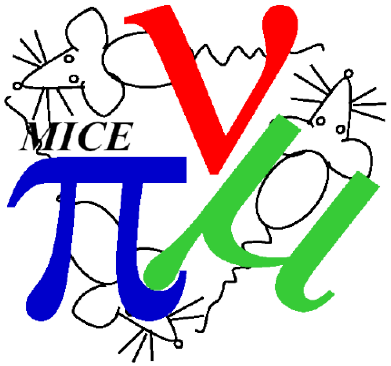
Emittance Evolution



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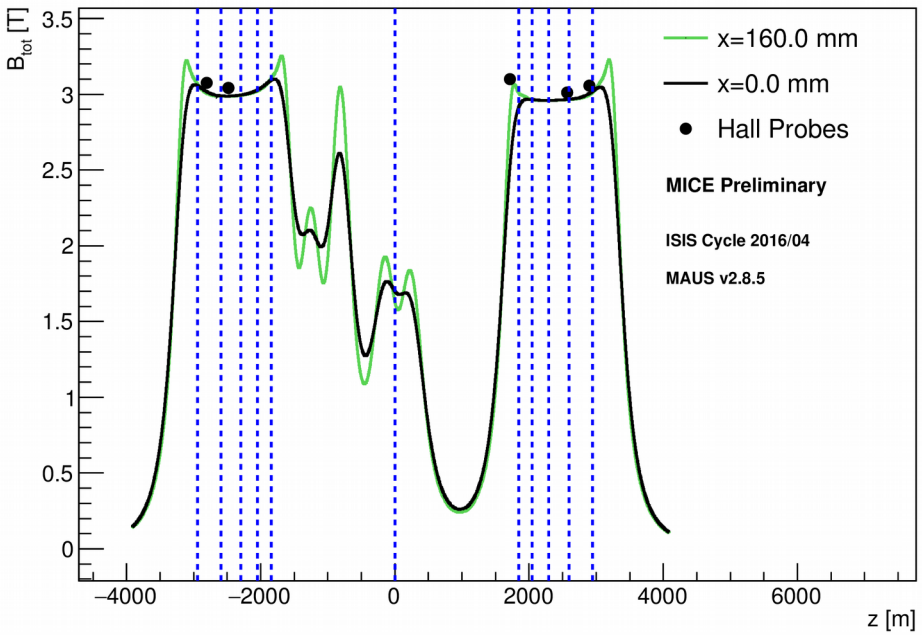
Introduction

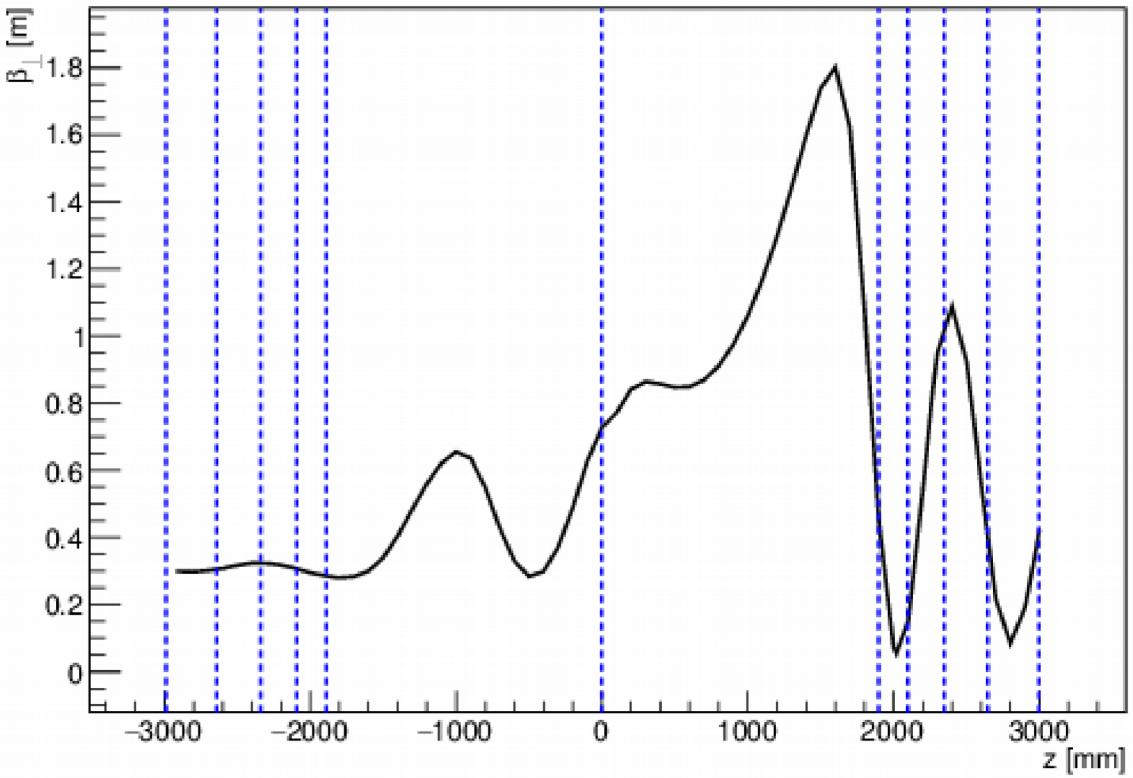
- With MICE Step IV, we aim to:
  - Measure material physics processes in MICE (energy loss and scattering)
  - Measure evolution of normalised transverse emittance through a single absorber
- Emittance is conserved, in the linear approximation, in a conventional accelerator
- Emittance can be reduced by ionisation cooling
  - The only process that is competitive with the muon lifetime
- We seek to measure evolution of the particle amplitude distribution through an absorber
  - This is the distribution that underlies emittance
  - Emittance is biased by tail effects like scraping
  - Amplitude can be calculated such that it is not biased by tail effects
- An increase in particle amplitude in the core of the beam is consistent with cooling

Magnet Configuration



- In this paper, we consider MICE Step IV in the 2016-04 1.2 configuration
  - Thought to be the “best” of the 2016-04 data
- Magnets were configured in solenoid mode
- M1D and M2D were not powered

Design optics

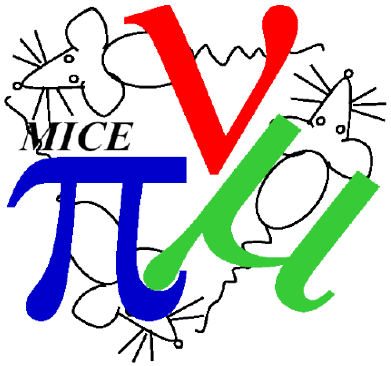


- Beta is about 0.7 m in AFC
  - Focus upstream of the absorber to avoid too much scraping in M2D region

Analysis

- Data analysis proceeds as follows
- Sample the data in upstream detectors
  - Reject beam impurities
  - Select for the design momentum
- Calculate amplitudes and associated uncertainties
- Uncertainties arise from:-
  - Fluctuations in scattering and energy loss
  - Intrinsic detector resolution
  - Inefficiency and purity
  - Uncertainty in magnetic field on tracker
- I will present some MC results also
  - MC is only used in estimation of uncertainties
- I have many, many backup slides with various validation steps (&c)

Event Selection



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Event selection

- Following cuts are enabled:
  - Exactly one track in TKU
  - Exactly one space point in TOF0
  - Exactly one space point in TOF1
  - TKU p-value > 0.02
  - tof01 > 28 ns
  - tof01 < 32 ns for run 8681
  - tof01 < 31 ns for run 8699
  - tof01 < 30 ns for run 8685
  - Require 135 < p(tku) < 145 MeV/c

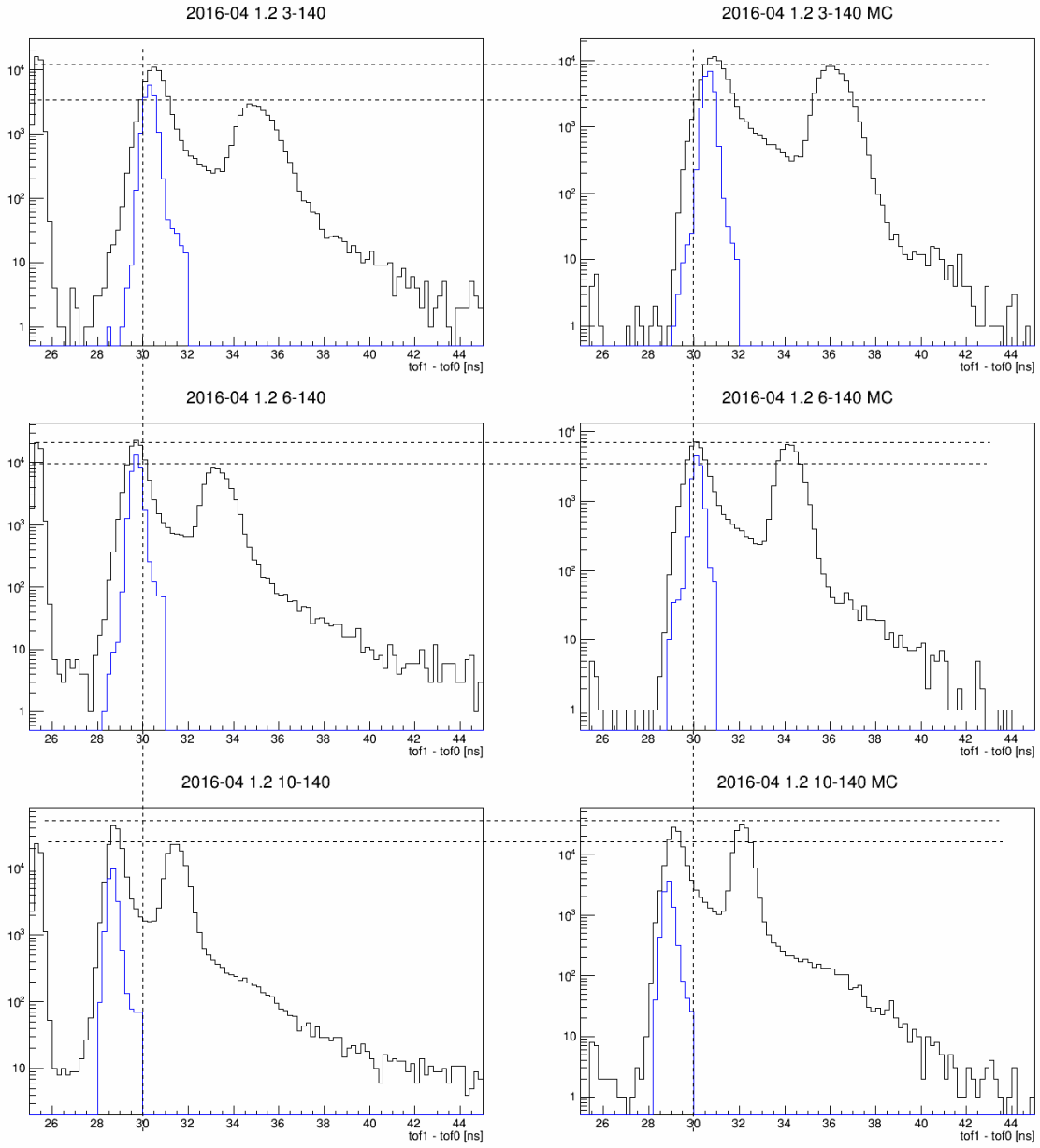
Cut accountancy

List of numbers surviving each cut:

	3-140	6-140	10-140
All events	133185	221174	359155
TKU Momentum	24599	40338	28430
TKU P-Value	93337	157111	188989
One track in TKU	94196	154975	192764
TOF01	57386	94476	147607
One TOF0 SP	116063	190162	309600
One TOF1 SP	130903	217135	351445
Any cut	15935	31964	22115

Nb at this point the analysis is systematics limited

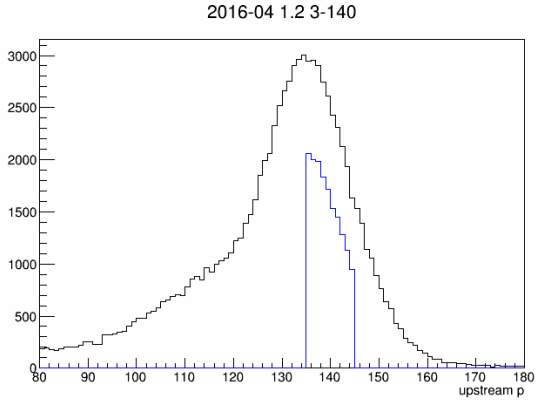
TOF 01 cuts

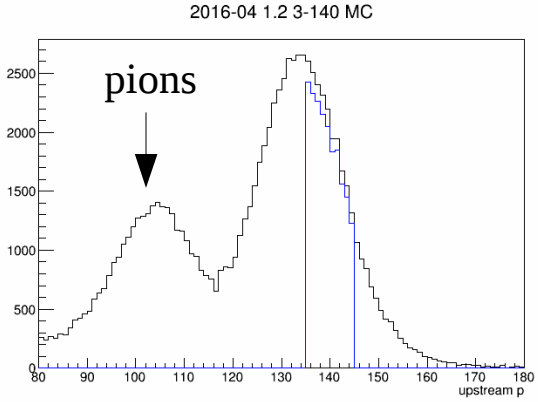


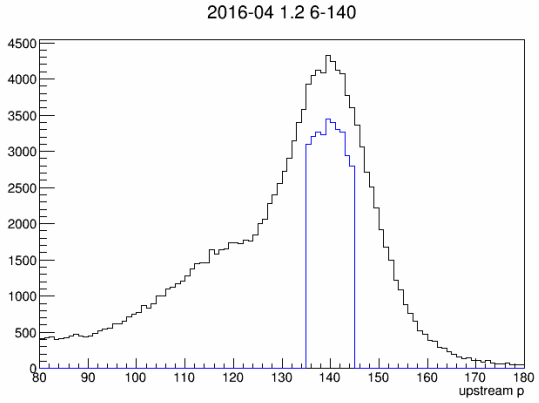
Note pion surplus

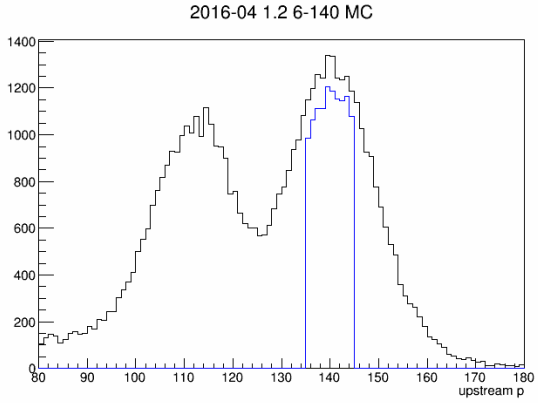
Note electron deficit

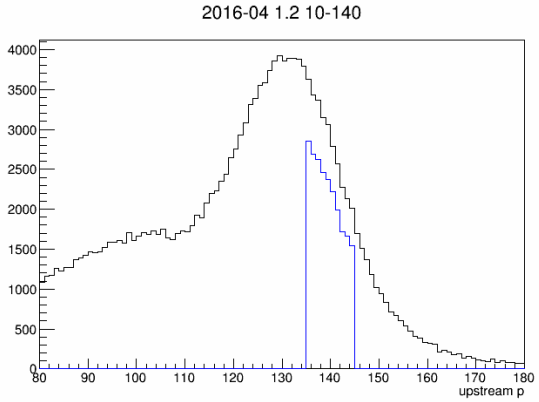
TKU Momentum

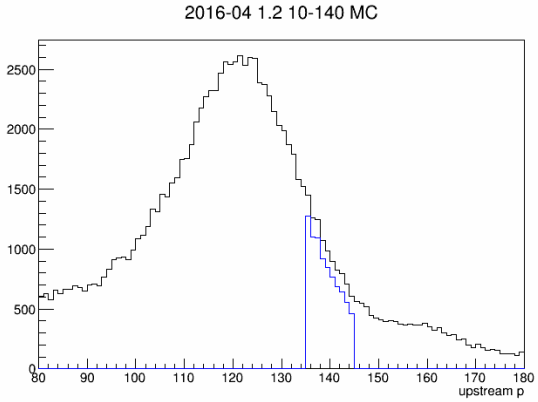






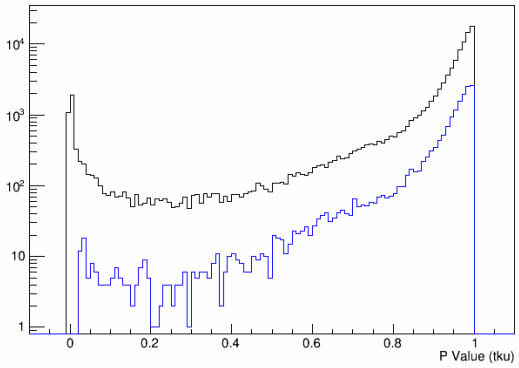




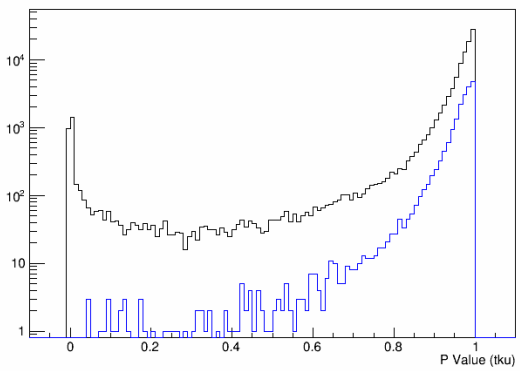


TKU P-Value

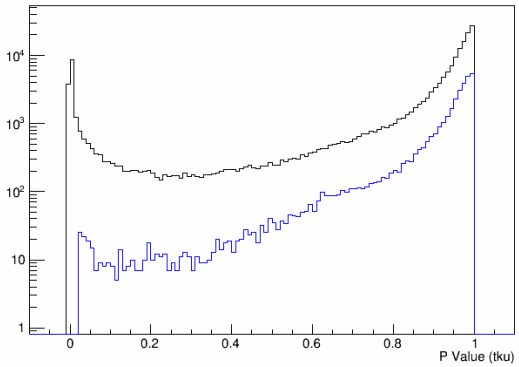
2016-04 1.2 3-140



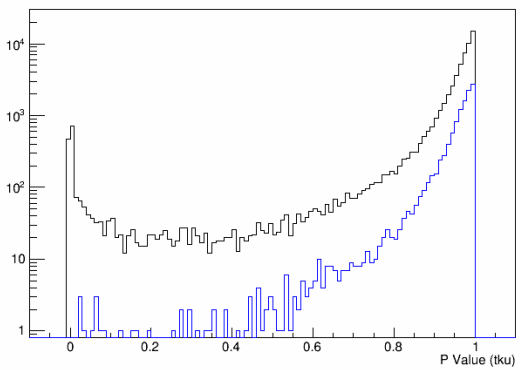
2016-04 1.2 3-140 MC



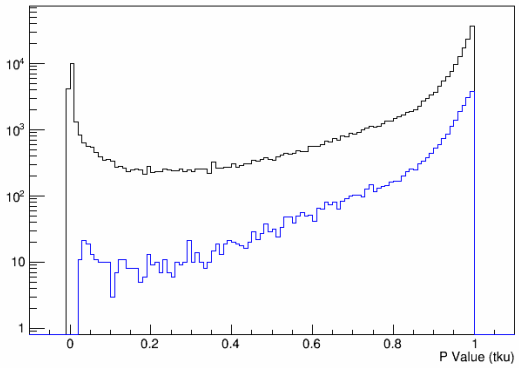
2016-04 1.2 6-140



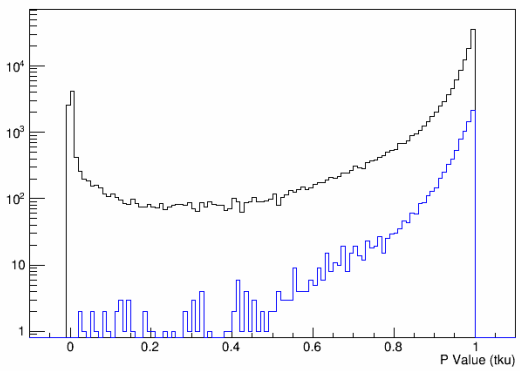
2016-04 1.2 6-140 MC



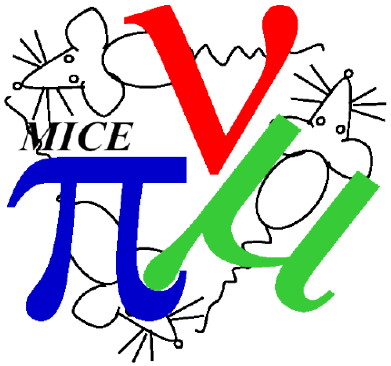
2016-04 1.2 10-140



2016-04 1.2 10-140 MC



Sources Of Uncertainty



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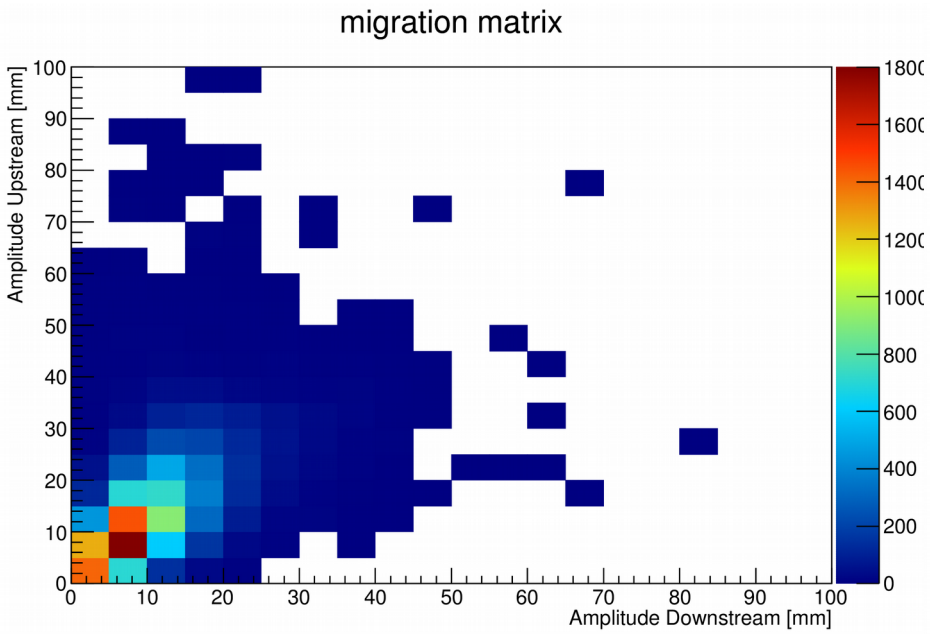
Sources of uncertainty

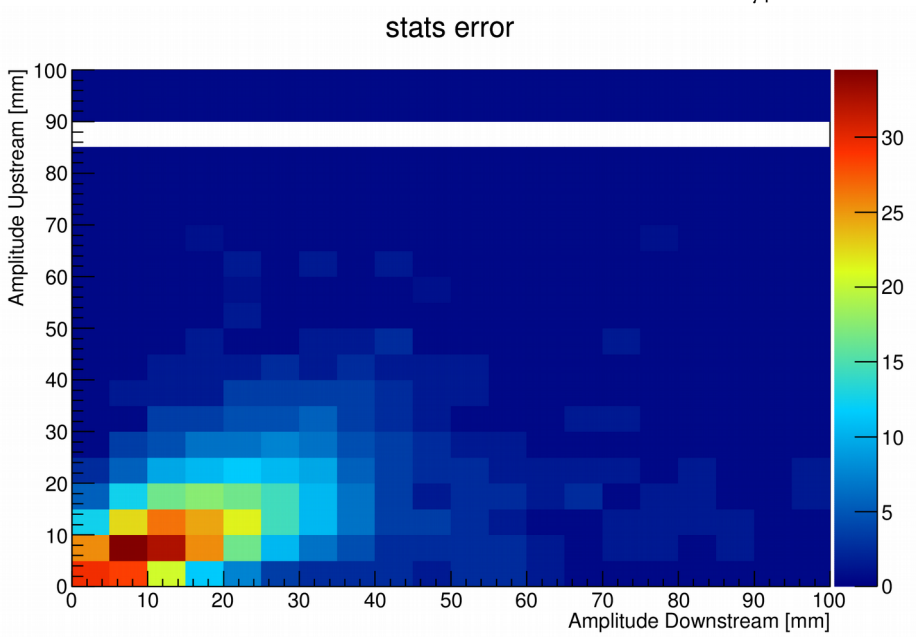
- Statistical uncertainty in the change in distribution
- Uncertainty due to intrinsic tracker resolution
  - Events measured in “this” amplitude bin were really in “that” amplitude bin
- Uncertainty due to inefficiency and purity
  - Reconstruction did not form a track when it should have done
  - An event outside fiducial volume was reconstructed
  - A non-muon was reconstructed
- Uncertainty due to incorrect tracker field
  - MAUS model says “3.01 T” when the field was really “3.03 T” (or whatever)
- It may be possible to assign a “correction” for some of these systematic effects
  - At this stage, I do not feel confident to do so
- Total uncertainty is given by sum in quadrature of each source of uncertainty (for each bin)

