Flip mode emittance analysis

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MICE VC

Overview

- Current status, most up to date results
- Outstanding issues
  - Data vs MC disagreement
  - Momentum reconstruction
- Next steps

Emittance change

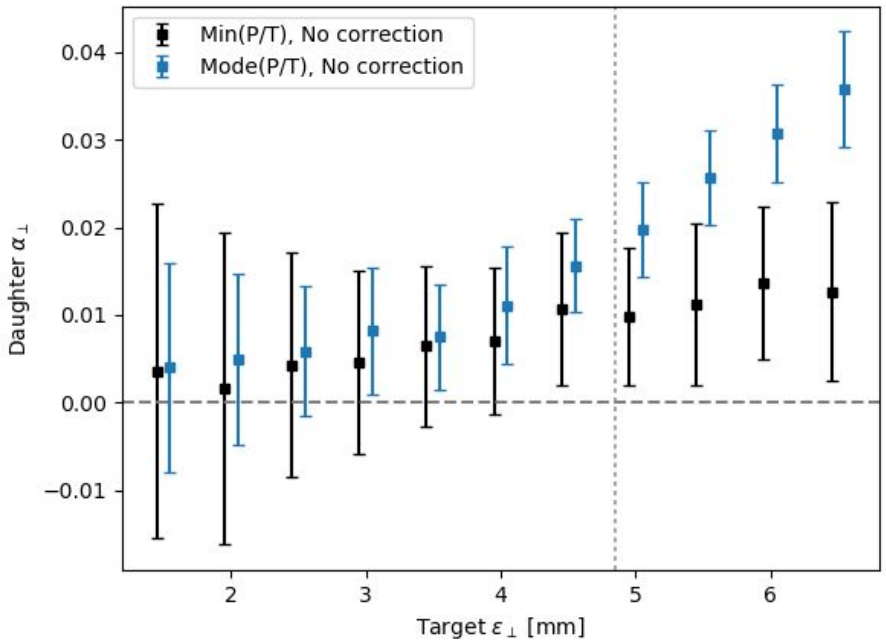
- The main focus of the analysis is to measure the transverse emittance change of beams passing through the LH2 and LiH absorbers for a range of input emittances, momenta and optics configurations ($\beta_\perp$ at the absorber)
- Used the 6mm - 140 MeV dataset while refining the analysis chain
- Study of all dataset available due soon
- Analysis chain:

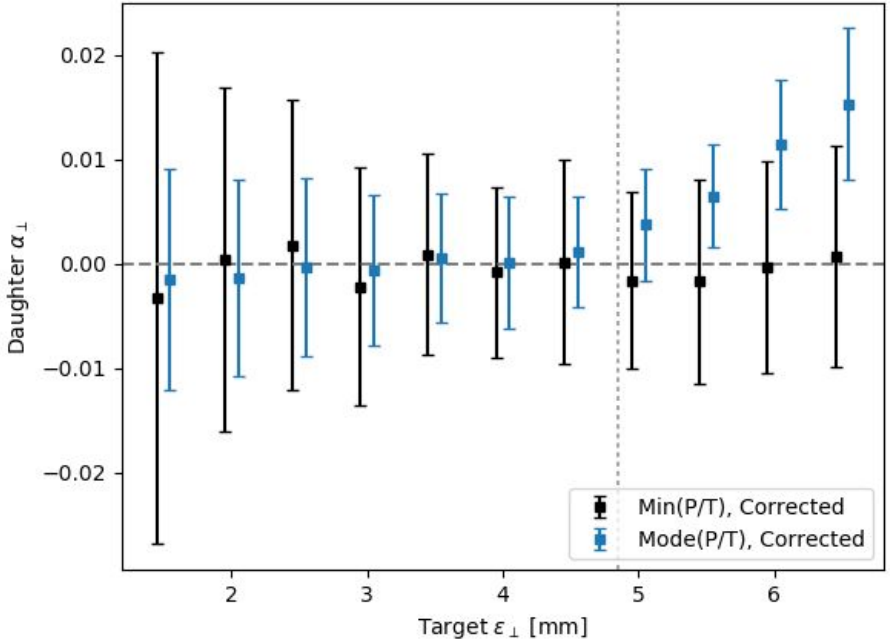
  Data / MC -> Cuts -> Parent sample -> Beam selection -> Emittance change calculation (applied to the improved optics sampled beams)

Beam selection

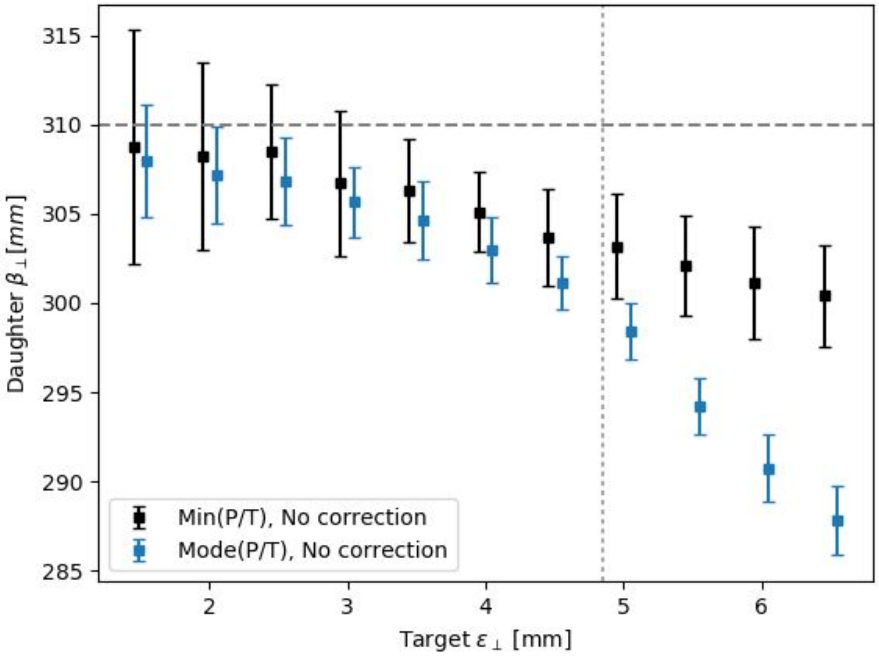
- Beam optics oscillates in the upstream tracker -> optics matching would reduce the betatron function at the absorber, improving the cooling measurement
- A beam selection algorithm based on rejection sampling is used to obtain beams with matched optics in TKU
- Recent efforts were dedicated towards improving the algorithm -> improved matching performance and (potentially) improved statistics in the sampled beams

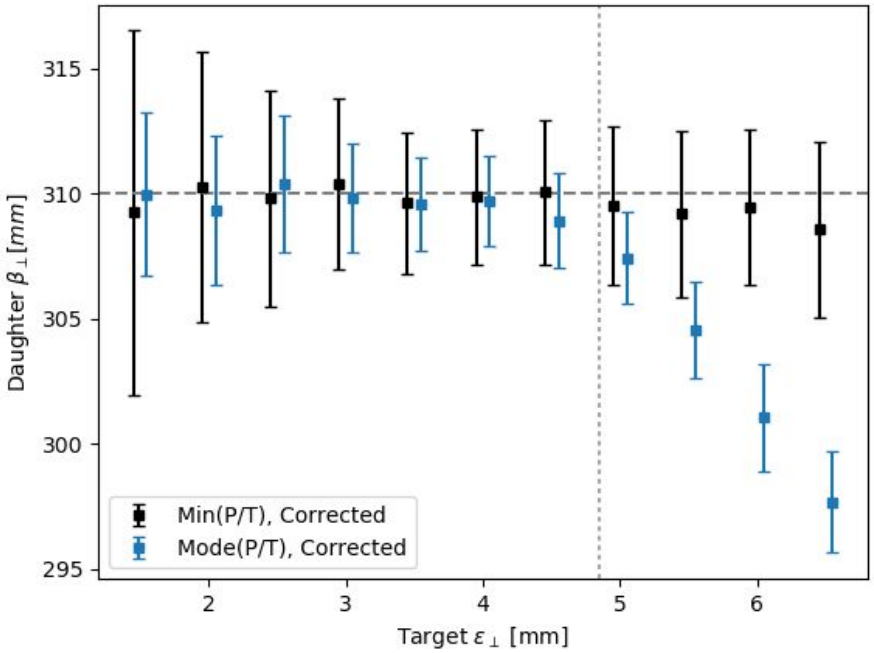
Matching: Alpha





Matching: Beta





Optics matching

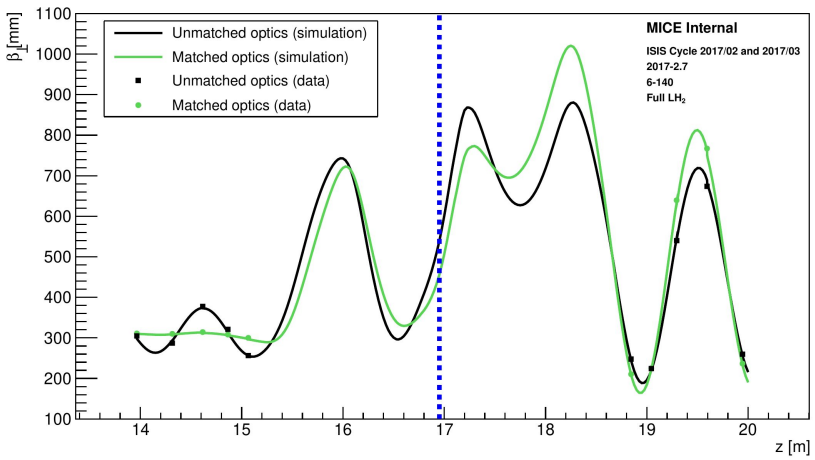
Black - parent beam optics (4.8 mm)

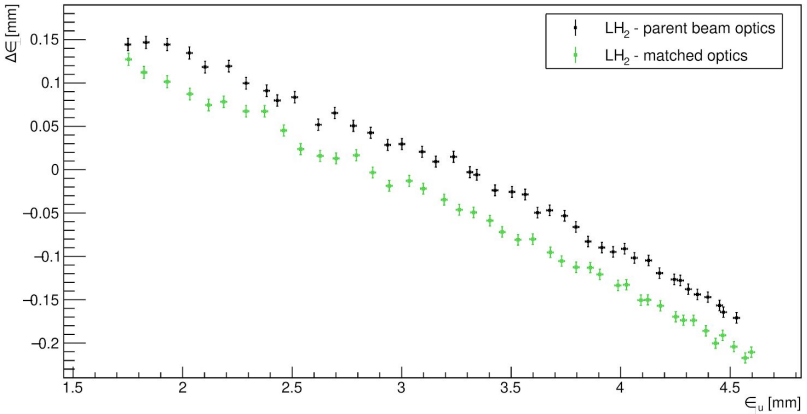
Green - sampled beam optics (4 mm)

Beta at absorber reduced from ~540 mm to ~ 450 mm (~17% reduction)

Results in an enhanced cooling effect, seen in the bottom plot

Bottom plot - absolute emittance change across the absorber for beams sampled from 6-140 LH2 data . More cooling observed in beams that have matched optics than for beams that keep the optics of the parent sample





Emittance change calculation

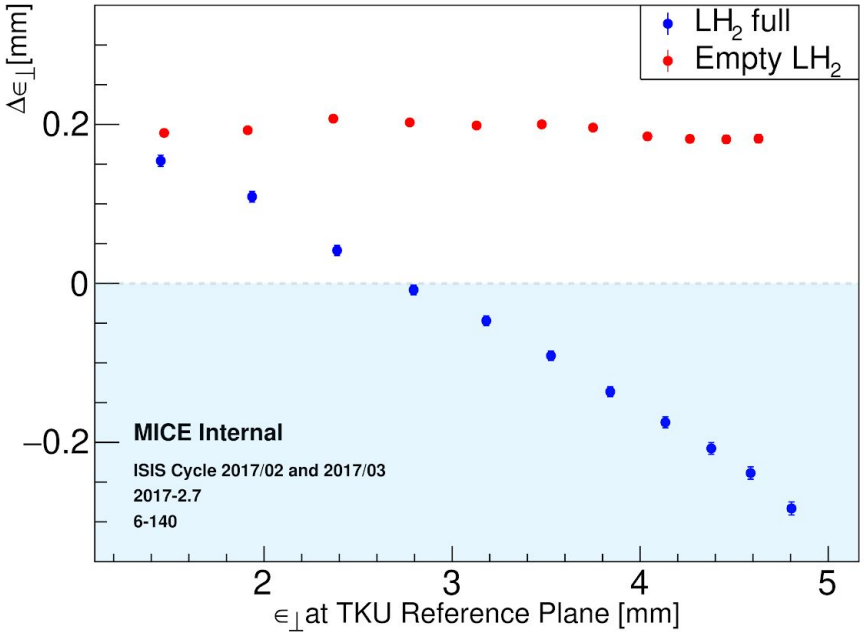
1) $\Delta\epsilon_\perp = \epsilon_d - \epsilon_u$ or $\Delta\epsilon_{\perp rel} = (\epsilon_d - \epsilon_u)/\epsilon_u$

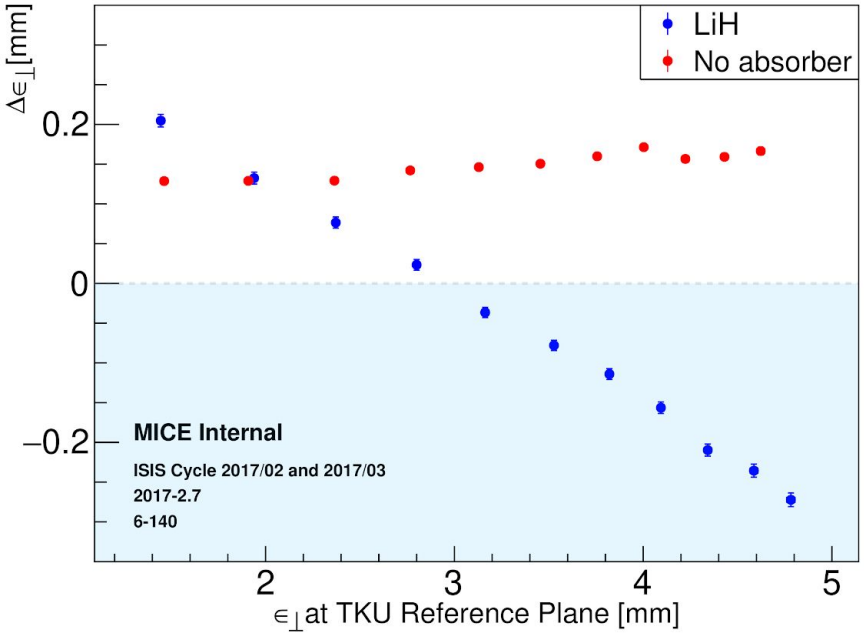
2) Amplitude migration at the core of the beam can also be used to estimate the emittance change. The ratio of the upstream and downstream emittances can be calculated from the ratio of upstream and downstream numbers of particles in the smallest amplitude bin (core), as shown below. (low statistics and efficiency in the core bin)

$$\lim_{A_\perp \to 0} \frac{f^d(A_\perp)}{f^u(A_\perp)} = \left(\frac{\varepsilon_\perp^u}{\varepsilon_\perp^d}\right)^2$$

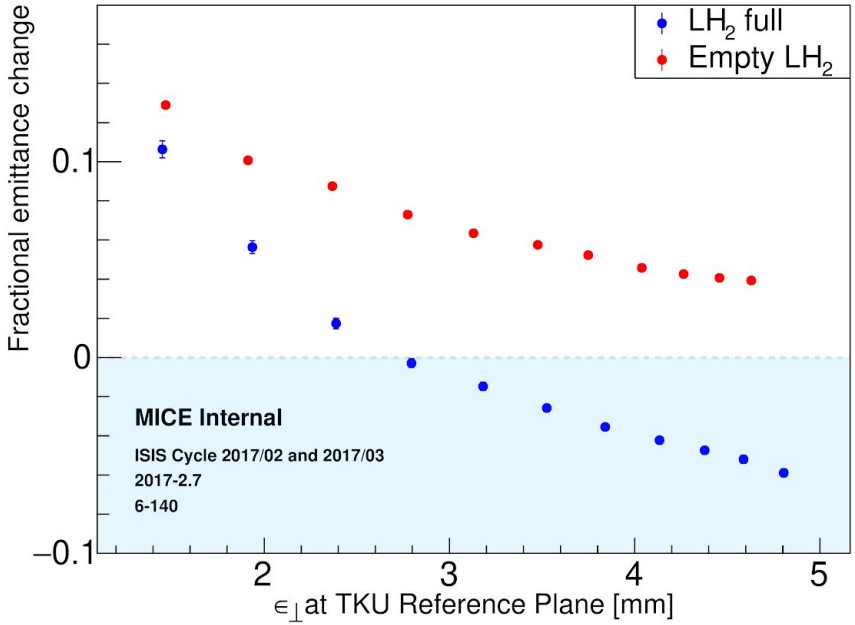
Results shown here using the **first** method.

