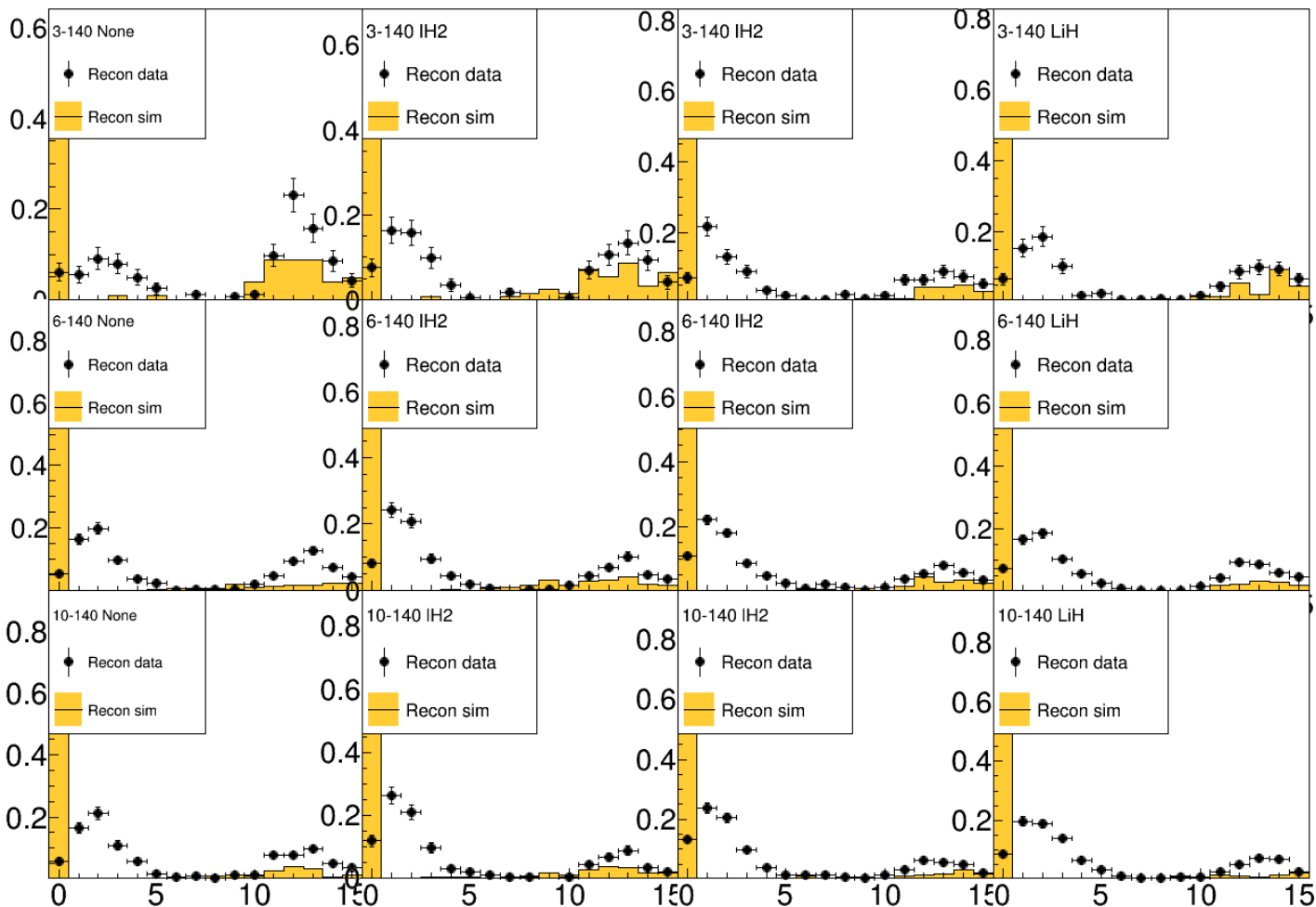
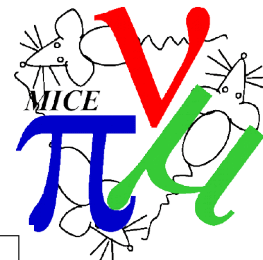
- MAUS model has been tuned to hall probes
 - About 2 % enhancement in MAUS model current to get agreement
 - During investigation of tracker/bore, formerly troublesome Hall probes have been shown to be physically displaced from “as-built” position – mystery solved!

TKU clusters



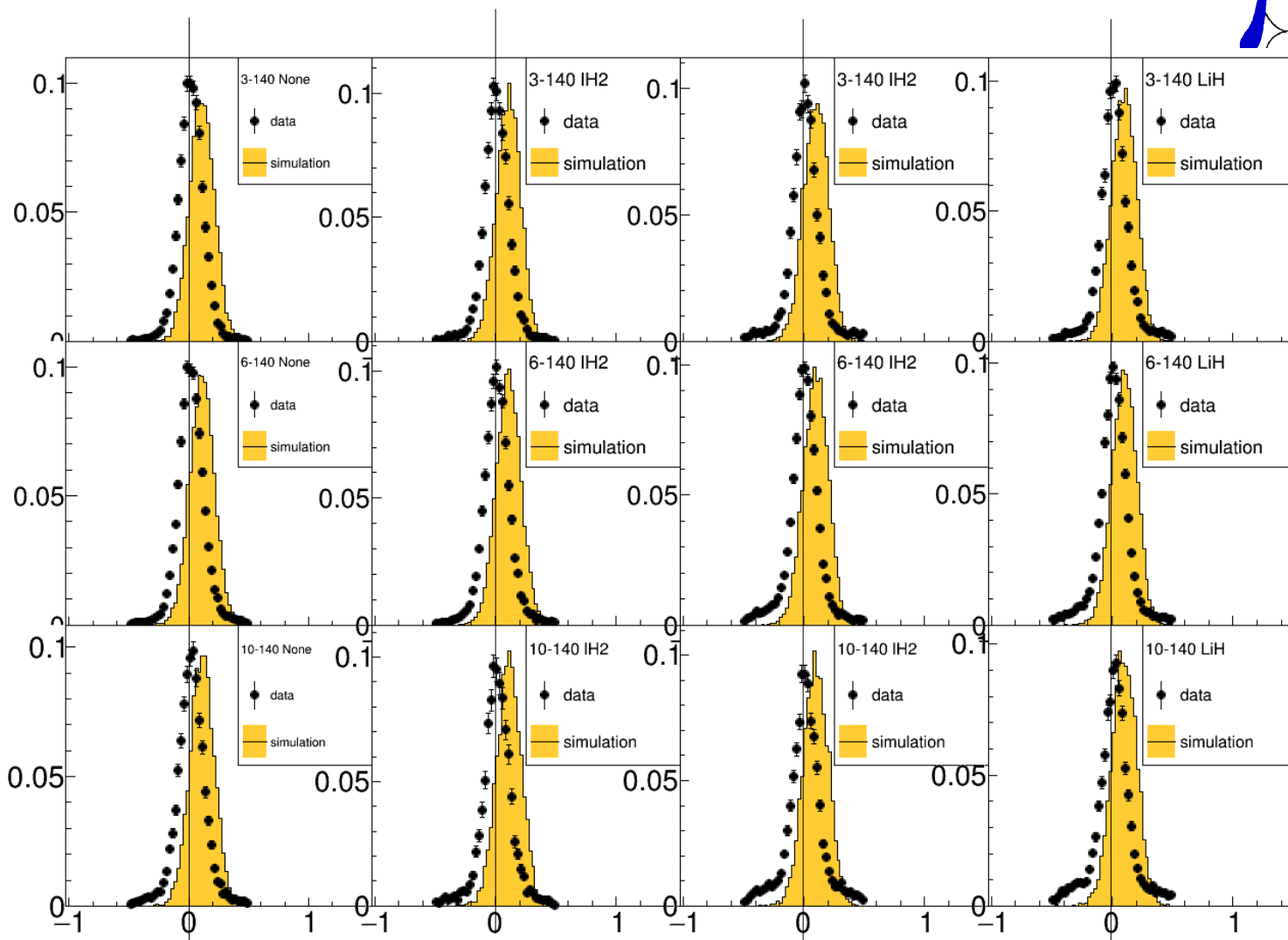
Number of planes with clusters in TKU
For events that DO NOT form a track

TKD clusters



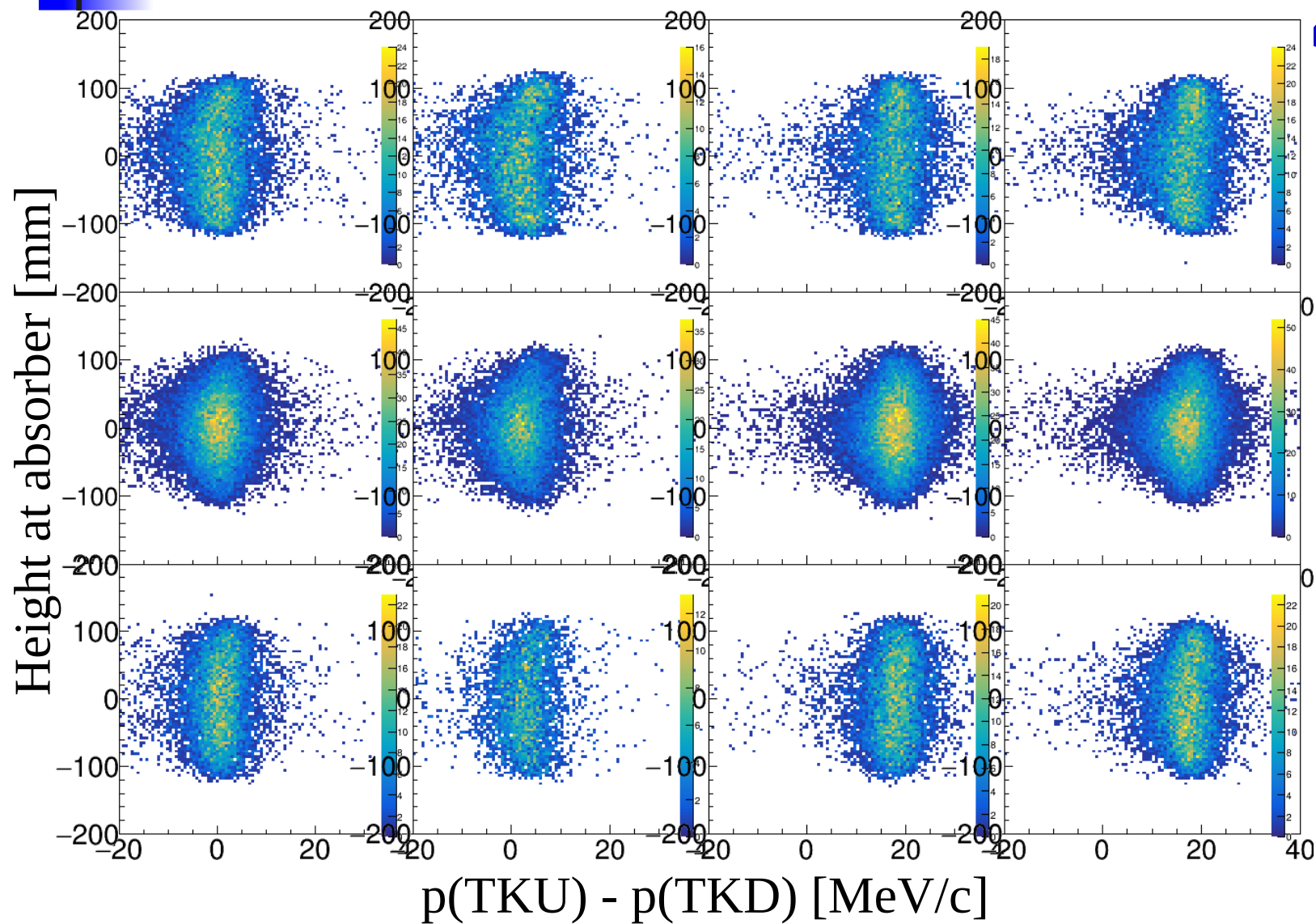
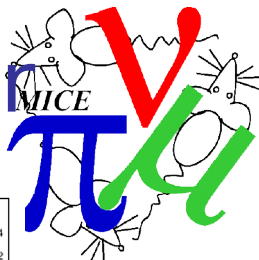
Number of planes with clusters in TKD
For events that DO NOT form a track

TOF slabs

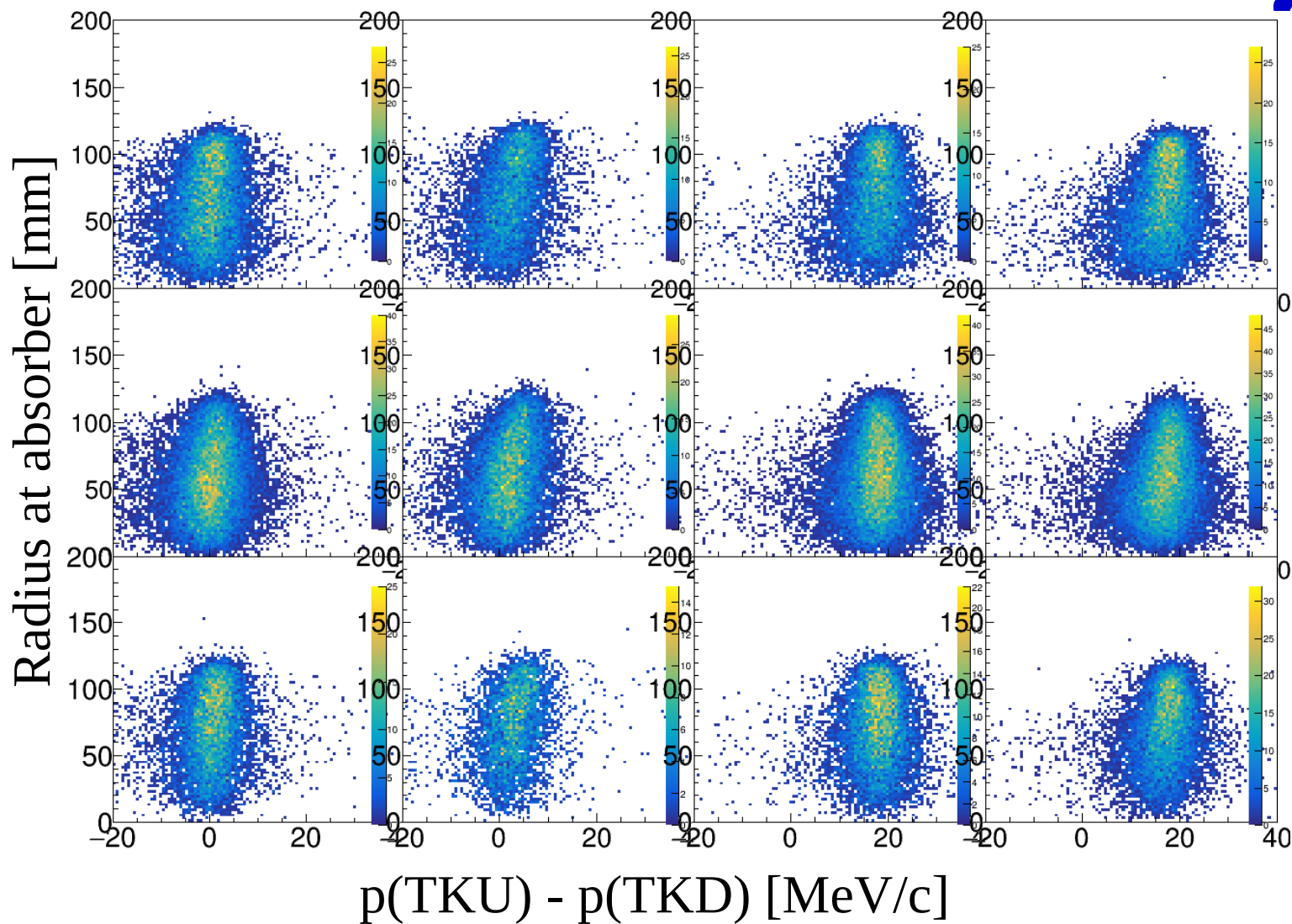
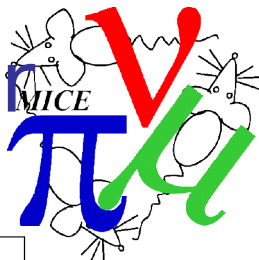