Statistical uncertainty

- Estimate of statistical uncertainty
- Build a migration matrix M with elements
  - M_{ij} = Number in i^{th} bin upstream and j^{th} bin downstream
- M_{ij} are binomial distributed
  - Number of samples = Sum over j (M_{ij})
  - Probability of success ~ M_{ij}
- Uncertainty on each $M_{ij,}$ E_{ij}, is determined by 68 % confidence interval of the binomial distribution
- Uncertainty on each downstream bin is given by sum in quadrature of E_{ij}
  - Uncertainty on downstream bin = Sum over i (M_{ij})

Statistical uncertainty



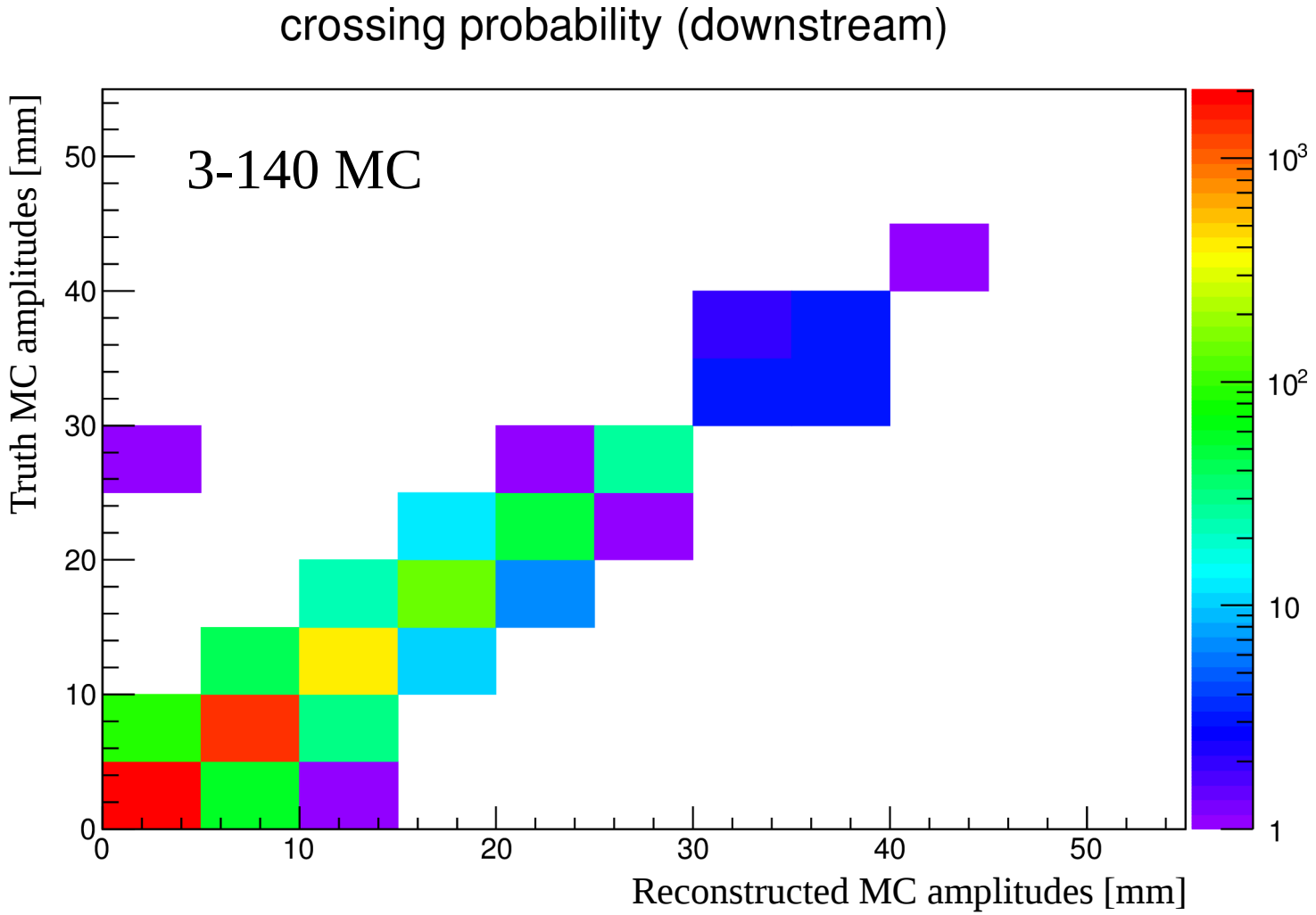


- Migration matrix shows number in each upstream/downstream bin
- Stats error shows width of 68 % confidence interval for each bin

Intrinsic Detector resolution

- Detector resolution can cause us to reconstruct events with wrong amplitude
  - This means we put them in the wrong bin
- Estimate the probability of assigning the wrong bin
  - Consider “recon mc” is Monte Carlo truth sample that was actually reconstructed
  - Consider “recon” is output from the reconstructed sample
  - N_{recon} is number in reconstructed bin
  - N_{recon_mc} is number in recon mc bin
  - Probability of assigning the wrong bin is given by
    - $(N_{recon_mc} - N_{recon})/N_{recon_mc}$

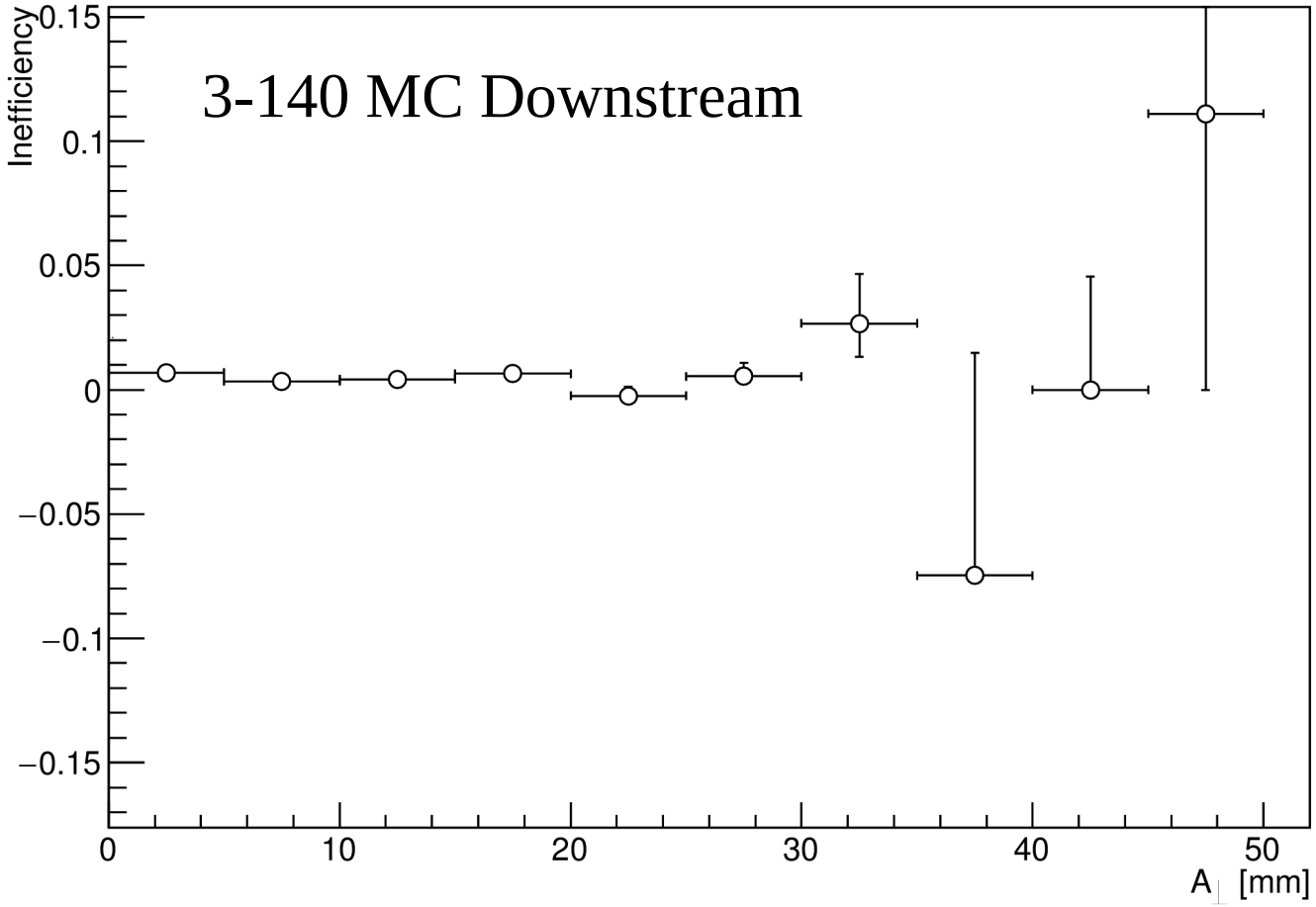
Intrinsic Detector resolution



Inefficiency and Impurity

- 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
- Estimate the probability of impurity or inefficiency
  - Consider “recon mc” is Monte Carlo truth sample that was actually reconstructed
  - Consider “mc” is the Monte Carlo truth sample that should have been reconstructed
    - MC truth at all tracker stations < 150 mm radius
    - MC truth muon at all tracker stations
  - N_{mc} is number in reconstructed bin
  - N_{recon_mc} is number in recon mc bin
  - Inefficiency/impurity is given by
    - $(N_{mc} - N_{recon_mc})/N_{mc}$
- Nb: upstream is 100 % efficient by definition (but can still be impure)

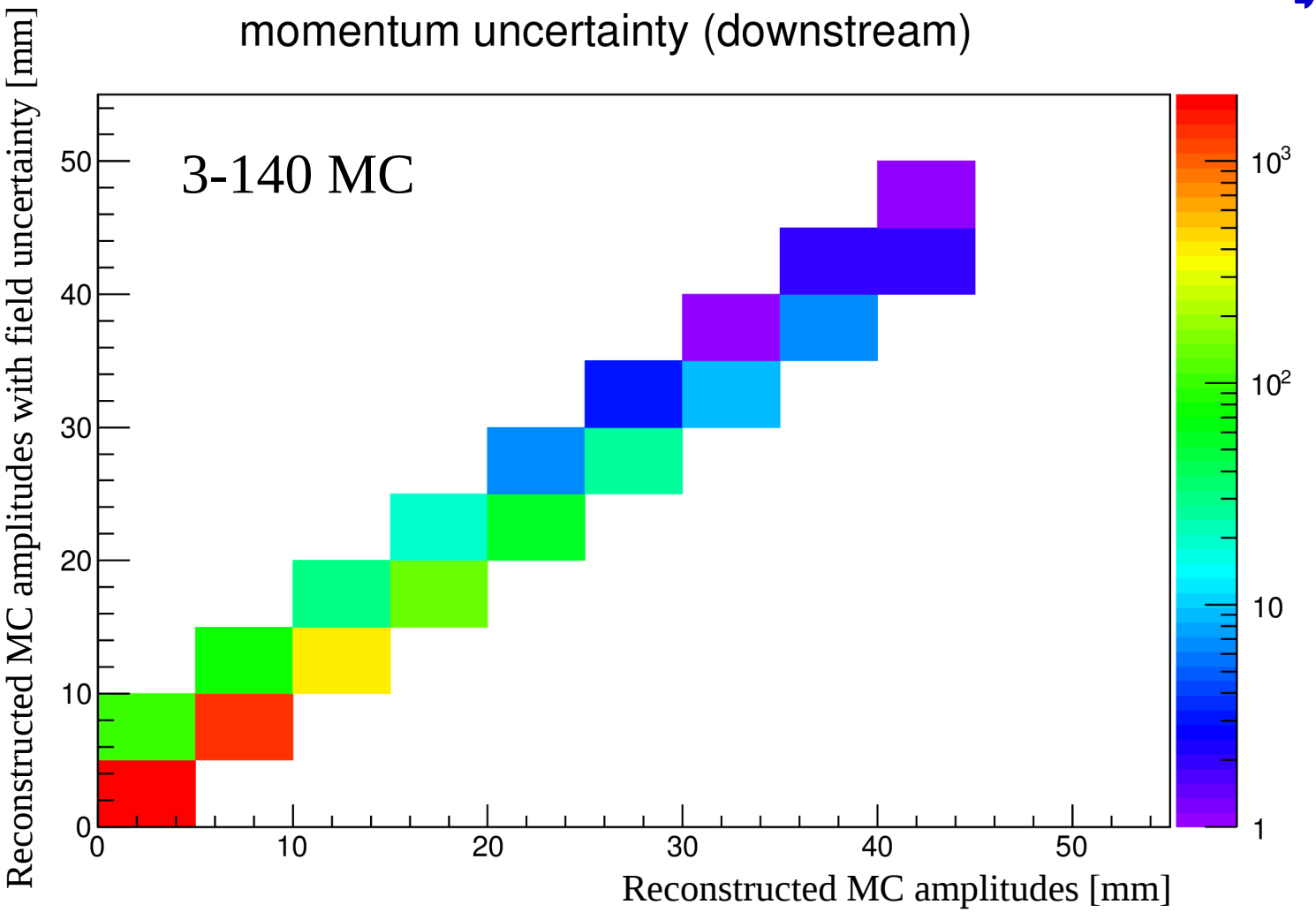
Intrinsic Detector resolution



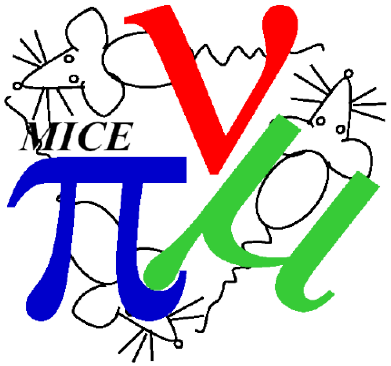
Field Uncertainty

- The hall probes and MAUS model disagree by about 2 %
  - Assign a “2 %” field uncertainty
  - All of the transverse momenta are uncertain by 2 %
  - => All of the amplitudes are uncertain by 2 %
- What happens if we systematically increase or decrease amplitudes by 2 %?
  - Events migrate into neighbouring bins
  - This can be significant at large amplitudes
  - This can be significant if the number of events in nearby bins varies a lot
- Estimate proportion of events with the wrong bin
  - For bin i
  - $(F_{i+1 \to i} - F_{i \to i+1}) - (F_{i-1 \to i} - F_{i \to i-1})$
  - $F_{i \to j}$ is the “number of events moving from bin i to bin j, given a 2 % change in amplitude
  - Note this is proportional to second derivative

Momentum uncertainty



Measured Amplitude Change



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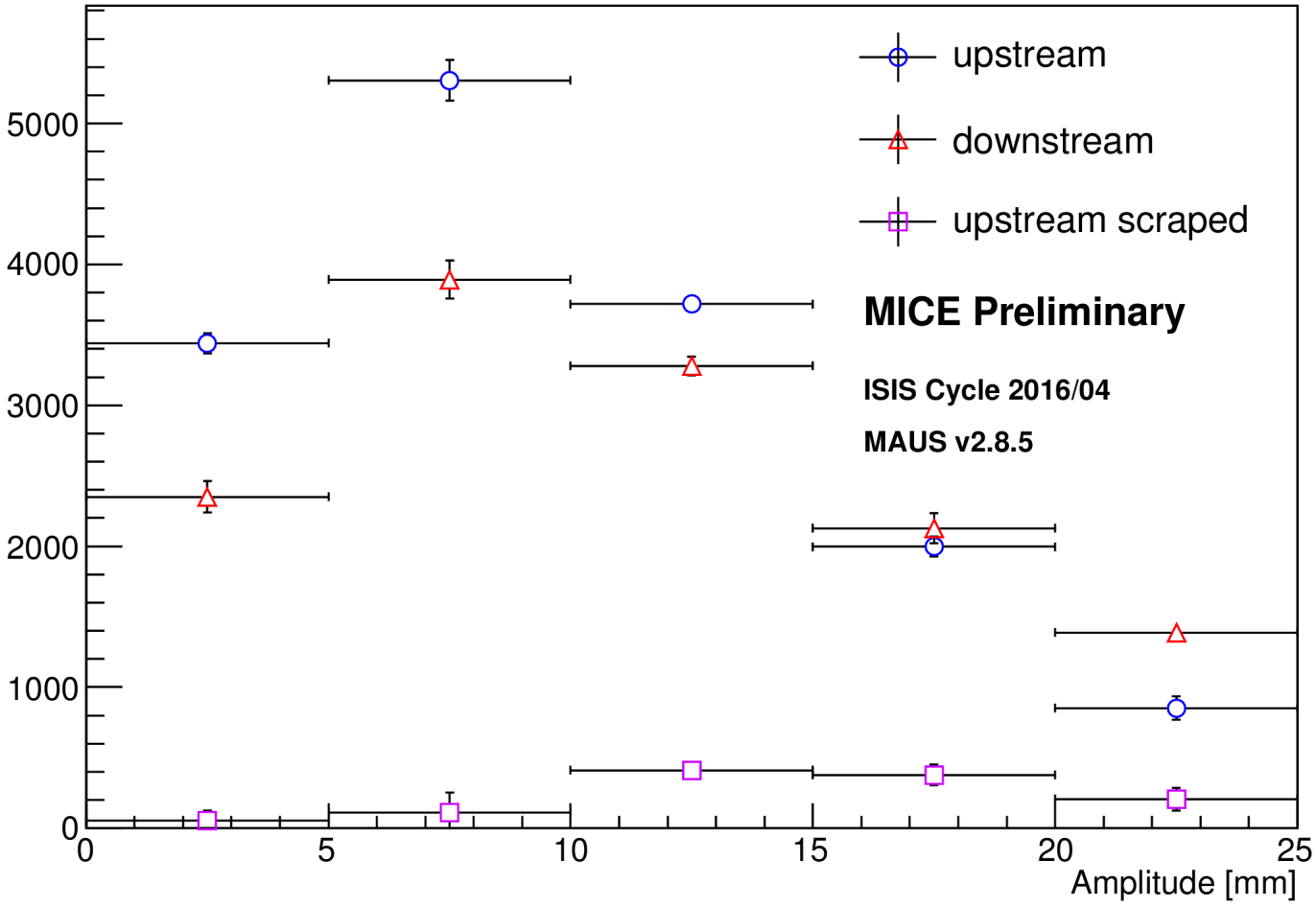
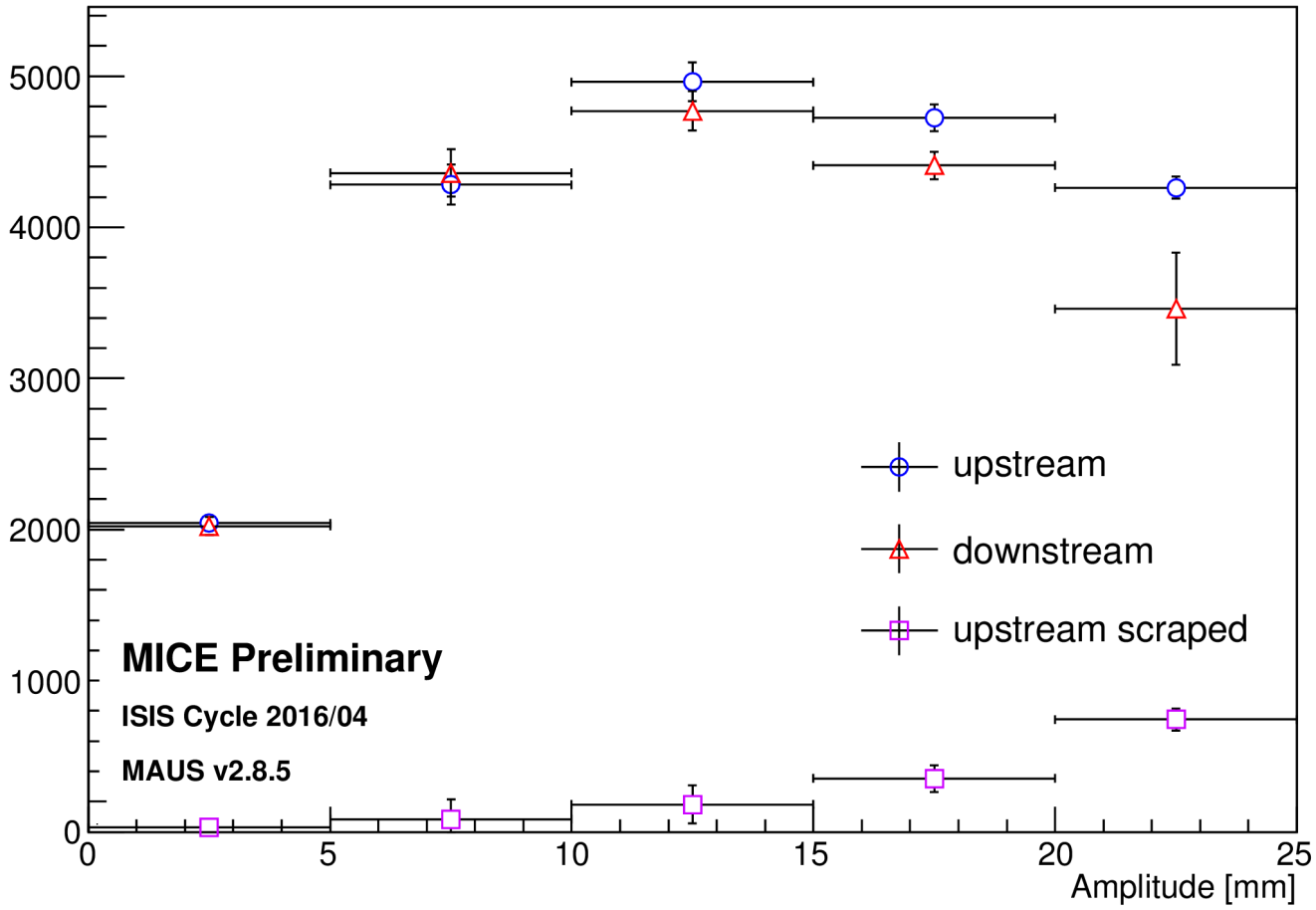
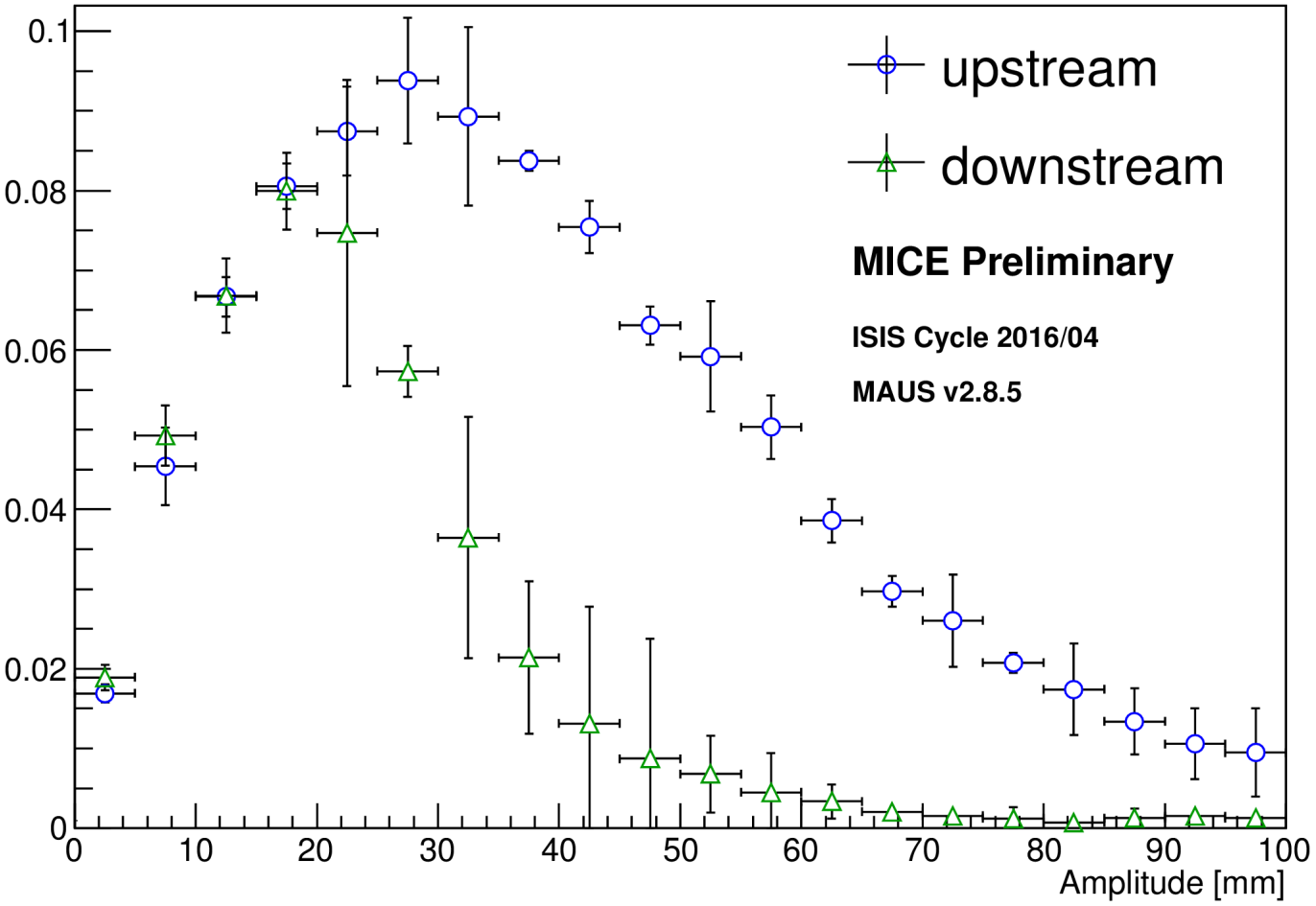
3-140


upstream
downstream
upstream scraped
MICE Preliminary
ISIS Cycle 2016/04
MAUS v2.8.5
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Amplitude [mm]