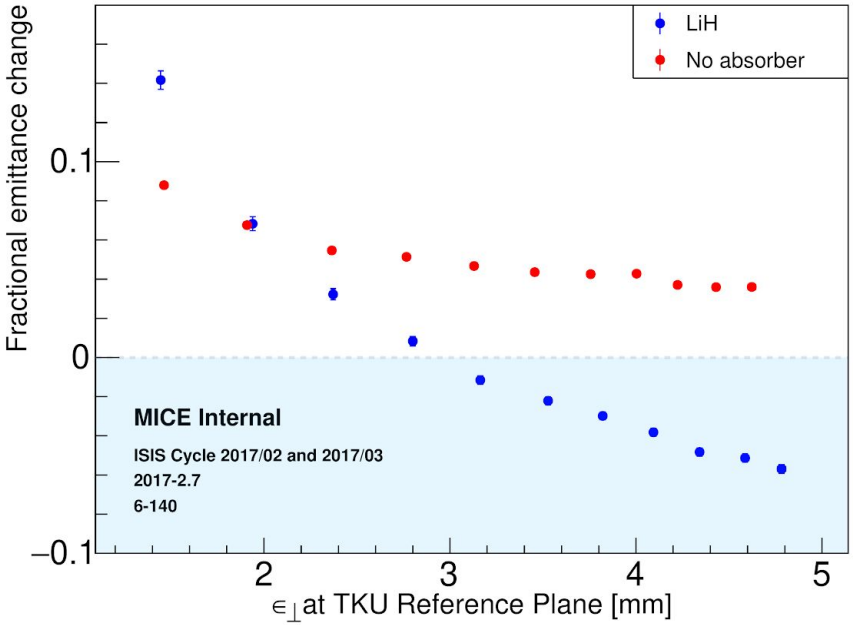
Absolute emittance change



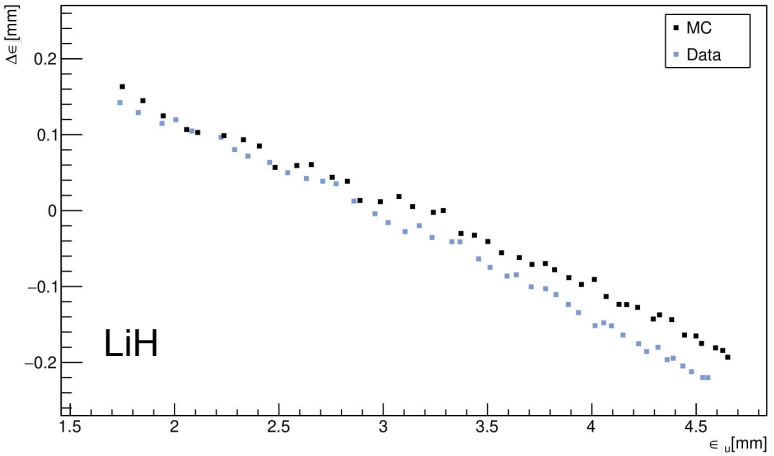


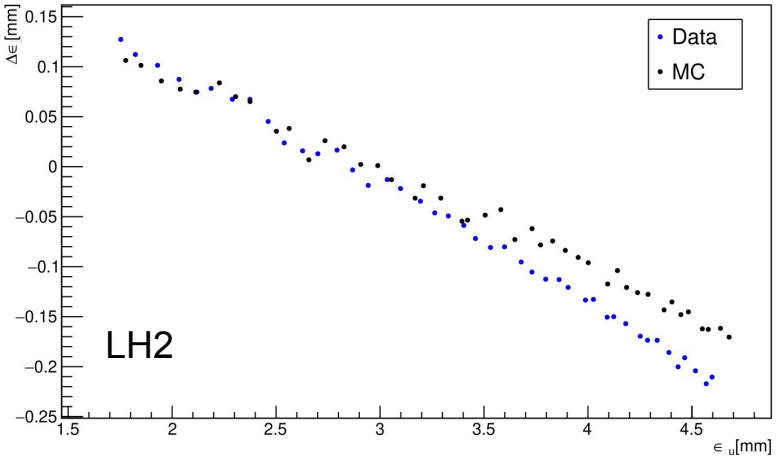
Fractional emittance change

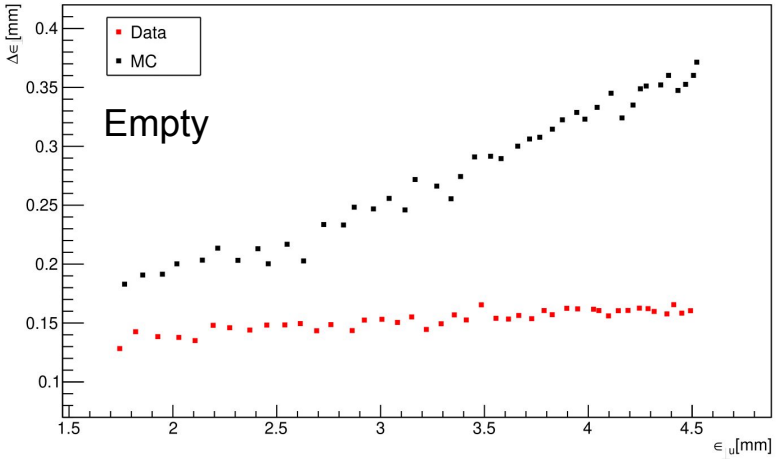


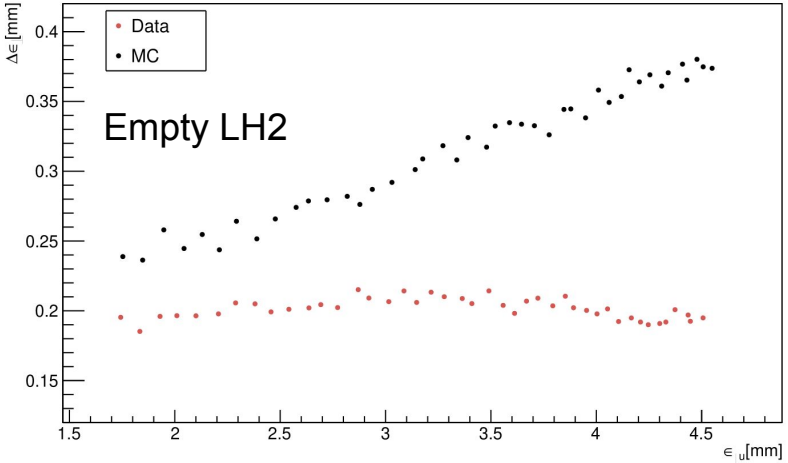


Data vs MC comparison



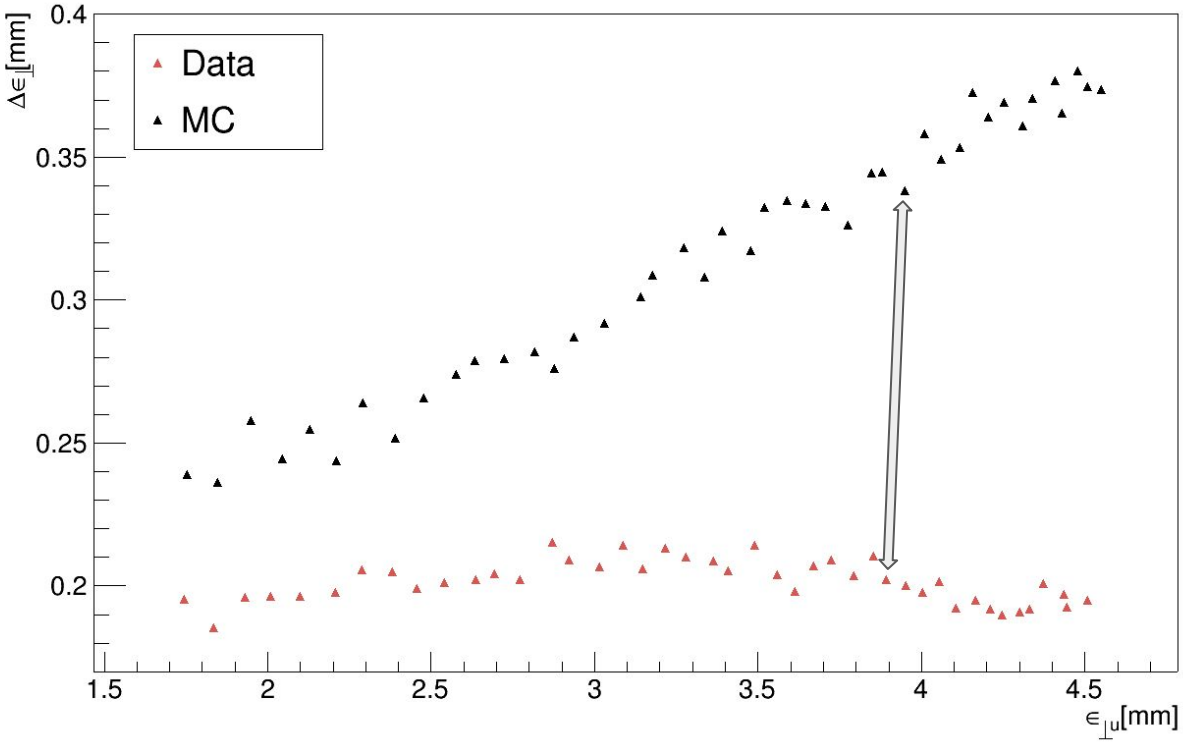






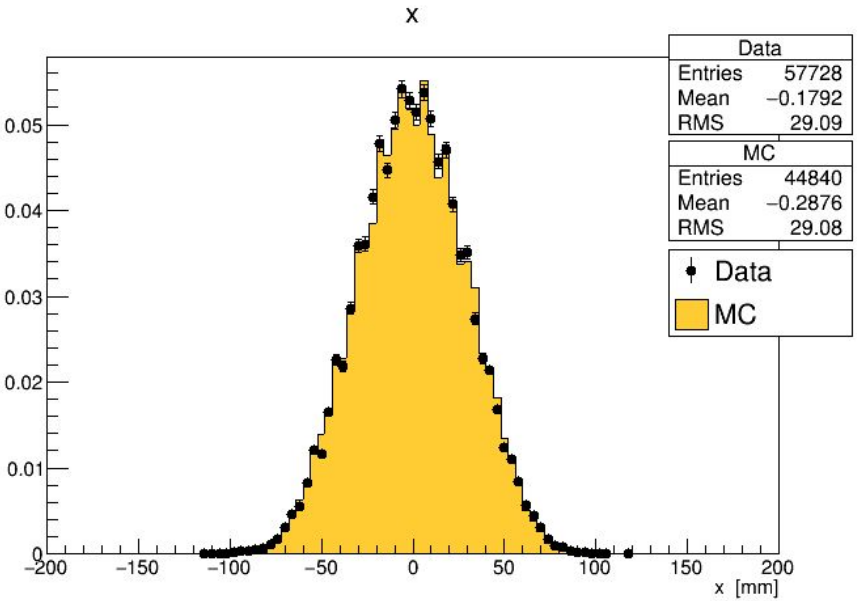
Empty LH2: Sampled beam phase space

- look at a pair of Data/MC sampled beams with the same target parameters
- the target sampling parameters are [ϵ=4.6 mm, β = 310 mm, α = 0, L = 1.1]
- next slides show the sampled (daughter) beam phase-space at the two reference planes

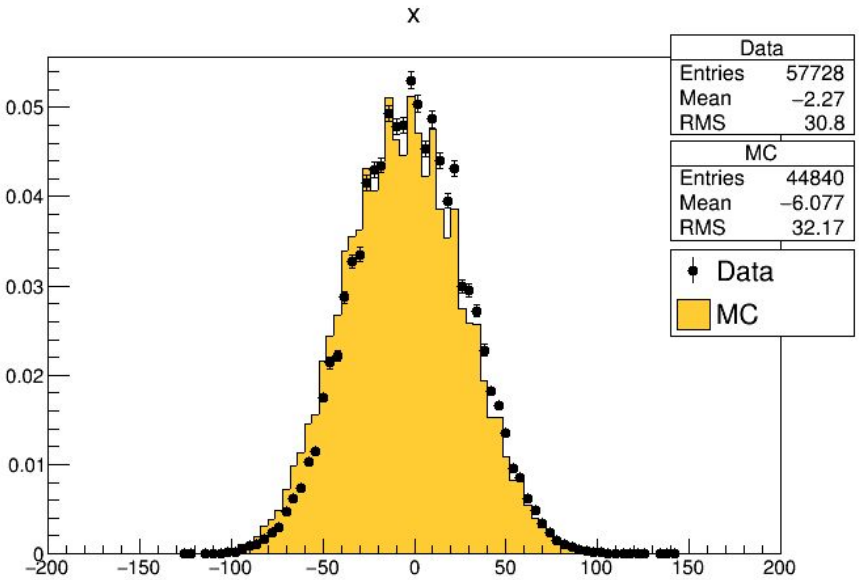


Beam Position: X

Upstream



Downstream



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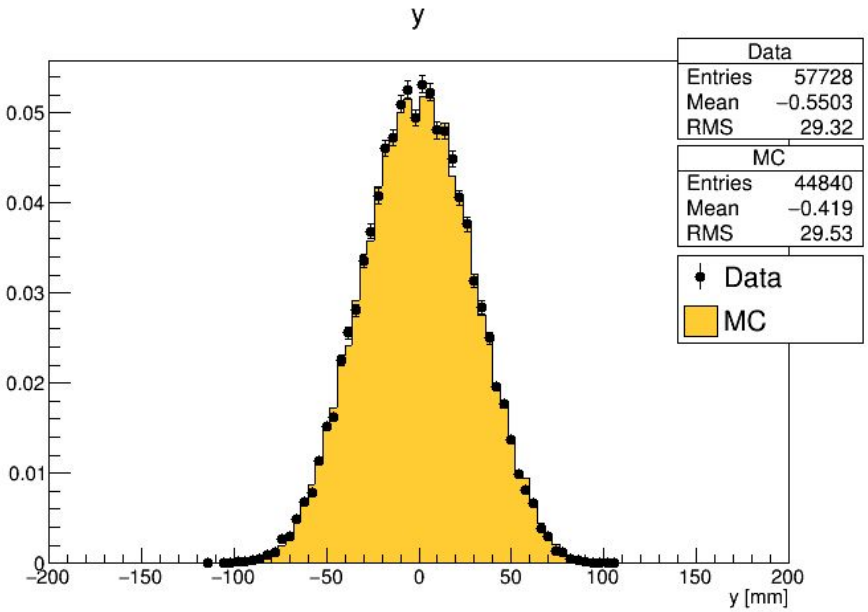
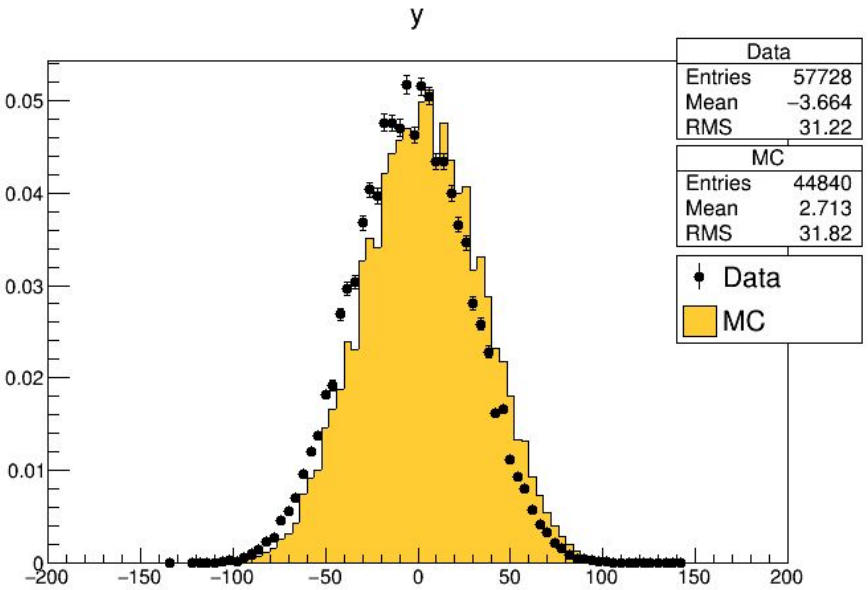
Beam Position: Y