Slab dt for TOF2 [ns]

Change in momentum in absorber

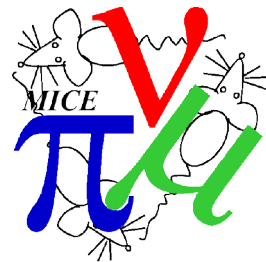


Change in momentum in absorber



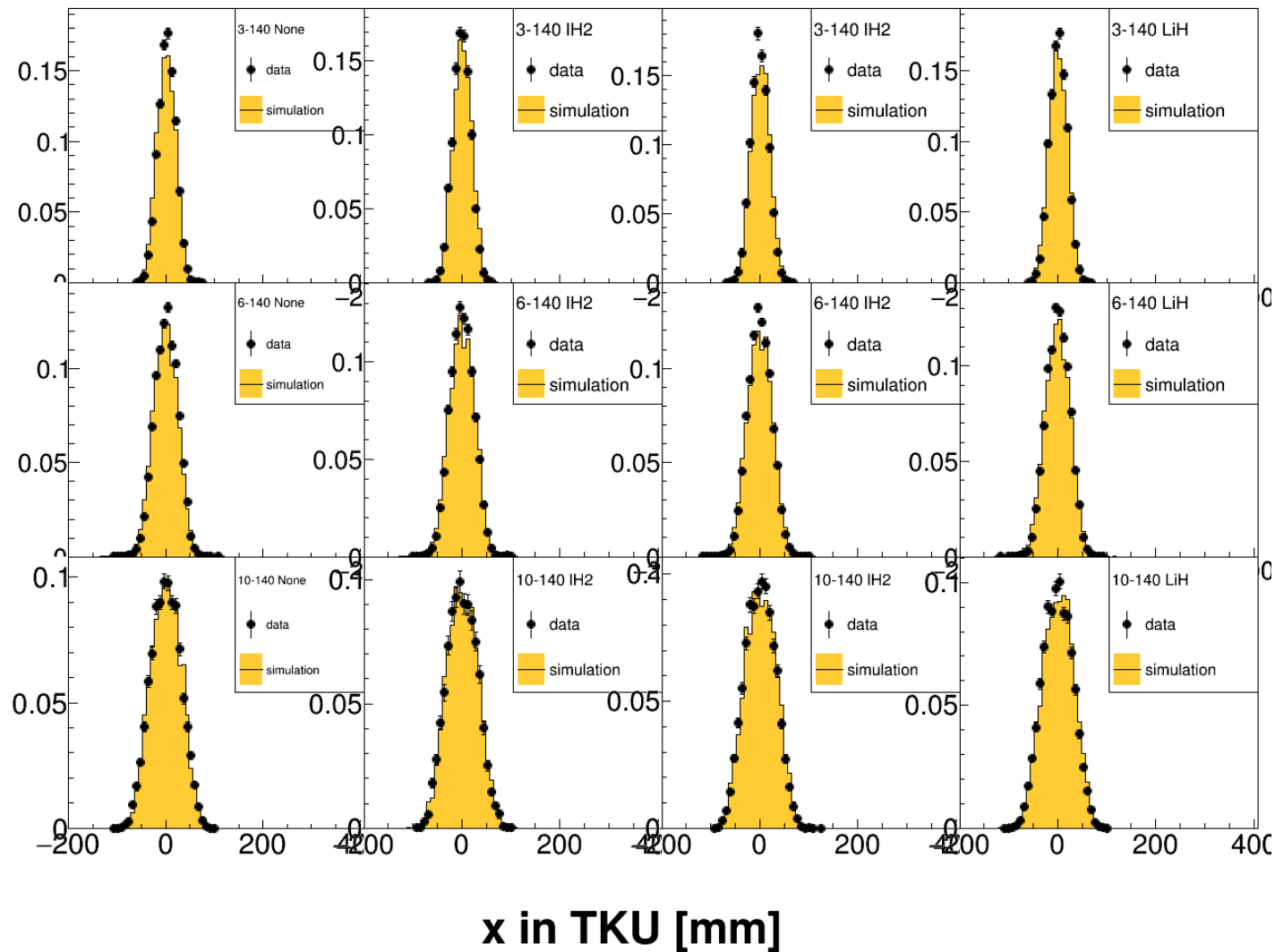
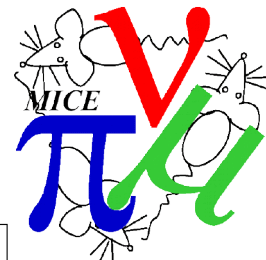


Beam distributions

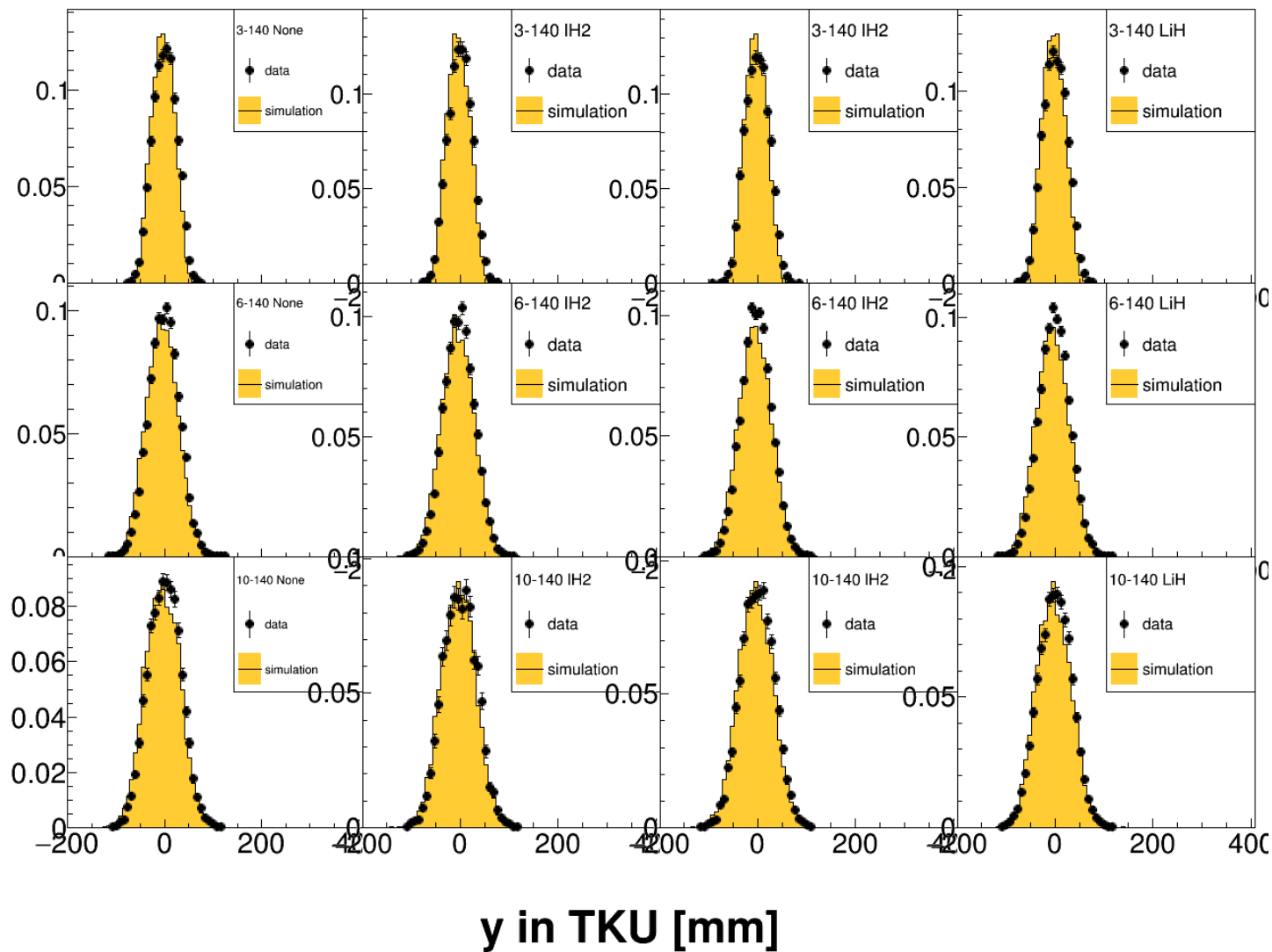
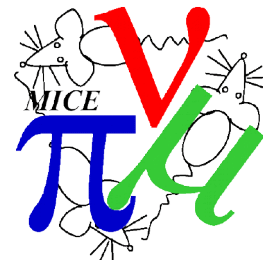


- Beam distributions
 - How well does MC agree with data?

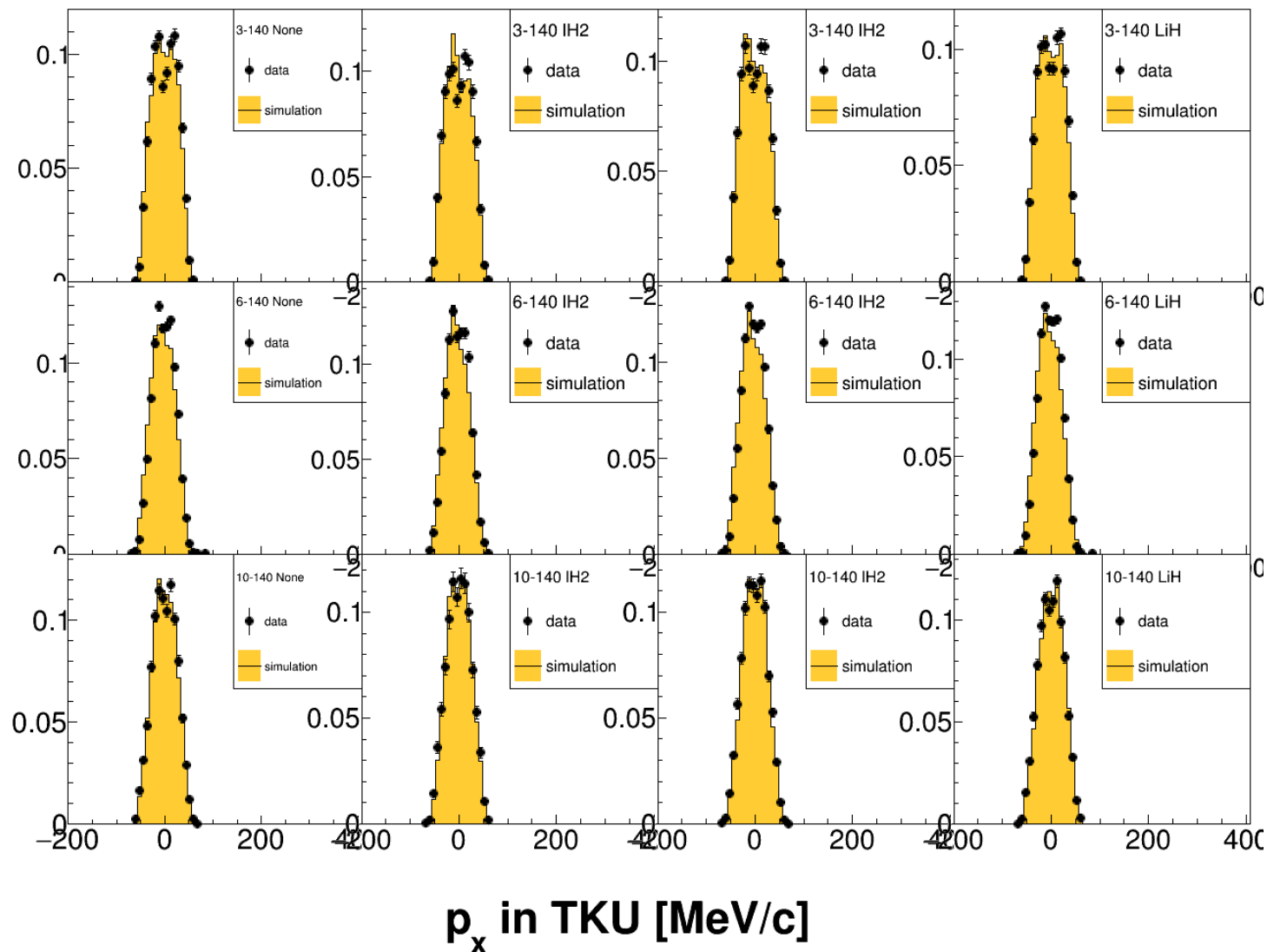
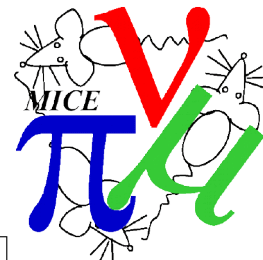
Beam distributions