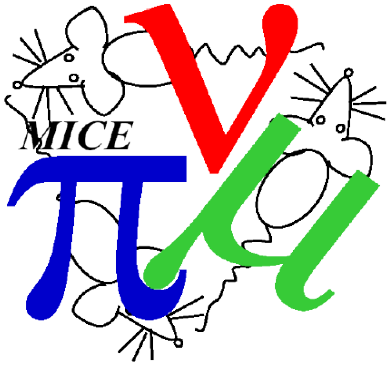
6-140


5000
4000
3000
2000
1000
0
0
5
10
15
20
25
Amplitude [mm]
upstream
downstream
upstream scraped
MICE Preliminary
ISIS Cycle 2016/04
MAUS v2.8.5

10-140


upstream
downstream
MICE Preliminary
ISIS Cycle 2016/04
MAUS v2.8.5
0.1
0.08
0.06
0.04
0.02
0
0
10
20
30
40
50
60
70
80
90
100
Amplitude [mm]

Work in Progress



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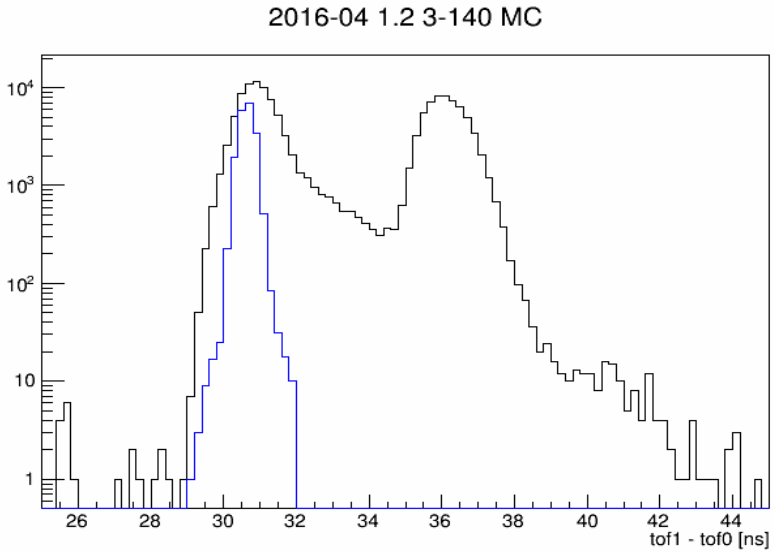
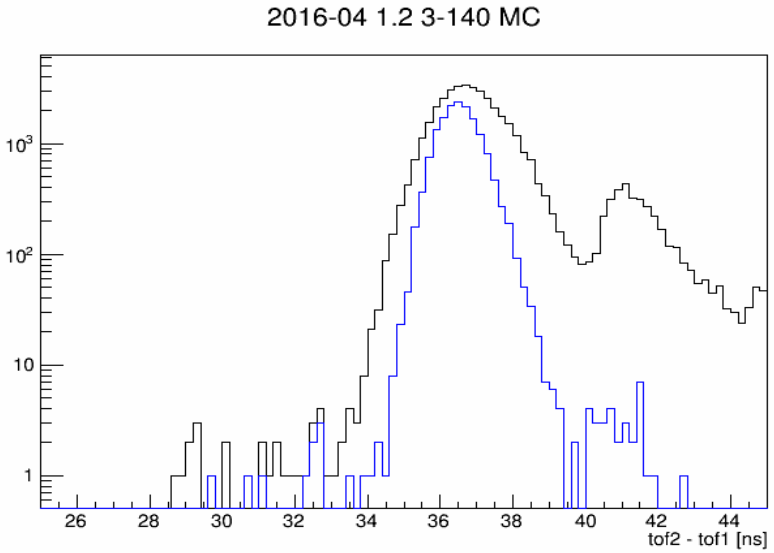
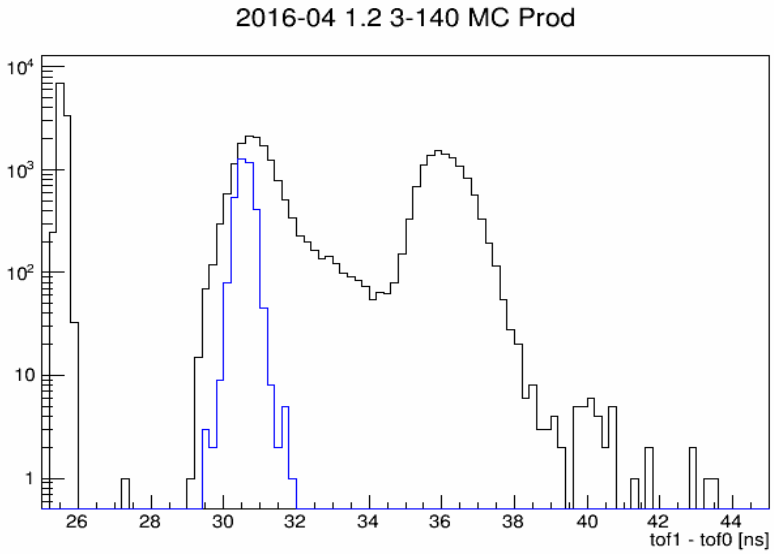
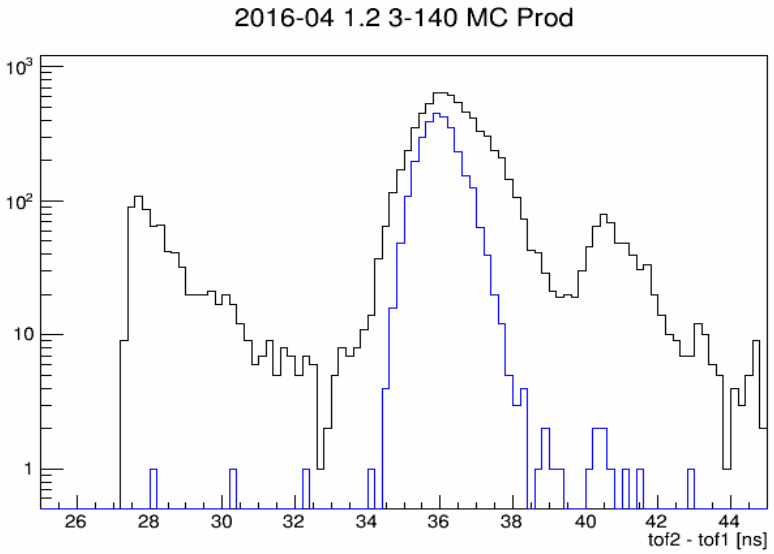
Production MC (TOF)

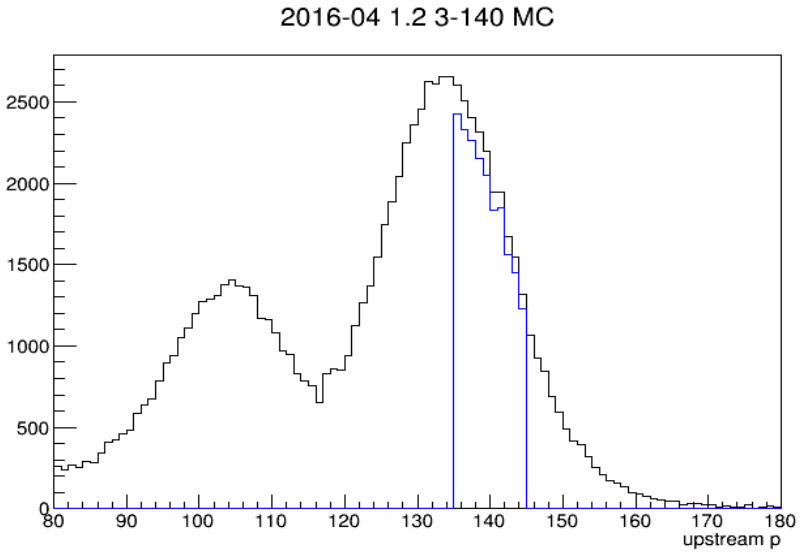


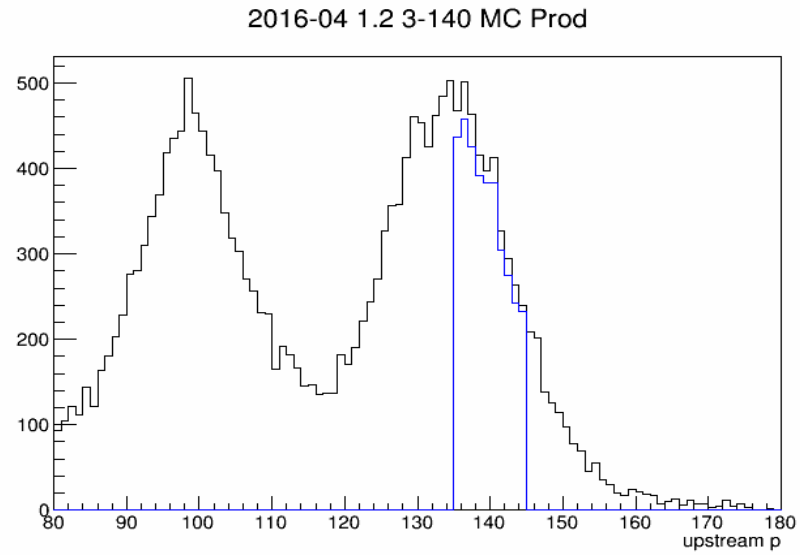




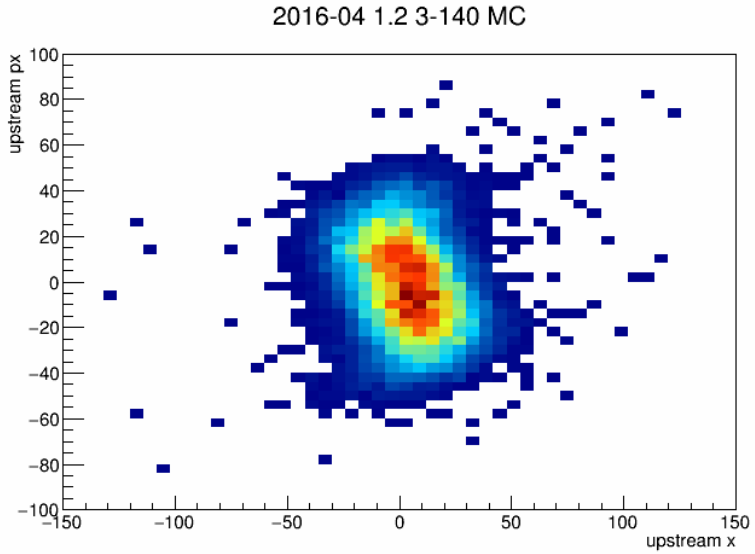


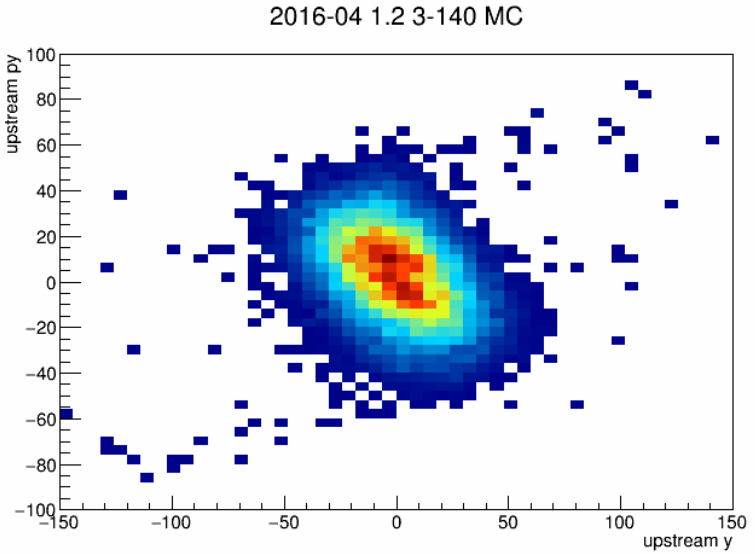
Production MC (TKU P)

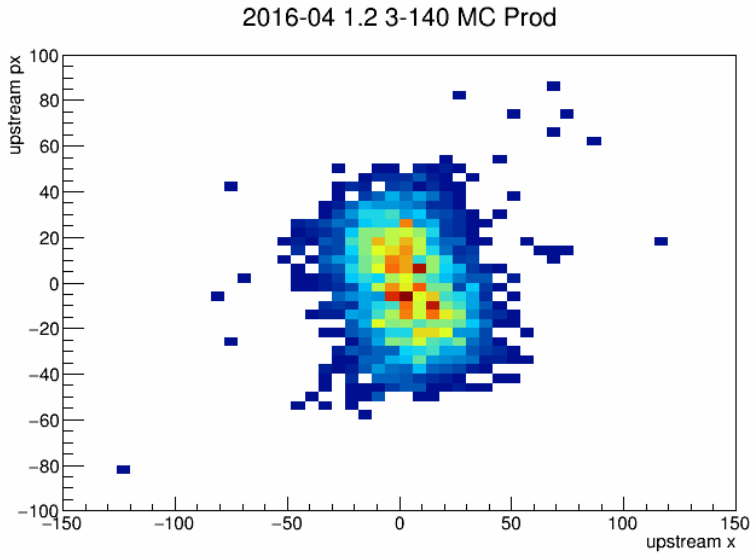


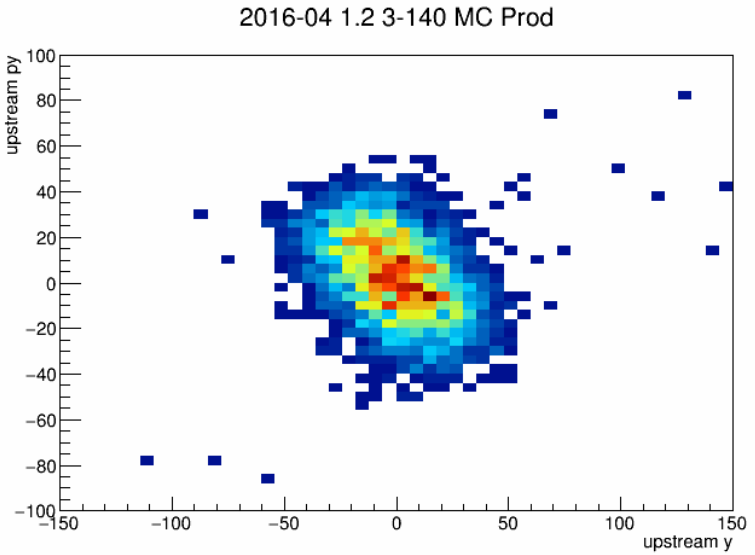


Production MC (TKU Distributions)







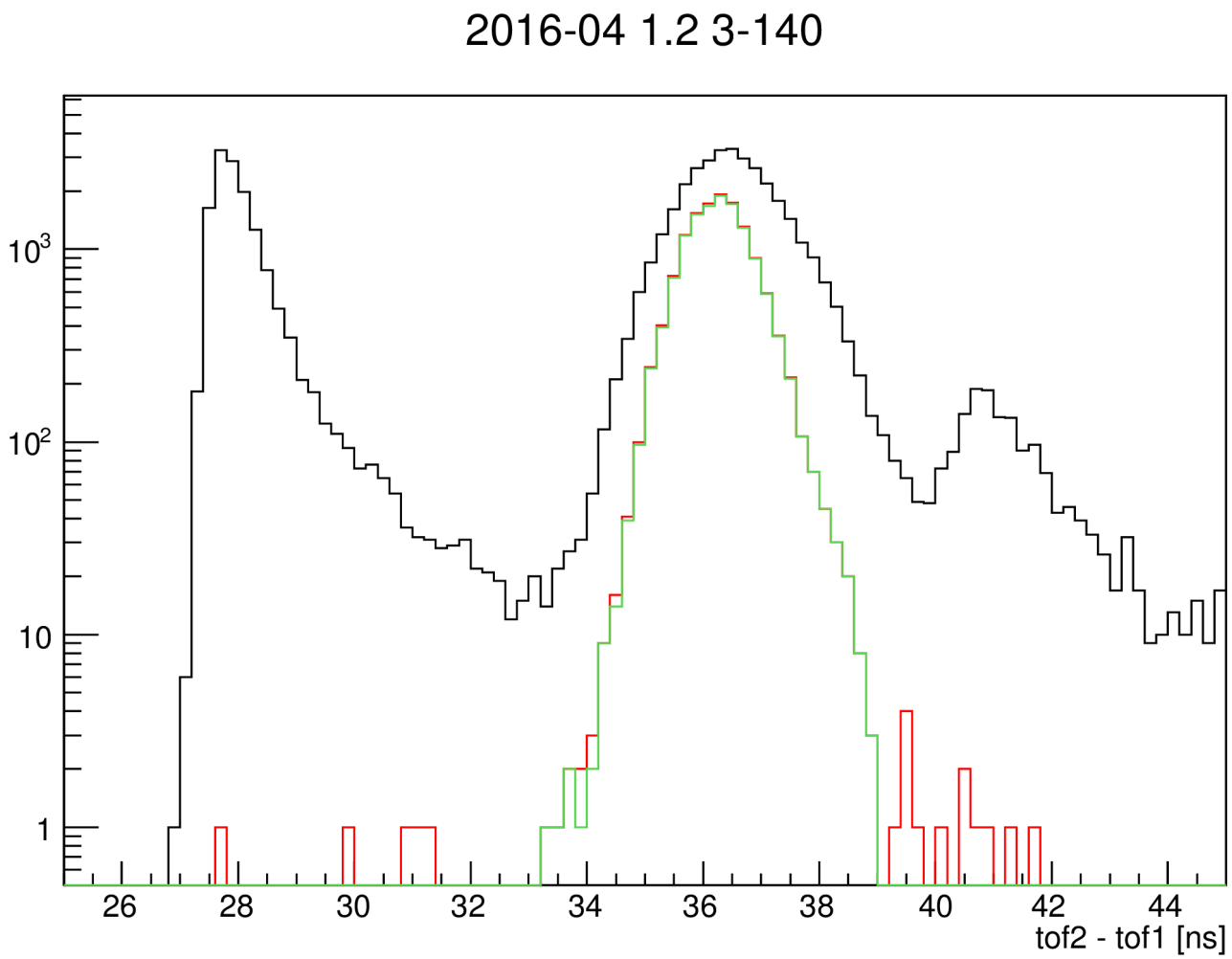


Downstream cuts

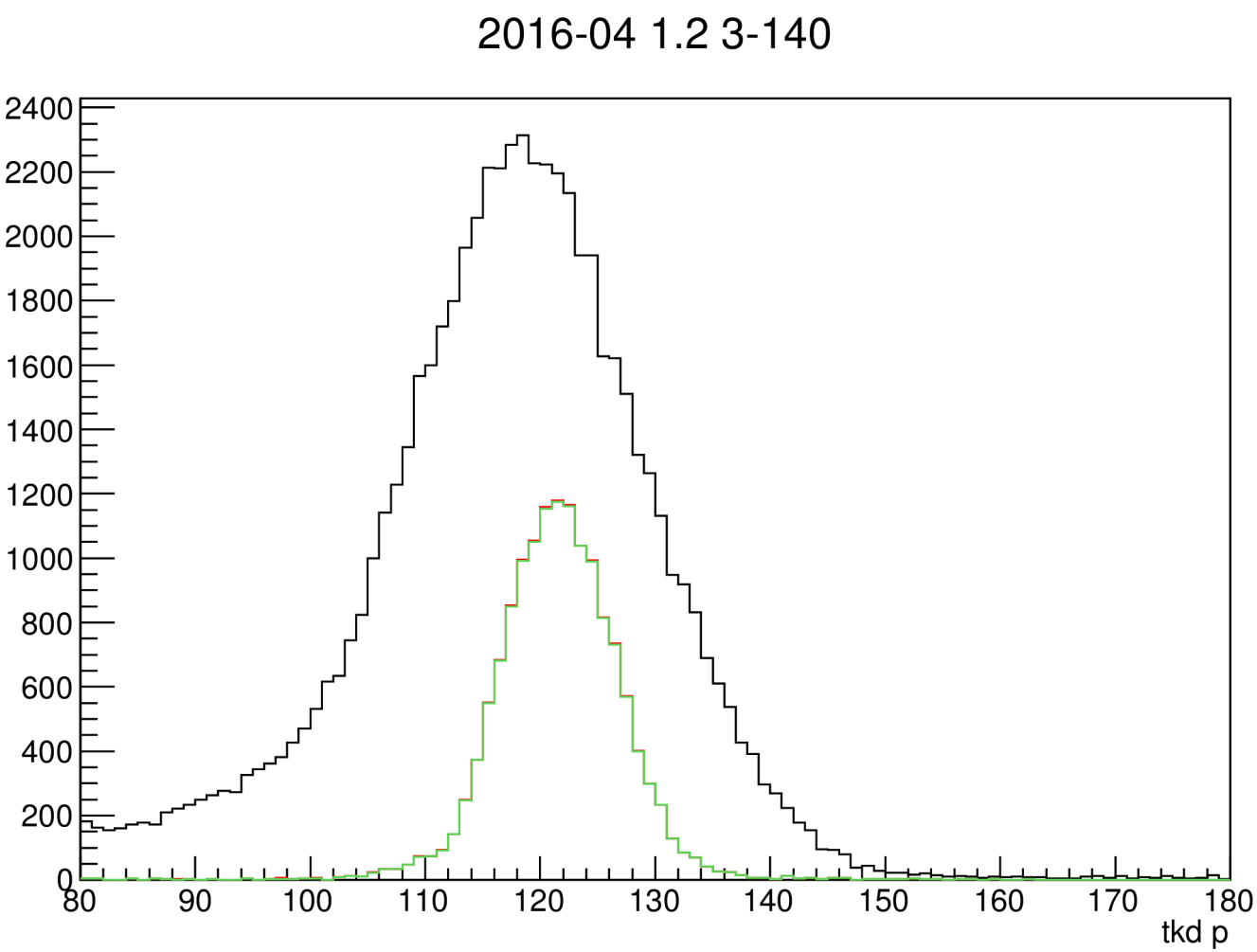
cut name	upstream?	downstream?	Number passing cut	Number passing cut and upstream cut
p_tot_us	TRUE	TRUE	24599	
pvalue_us	TRUE	TRUE	93337	
scifi_tracks_us	TRUE	TRUE	94196	
tof01	TRUE	TRUE	69094	
tof_0_sp	TRUE	TRUE	116063	
tof_1_sp	TRUE	TRUE	130903	
tof12	FALSE	TRUE	116370	15862
p_tot_ds	FALSE	TRUE	61442	14447
pvalue_ds	FALSE	FALSE	63482	14512
tof_2_sp	FALSE	FALSE	49719	13238
upstream_cut				15935
downstream_cut				14383