Upstream

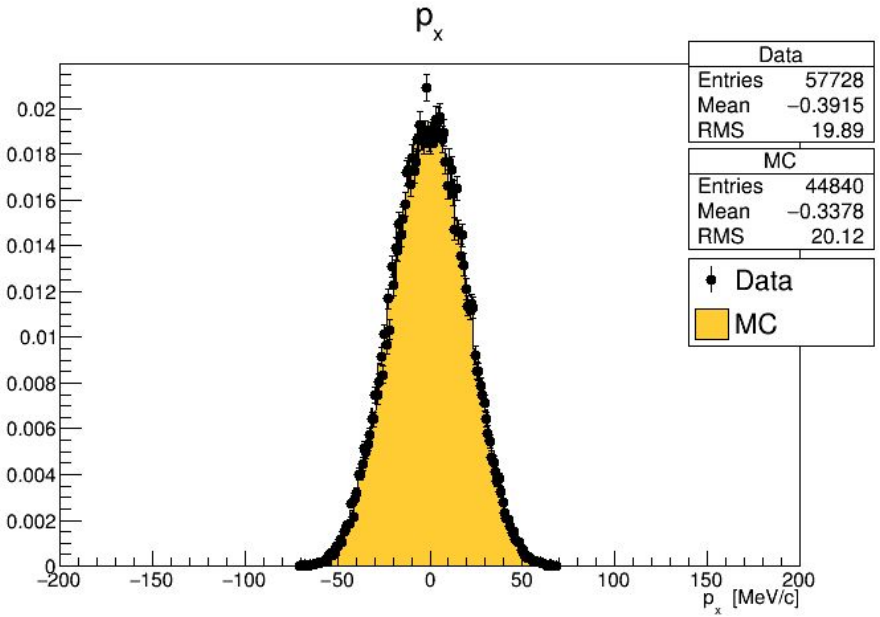


Downstream

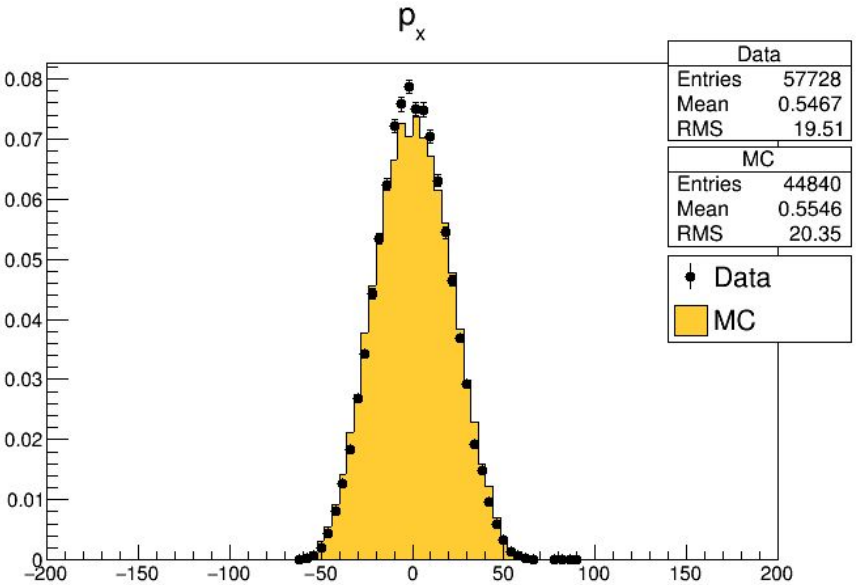


Beam Momentum: P_x

Upstream

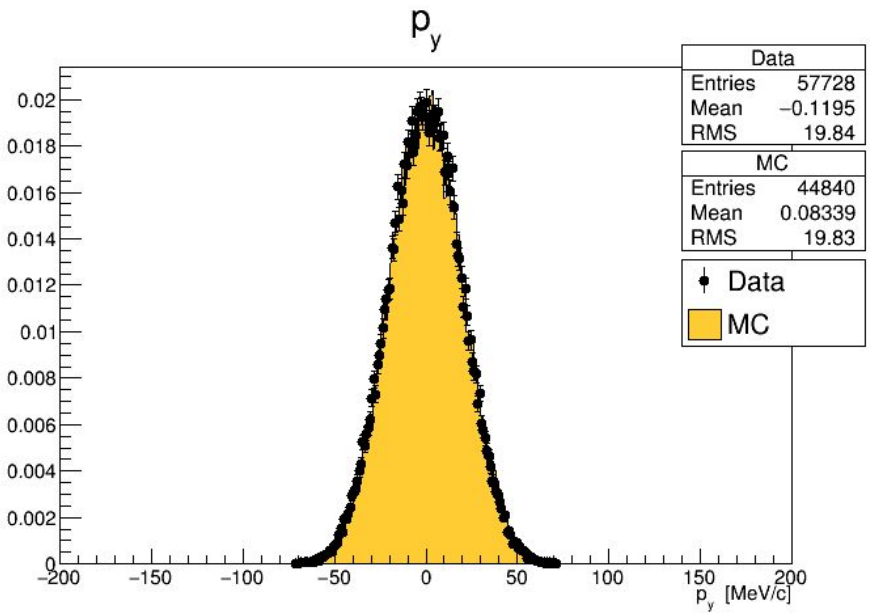


Downstream



Beam Momentum: P_y

Upstream



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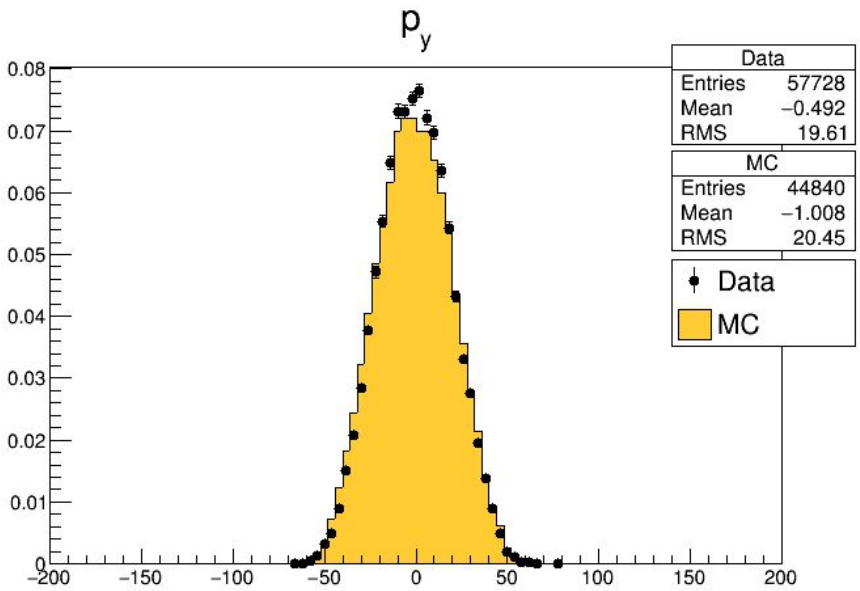
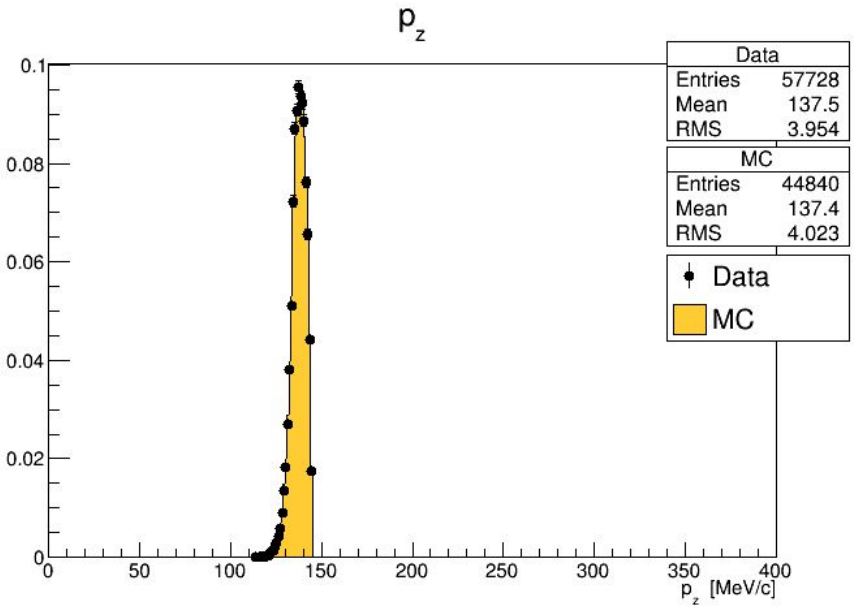
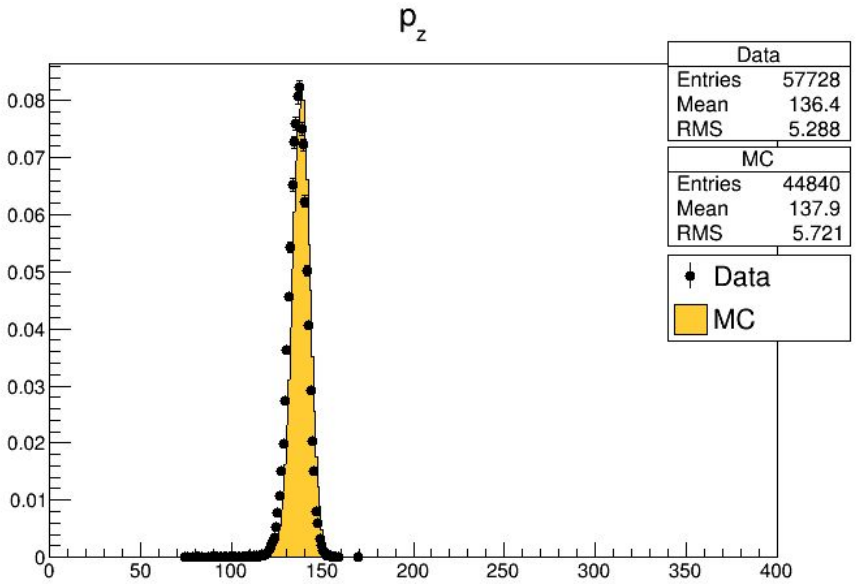


Beam Momentum: P_z

Upstream

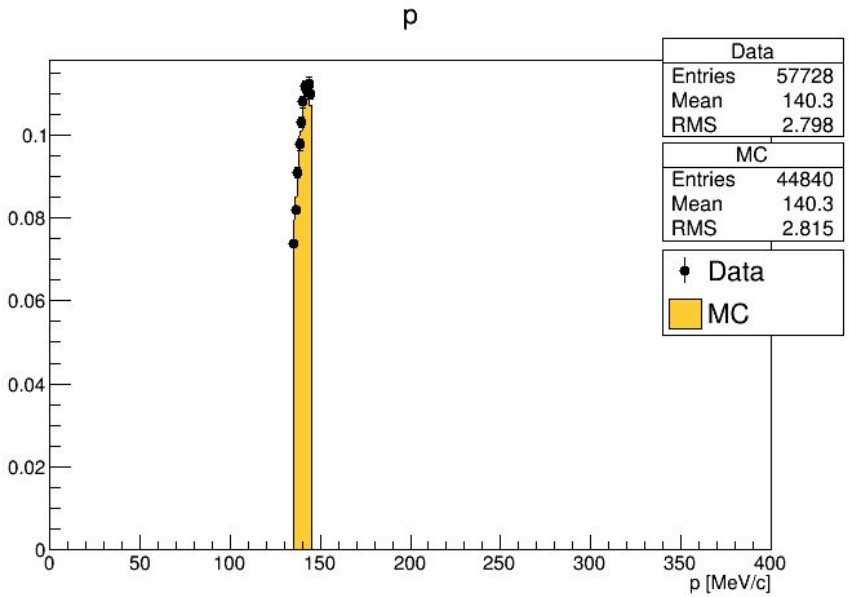


Downstream

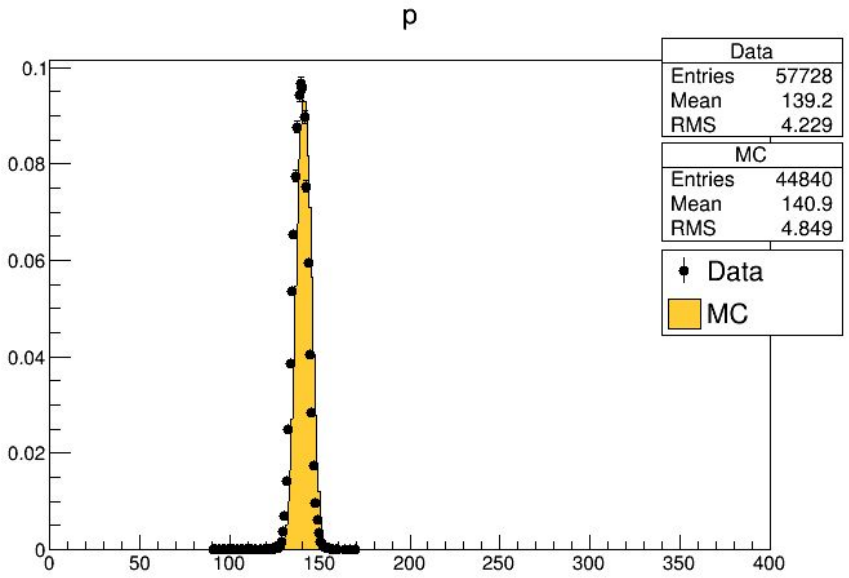


Beam Momentum: P

Upstream



Downstream



Data / MC disagreement

Good agreement upstream given by the sampling routines!

However, downstream:

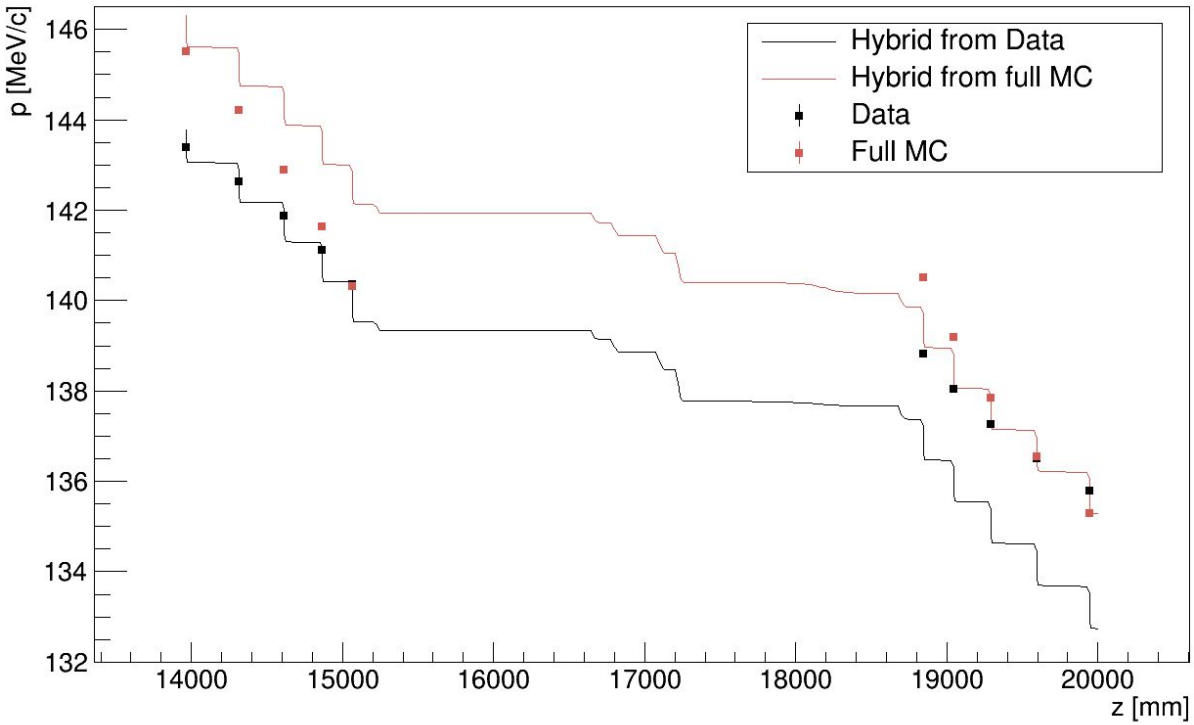
1) Wider distributions seen in MC
2) x,y centroid discrepancies -> misalignment (AFC, TKD)
3) Higher momentum in reco MC than in reco data

Momentum

LH2 empty - parent beams

Disagreements:

1) Energy loss at tracker stations (Reco Data vs Reco MC, also Reco vs Truth)
2) TKD ref plane Reco: higher in MC than Data, seen in all 4 analyses; also Reco higher than Truth
3) Potential energy loss mismodelling at the absorber module?