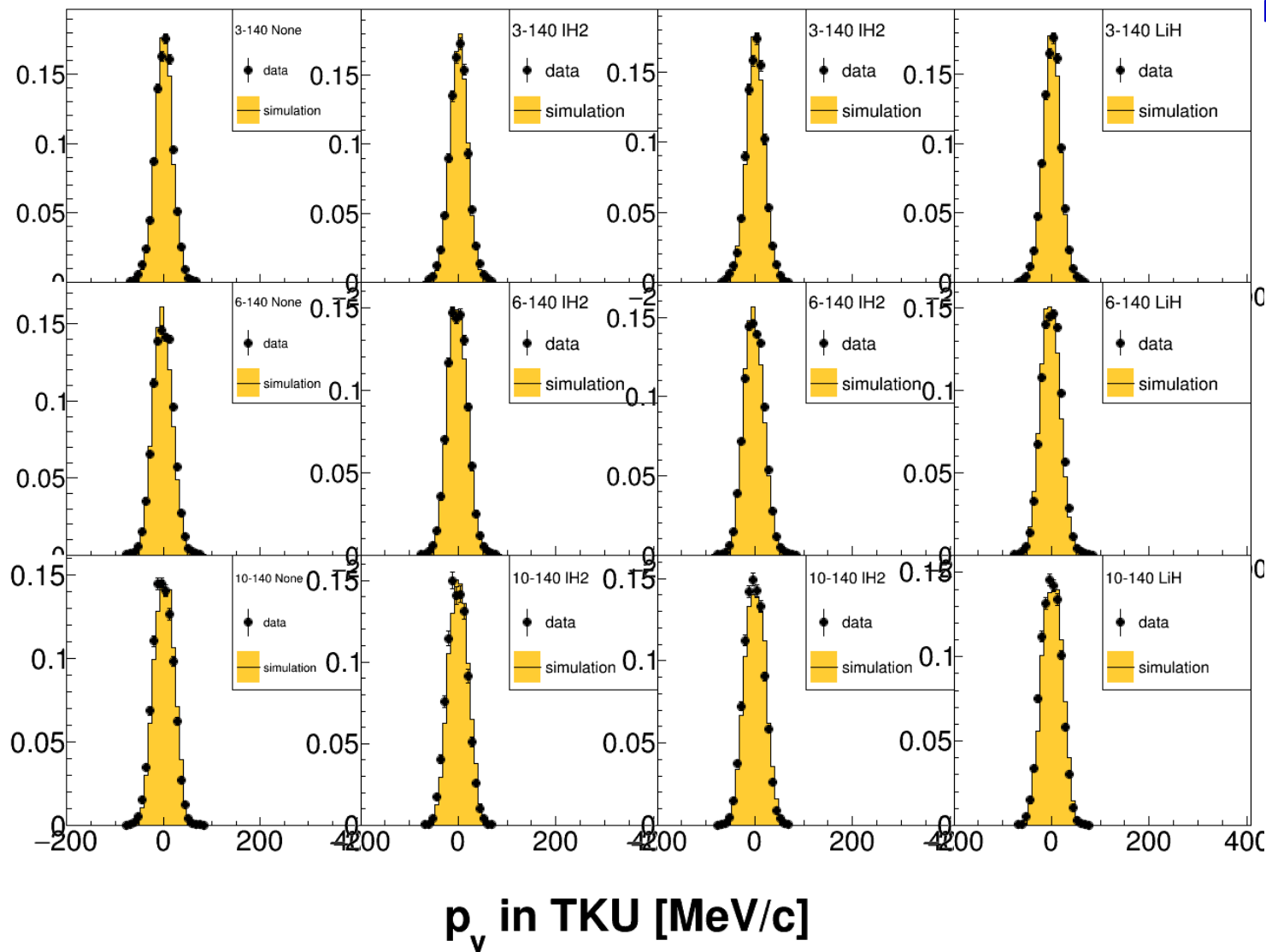
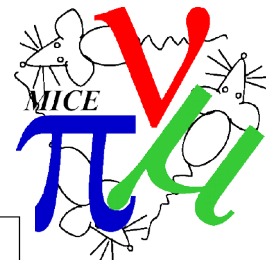
Beam distributions



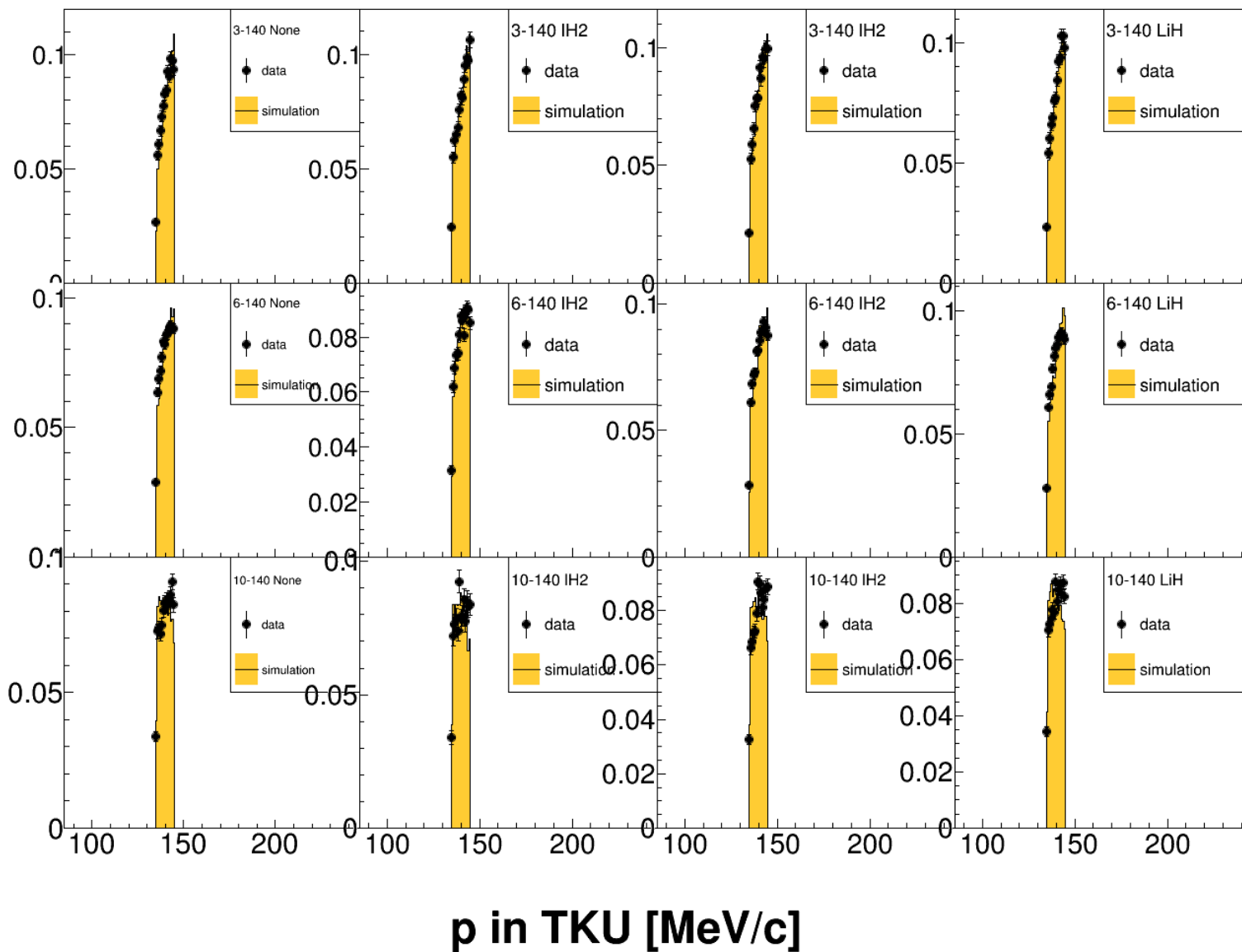
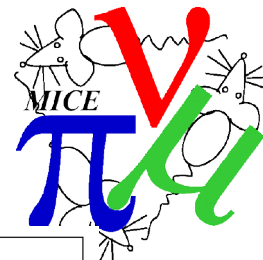
Beam distributions



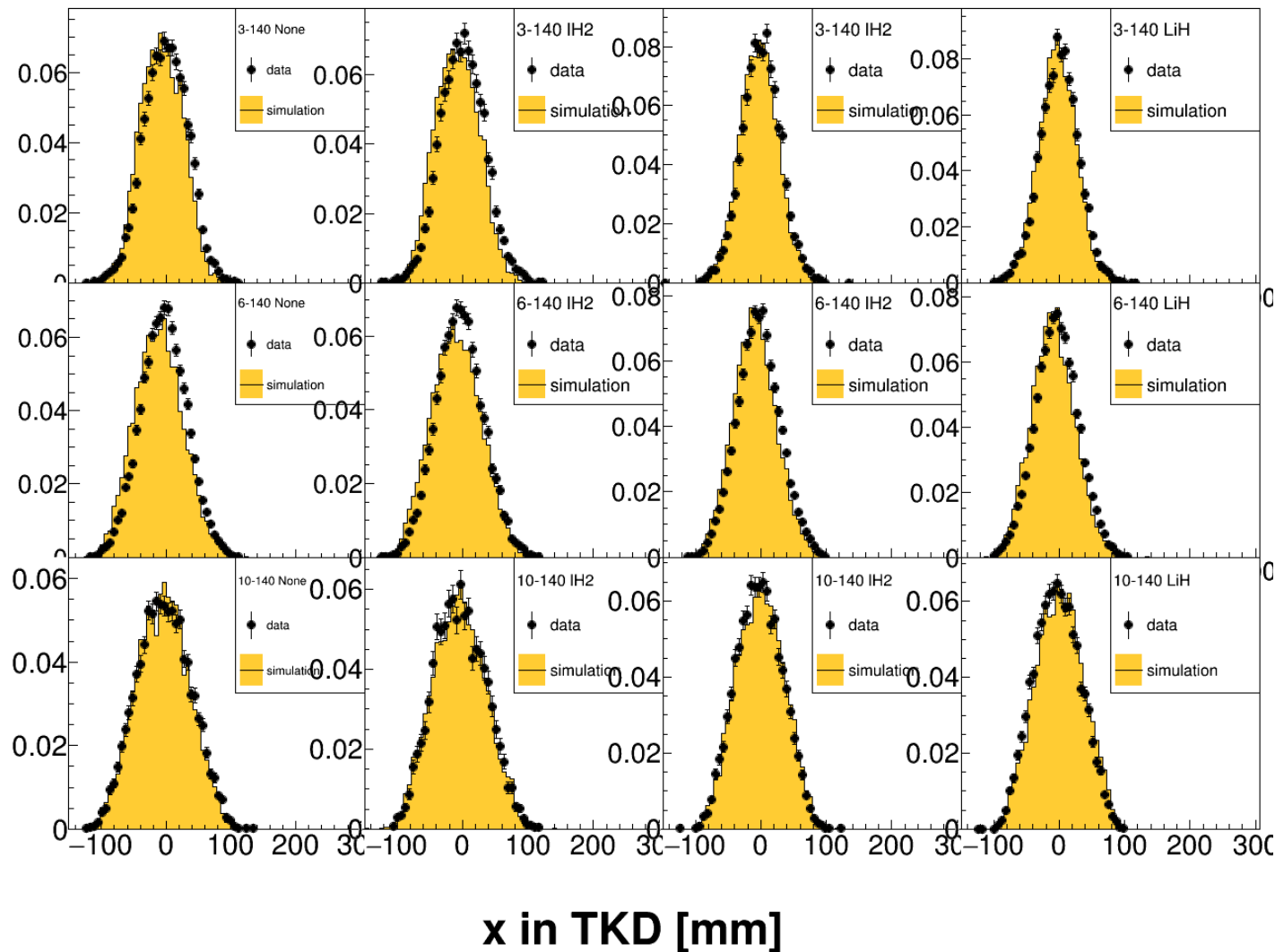
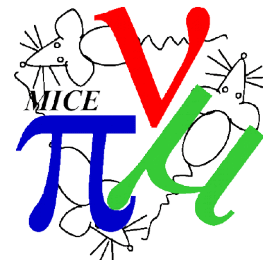
Beam distributions



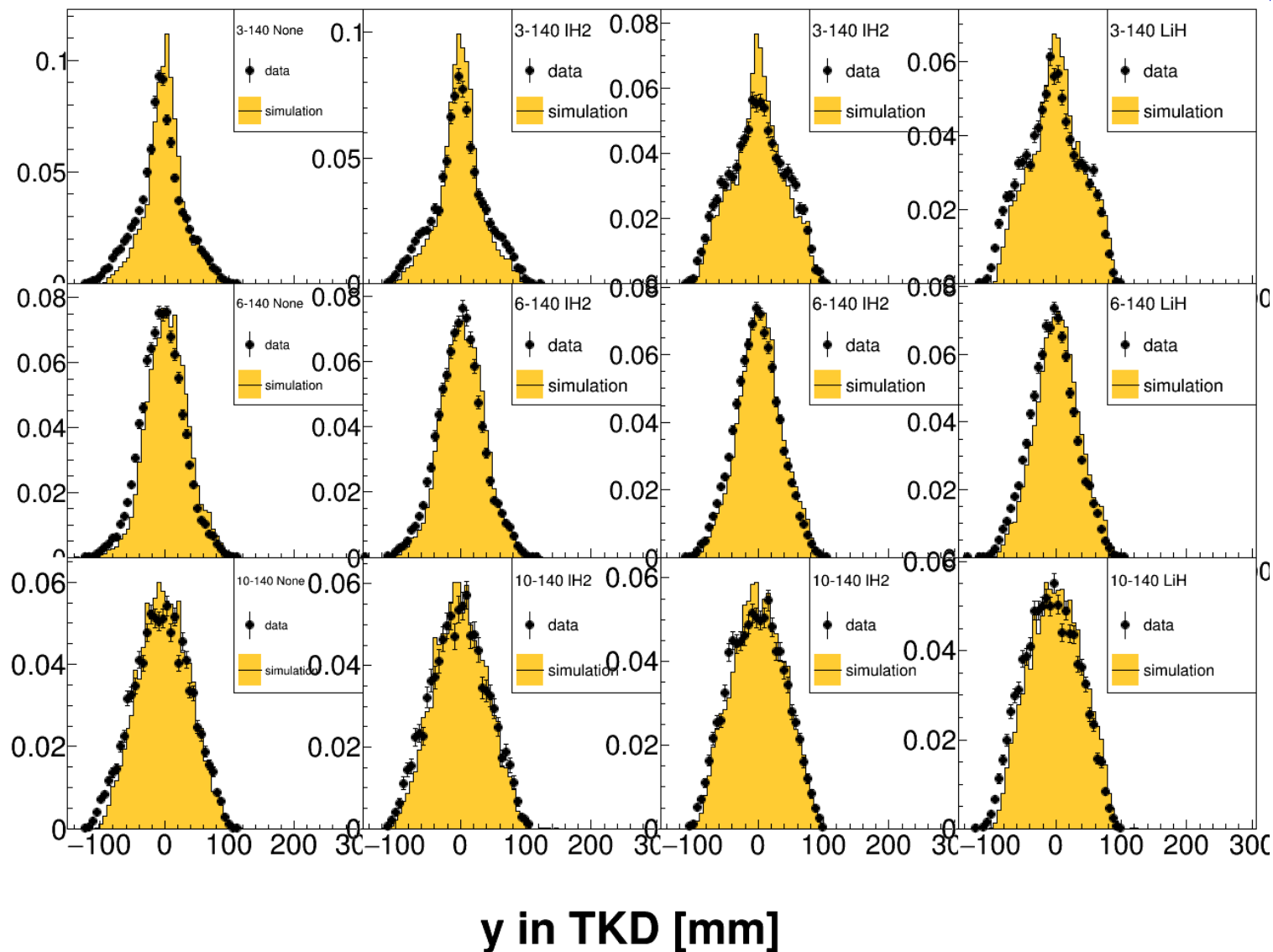
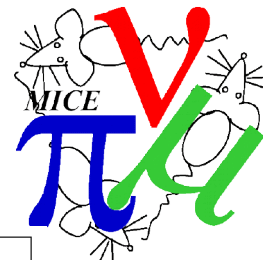
Beam distributions