P_{tot} ds includes transmission

TOF12


2016-04 1.2 3-140
10^3
10^2
10
1
26
28
30
32
34
36
38
40
42
44
tof2 - tof1 [ns]

P (downstream)



Plans

- Refactor analysis routines to deal with more data (30 hours)
- ~~Add downstream cuts for badly reconstructed events and decays~~ (~~20 hours~~/12 hours)
- Improved PID cut (6 hours)
- Analysis of apertures (40 hours)
- Event selection to get a matched beam (40 hours)
- Tidy up uncertainty analysis (40 hours/8 hours)
  - Second pass on the general approach
  - Field magnitude in tracker region
  - Effect of uncertainty in tracker alignment to field
- Improved amplitude calculation - beam ellipse calculation separate to amplitude calculation (10 hours)
- MC Uncertainties (geometry/densities, fields) (40 hours)

Conclusions

- We have measured amplitude upstream and downstream of the cooling channel
- Results are consistent with emittance reduction but with not much significance
- The collaboration continues to work towards reduction of systematic uncertainties in the measurement

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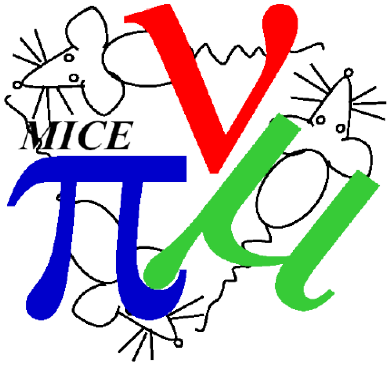
Backup Slides



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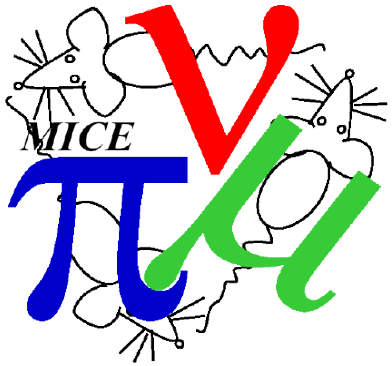
Track Extrapolation



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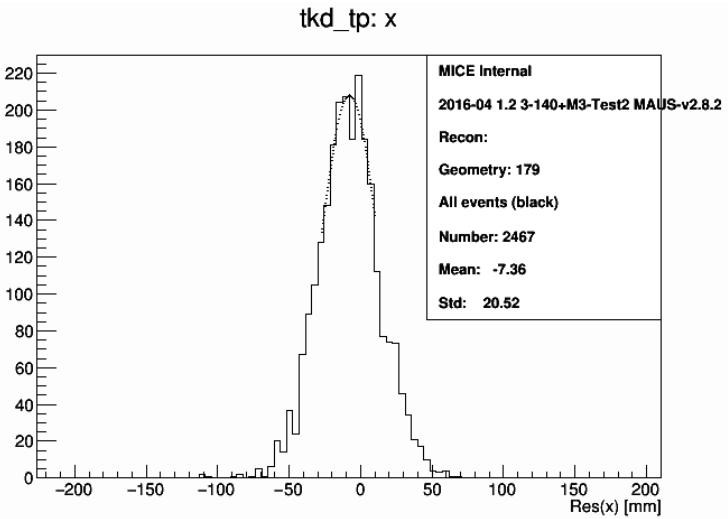
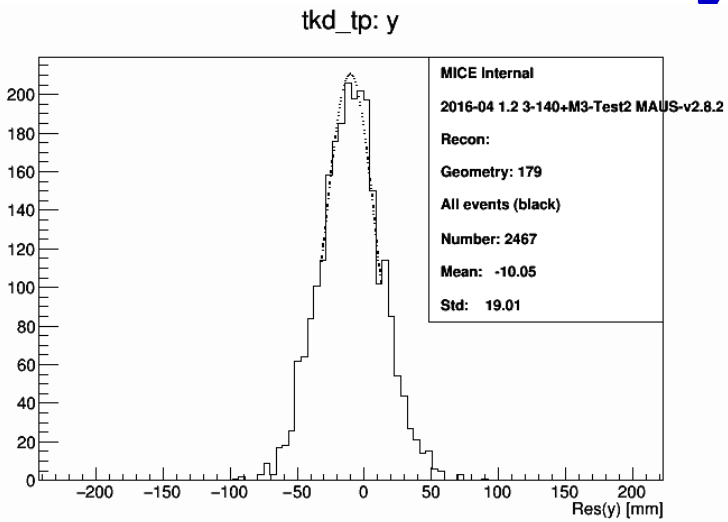
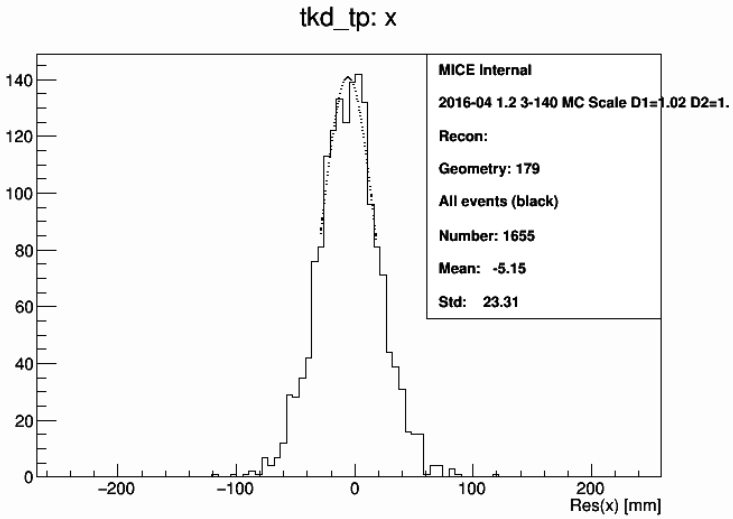
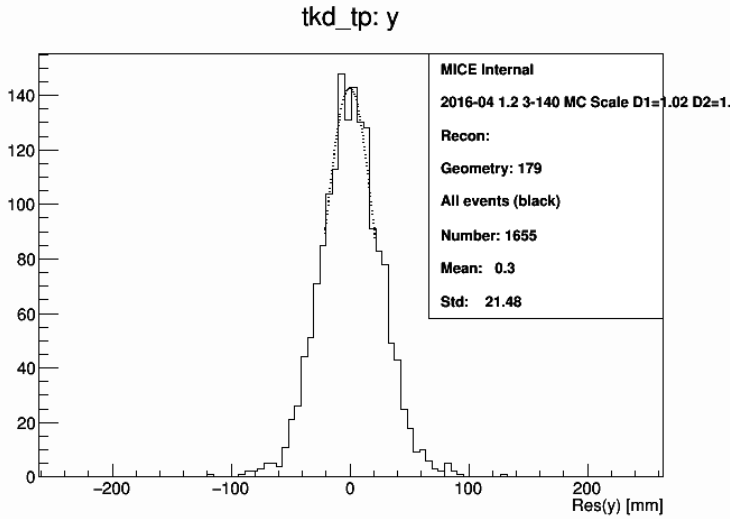
Track extrapolation









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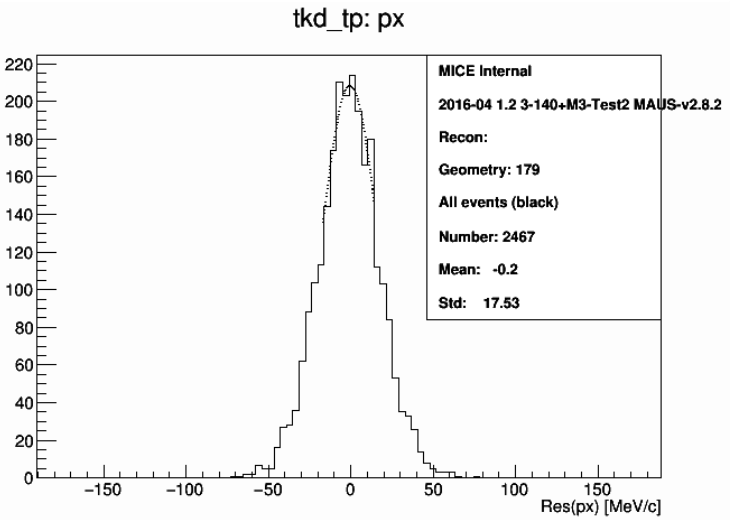

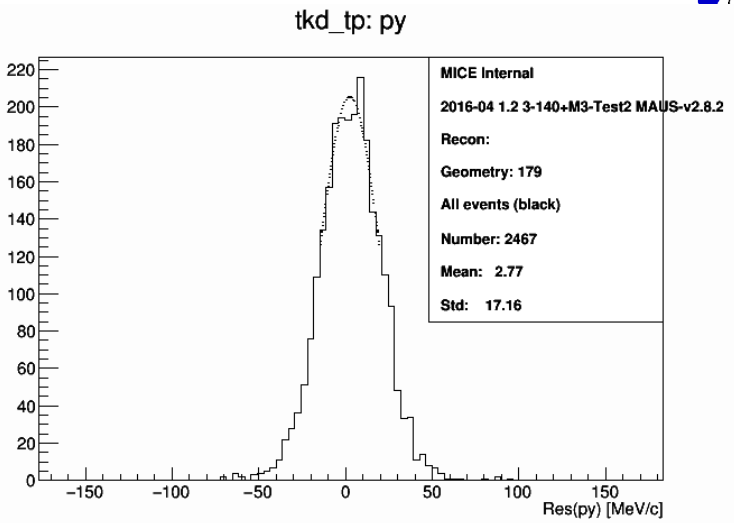

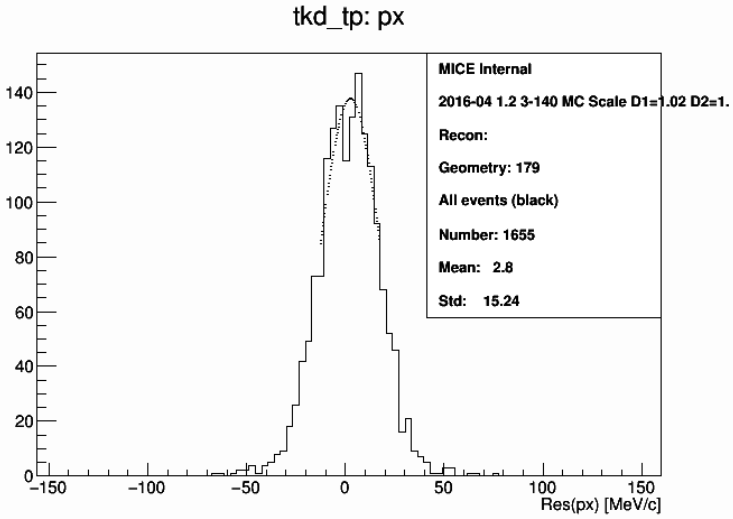

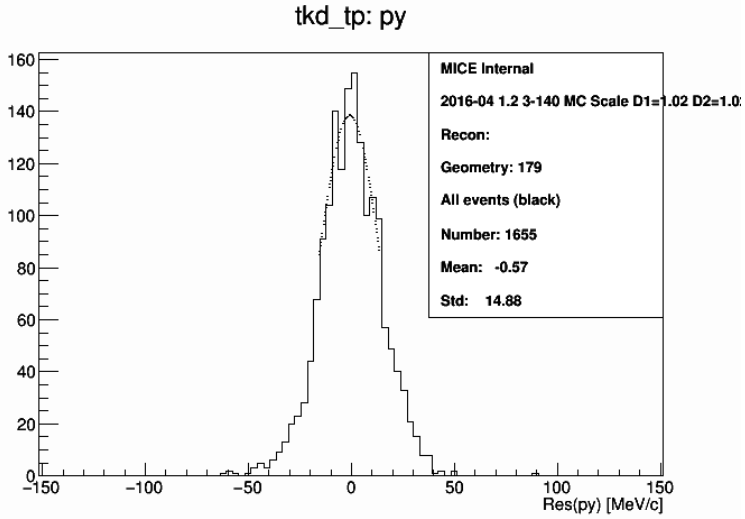

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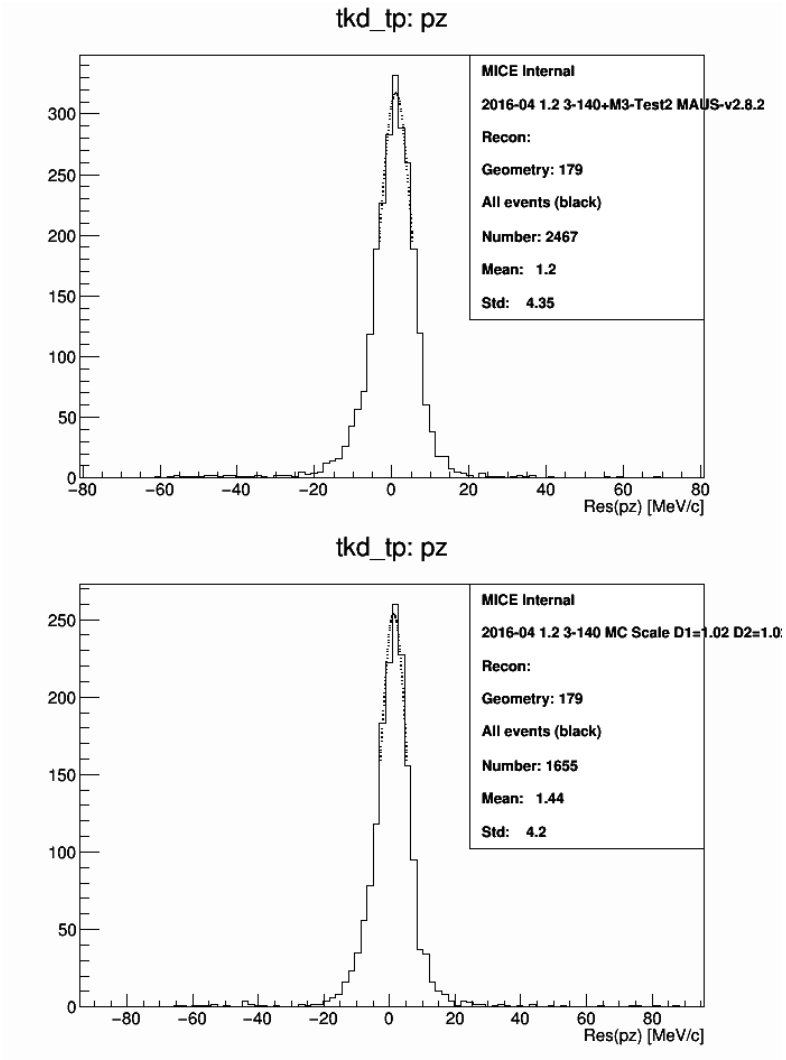

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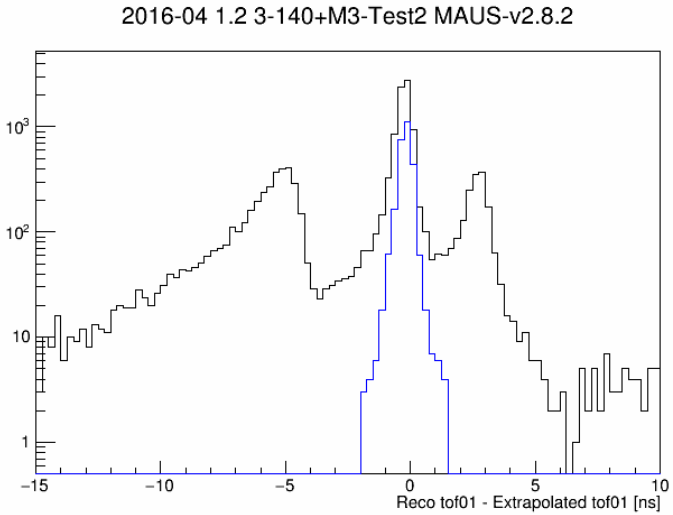
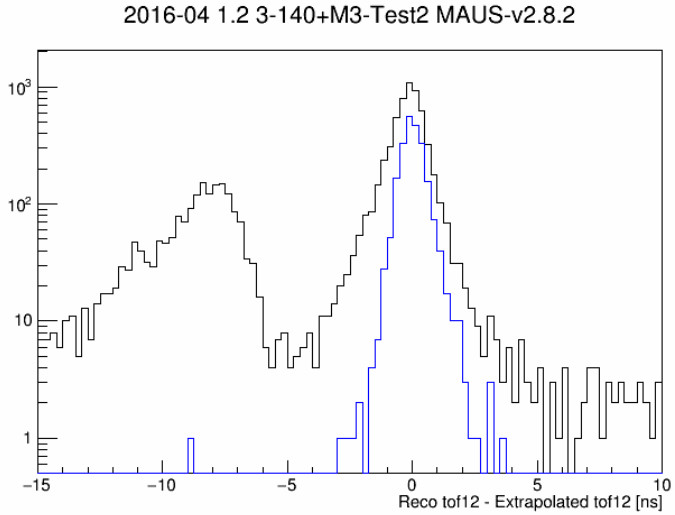
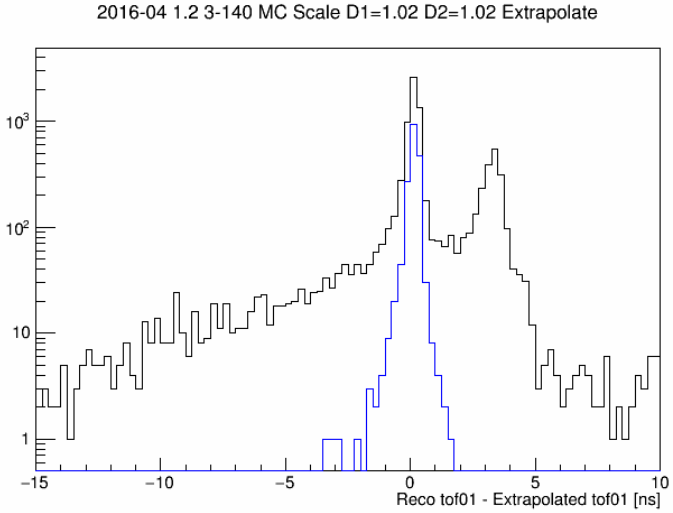
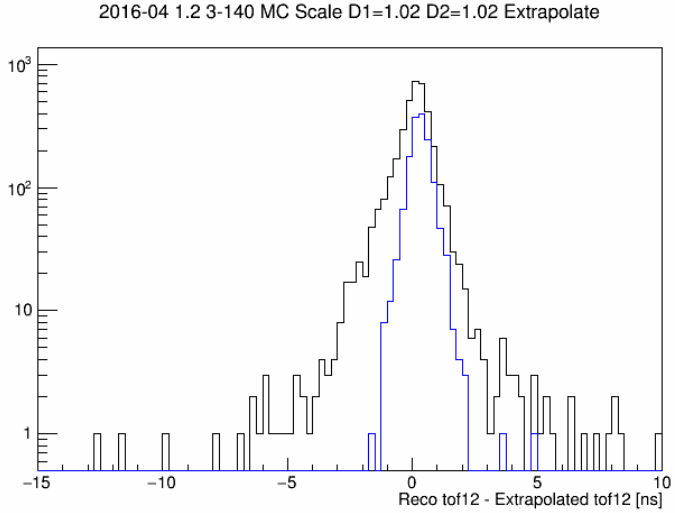
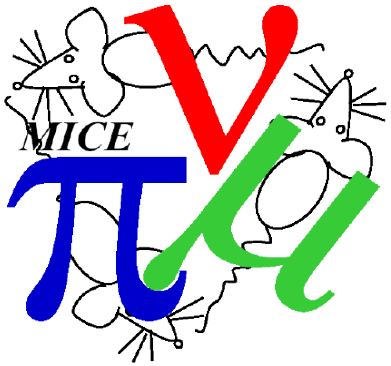








MC – Data Comparison



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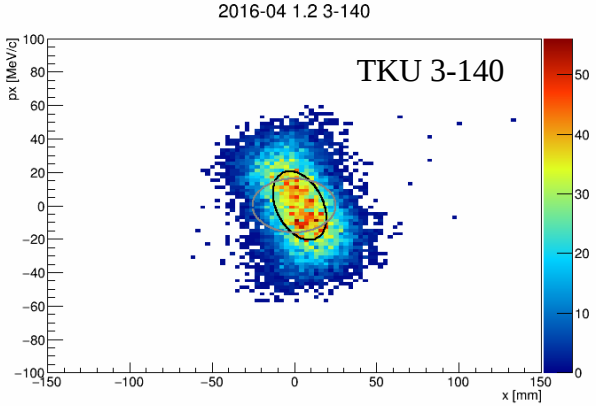
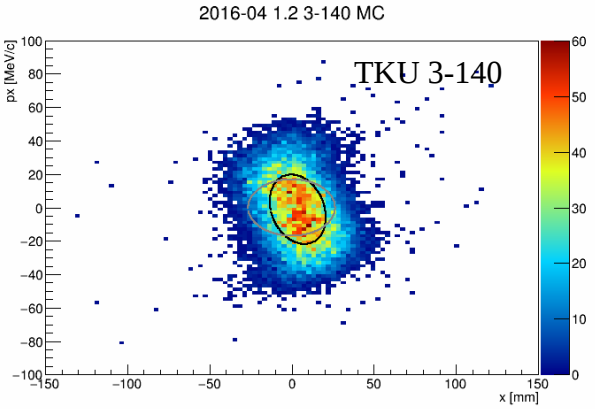
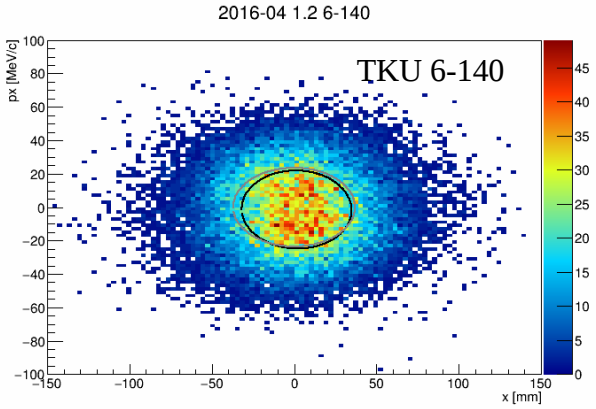
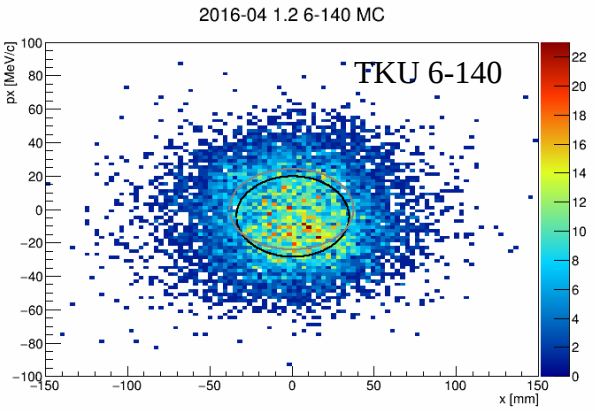
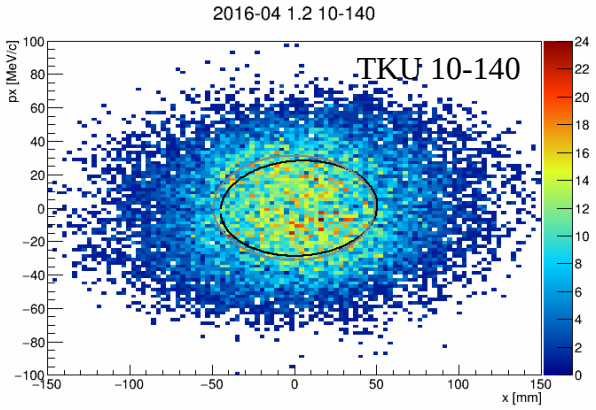
MC vs Data x-px