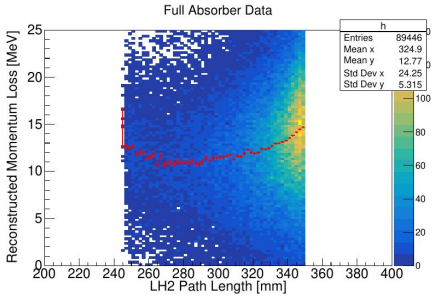
Initial digging

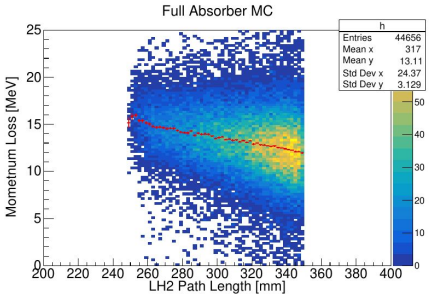
Trackers, C. Hunt thesis:

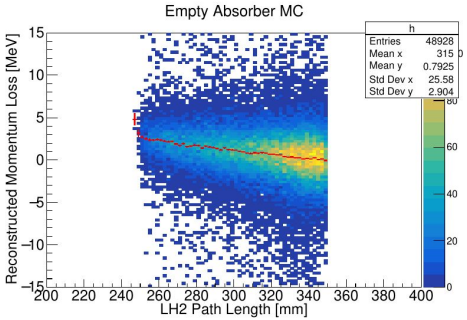
a) Pattern recognition -> momentum reconstruction bias. Bias depends on the beam momentum, bias increases with decreasing momentum (at 145 MeV/c, -0.4 MeV/c in TKU & +1.0 MeV/c in TKD). Corrected for using a simplistic linear fit. This should affect both Data and MC Reco in the same manner?

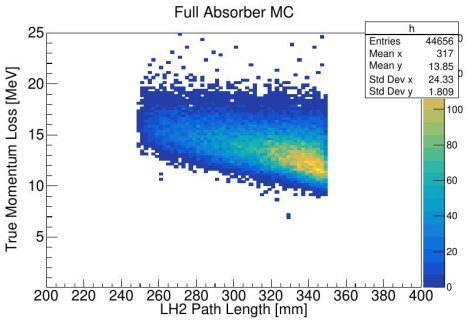
b) “known discrepancies between material model in the reconstruction, MC model and the true geometry -> systematic mis-estimate of energy loss / plane”. No results or further specifics to back up this statement found yet

Energy loss at the absorber, S. Wilbur: wrong momentum loss vs path length correlation in MC truth; no final conclusion/fix found so far for this issue









Job List

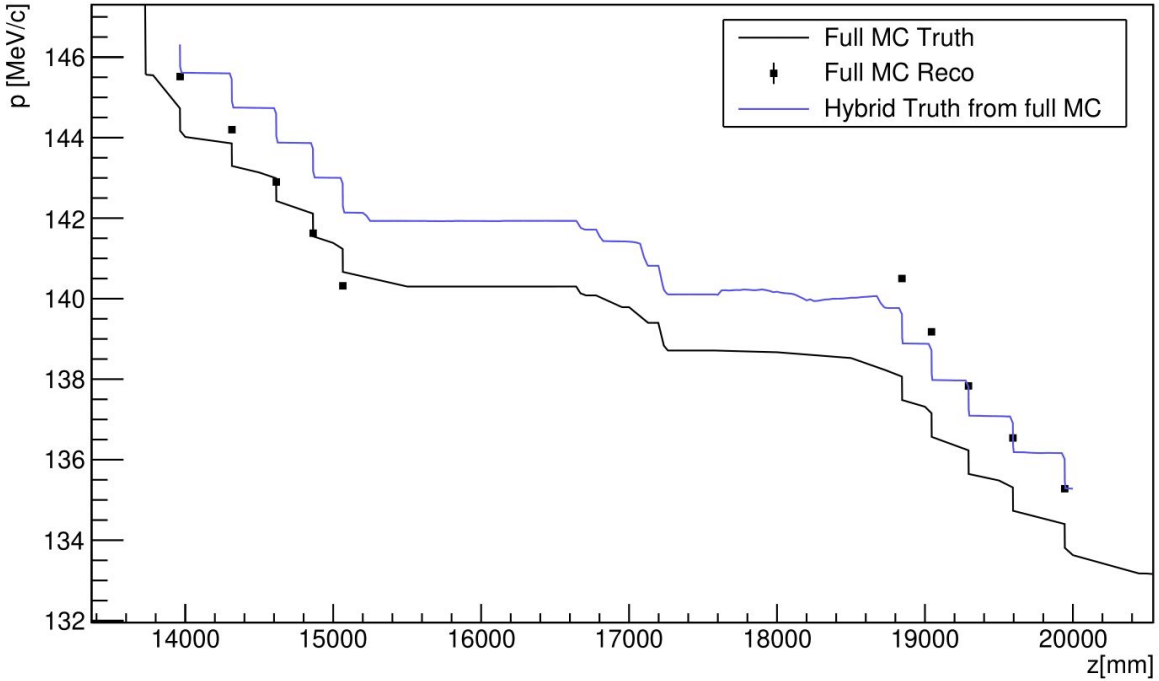
- DATA / MC disagreement
  - look into momentum reconstruction
  - absorber module energy loss
  - check for AFC, TKD misalignment
- Expansion to multiple data sets
  - use 4, 6, 10 mm data to sample beam with emittances in the [1,8] mm range
  - repeat for different momentum and cooling channel settings
- Systematics

Backup

Full MC: Momentum Update

Same momentum loss observed in Full MC Truth and Hybrid Truth -> geometry descriptions consistent between the two