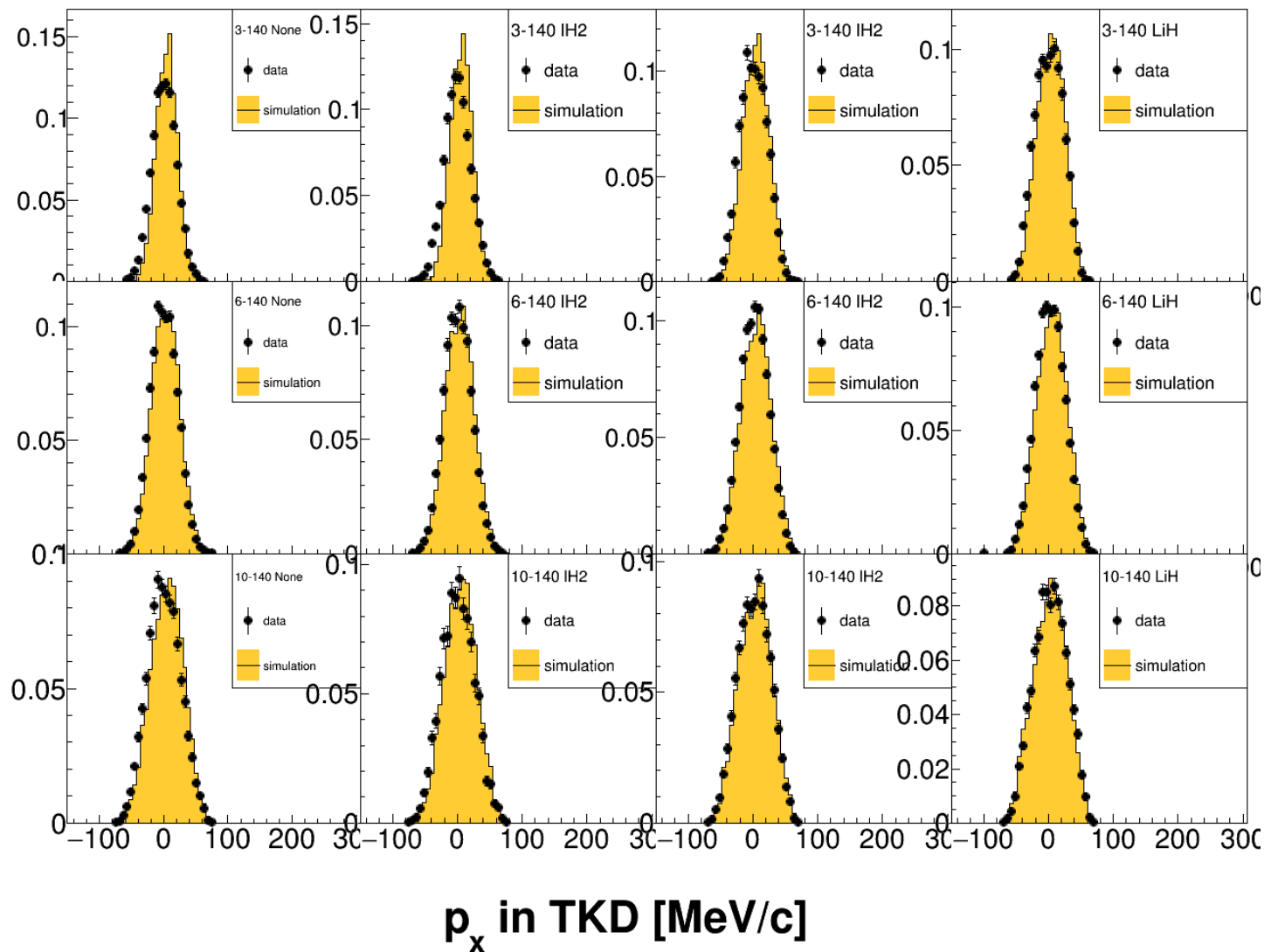
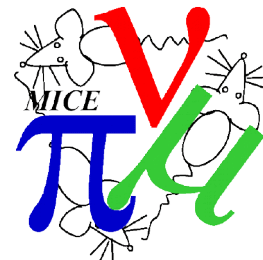
Beam distributions



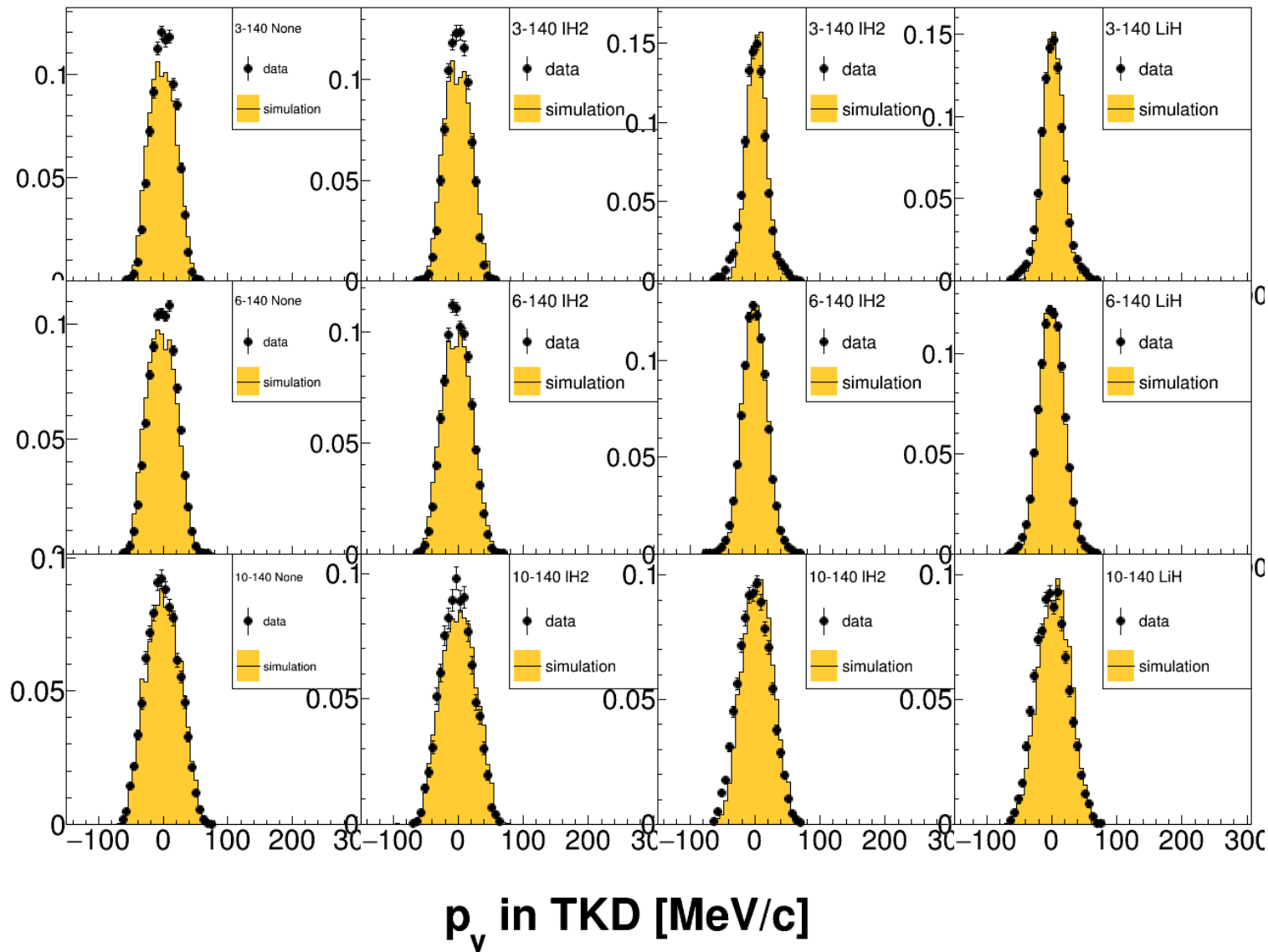
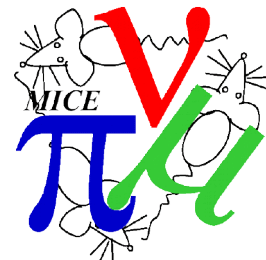
Beam distributions



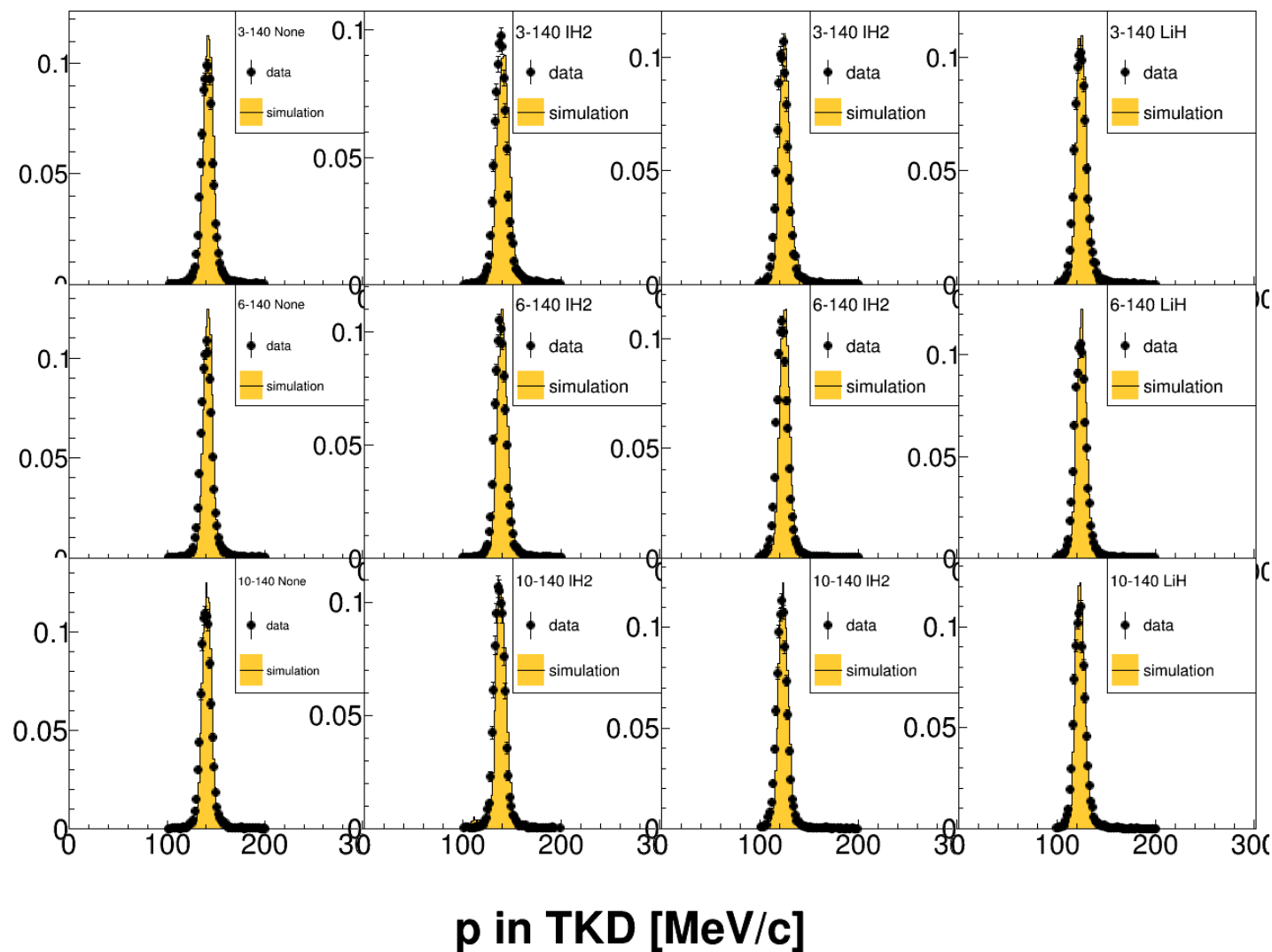
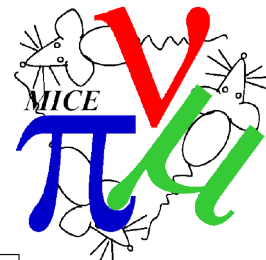
Beam distributions



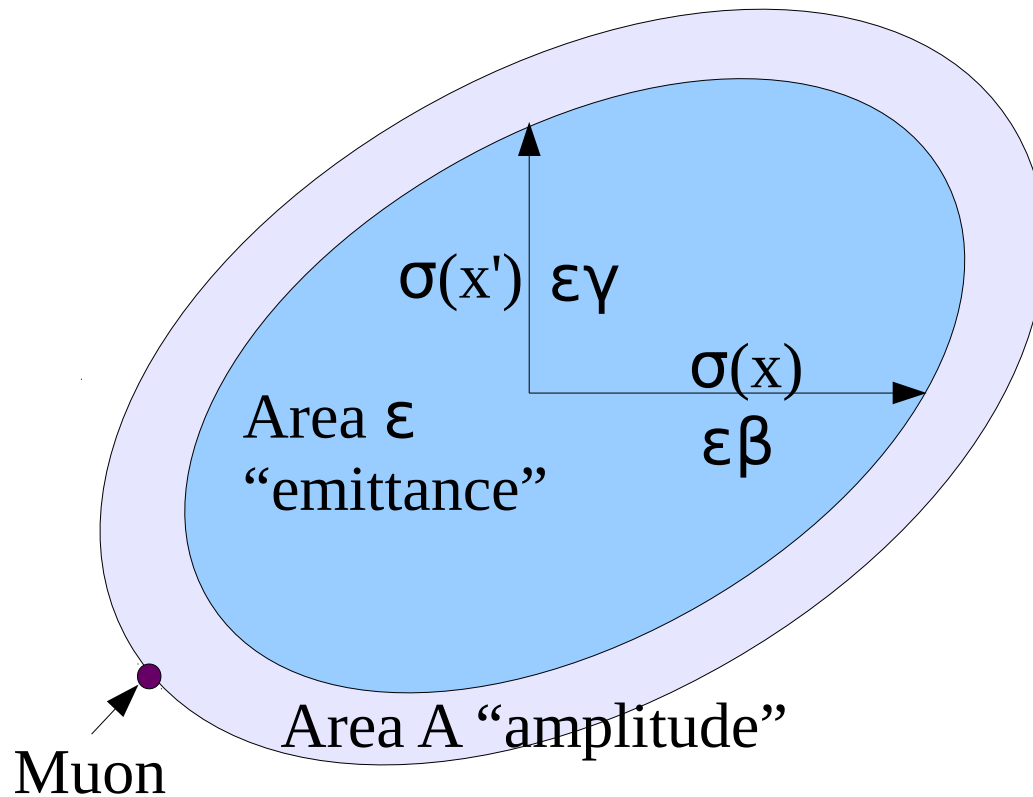
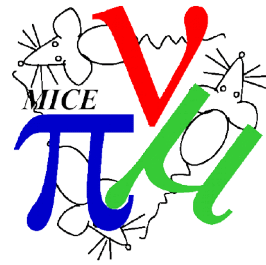
Beam distributions