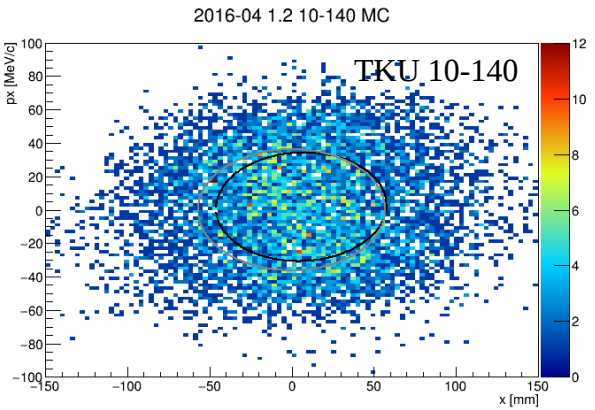




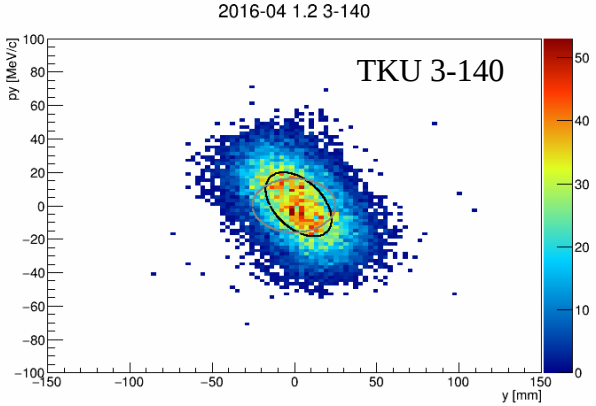


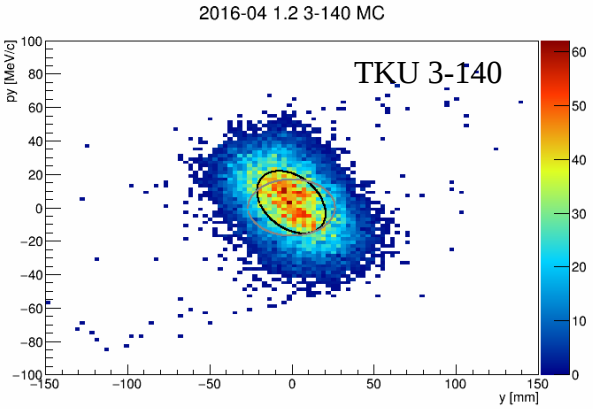


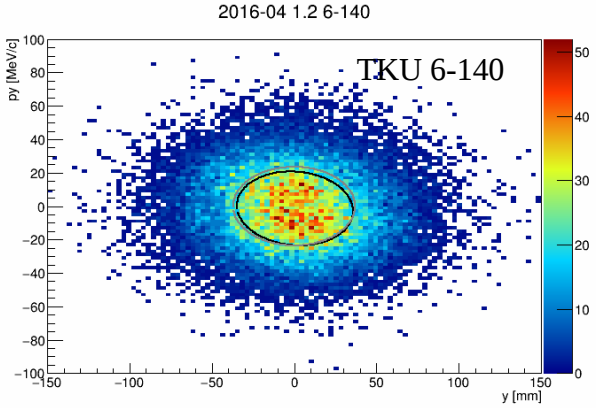


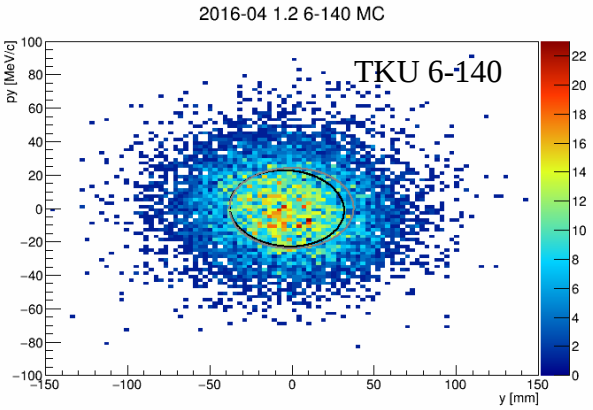


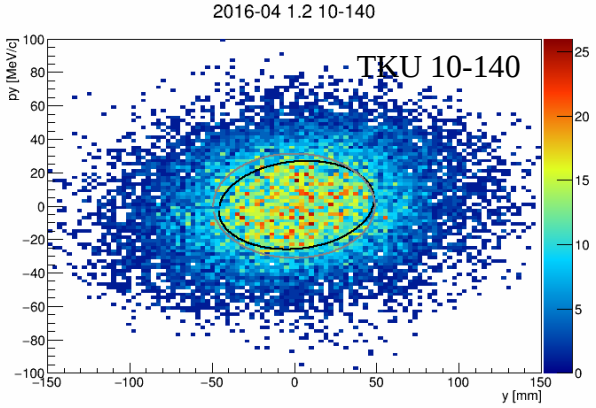
MC vs Data y-py

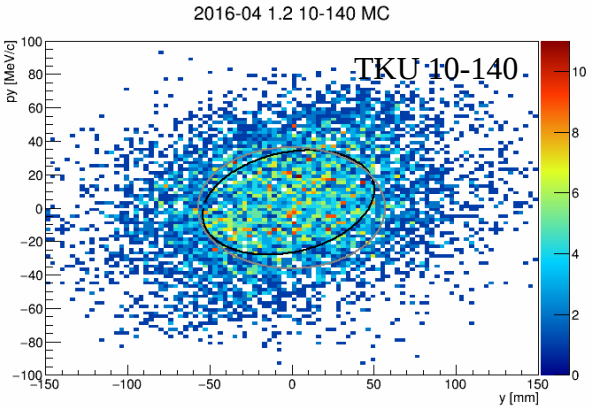




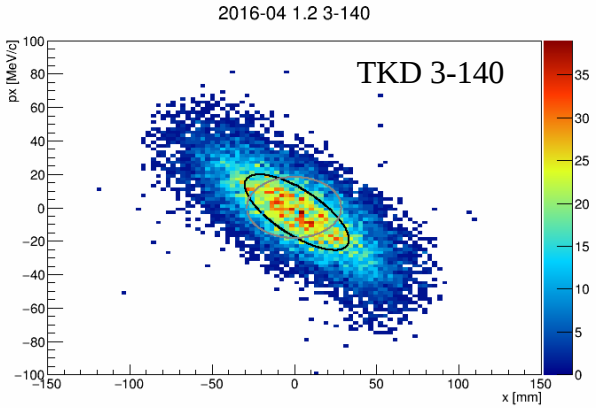


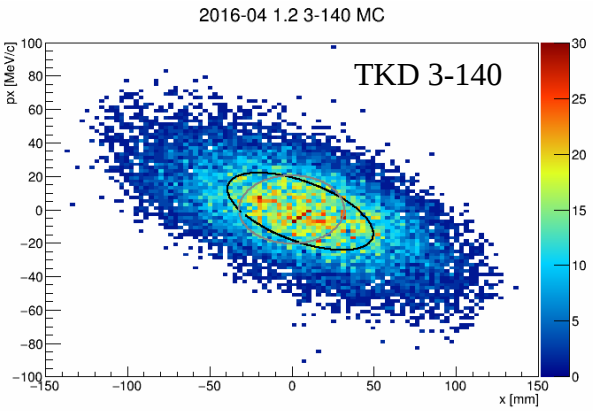


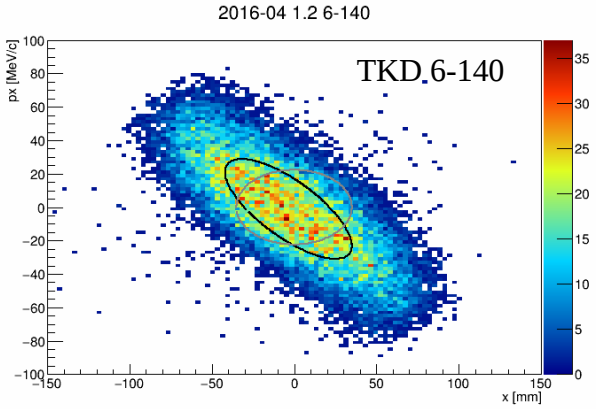


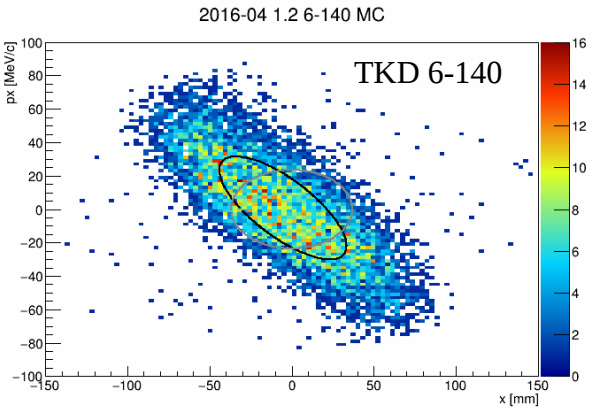


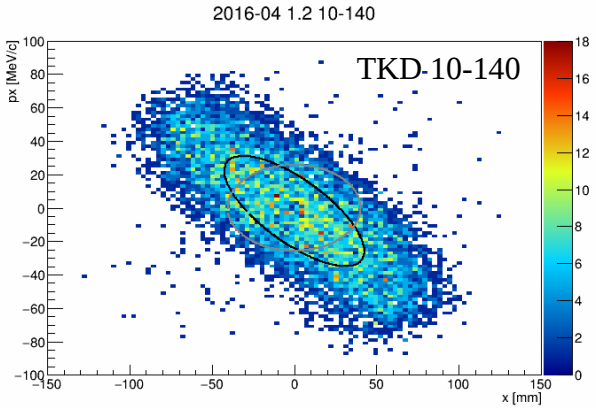
MC vs Data x-px

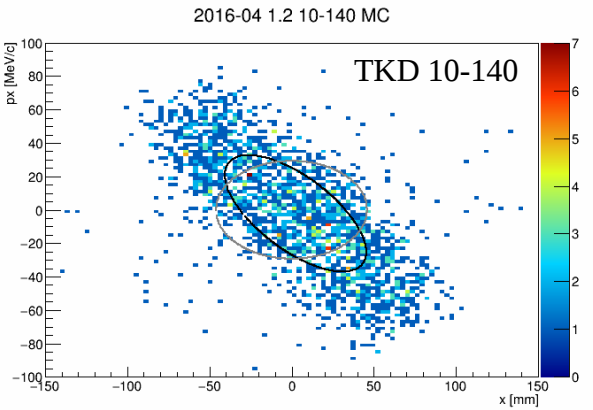




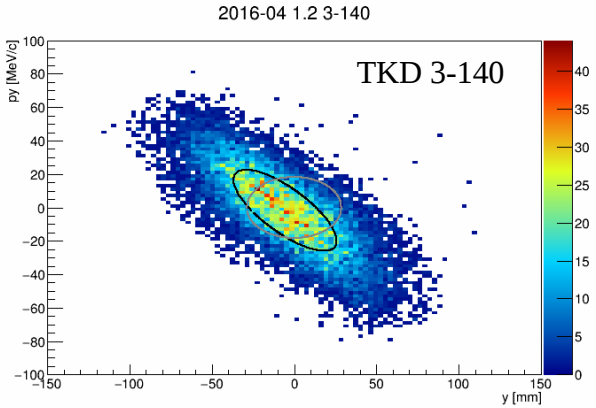


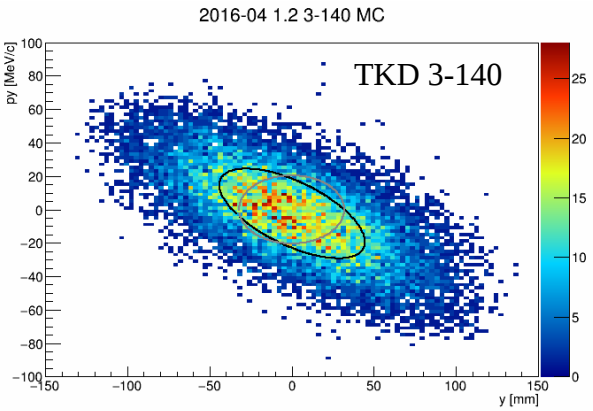


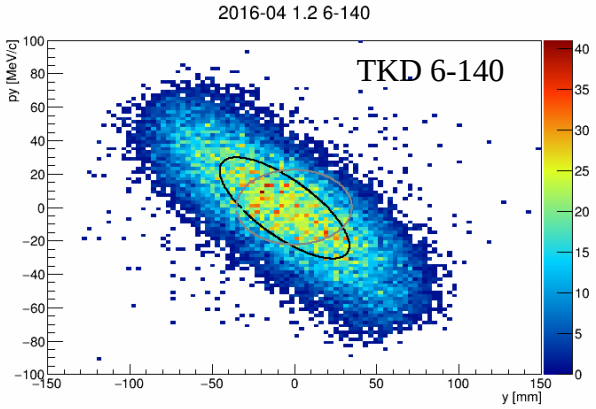


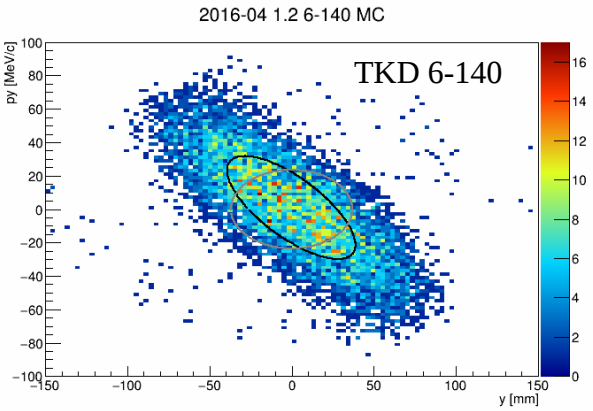


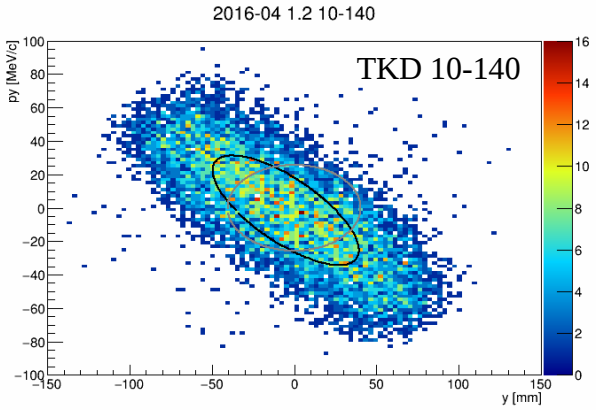
MC vs Data y-py

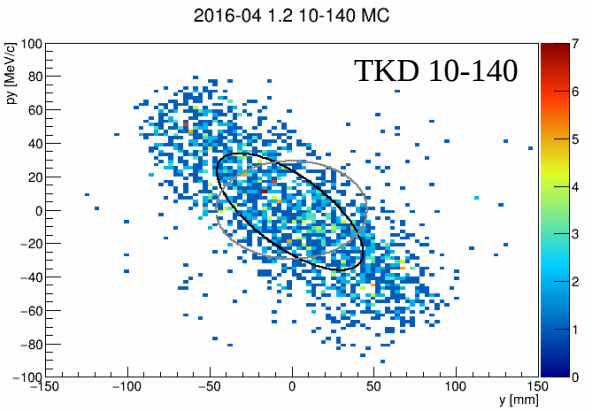












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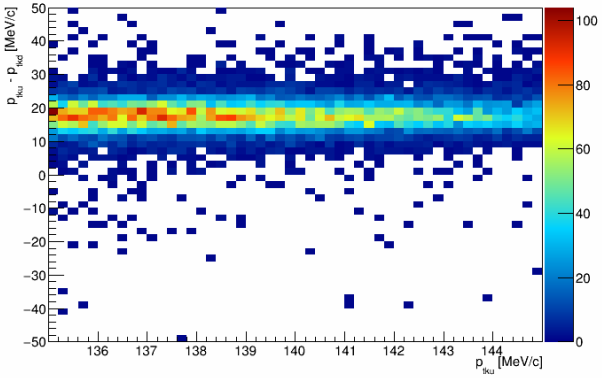
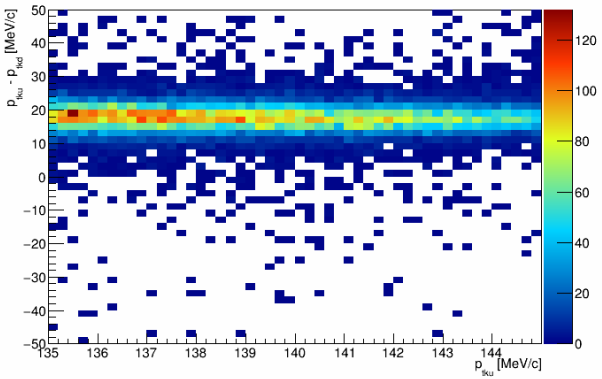
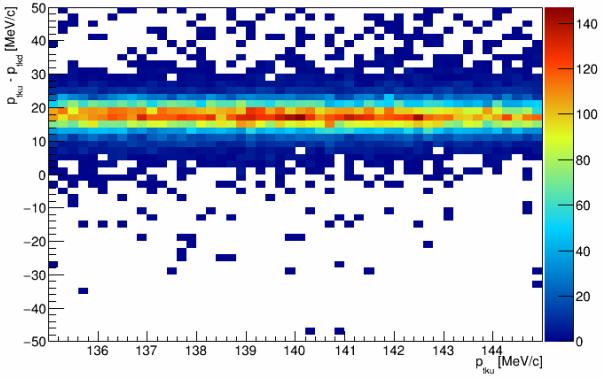
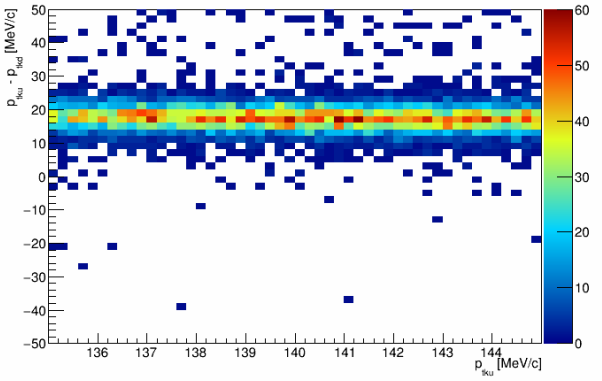
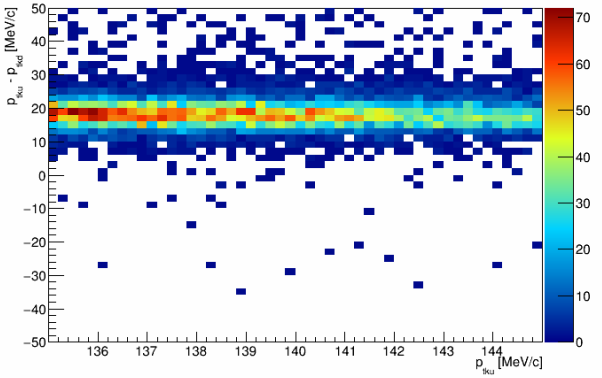
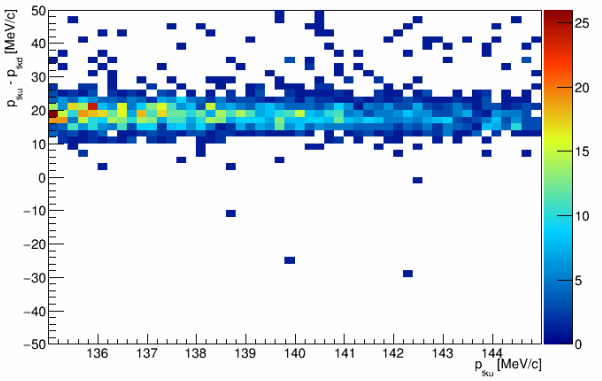