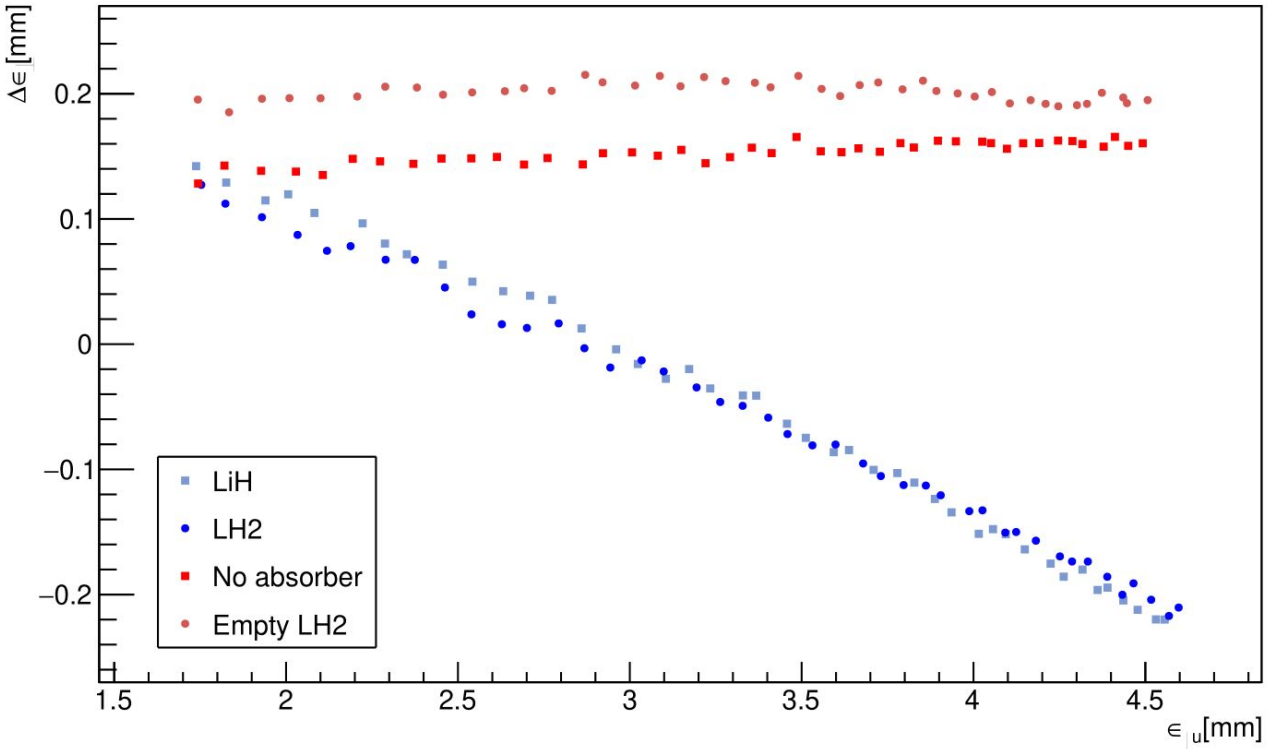
Biased reconstruction



Analysis update: Emittance change

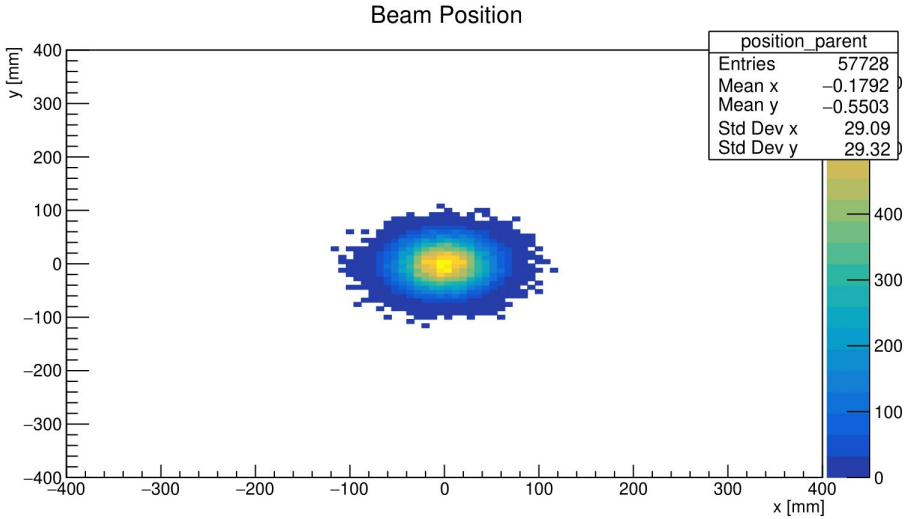
LiH analysis added

Data, 6 mm 140 MeV/c, flip mode parent beams

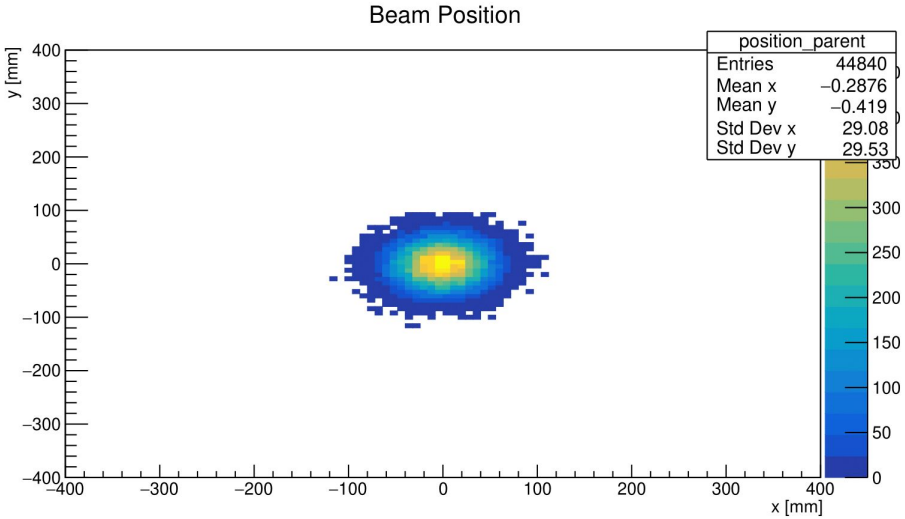


Beam Position Upstream

Data

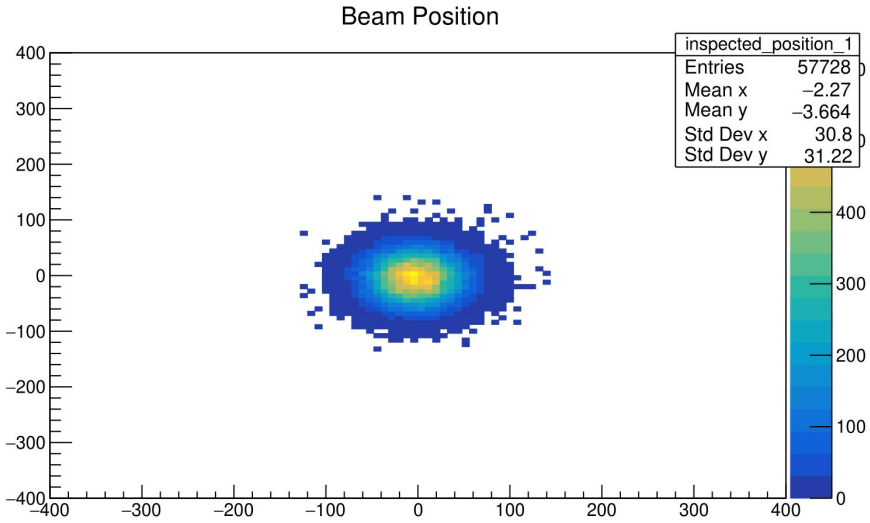


MC

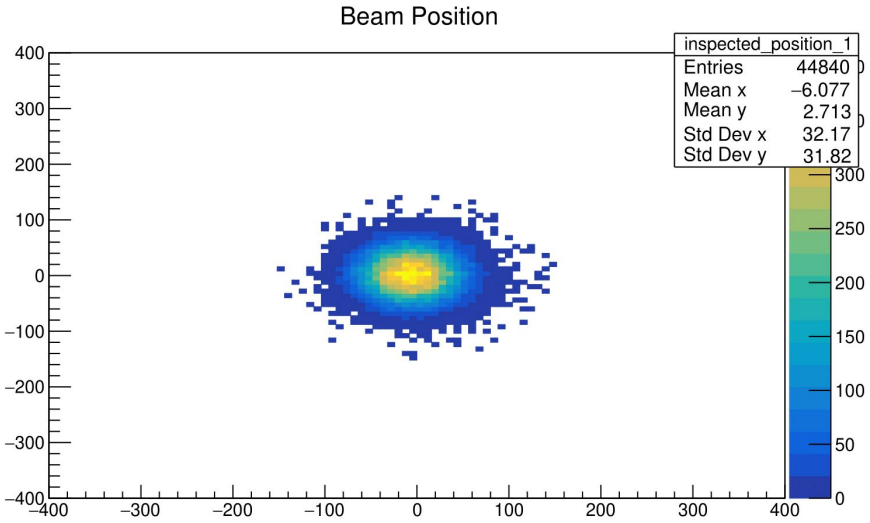


Beam Position Downstream

Data

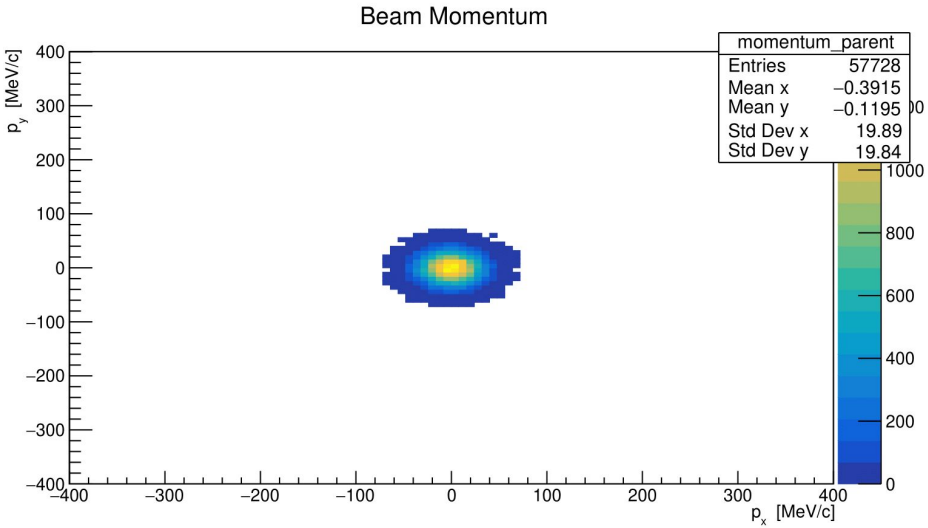


MC

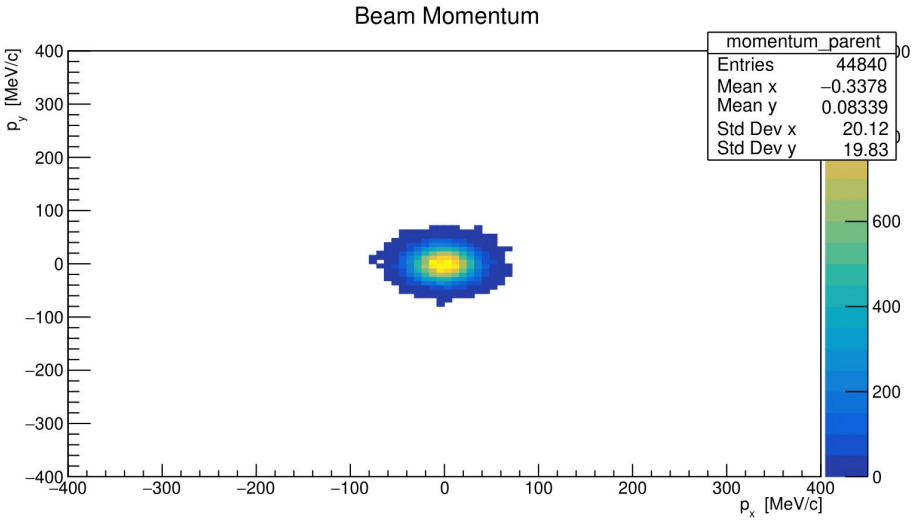


Beam Momentum Upstream

Data

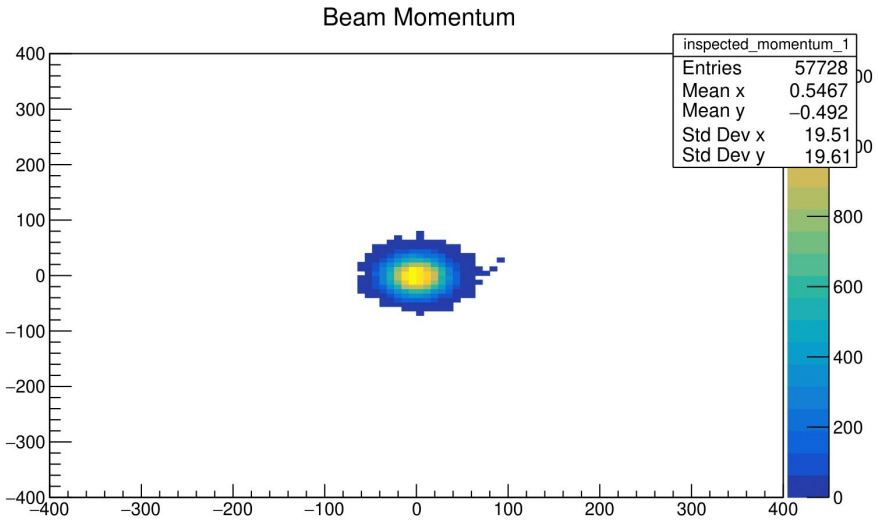


MC

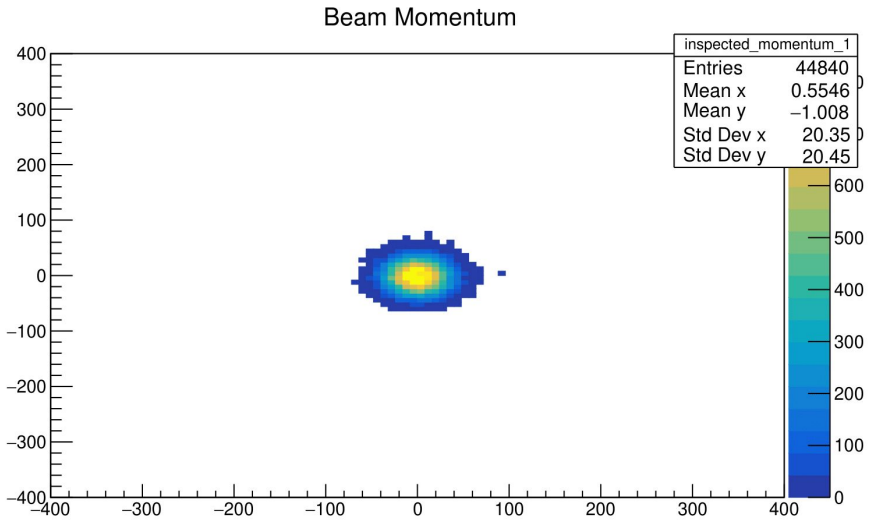


Beam Momentum Downstream

Data



MC



Data VC MC discrepancy

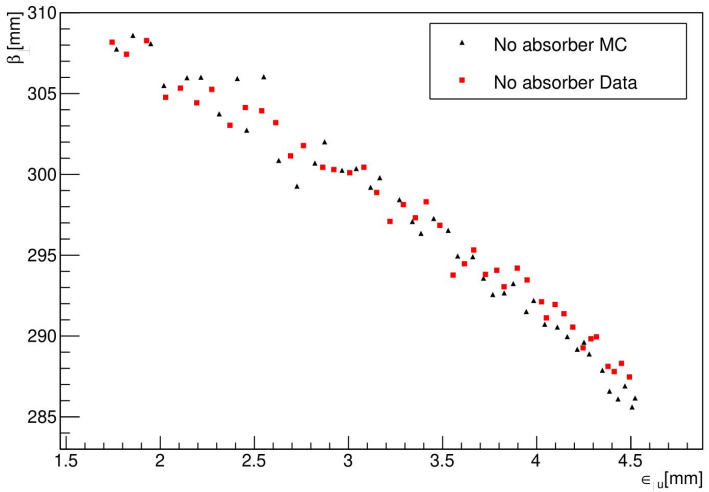
Currently, discrepancy between Data and MC parent beam optics.

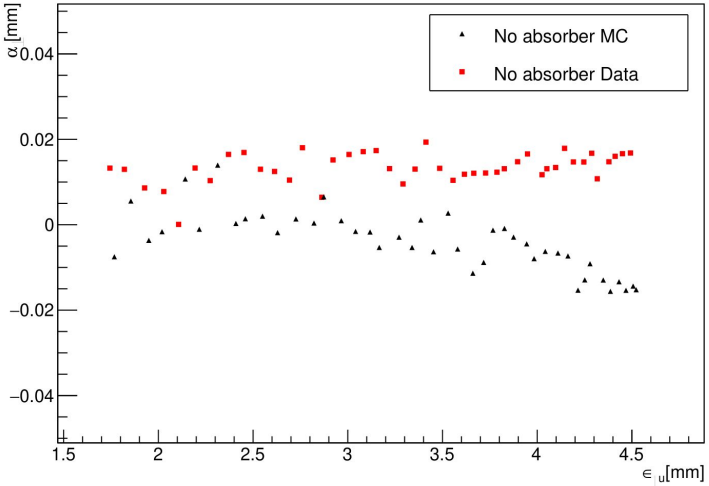
Beam sampling should theoretically allow us to (i) impose matched beam optics to all of the sampled beams and (ii) get rid of the optics discrepancy in the parent beams.

However, this is not the case: the closer the sampled beam emittance is to the parent beam emittance, the more the sampled beam β is pulled towards the parent beam β, away from the matched condition.

Also, the sampled beams α is overall biased by the parent beam α.

So if the Data and MC parent beam optics parameters are different, this discrepancy is carried over to the sampled beams to a certain extent.



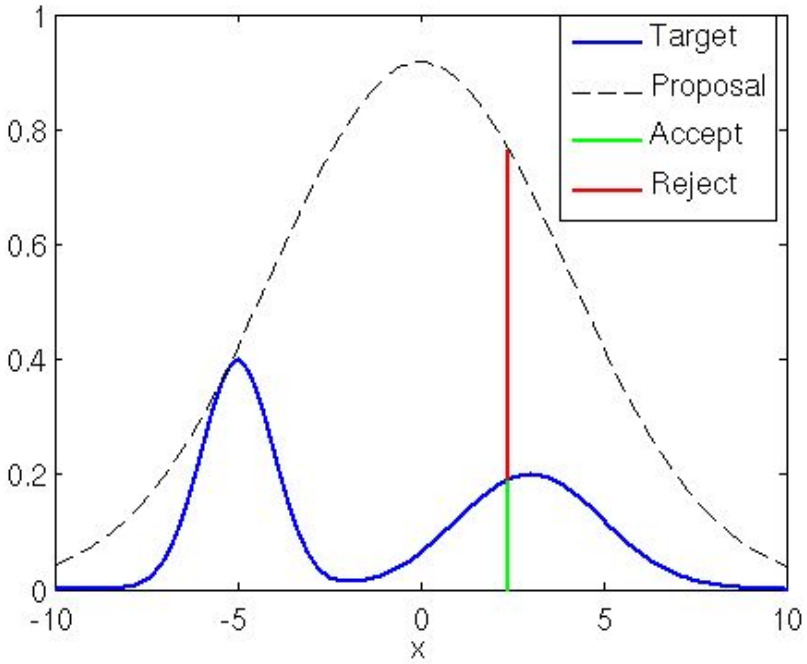


Possible mitigation

1. Have Data vs MC parent beam optics agreement. However, the sampled beams optics parameters would still deviate from the matched condition
2. Improve the sampling routine -> for each sampled beam retrieve the desired (matched) optics irrespective of the parent optics

Decided to look into the sampling routine as there was another outstanding issue that needed improvement - the number of particles in the sampled (daughter) beams was relatively low.

Rejection Sampling



- $P_{selection}(x) = Norm * Target(x) / Parent(x)$
- Draw u from $U[0,1]$. If $u < P_{selection}(x)$ then accept event. Otherwise reject it.
- Normalisation calculation:
  - draw samples from the parent beam and take the minimum of *Parent (x) / Target (x)*
  - Normalisation ensures that $P_{selection}(x) <= 1$
  - **# of particles in the daugher beam ~ Norm** (currently rejection rate relatively high - can we improve?)

Normalisation: Event likelihoods

Draw an particle from the parent distribution.

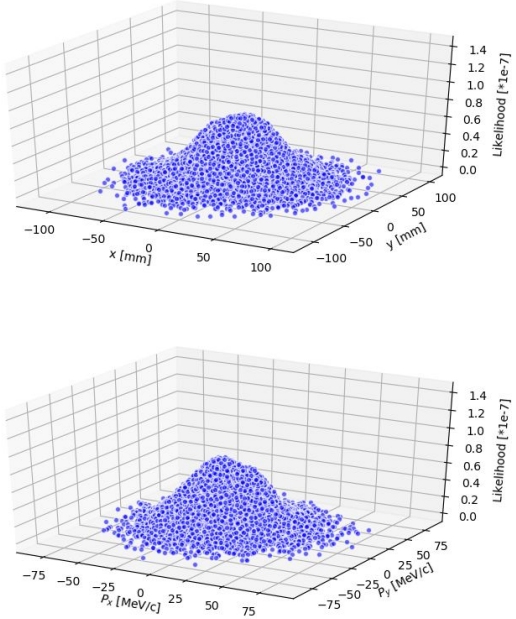
Calculate its likelihood of being sampled from the parent (KDE) and target (analytical 4D Gaussian) PDFs.

Here, likelihoods projected on the (x,y) and (p_x, p_y) subspaces.

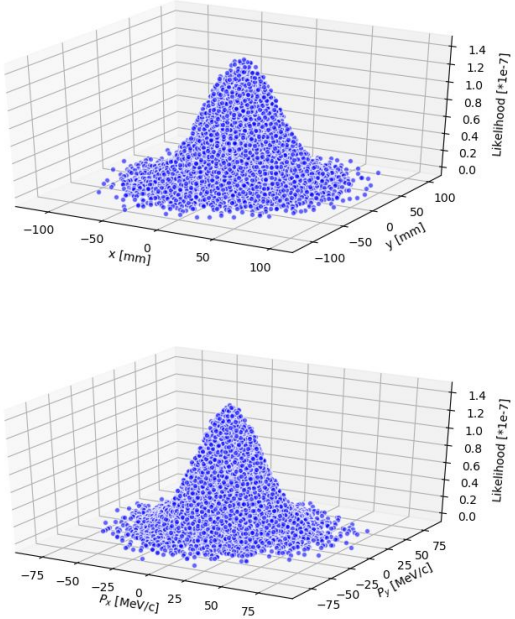
Beam parameters:

- Parent: [ϵ=4.85 mm, β = 282 mm, α = 0.045, L = 1.1]
- Target: [ϵ=4 mm, β = 310 mm, α = 0, L = 1.1]

Parent (KDE)



Target (4D Gaussian)



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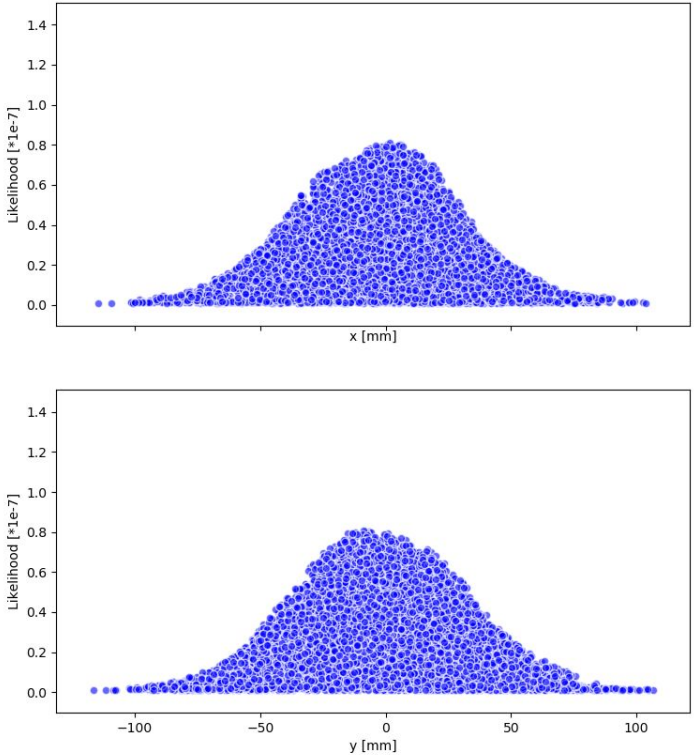
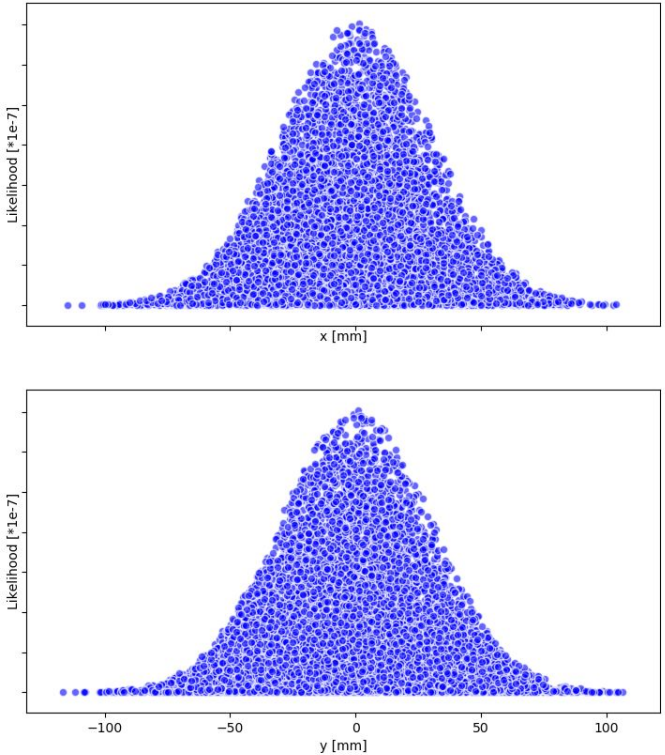
Event likelihood: 1D projections (position space)