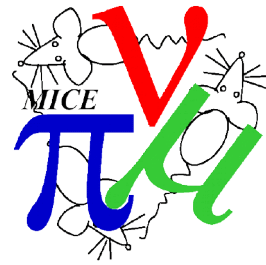
Beam distributions



Beam ellipse and amplitude



Amplitude algorithm

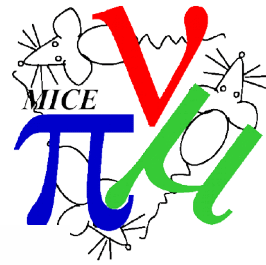


- Algorithm to calculate amplitude distribution

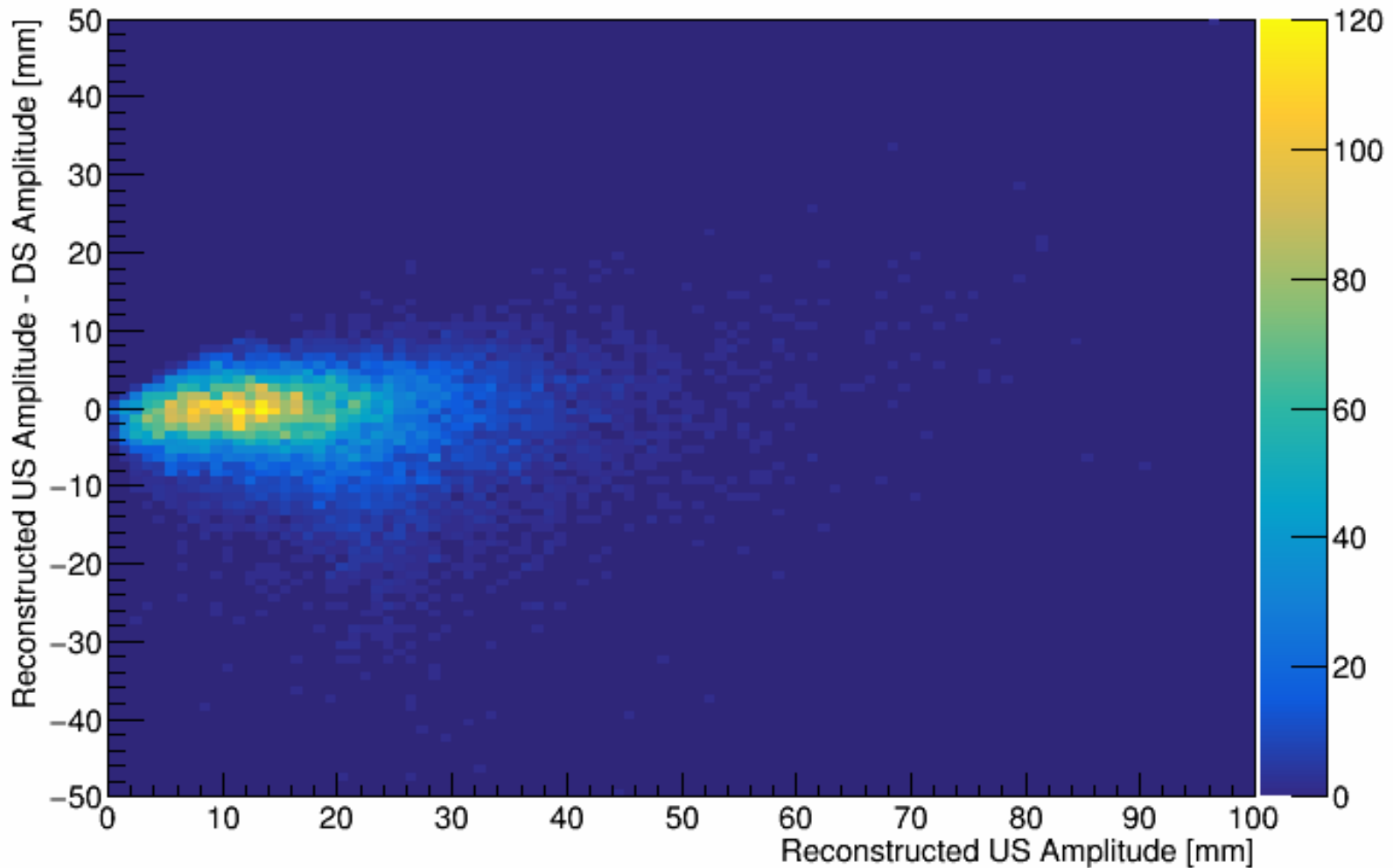
```
Split data into equal size "ref bin" and "test bin"
while number of events in "ref bin" > 10 {
    calculate amplitudes in "ref bin"
    designate highest amplitude in the "ref bin" as "amp cut"
    remove highest amplitude event from the "ref bin"
    update covariance matrix
    loop over "test bin" {
        calculate amplitudes
        if amplitude > "amp cut" {
            remove event from "test bin"
            store the amplitude
        }
    }
}
swap the "ref bin" and "test bin" designation and repeat
```

- Avoid pulling amplitude distribution in the core by effects in the tails
- Avoid sampling bias by splitting into reference and test samples

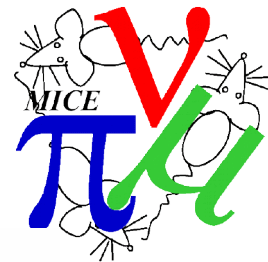
Amplitude vs Delta amplitude



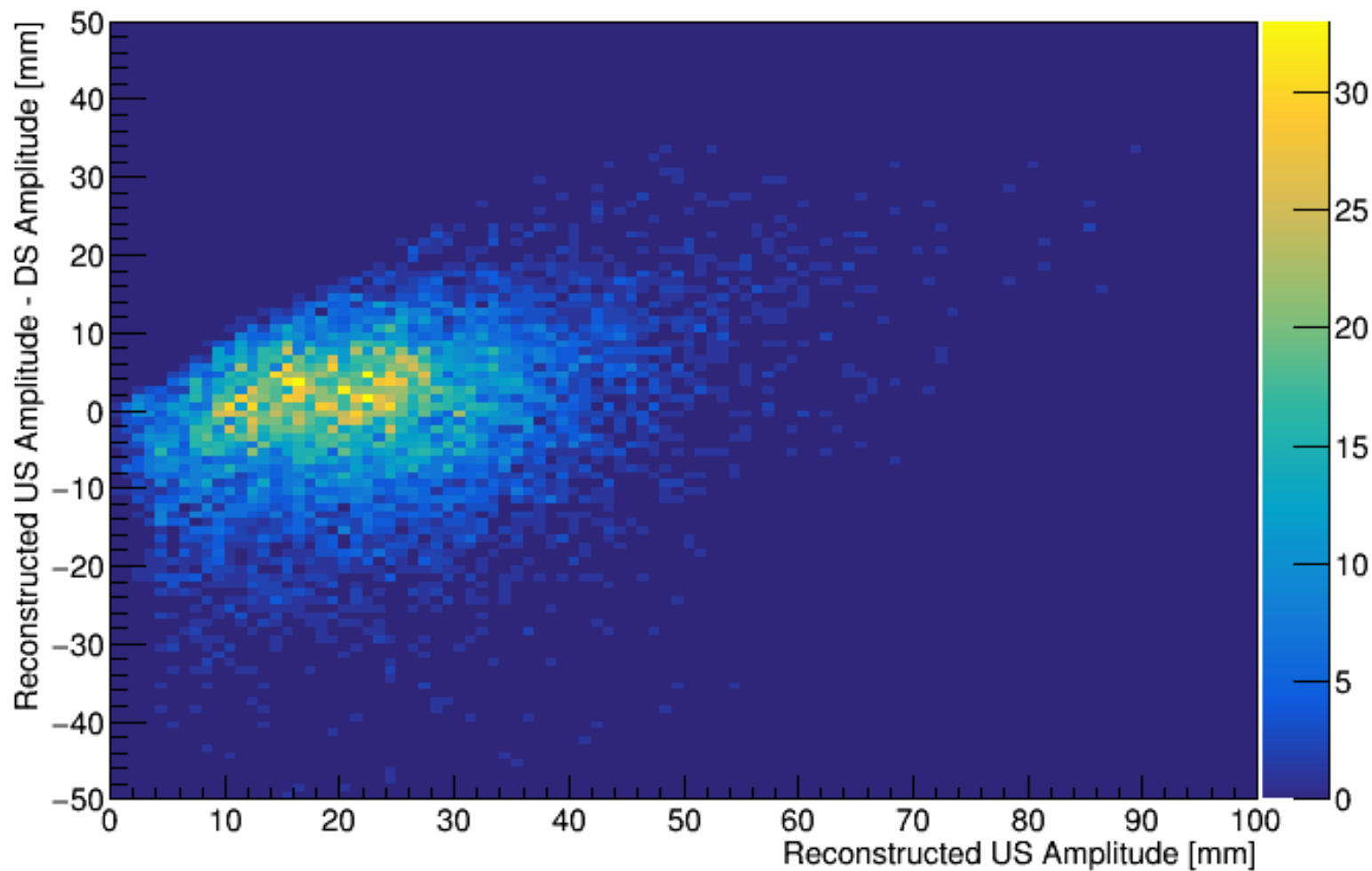
2017-2.7 6-140 None



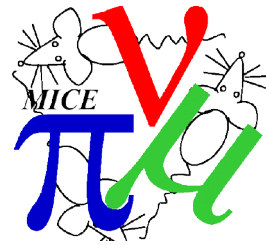
Amplitude vs Delta amplitude



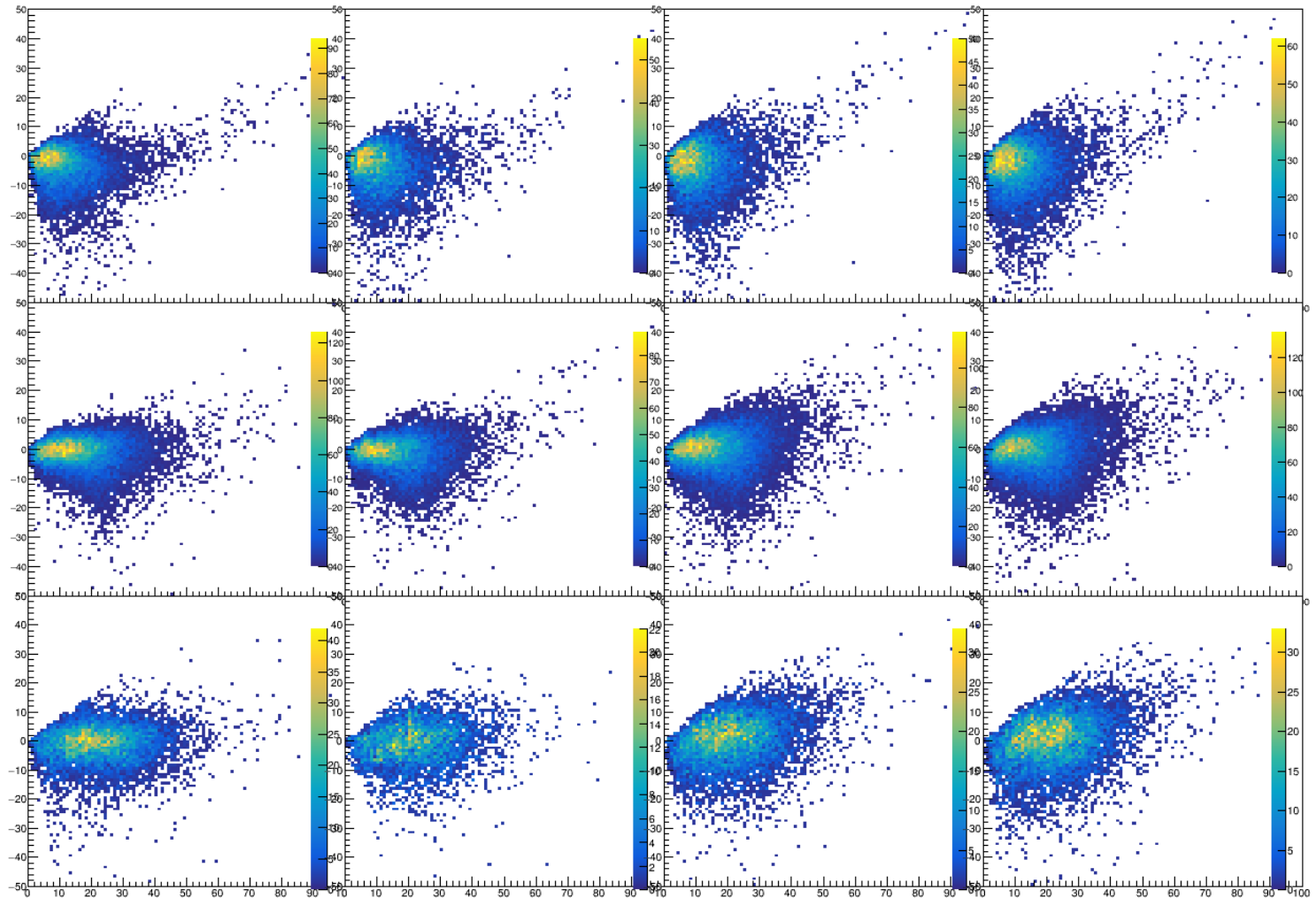
2017-2.7 10-140 LiH



Amplitude vs Delta amplitude

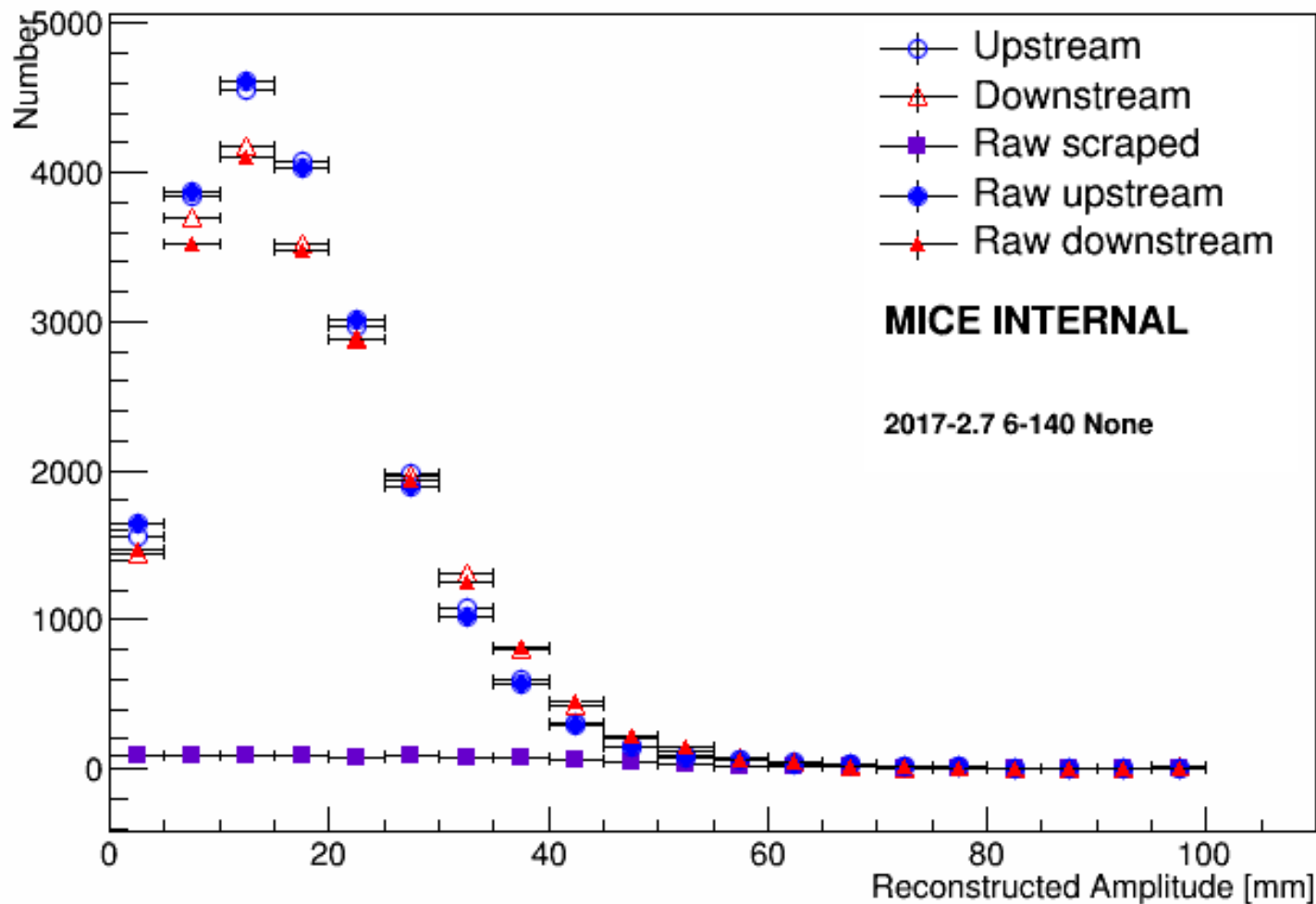
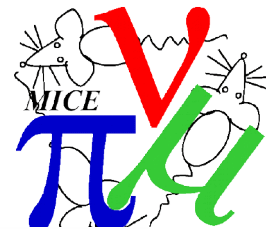