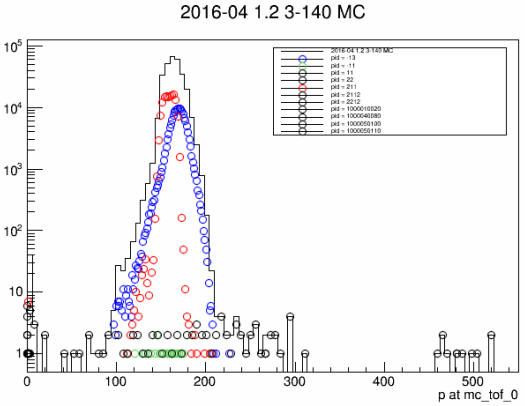


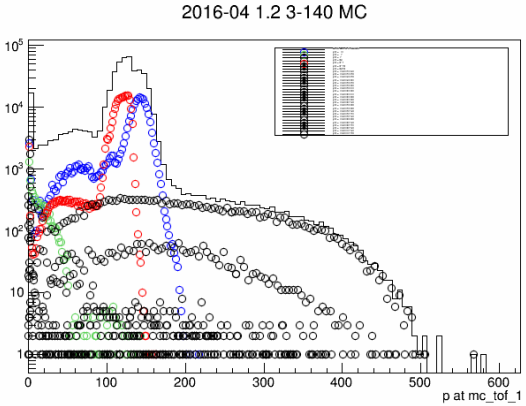


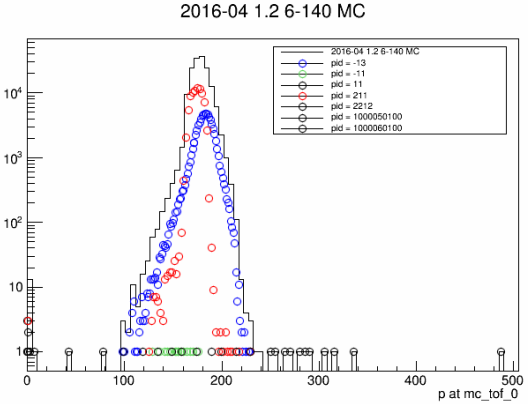


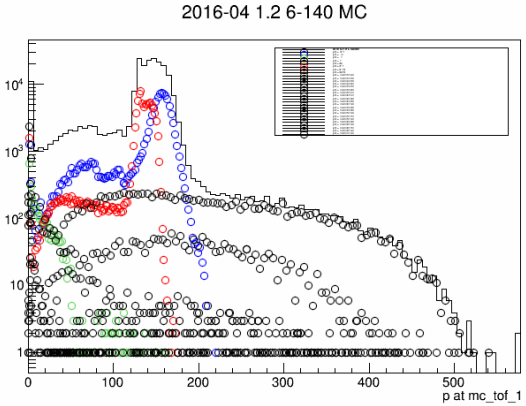


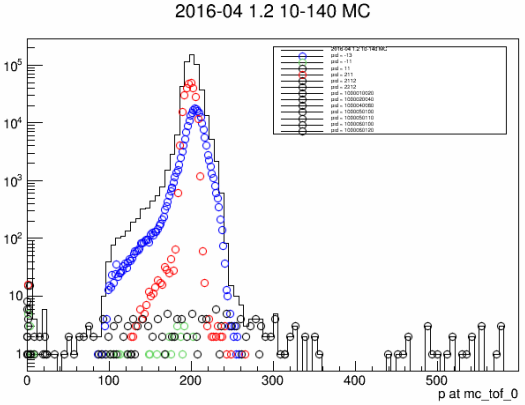
Momentum by species

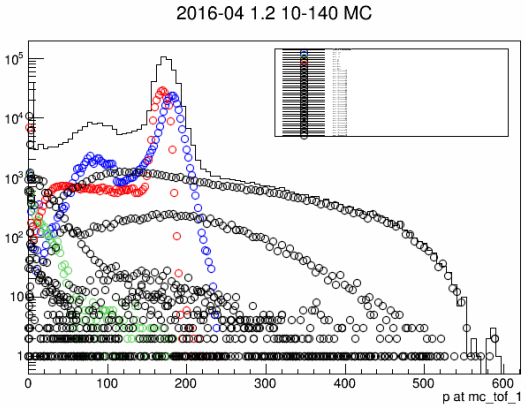




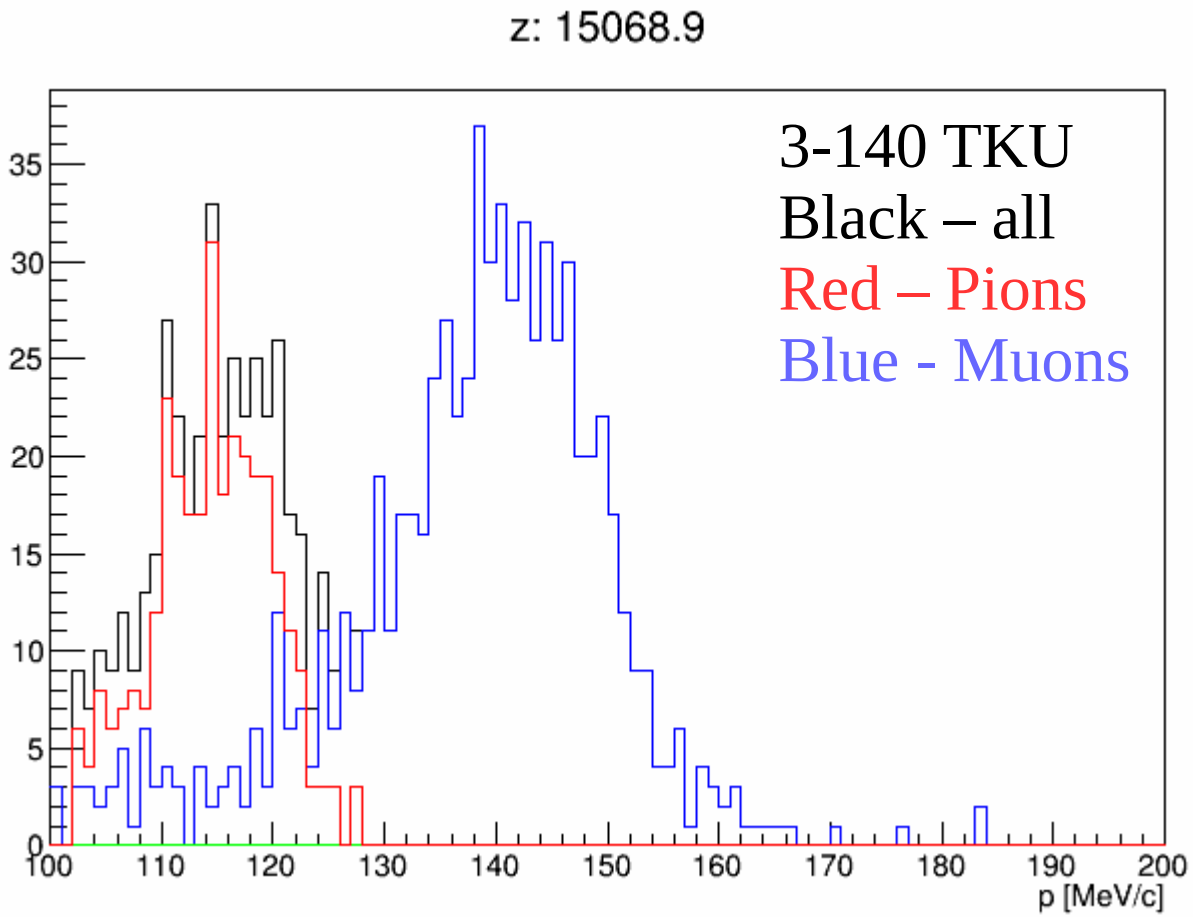




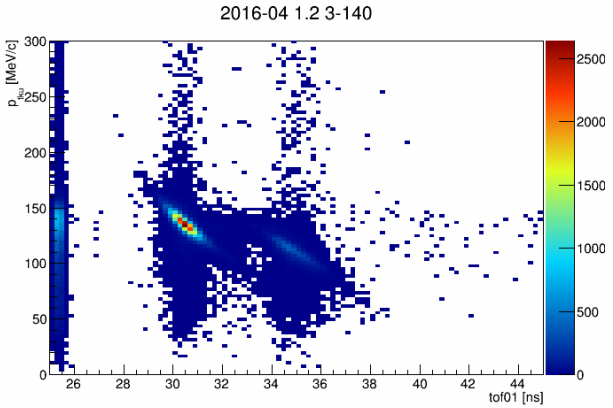


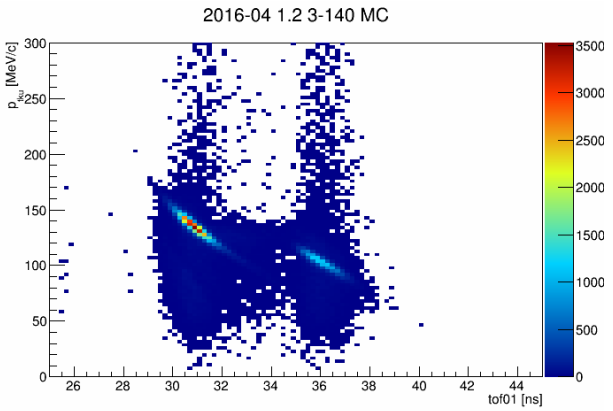


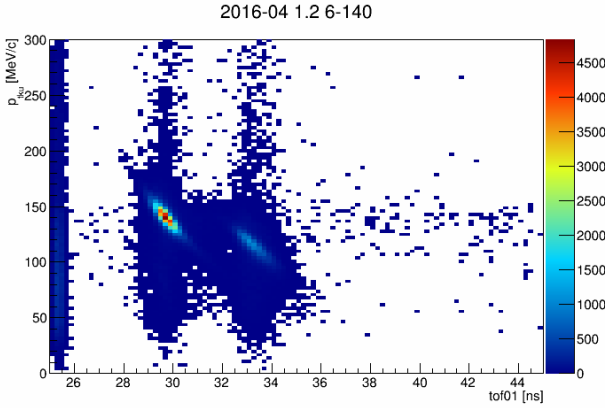
Momentum by species at TKU st1

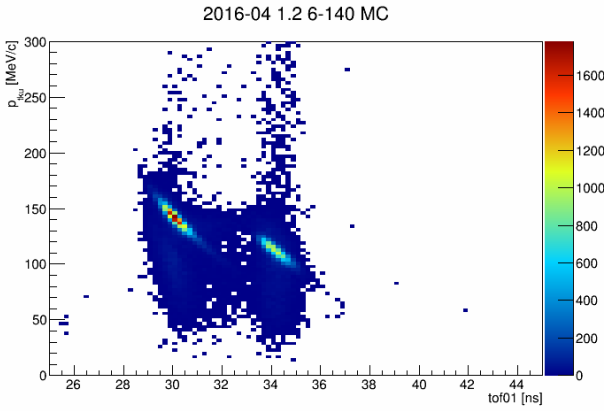


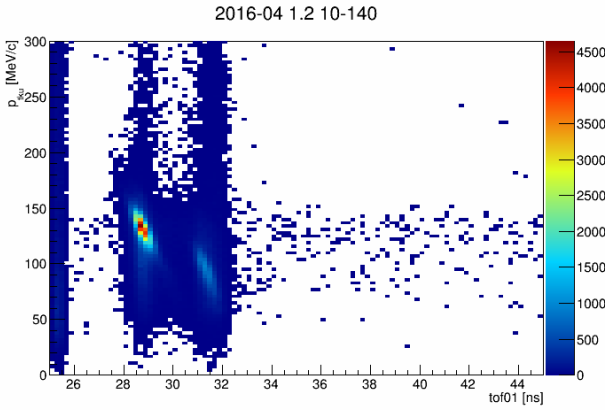
MC vs Data tof01 vs TKU P

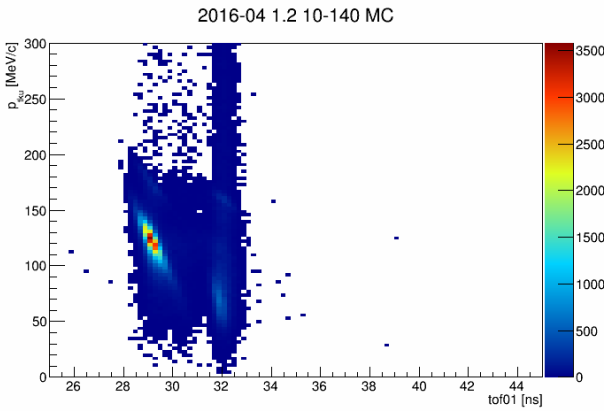




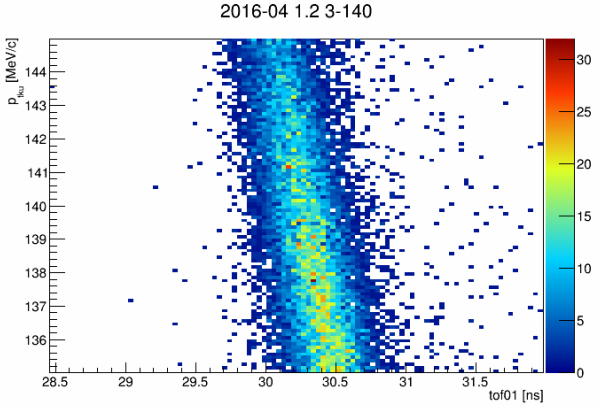


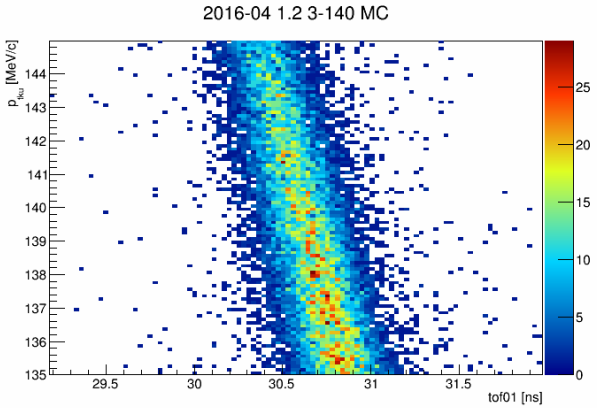


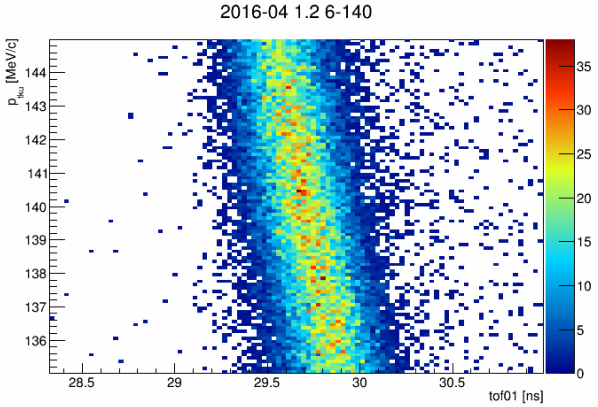


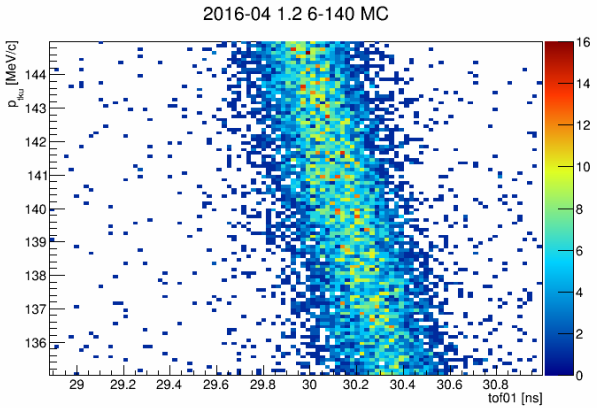


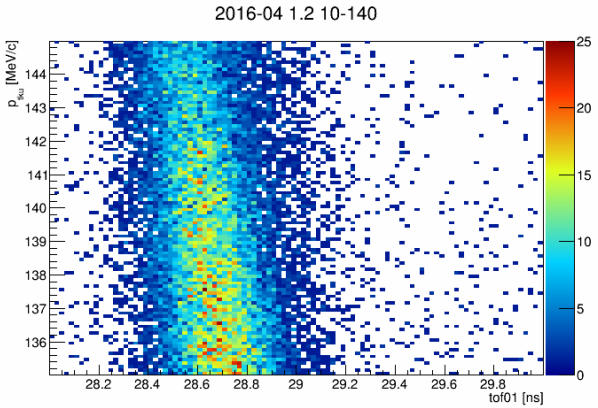
MC vs Data tof01 vs TKU (zoom)

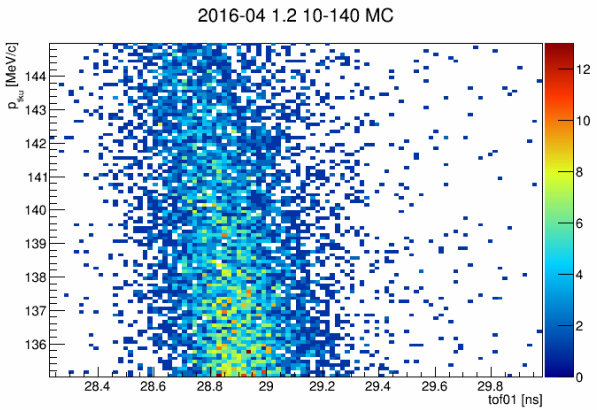




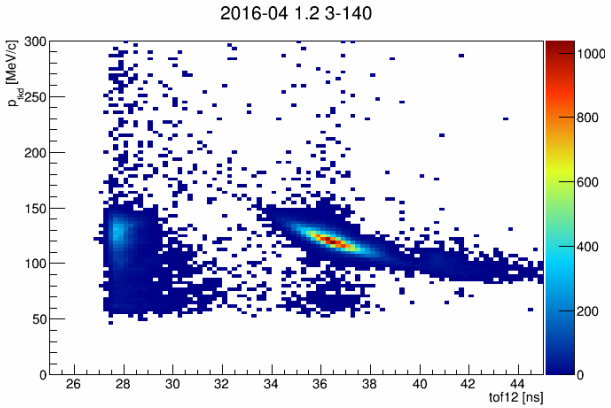


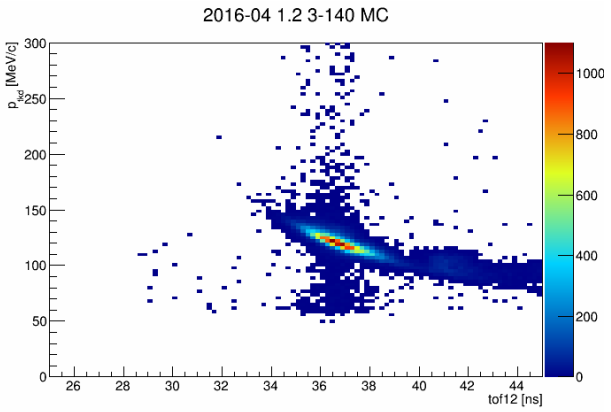


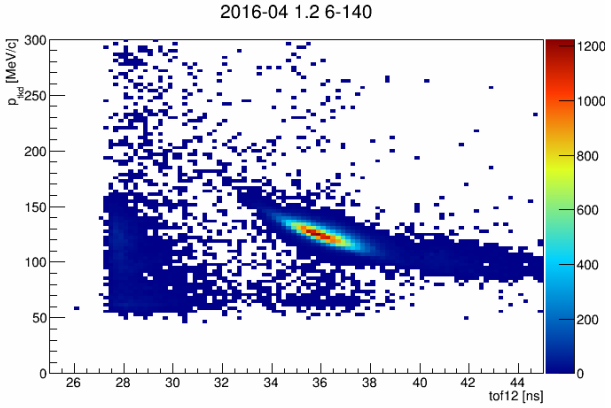


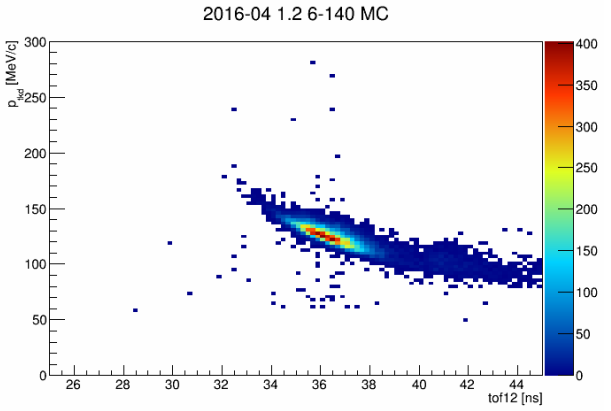


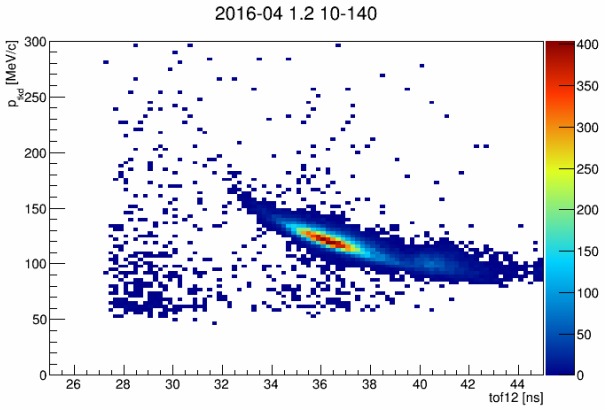
MC vs Data tof12 vs TKD P

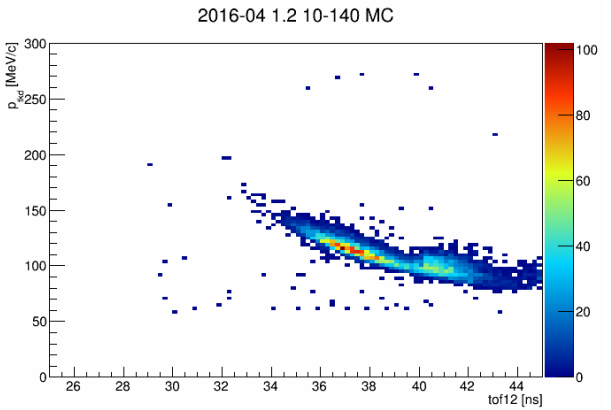




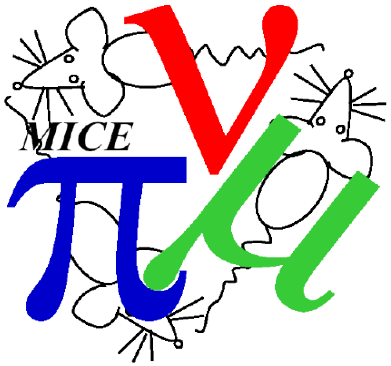








Detectors etc



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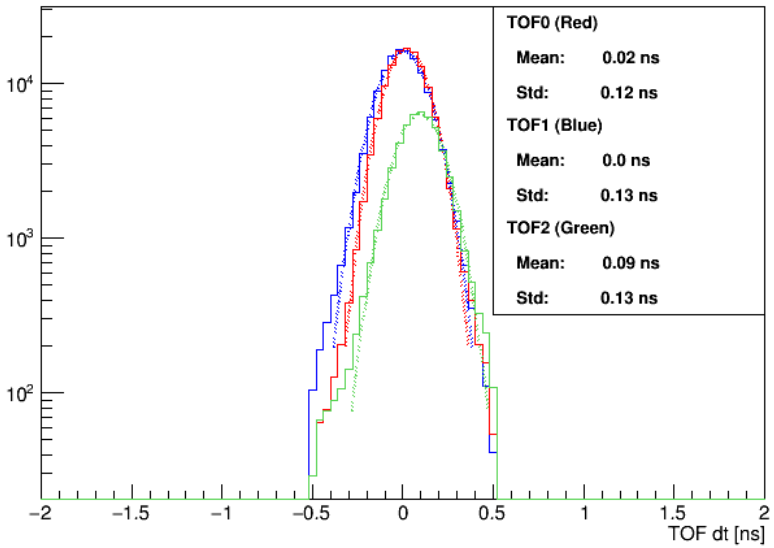
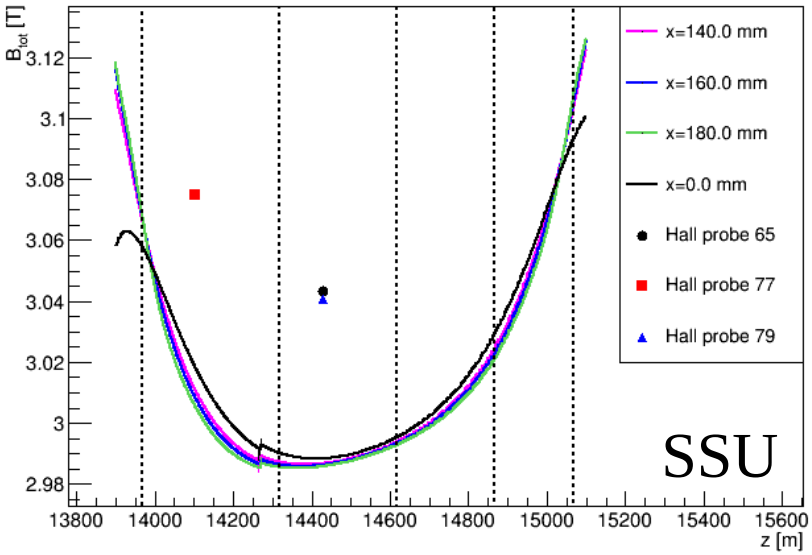
TOF Recon - resolutions

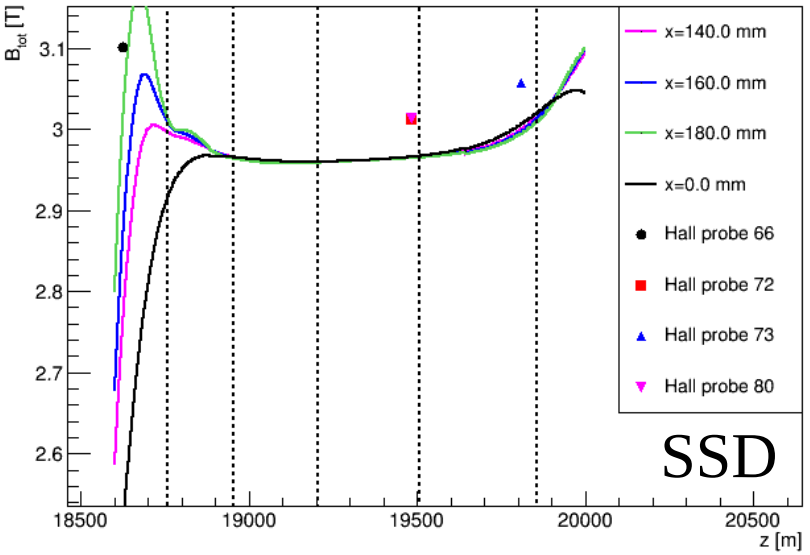


	Record 2 slab hits but failed calibration	Calibration okay but failed 0.5 ns cut	Okay
TOF0	0.03 %	1.58 %	98.39 %
TOF1	0.0 %	0.0 %	100.0 %
TOF2	4.16 %	2.06 %	93.78 %

- Difference between the calibrated TOF slab times
  - Width should be twice resolution
  - Mean should be 0
- Note this analysis is on all events that record at least one TOF1 space point
  - i.e. the “uncut“ dataset
  - Needs to be repeated on “cut” dataset