Parent (KDE)



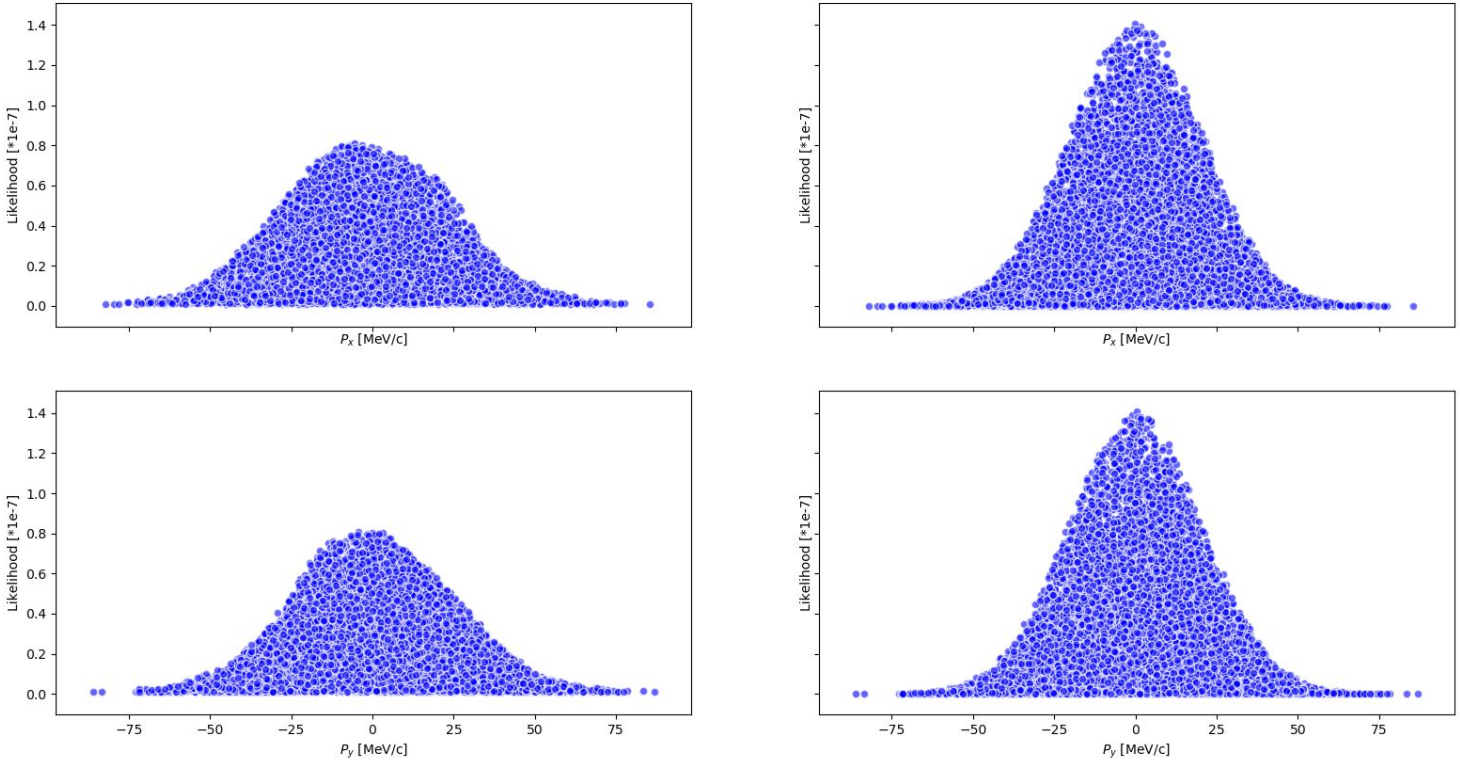
Target (4D Gaussian)



Event likelihood: 1D projections (momentum space)

Parent (KDE)

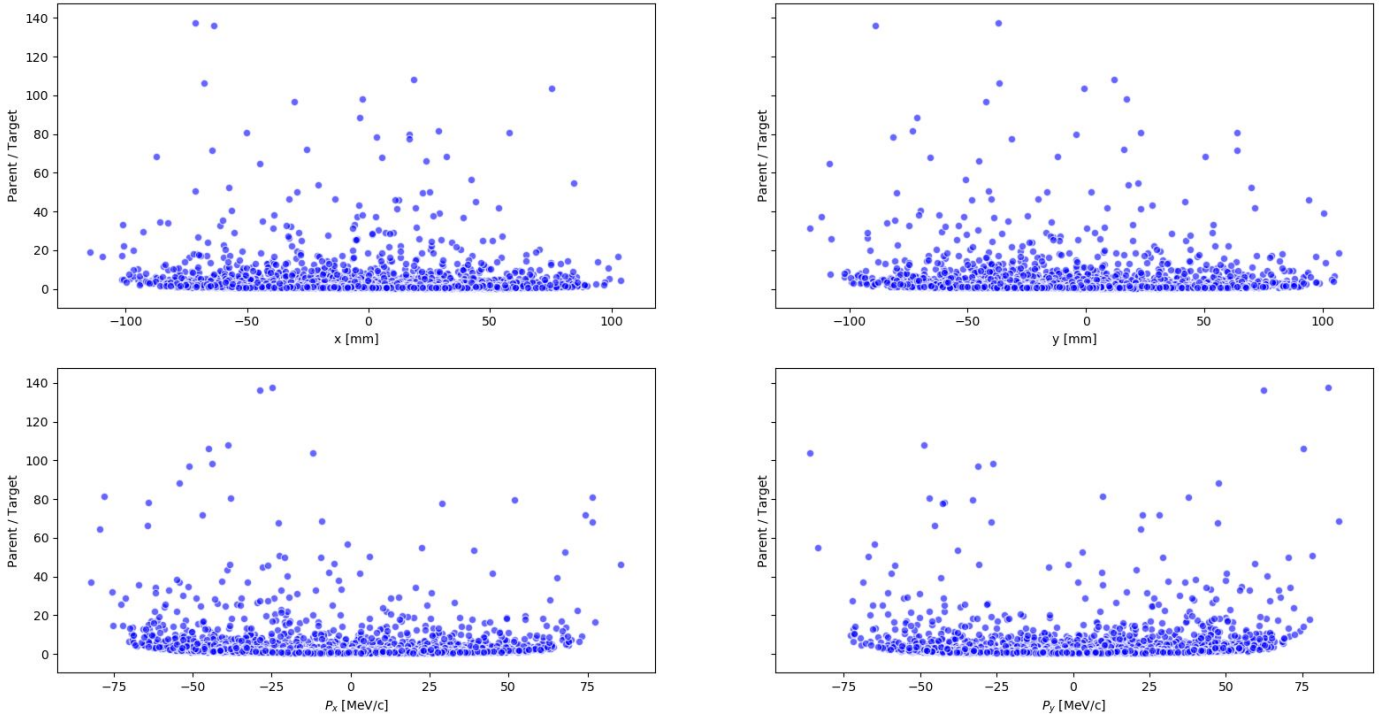
Target (4D Gaussian)



Parent (x) / Target (x)

Ratio of likelihoods projected on the 4D phase-space components.

Current procedure takes the normalisation as the minimum of these ratios.

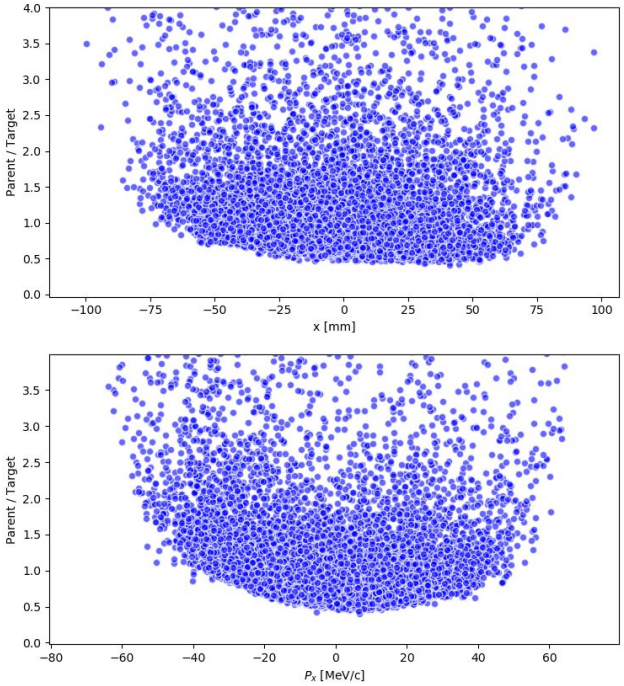


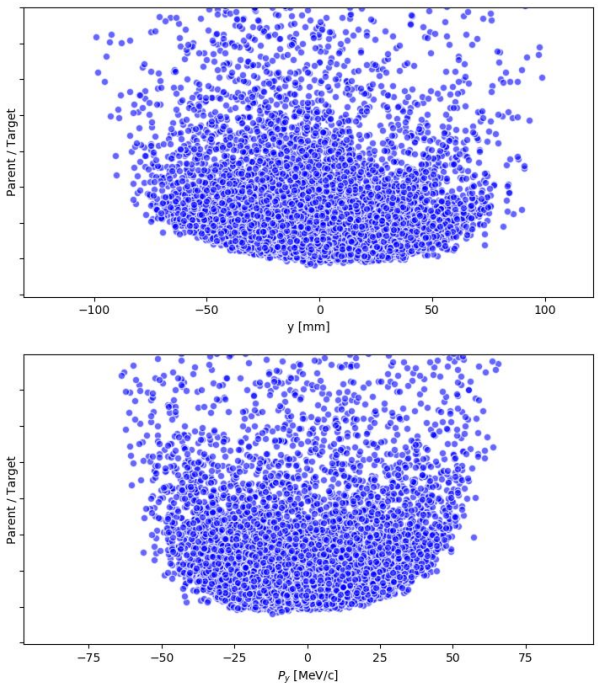
Rejection Sampling Normalisation - Parent (x) / Target (x)

The higher likelihood of particles coming from the target distribution leads to N < 1. In this case N ~ 0.5.

Tails seem not to impact the N estimation for this combination of parent and target parameters.

Seek to change the N estimation method such that more particles are accepted into the daughter beam, without significantly impacting the selection performance.

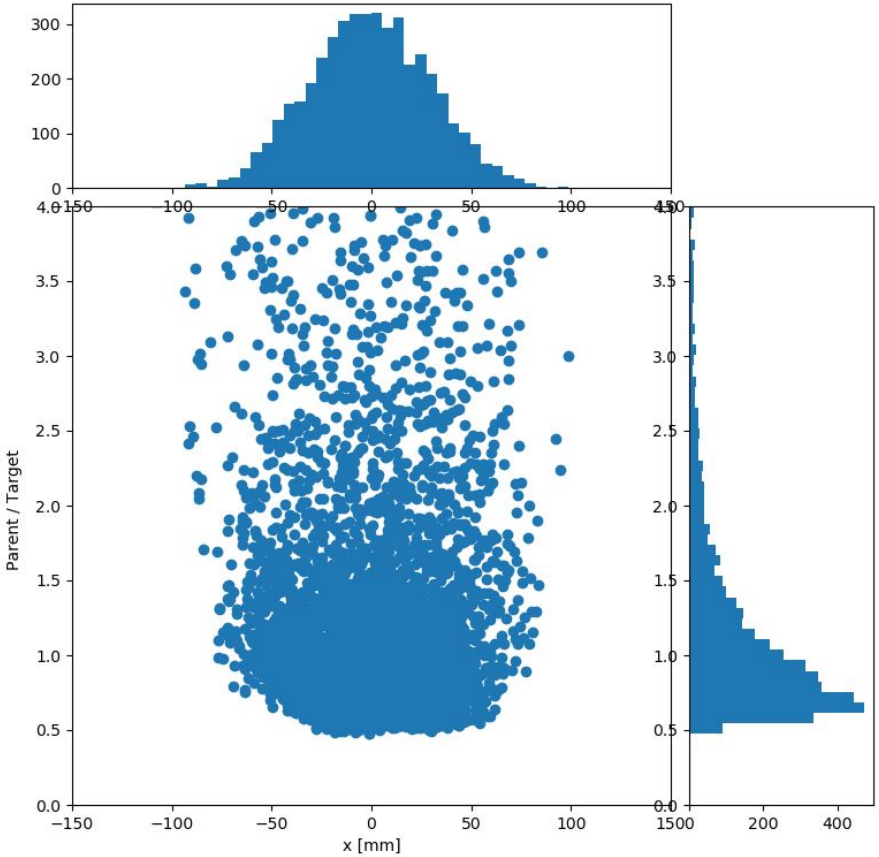




Mode?

Choose N as the *most probable value* of Parent(x) / Target(x) distribution, rather than the minimum.

Study the improvement in the number of particles accepted in the daughter beams and the impact on the daughter beam parameters.



Normalisation: Toy study

Generate toy parent beams (10k particles) with a specific set of parameters: [ϵ=4.85 mm, β = 282 mm, α = 0.045, L = 1.1]

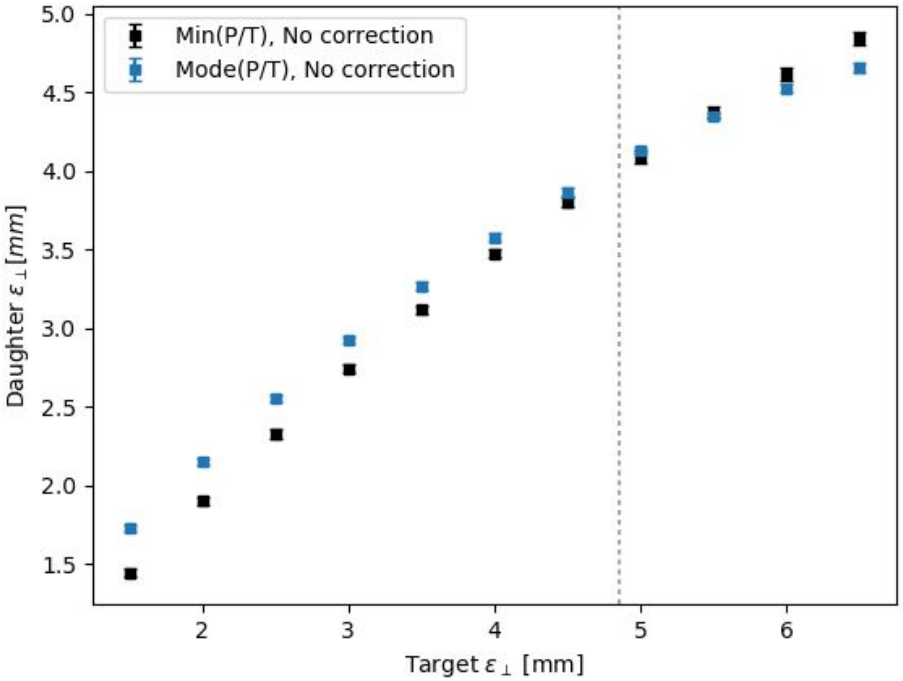
Target parameters: [ϵ= [1.5 - 6.5; 0.5] mm, β = 310 mm, α = 0.0, L = 1.1]