Reconstructed US Amplitude – DS Amplitude [mm]

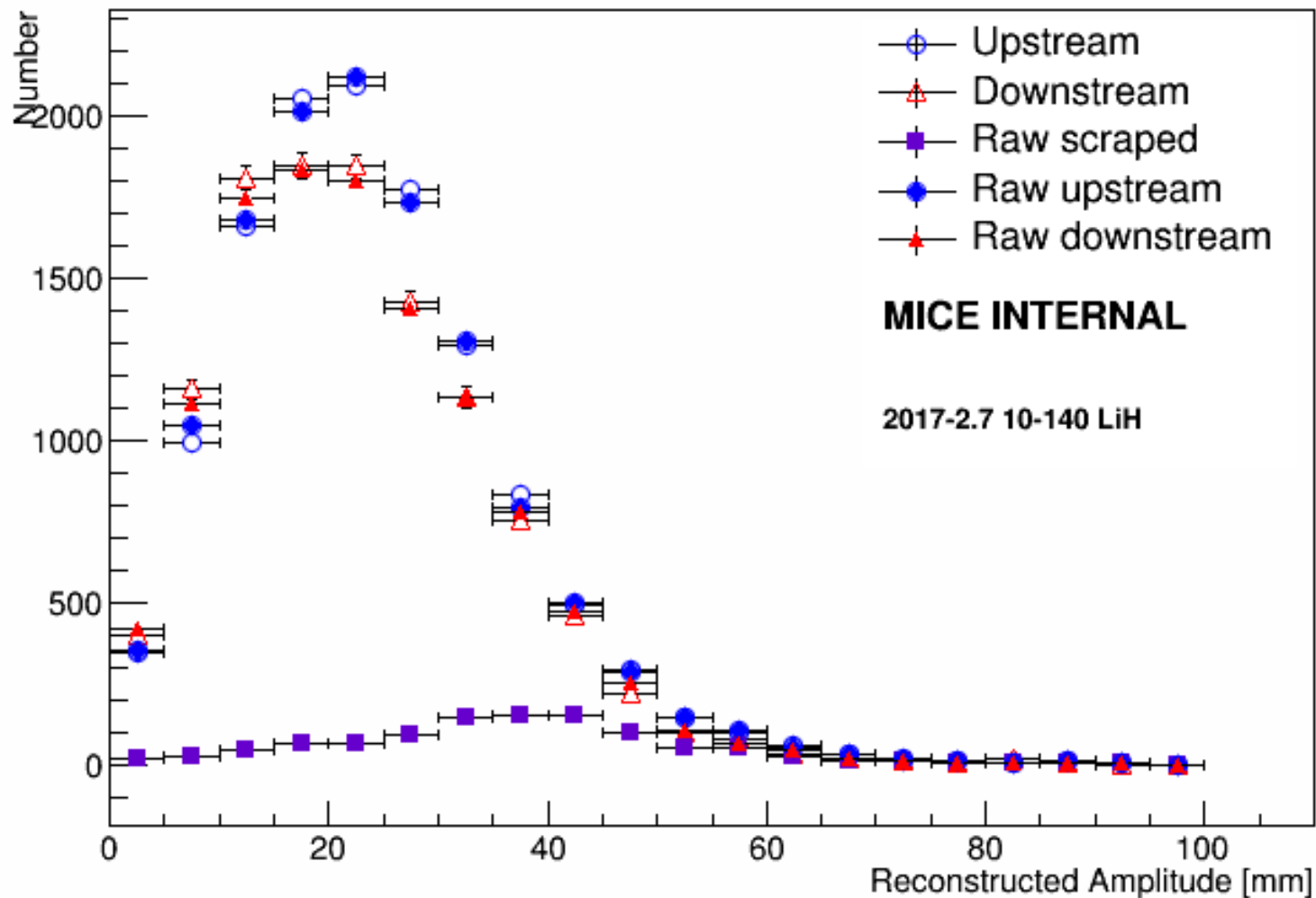
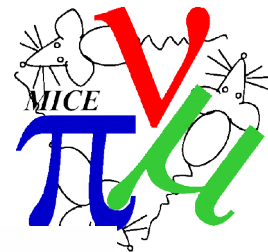


Reconstructed US Amplitude [mm]

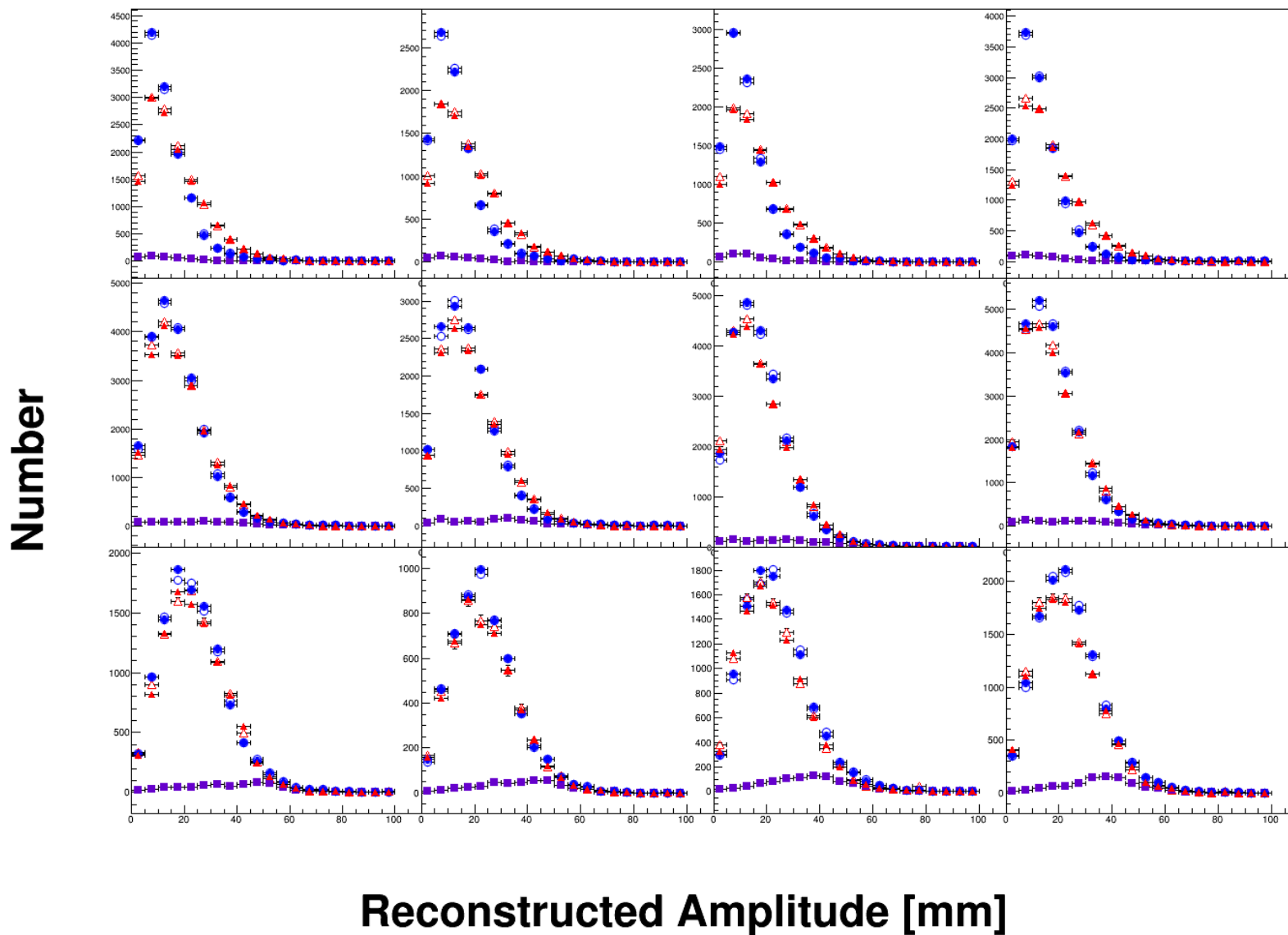
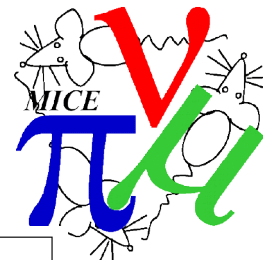
Amplitude (6 mm None)



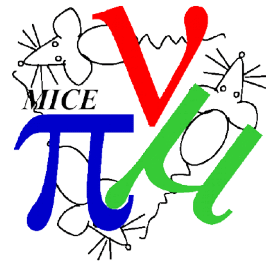
Amplitude (10 mm LiH)



Amplitude algorithm

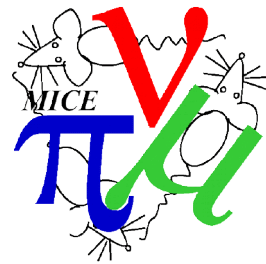


Systematic corrections



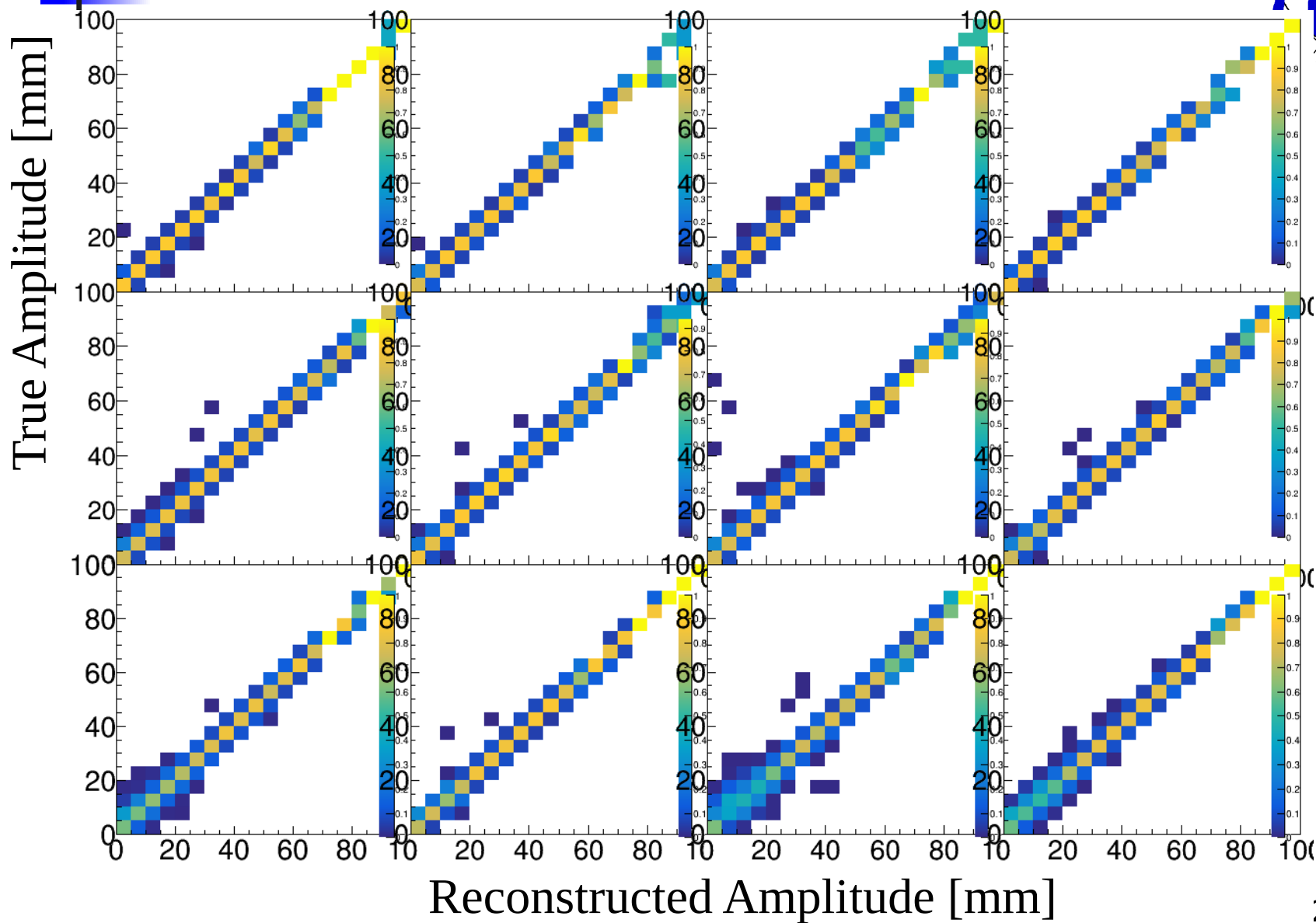
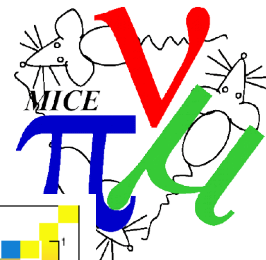
- Uncertainty due to intrinsic tracker resolution
 - Events measured in “this” amplitude bin were really in “that” amplitude bin
 - Can estimate magnitude of the effect → **correction**
 - **Migration matrix**
- Uncertainty due to inefficiency and purity
 - Reconstruction did not form a track when it should have done
 - An event outside fiducial volume was reconstructed
 - A non-muon was reconstructed
 - Can estimate magnitude of the effect → **correction**
 - **Bin by bin estimate of delta**
- Uncertainty due to incorrect tracker field
 - MAUS model says “3.01 T” when the field was really “3.03 T” (or whatever)
 - Tracker is not aligned to solenoid correctly
 - Plan to use better MAUS model (i.e. correct indirectly)
 - Have corrected the field; need estimate for correction quality