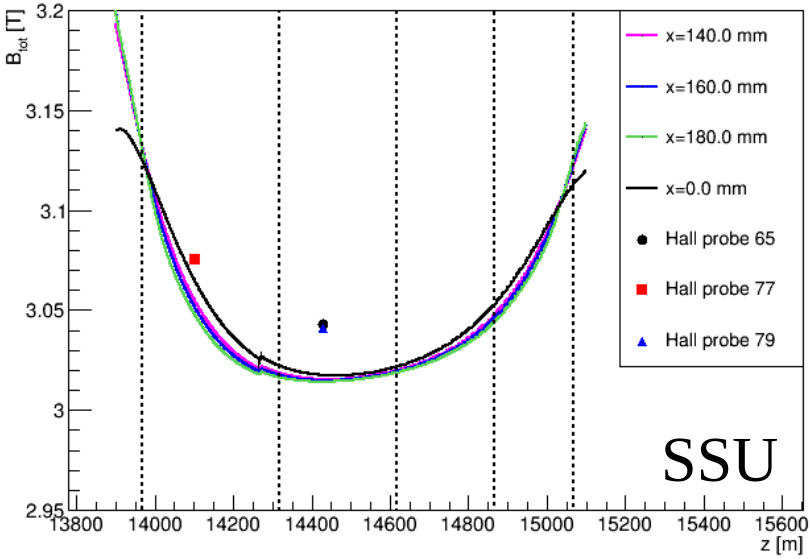
Hall Probes vs MAUS

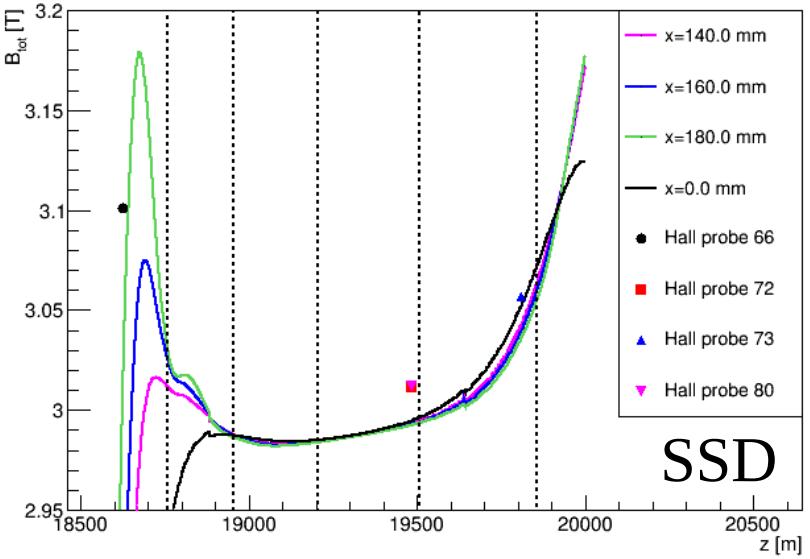




- Hall probes are mounted at r ~ 160 mm
- Approx 2 % discrepancy between MAUS and hall probes
- Nb: trajectory in B-field scales with B/p
  - i.e. if we get B-field high by 10 %, it looks exactly like a track with 10 % higher momentum

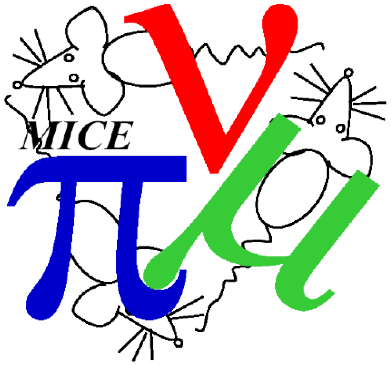
Hall Probes vs MAUS





- Less than 1 % discrepancy between MAUS and hall probes incl PRY effect
  - Calculated using Holger/Pasternak “correction factors”
  - Excepting Hall probe 66
- Not included in Recon/MC yet

Uncertainties



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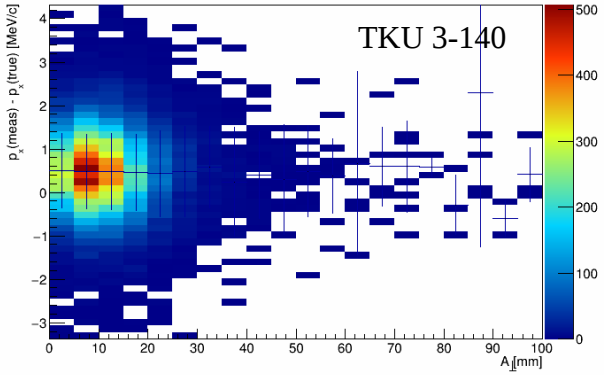
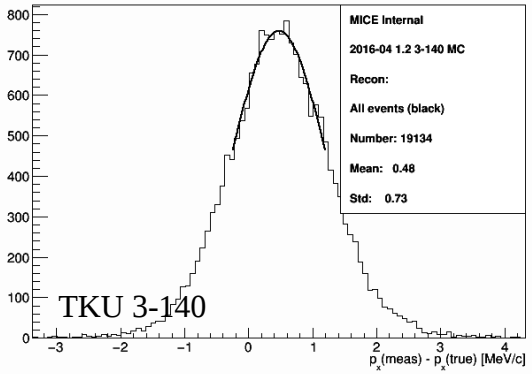
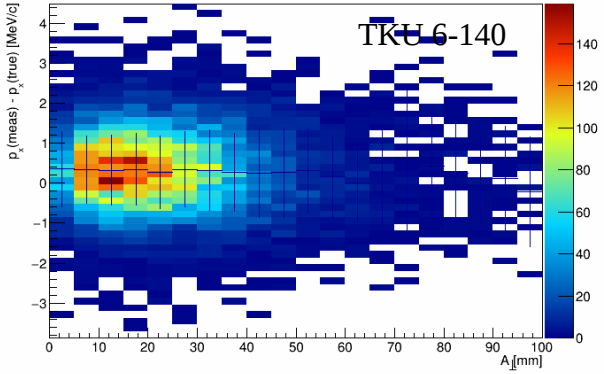
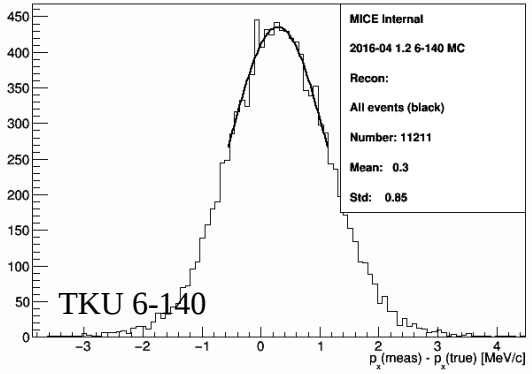
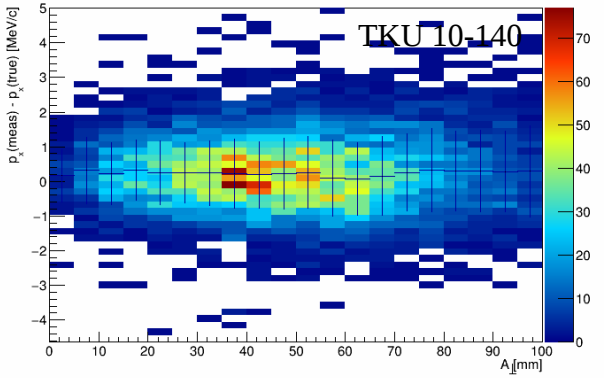
Intrinsic Detector Resolution -px