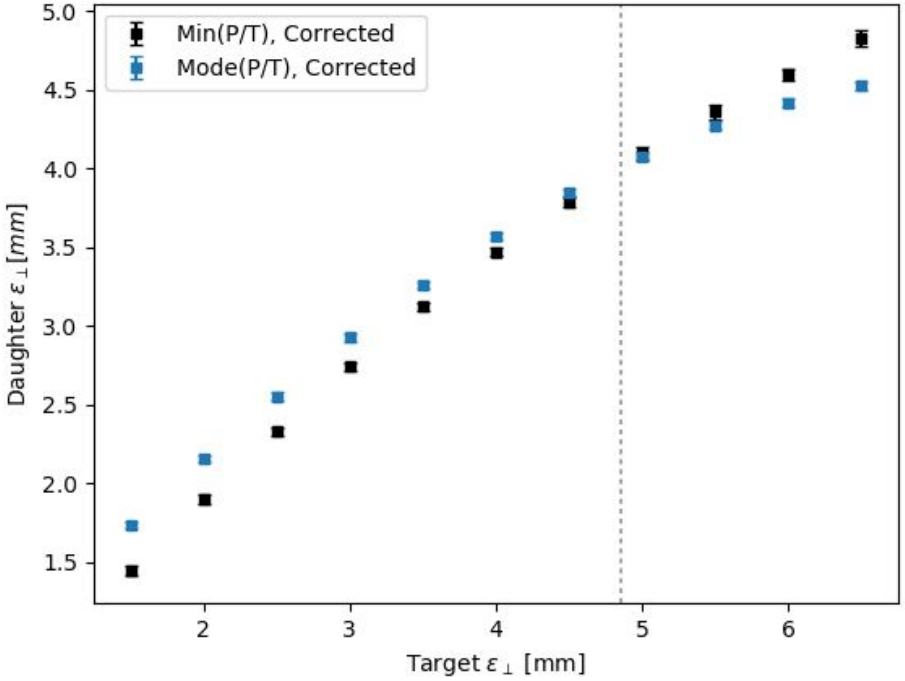
For each combination of parent and target parameters, repeat procedure 100 times

To both normalisation calculations (min(P/T) vs mode(P/T)) apply individual corrections in order to obtain daughter values close to α = 0.0 and β = 310 mm ie remove the bias

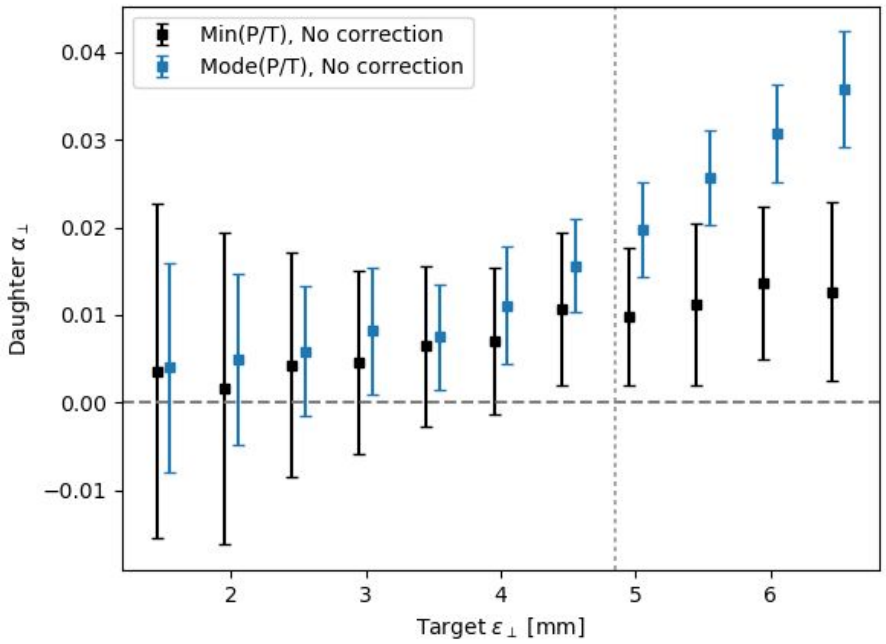
Correction for α and β: *New target parameter = Old Target parameter (matched) +/- bias*

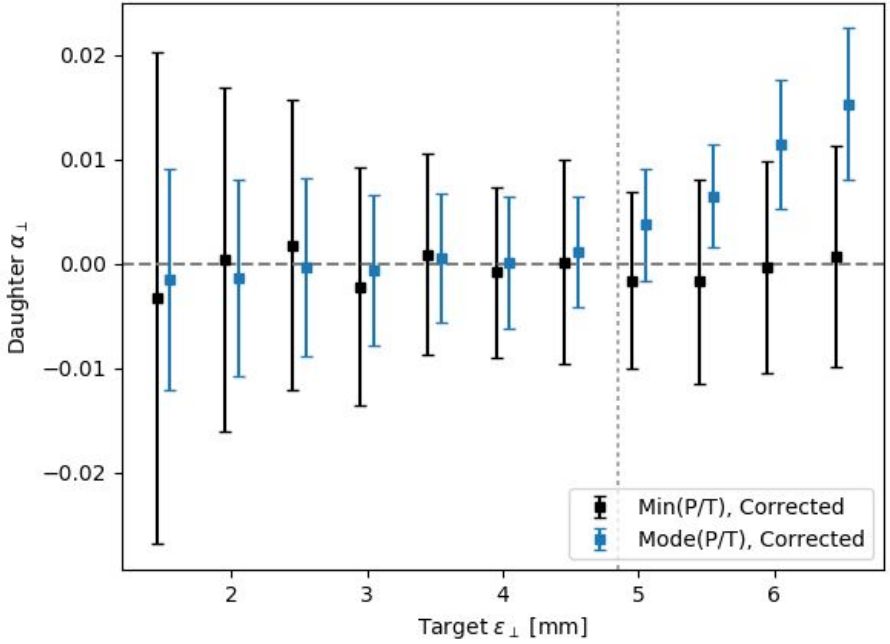
Emittance


Min(P/T), No correction
Mode(P/T), No correction
Daughter $\varepsilon_\perp$ [mm]
Target $\varepsilon_\perp$ [mm]
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
2
3
4
5
6

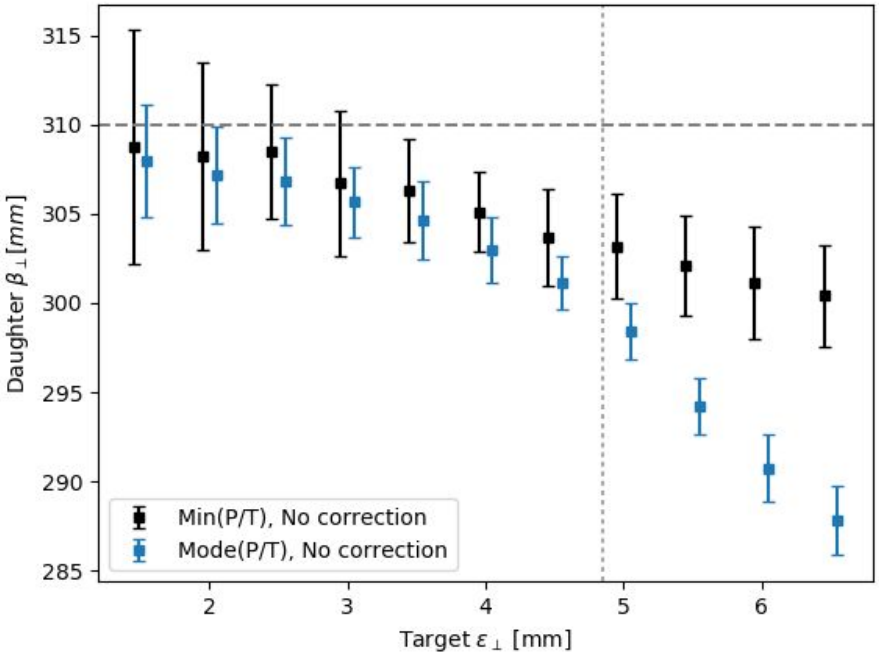

Min(P/T), Corrected
Mode(P/T), Corrected
Daughter $\varepsilon_\perp$ [mm]
Target $\varepsilon_\perp$ [mm]
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
2
3
4
5
6

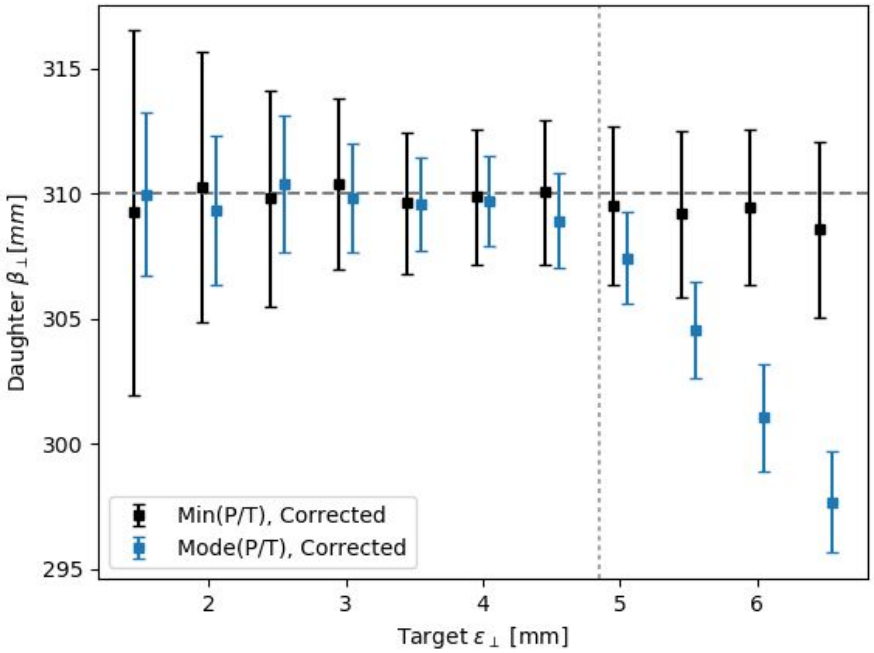
Alpha


Min(P/T), No correction
Mode(P/T), No correction
Daughter $\alpha_\perp$
Target $\varepsilon_\perp$ [mm]
0.04
0.03
0.02
0.01
0.00
−0.01
2
3
4
5
6

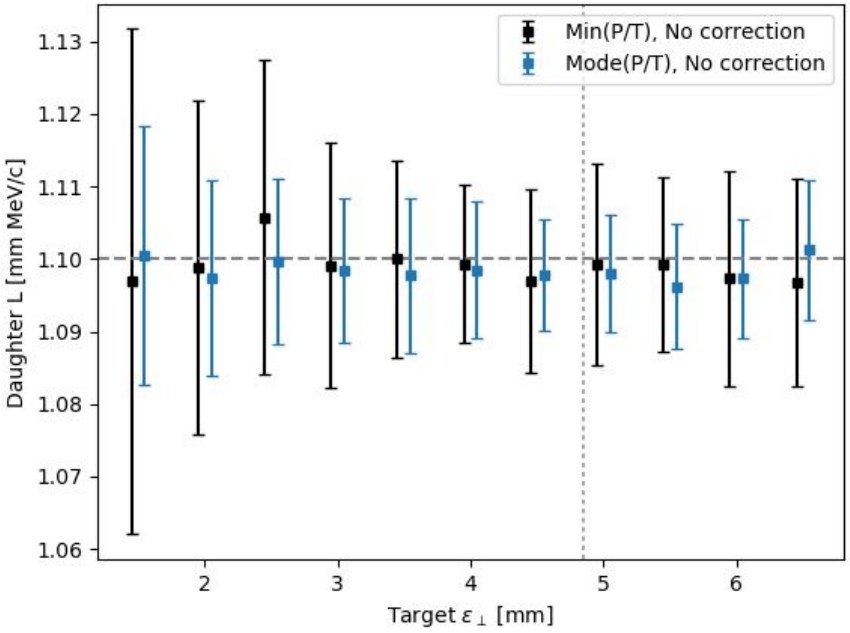

Min(P/T), Corrected
Mode(P/T), Corrected
Daughter $\alpha_\perp$
Target $\varepsilon_\perp$ [mm]
0.02
0.01
0.00
−0.01
−0.02
2
3
4
5
6

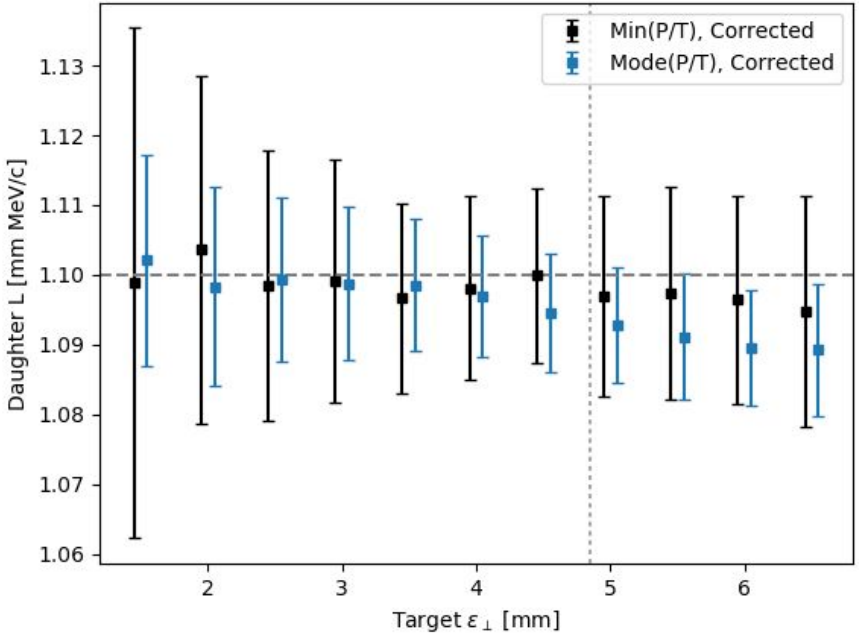
Beta


315
310
305
300
295
290
285
Daughter $\beta_\perp$ [mm]
2
3
4
5
6
Target $\varepsilon_\perp$ [mm]
Min(P/T), No correction
Mode(P/T), No correction

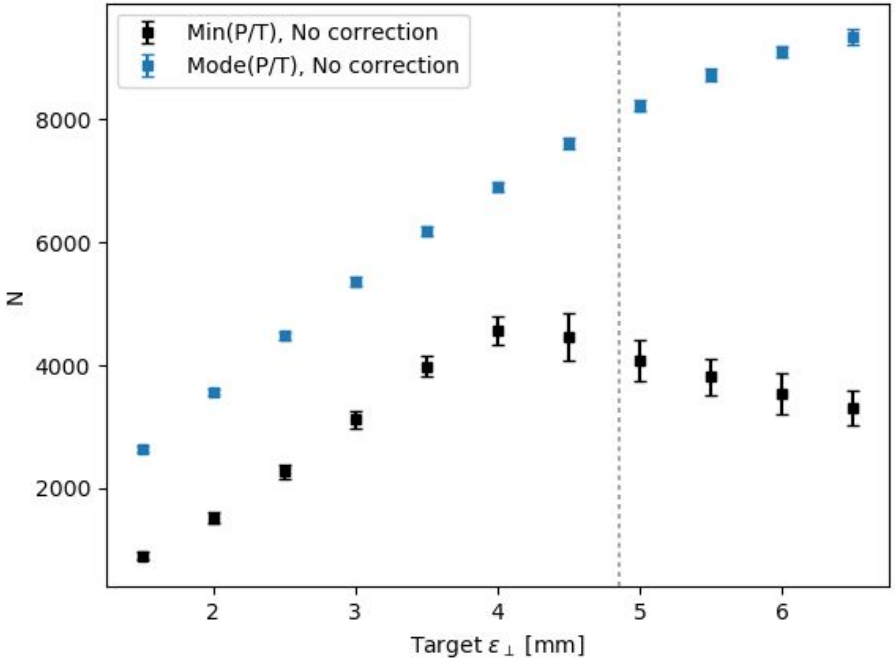

315
310
305
300
295
Daughter $\beta_\perp$ [mm]
2
3
4
5
6
Target $\varepsilon_\perp$ [mm]
Min(P/T), Corrected
Mode(P/T), Corrected