Comment on migration matrix

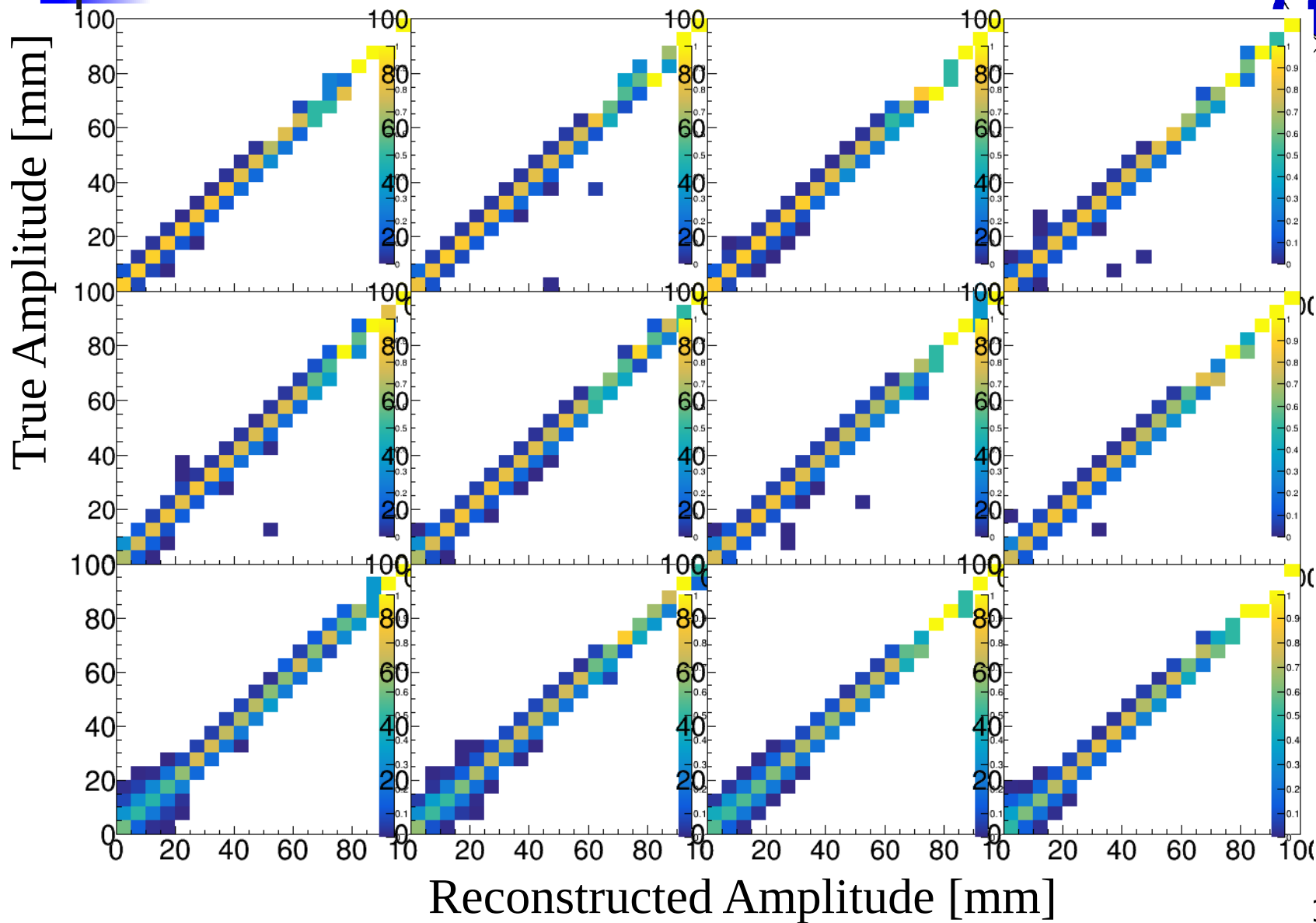
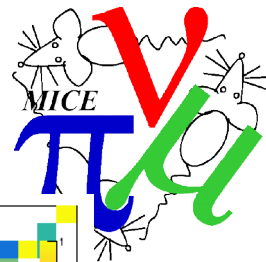


- Migration matrix technique
 - Correction given by simulated MC truth compared to simulated MC recon
 - Entirely motivated by Monte Carlo
- N_{ij} is number of events in i th bin in truth and j th bin in recon
- Then Migration matrix is
 - $M_{ij} = N_{ij} / \text{Sum}_j(N_{ij})$
- Analogous to deconvolution of the resolution and the measured distributions
 - Assumes the resolution is understood
 - Refer to chi2 distribution

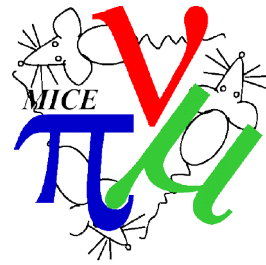
Migration matrix - upstream



Migration matrix - downstream

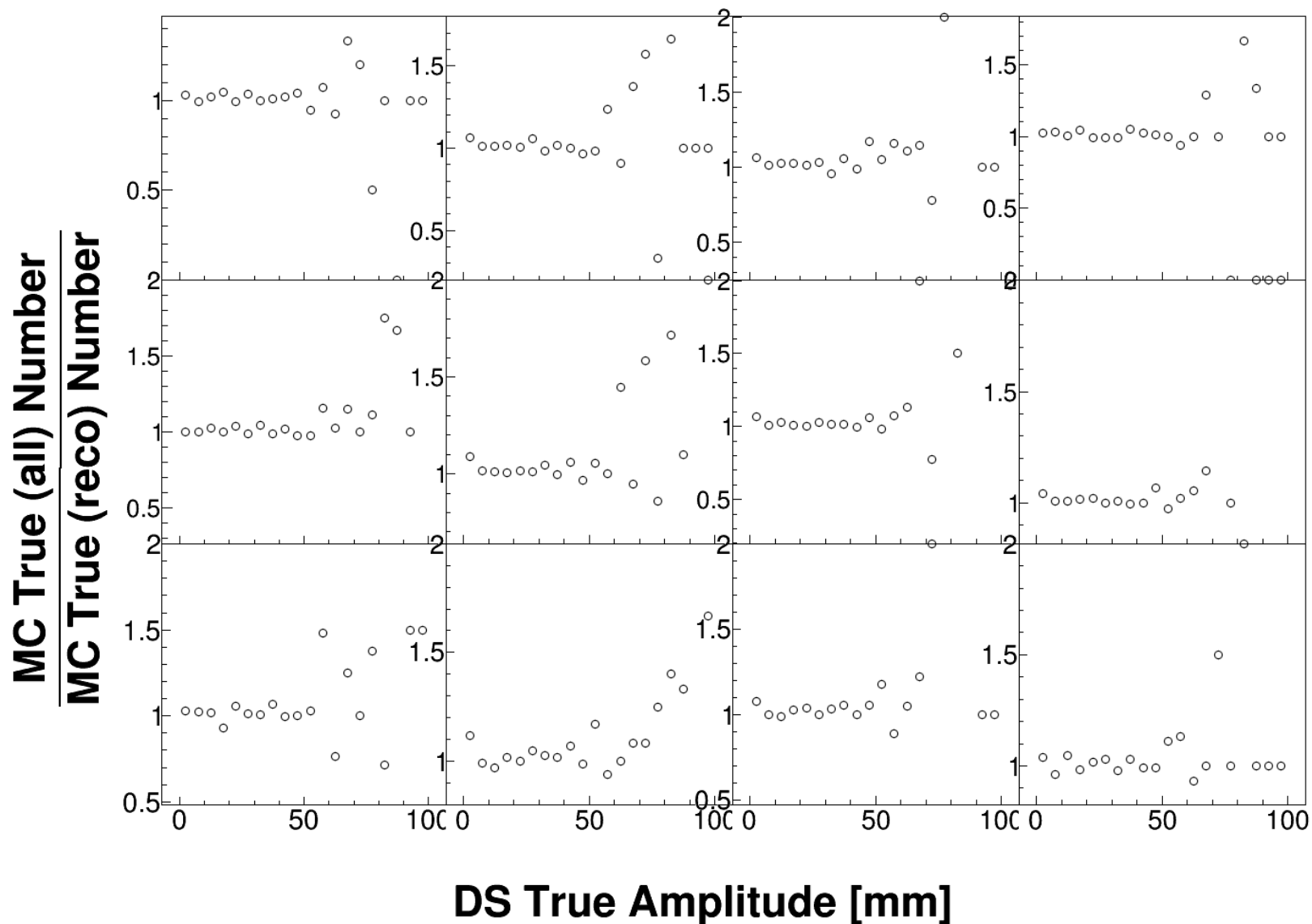
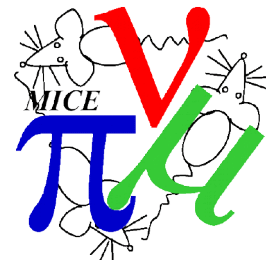


Comment on efficiency

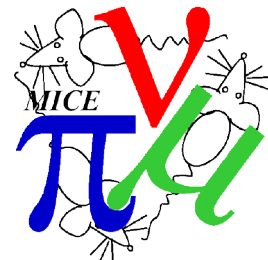


- Efficiency and impurity
- MC truth sample
- Entirely motivated by Monte Carlo
- But cluster distributions indicate that inefficiency is not well-understood