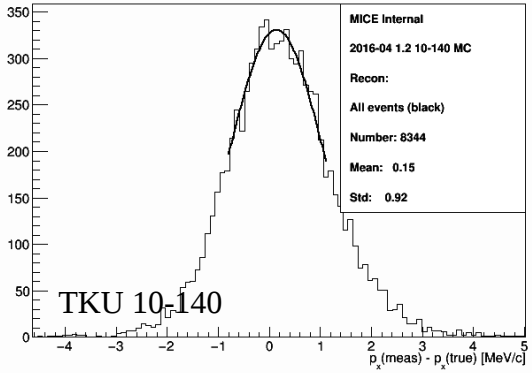




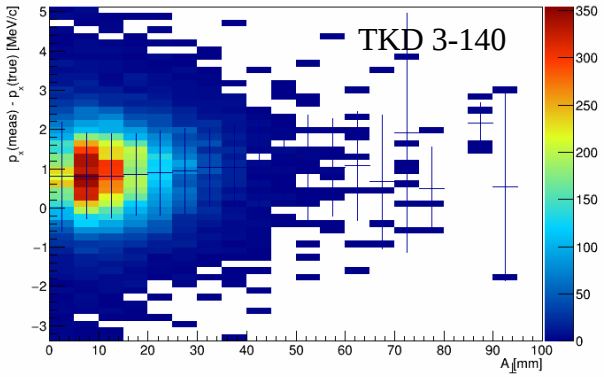


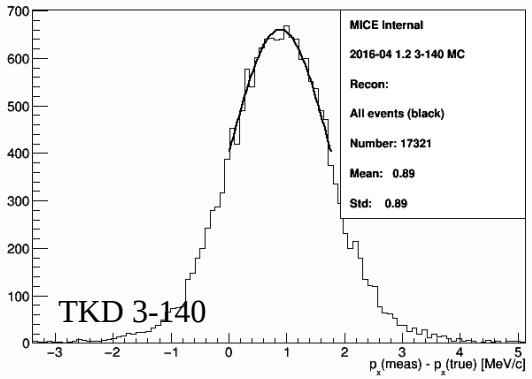


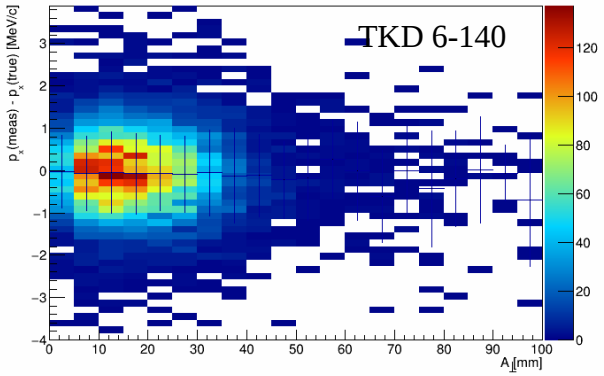


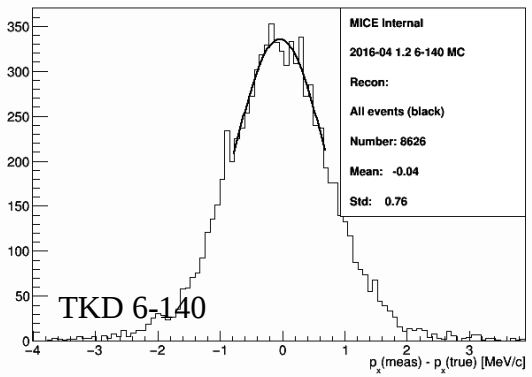


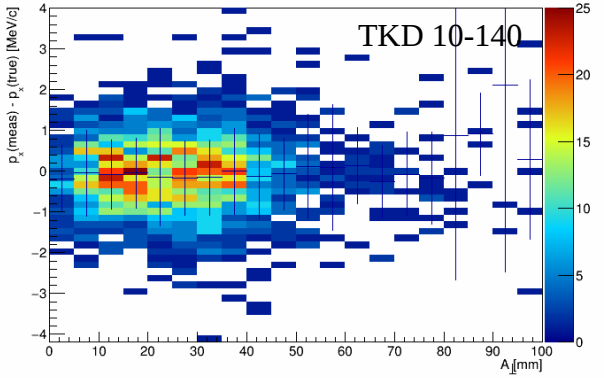
Intrinsic Detector Resolution -px

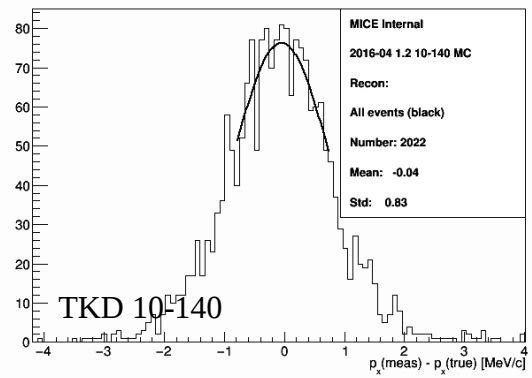




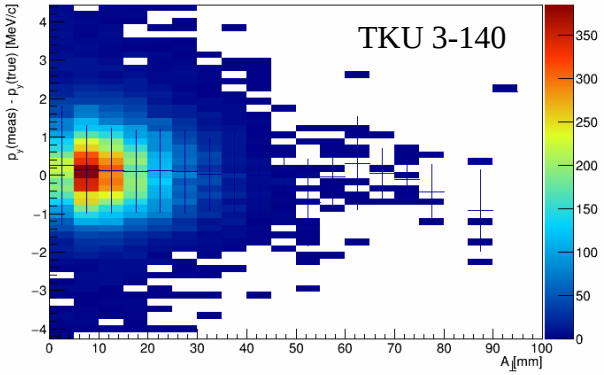


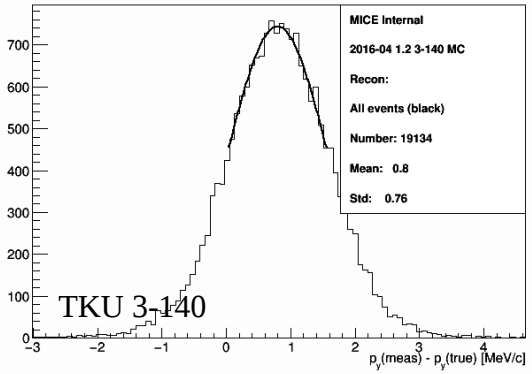


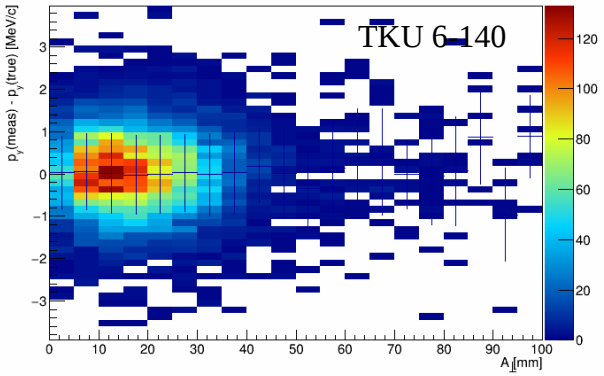


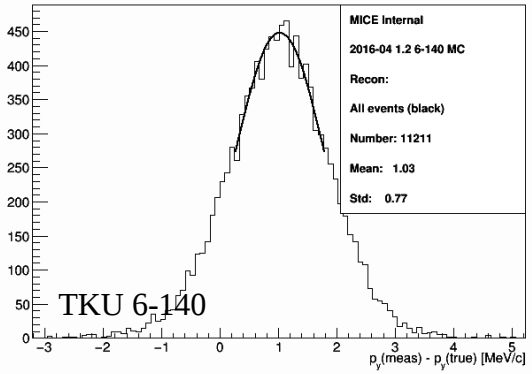


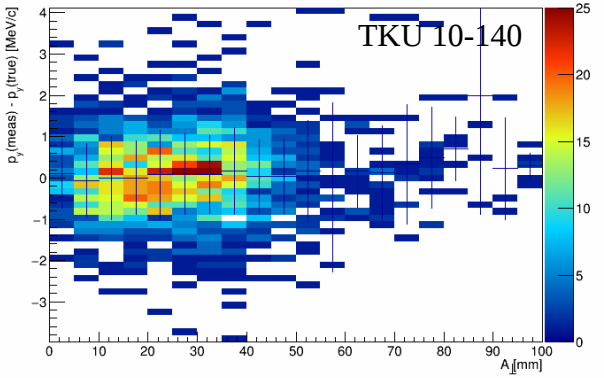
Intrinsic Detector Resolution -py

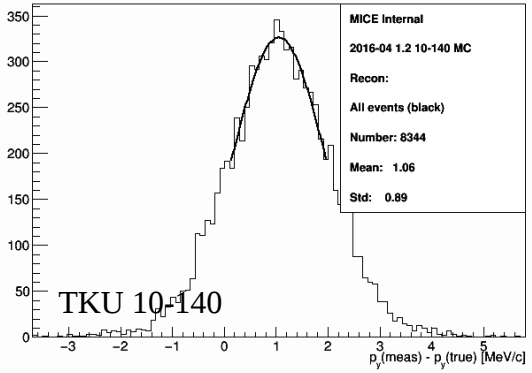




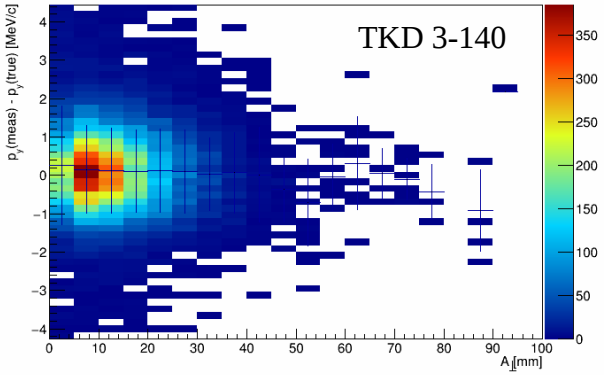


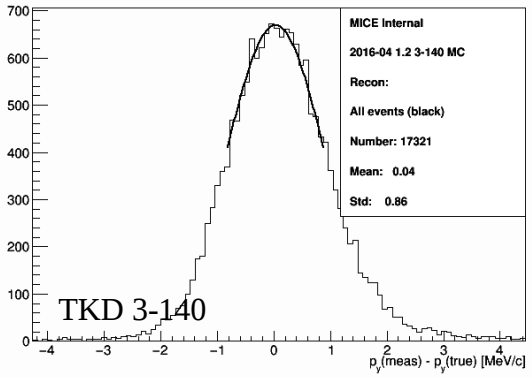


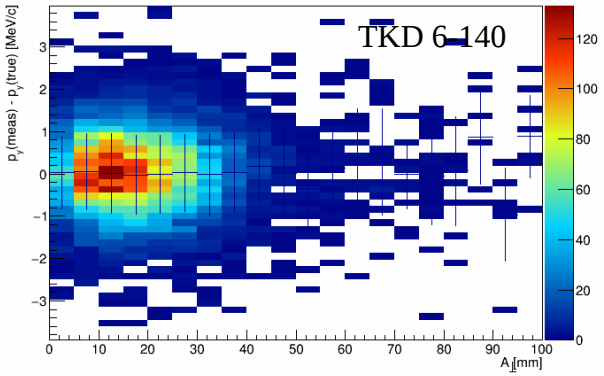


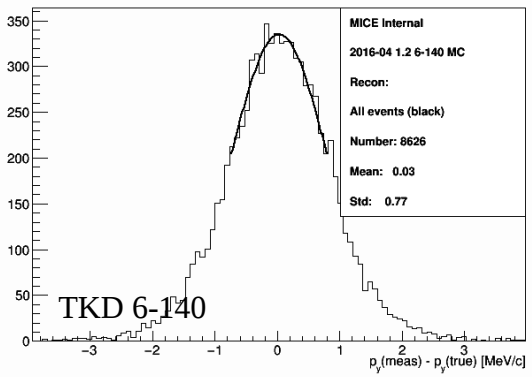


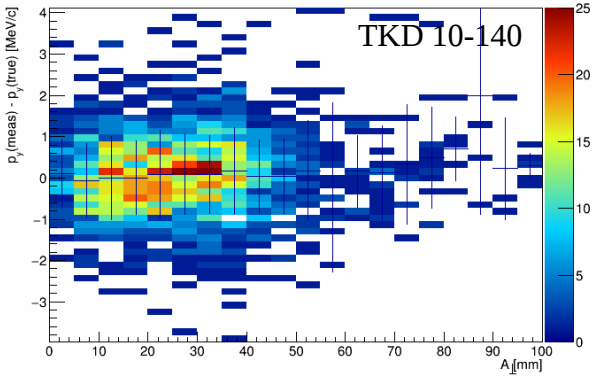
Intrinsic Detector Resolution -py

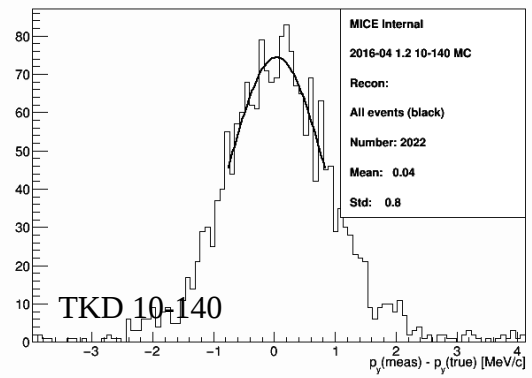




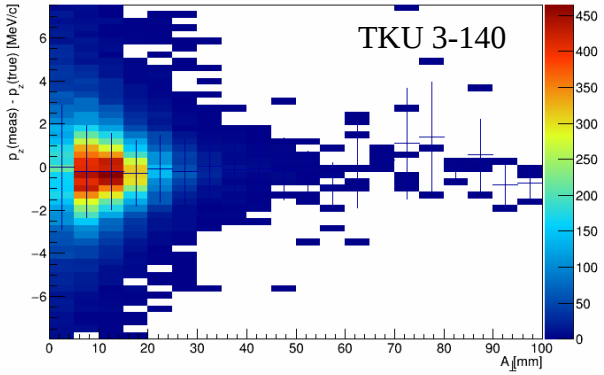


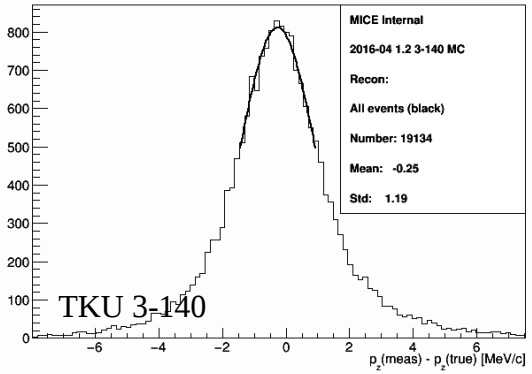


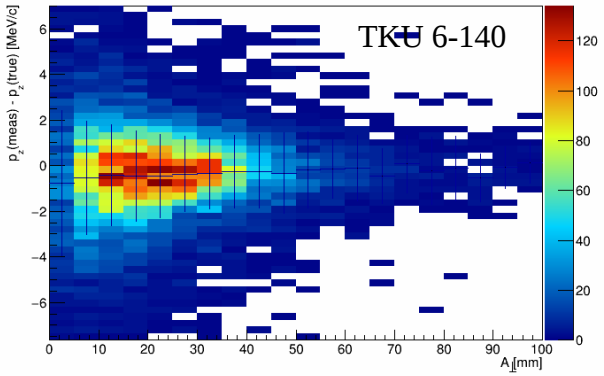


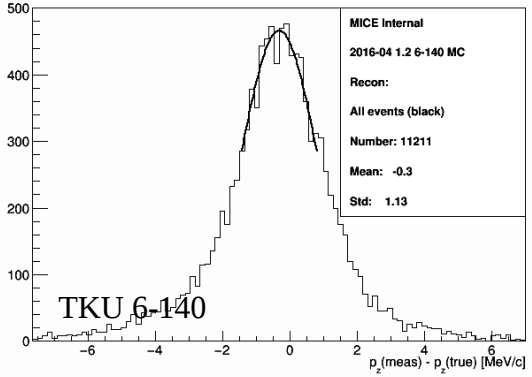


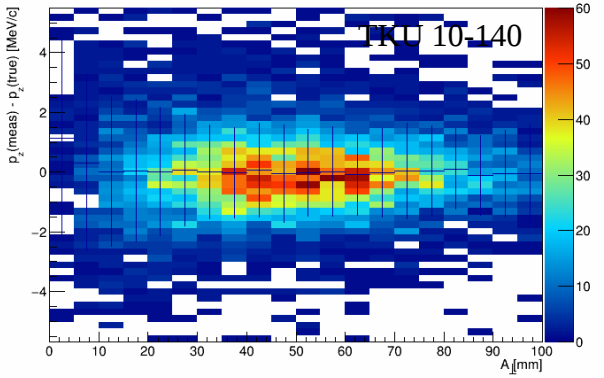
Intrinsic Detector Resolution -pz

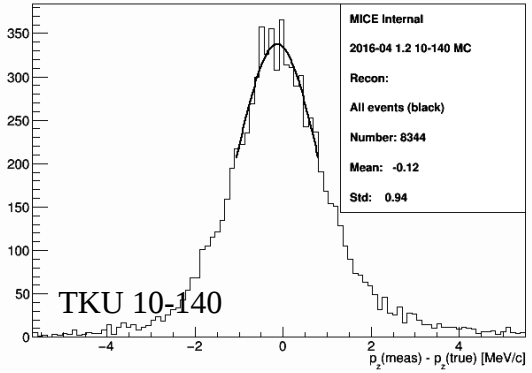




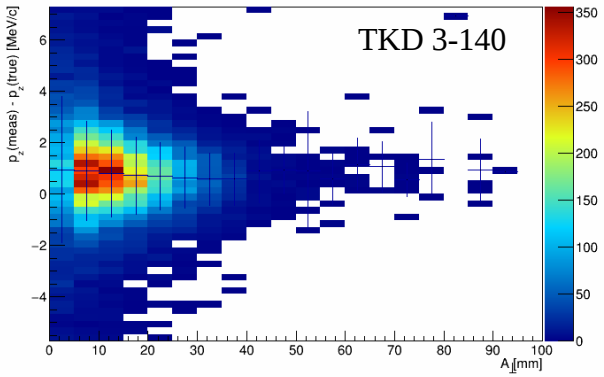


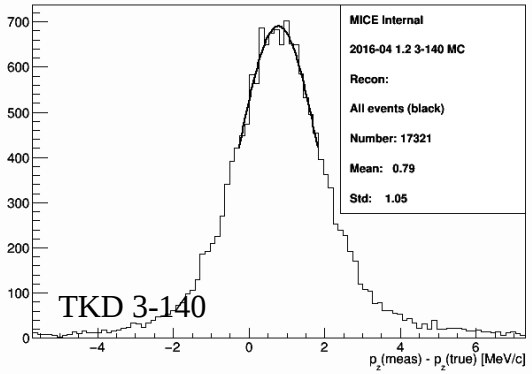


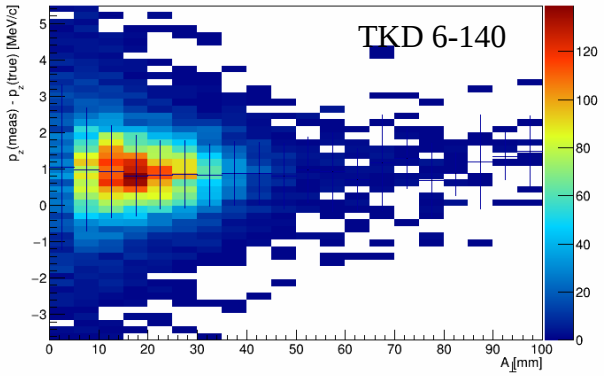


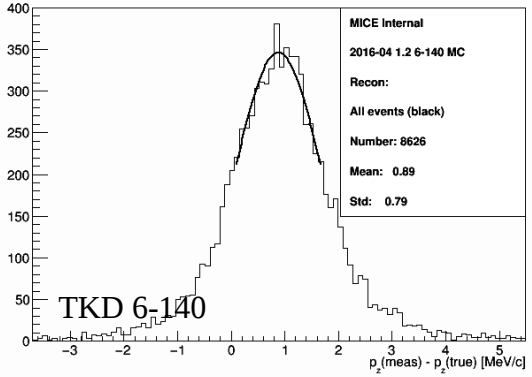


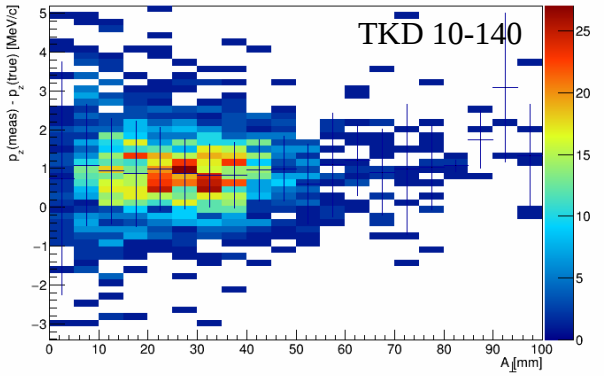
Intrinsic Detector Resolution -pz

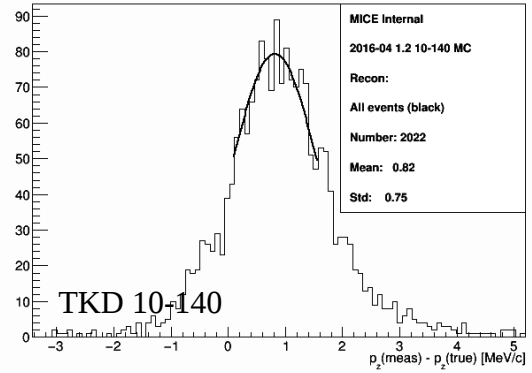




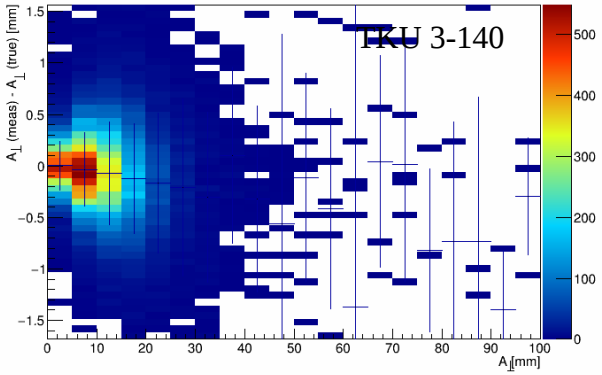


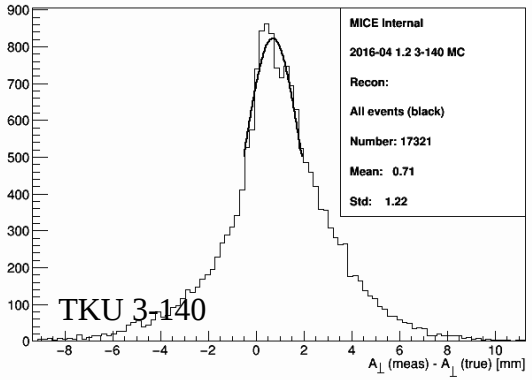


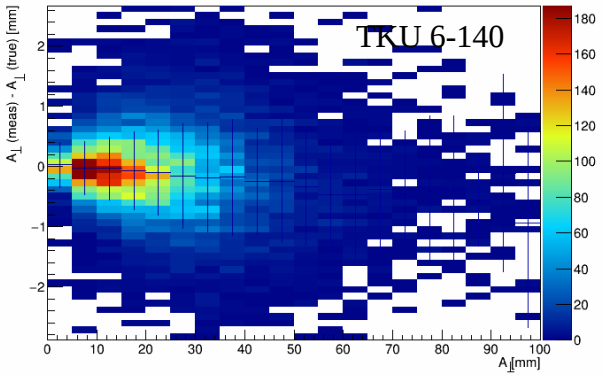


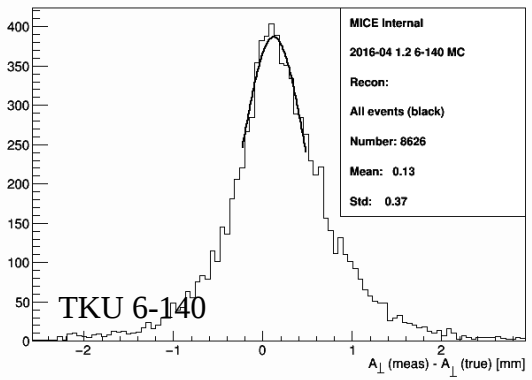


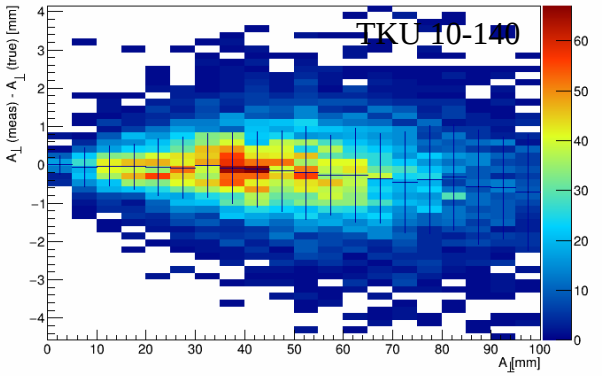
Intrinsic Detector Resolution

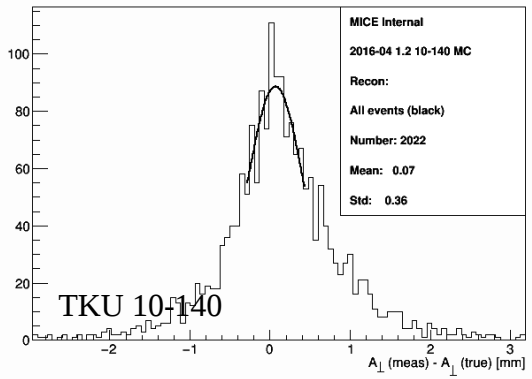




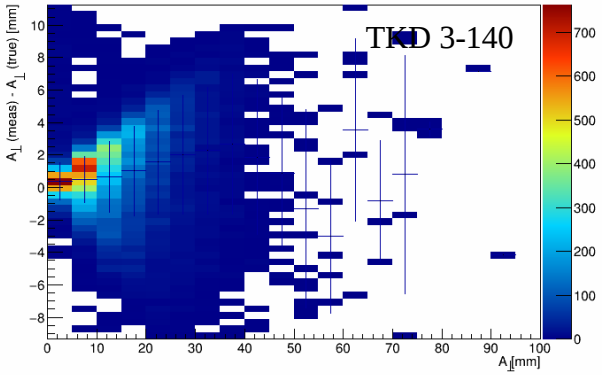


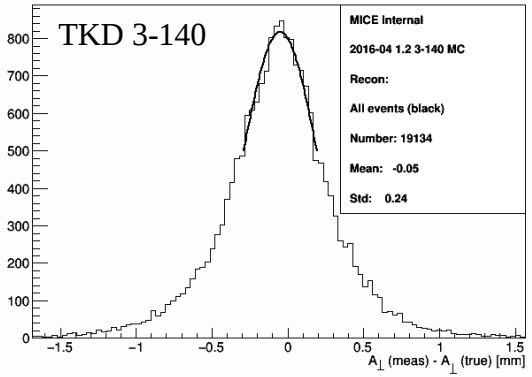


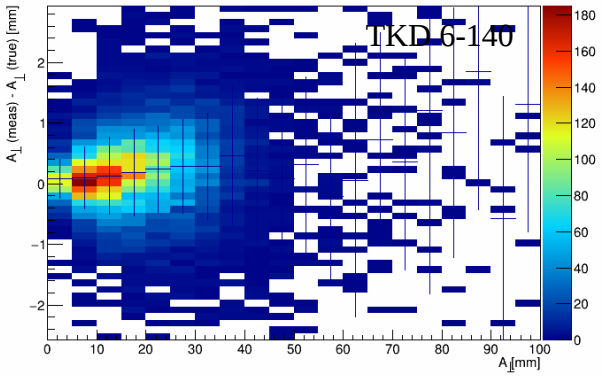


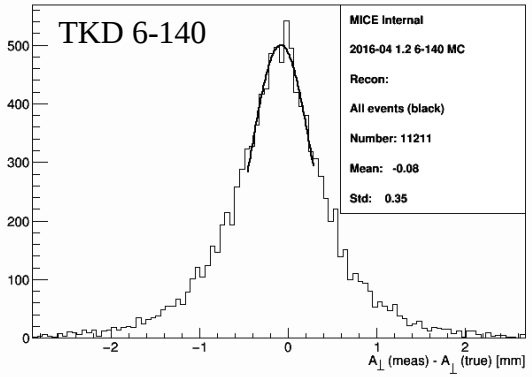


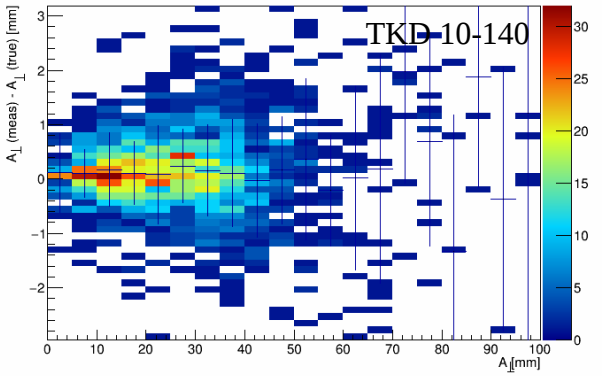
Intrinsic Detector Resolution

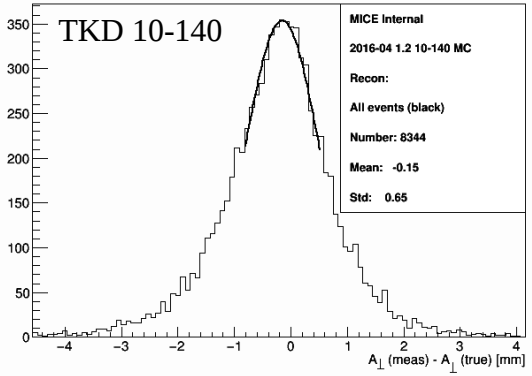




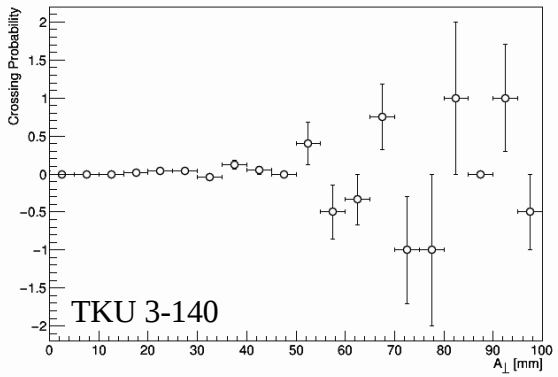


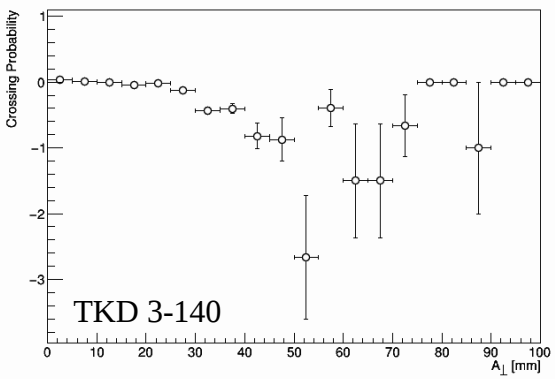


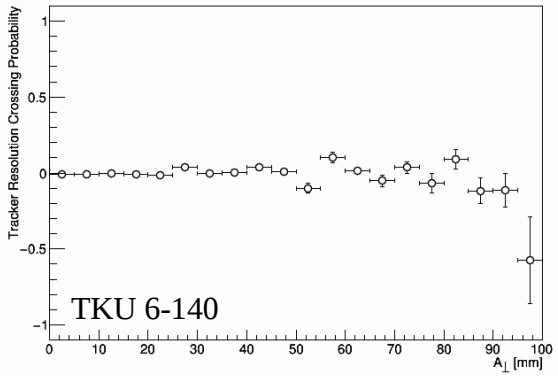


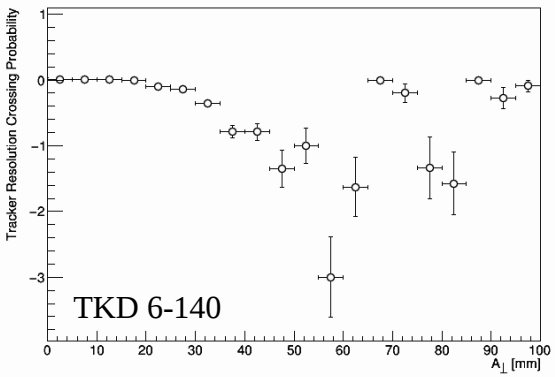


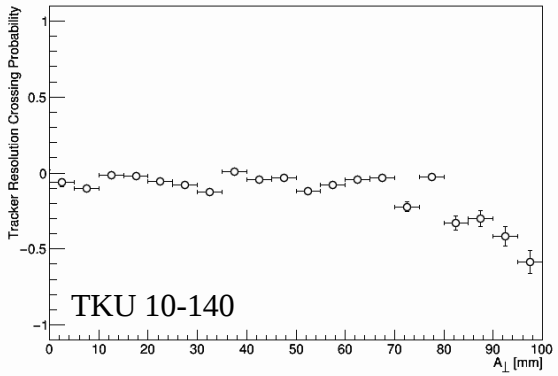
Crossing Probability

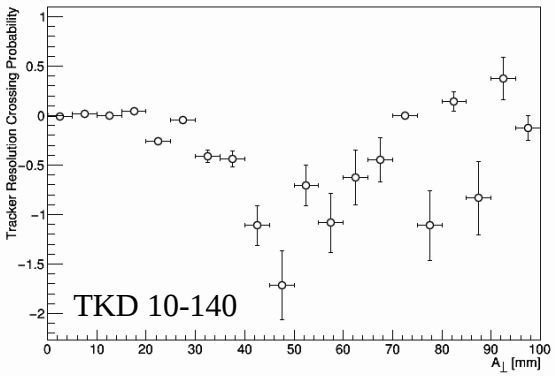






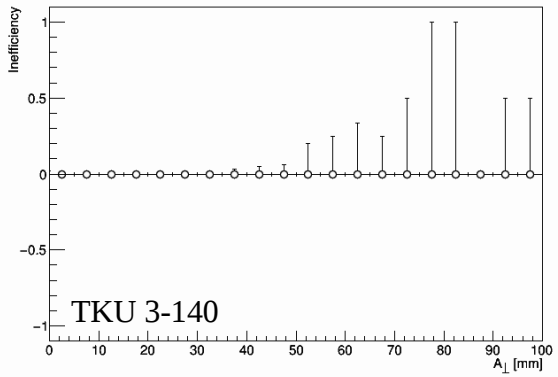


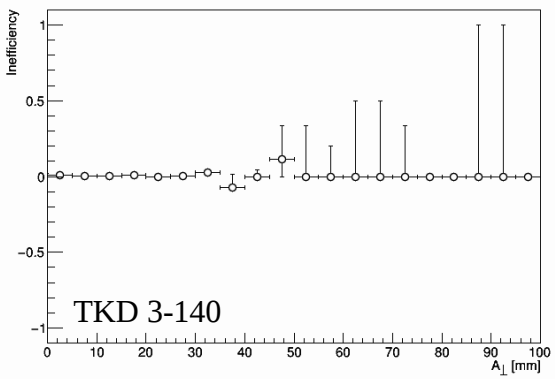


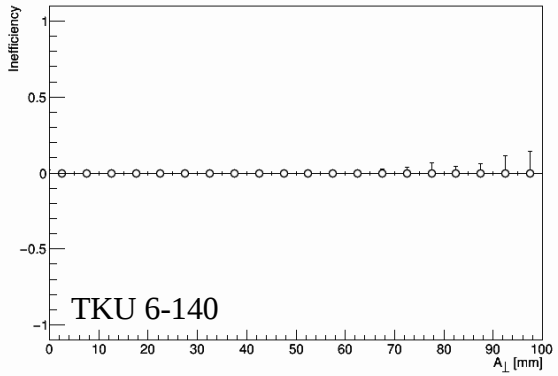


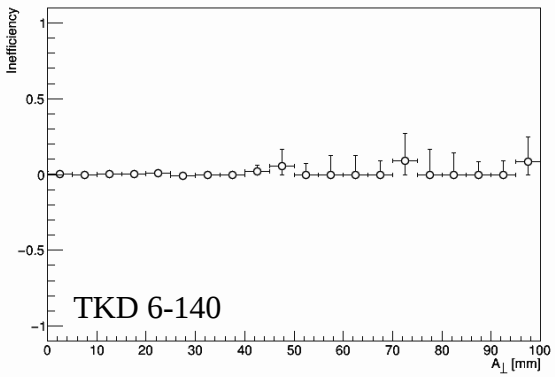
Why so much “pull” in high amplitude events?

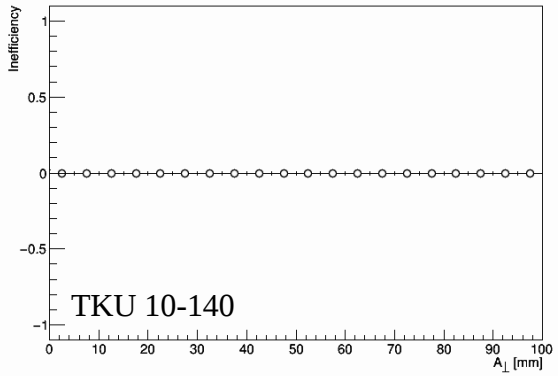
Inefficiency

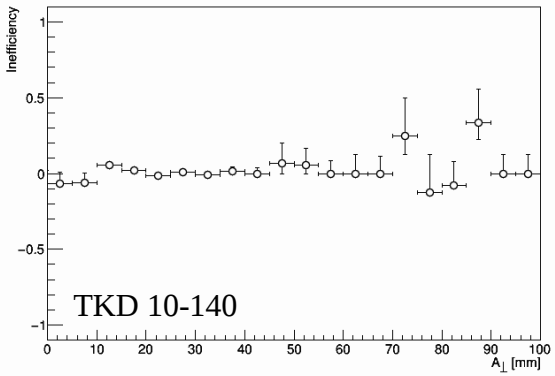
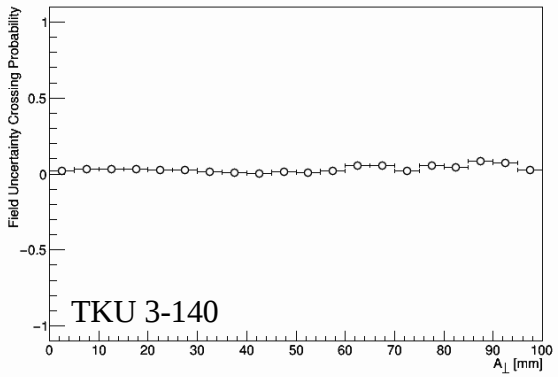
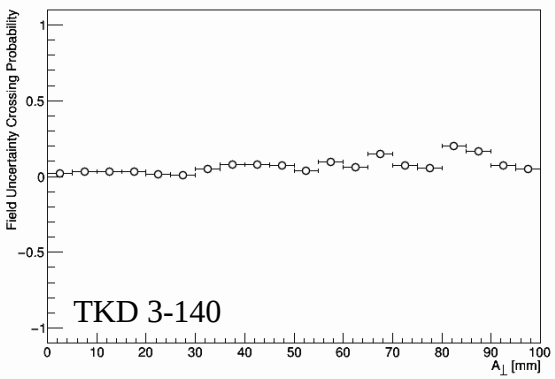
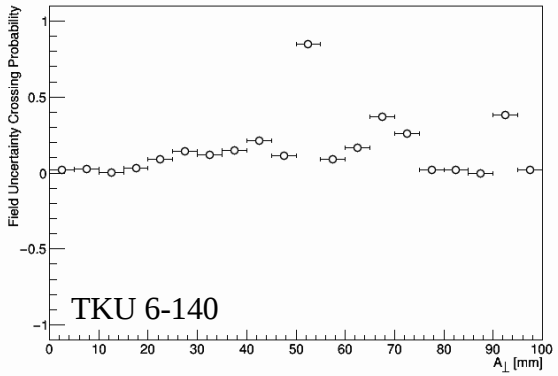
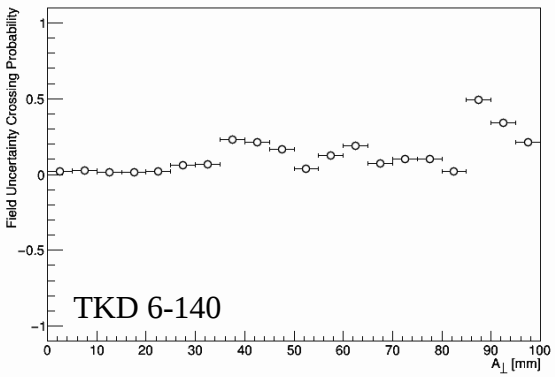
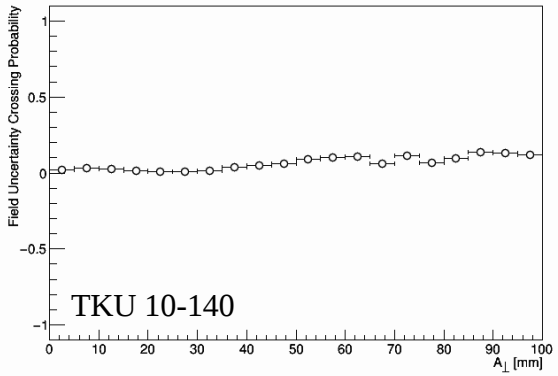
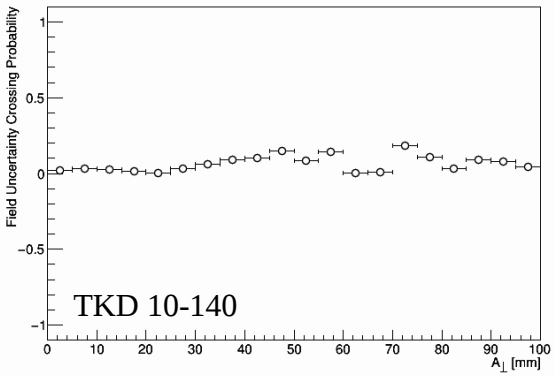












Field Uncertainty