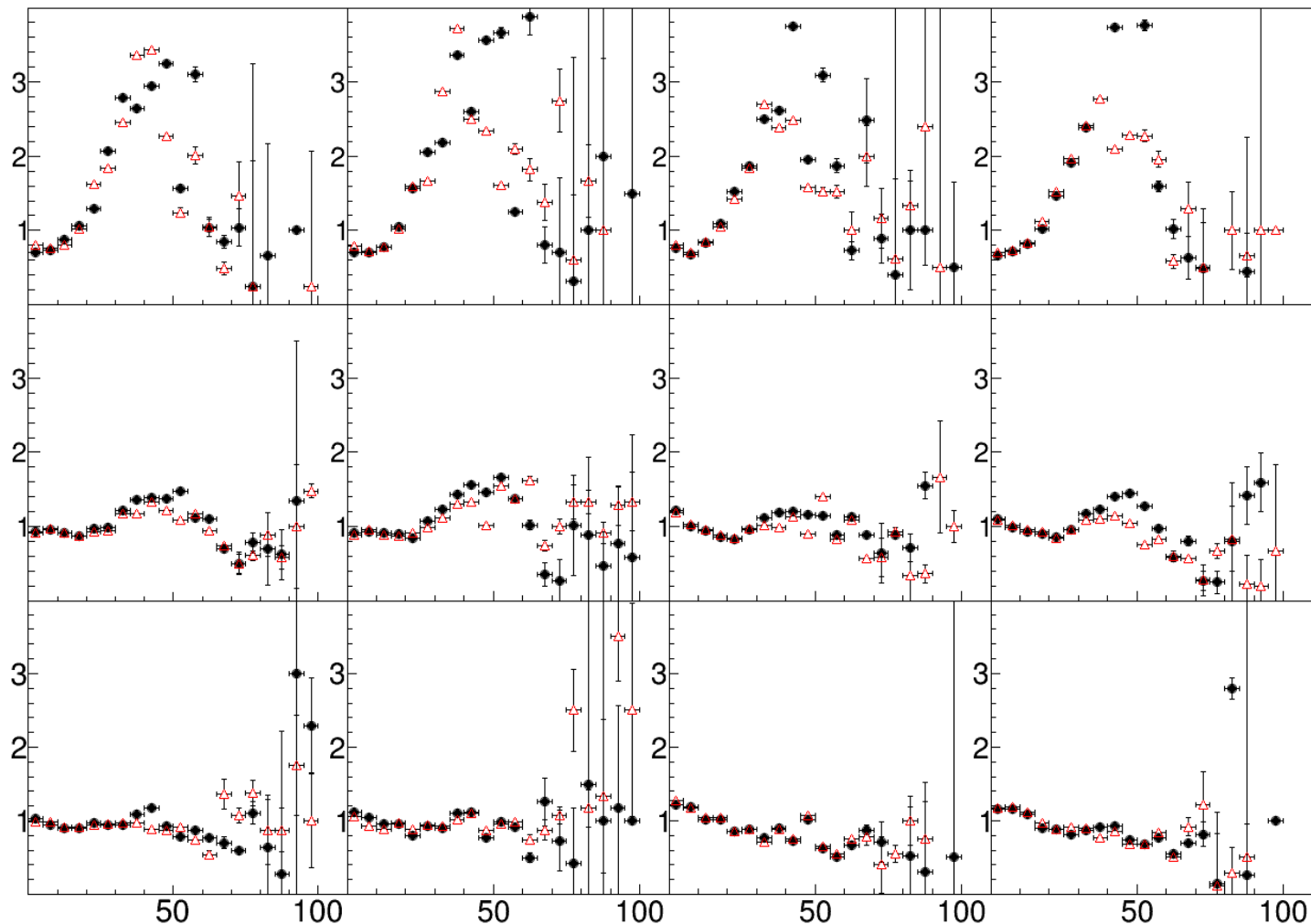
Efficiency and impurity



Ratio of amplitude pdf



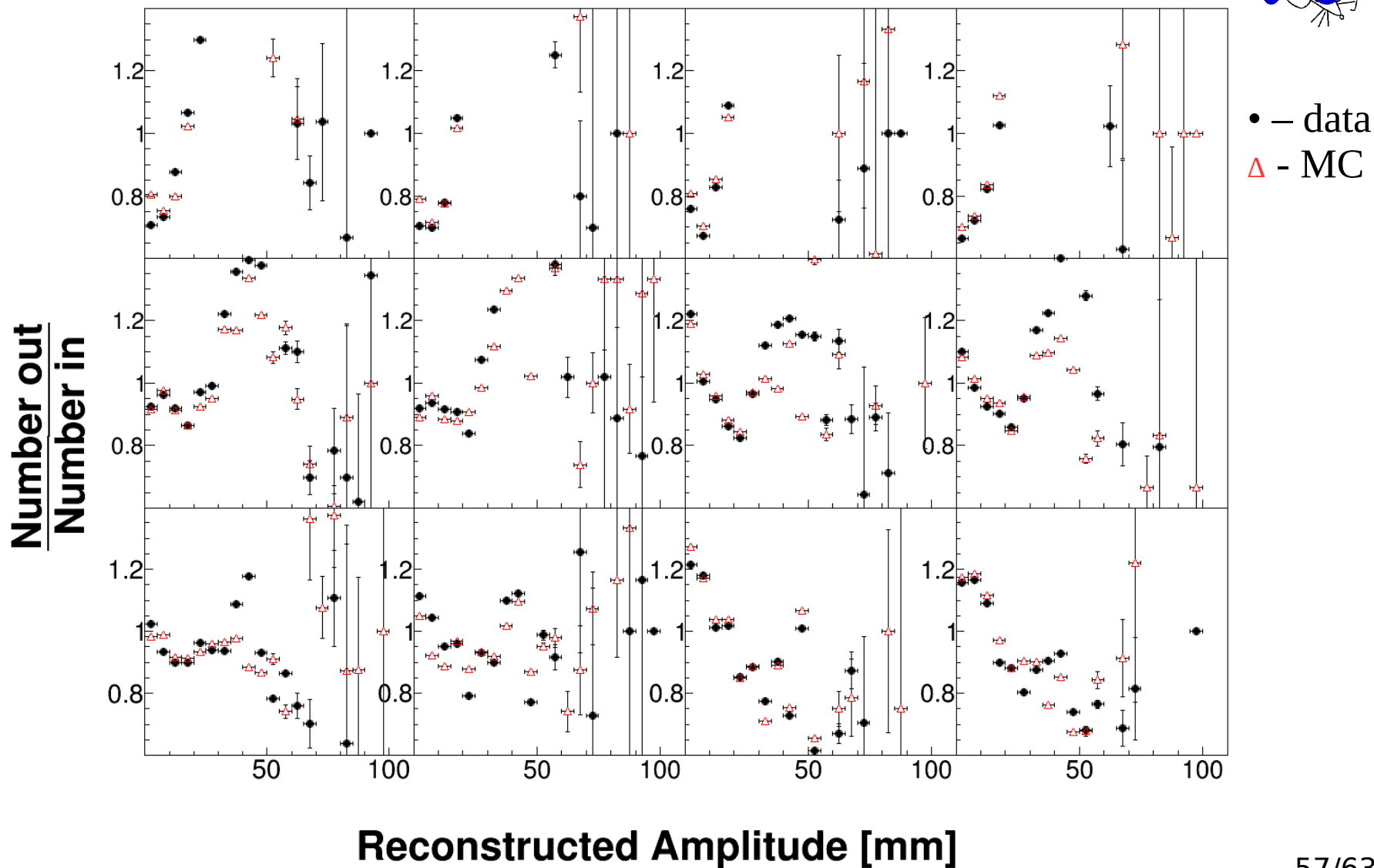
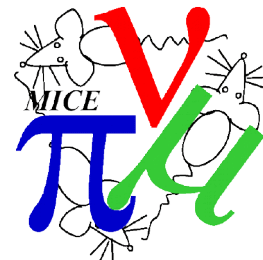
Number out
Number in



• – data
△ - MC

Reconstructed Amplitude [mm]

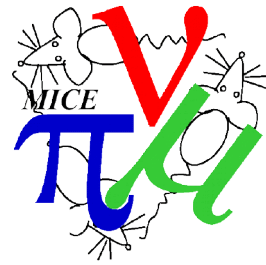
Ratio of amplitude pdf



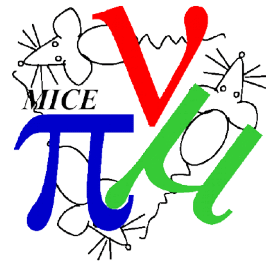


CDF

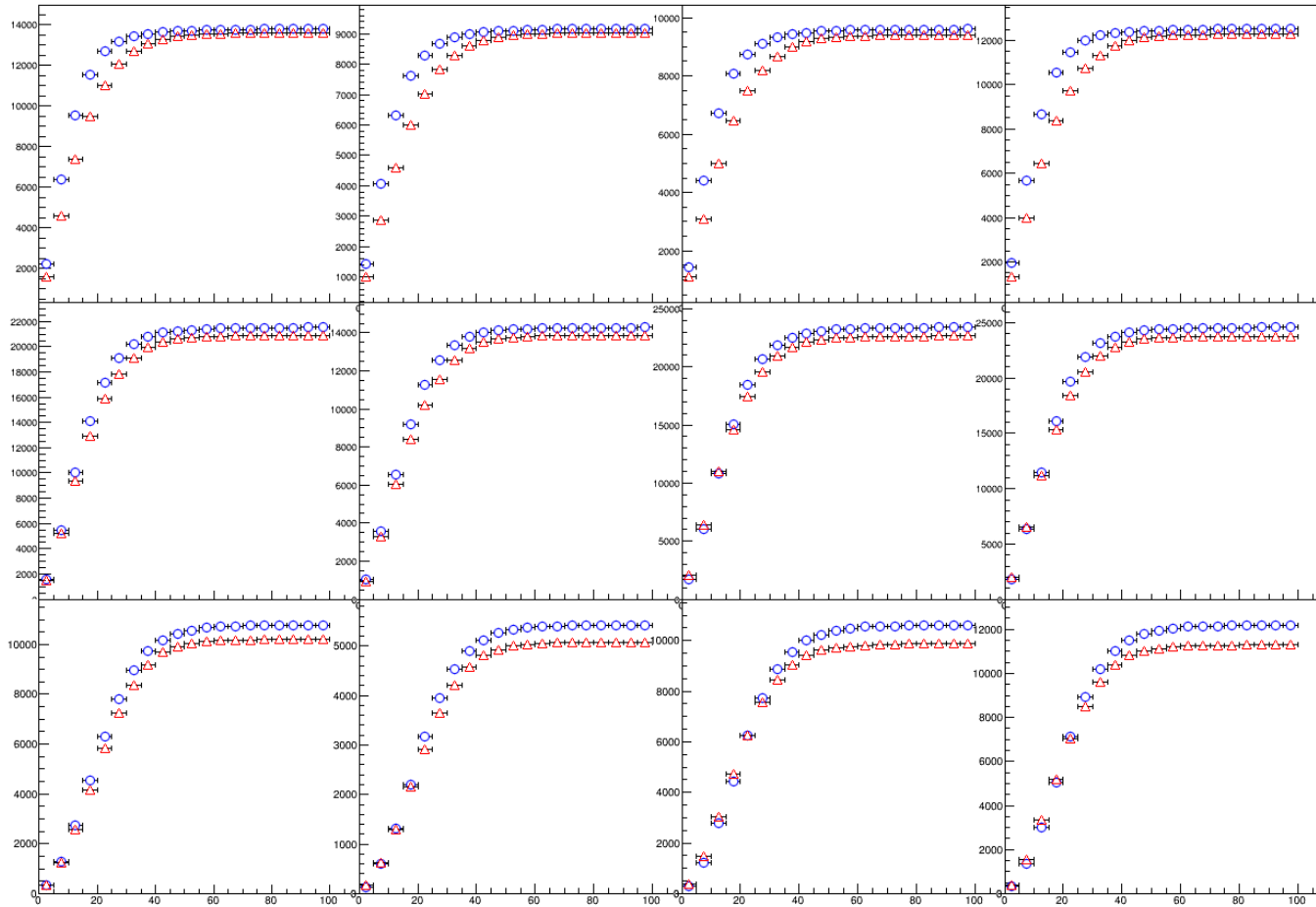
- Cumulative density function
 - Sum of all amplitude bins with amplitude $\leq A$



Amplitude cumulative density

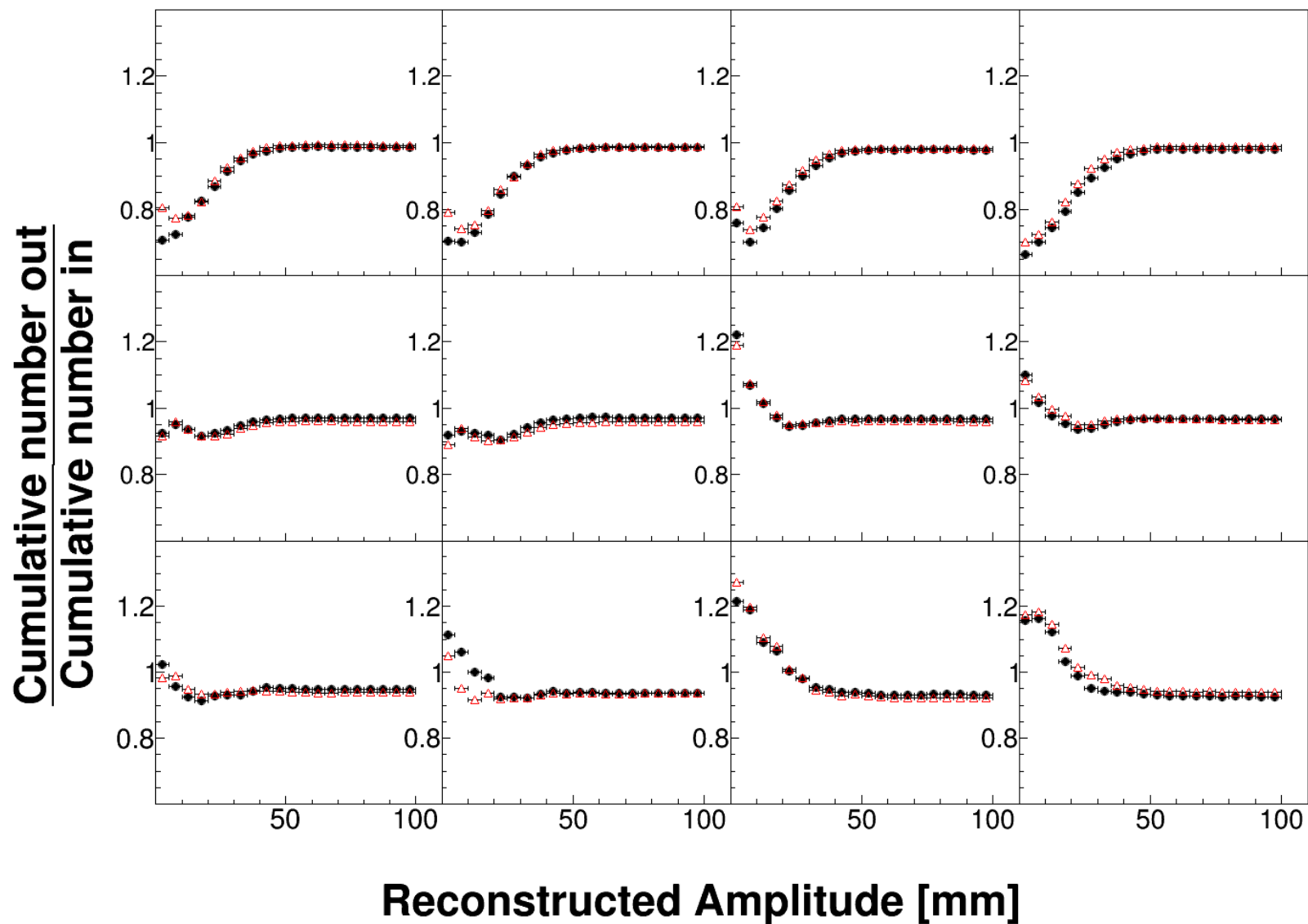
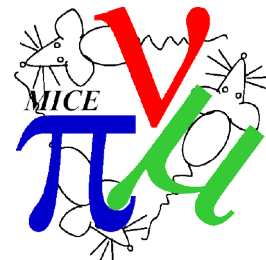


Cumulative density

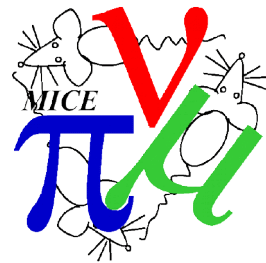


Reconstructed Amplitude [mm]

CDF Ratio

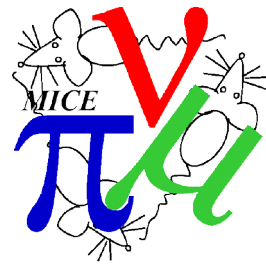


Conclusions



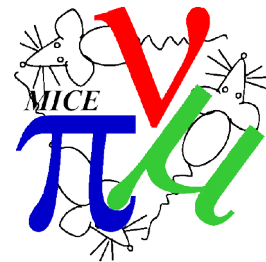
- Analysis is shaping up
- A few “routine” features in Monte Carlo
- More work needed on tracker model
 - Chi2 does not agree well enough data vs MC – noise?
 - Inefficiency (clusters) in TKD does not agree well enough
- Uncertainty from downstream sampling
 - Expect negligible effect
- Uncertainty from beam impurity
- Uncertainty due to field in TKU/TKD
- More analysis code validation
- Need to bring in more statistics
 - Once everything is working okay
- 4 mm setting?

Cuts summary



cut	2017-2.7 3-140 None	2017-2.7 3-140 IH2 empty	2017-2.7 3-140 IH2 full	2017-2.7 3-140 LiH	2017-2.7 6-140 None	2017-2.7 6-140 IH2 empty	2017-2.7 6-140 IH2 full	2017-2.7 6-140 LiH	2017-2.7 10-140 None	2017-2.7 10-140 IH2 empty	2017-2.7 10-140 IH2 full	2017-2.7 10-140 LiH
all events	258683	172444	183035	240396	258972	177328	283405	307300	391666	209994	374910	471965
tof 1 sp	249235	166313	177064	231587	250774	171124	275269	296958	370498	196606	356829	441852
tof 0 sp	196955	133090	146186	183288	198333	132548	226008	229741	283105	144999	281242	326715
scifi tracks us	74993	51170	56756	70331	135115	91156	152464	158491	150299	77015	148135	174896
scifi nan us	74993	51170	56756	70331	135115	91156	152464	158491	150299	77015	148135	174896
chi2 us	74993	51170	56756	70331	135115	91156	152464	158491	150299	77015	148135	174896
scifi fiducial us	74845	51083	56614	70188	134952	91058	152294	158341	149056	76395	146885	173477
delta tof01	42256	28799	32738	41667	65251	44170	83405	84264	74228	38726	87960	99222
tof01	38706	26179	28150	36889	56501	37444	63544	66922	56341	28995	61434	68642
p tot us	14291	9372	9836	12956	21985	14575	24002	25181	14541	7507	15353	17275
global through tof0	14283	9365	9817	12945	21924	14508	23799	25001	13779	6957	13177	15170
upstream aperture cut	13789	9158	9605	12536	21532	14283	23398	24589	10779	5418	10607	12188
upstream cut	13789	9158	9605	12536	21532	14283	23398	24589	10779	5418	10607	12188

Cuts summary



cut	2017-2.7 3-140 None	2017-2.7 3-140 IH2 empty	2017-2.7 3-140 IH2 full	2017-2.7 3-140 LiH	2017-2.7 6-140 None	2017-2.7 6-140 IH2 empty	2017-2.7 6-140 IH2 full	2017-2.7 6-140 LiH	2017-2.7 10-140 None	2017-2.7 10-140 IH2 empty	2017-2.7 10-140 IH2 full	2017-2.7 10-140 LiH
scifi tracks ds	13615	8986	9315	12293	20929	13795	22504	23798	10220	5051	9787	11296
scifi nan ds	13615	8986	9315	12293	20929	13795	22504	23798	10220	5051	9787	11296
chi2 ds	13615	8986	9315	12293	20929	13795	22504	23798	10220	5051	9787	11296
scifi fiducial ds	13615	8986	9315	12293	20929	13795	22504	23798	10220	5051	9787	11296
p tot ds	13365	8845	9169	12093	20634	13589	22163	23482	10093	4994	9655	11188
downstream cut	13365	8845	9169	12093	20634	13589	22163	23482	10093	4994	9655	11188