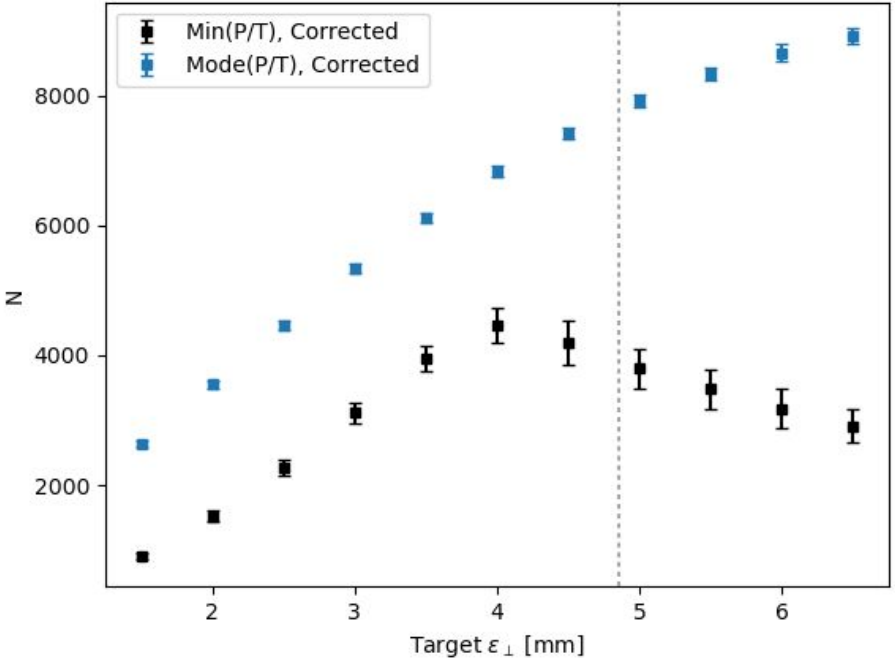
Angular momentum term





Number of particles in the sampled beams



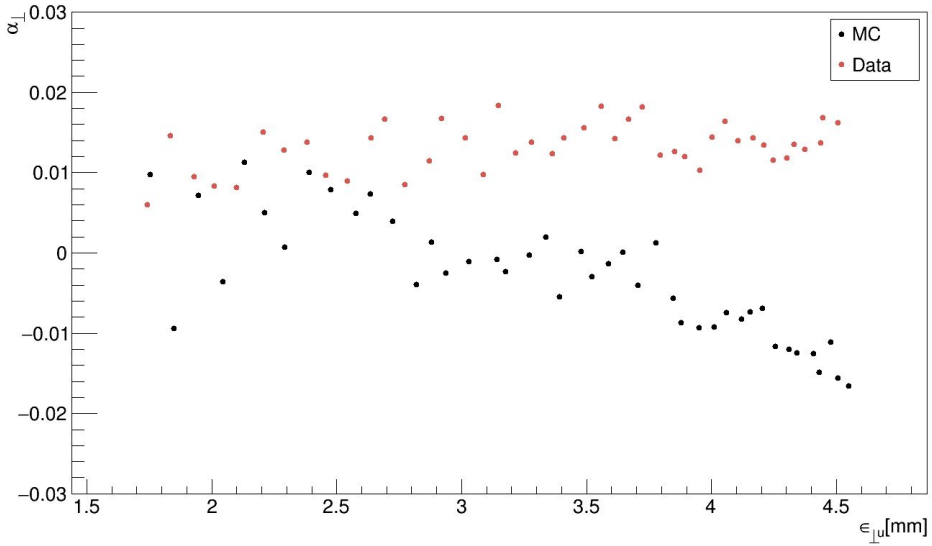


Empty LH2: Optics corrections applied

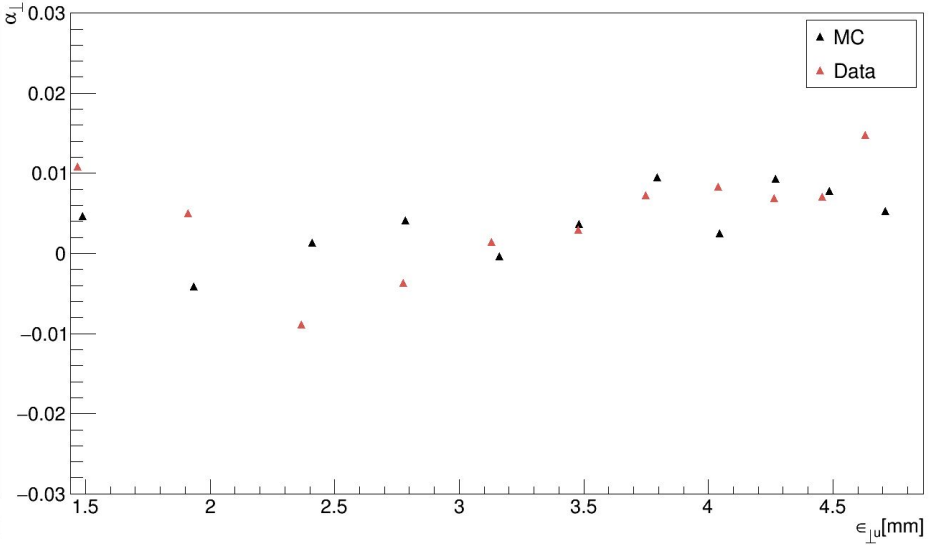
- preliminary results
- Target parameters: [ϵ= [1.5 - 6.5; 0.5] mm, β = 310 mm, α = 0.0, L = 1.1], corrections applied to α and β target values

- Normalization as min(P/T) in this study

Alpha



No correction

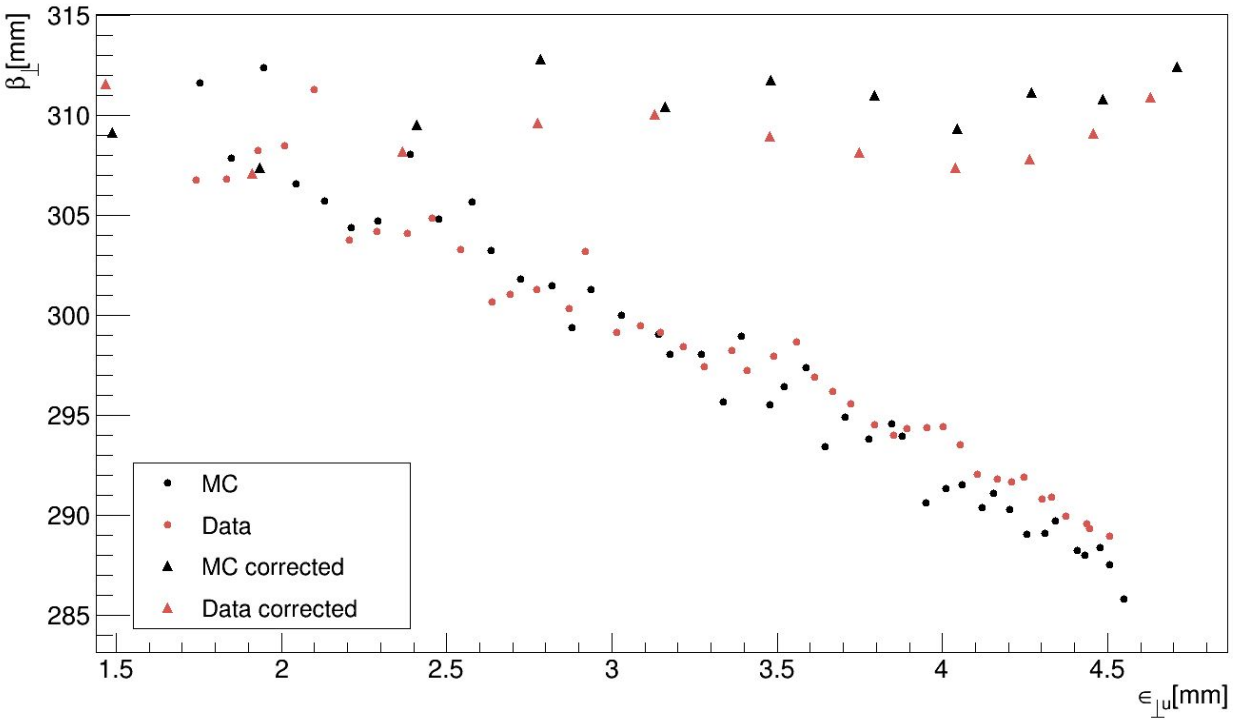


Corrected

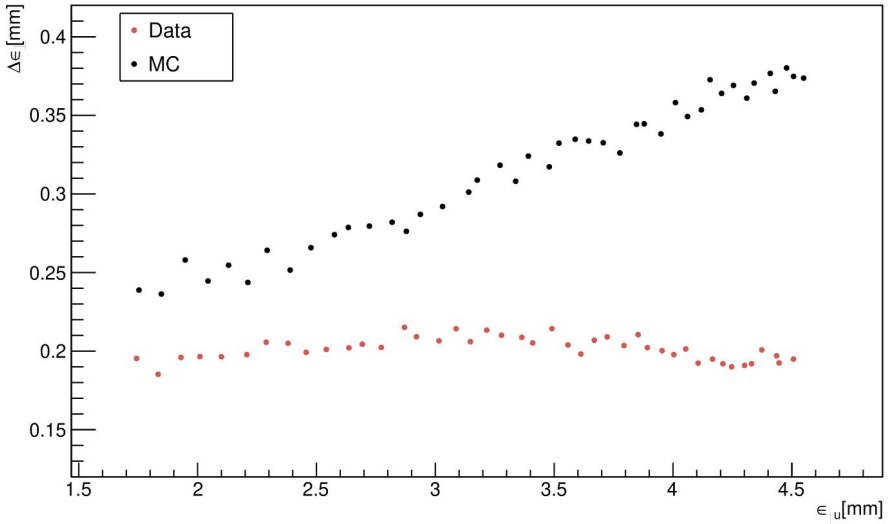
Aims: (a)Data - MC agreement, (b) Agreement with the matched optics values (α = 0.0)

Beta

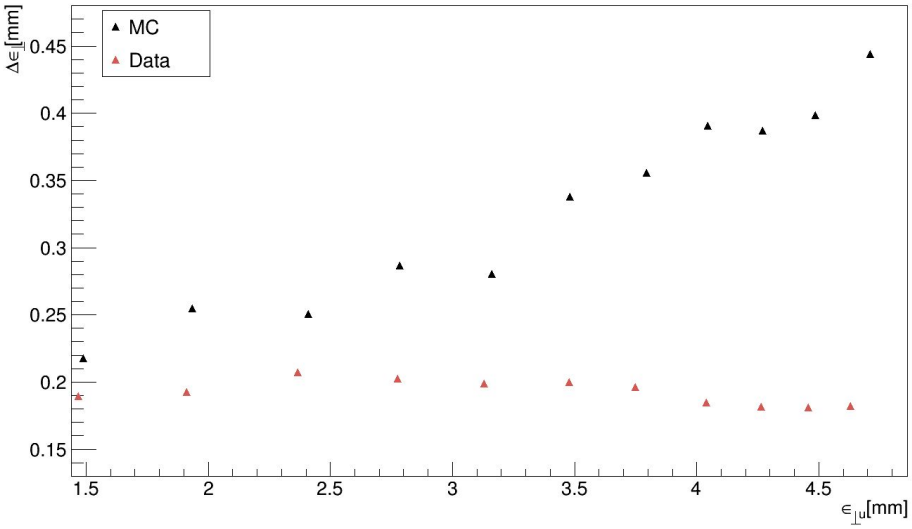
Improved agreement with the β = 310 mm target value



Emittance change



No correction

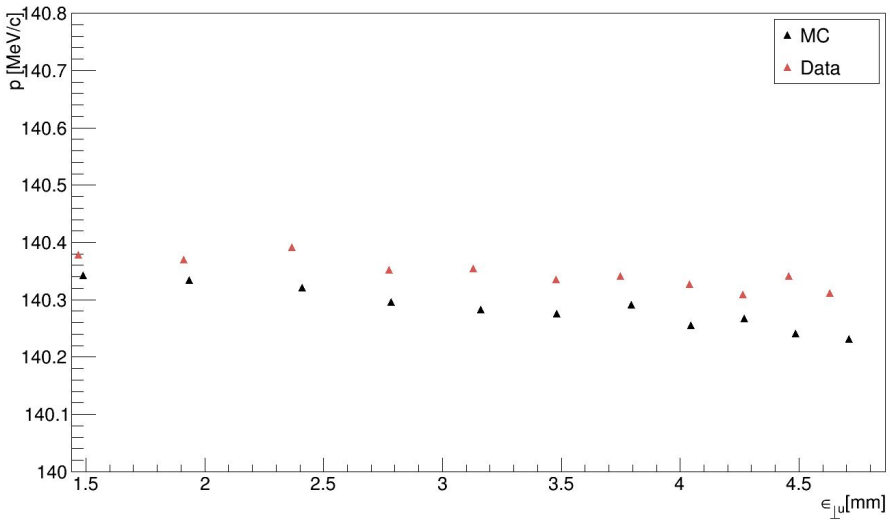


Corrected

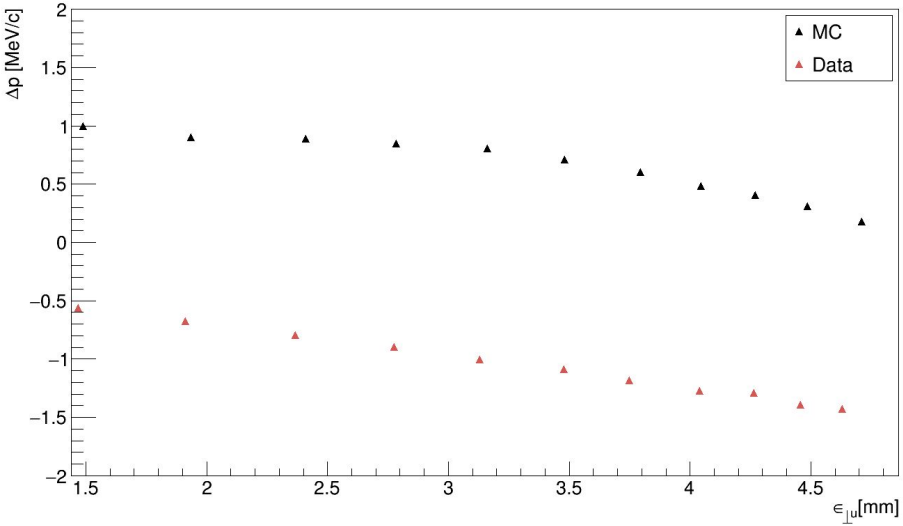
Discrepancy still present. The initial optics discrepancy at TKU ref plane does not explain the difference in emittance growth between Data and MC.

Slightly less heating observed in corrected data and more heating observed at higher emittances in corrected MC.

Momentum (only corrected)



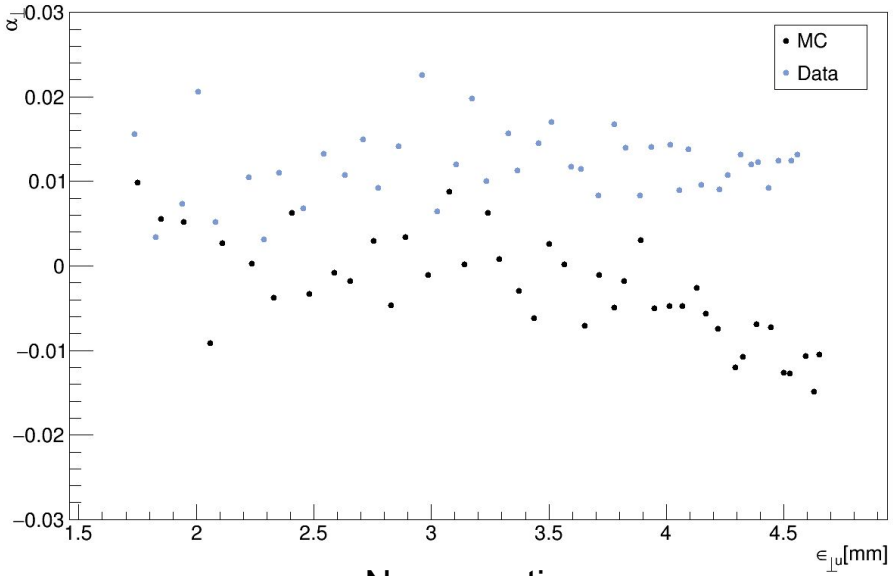
TKU momentum



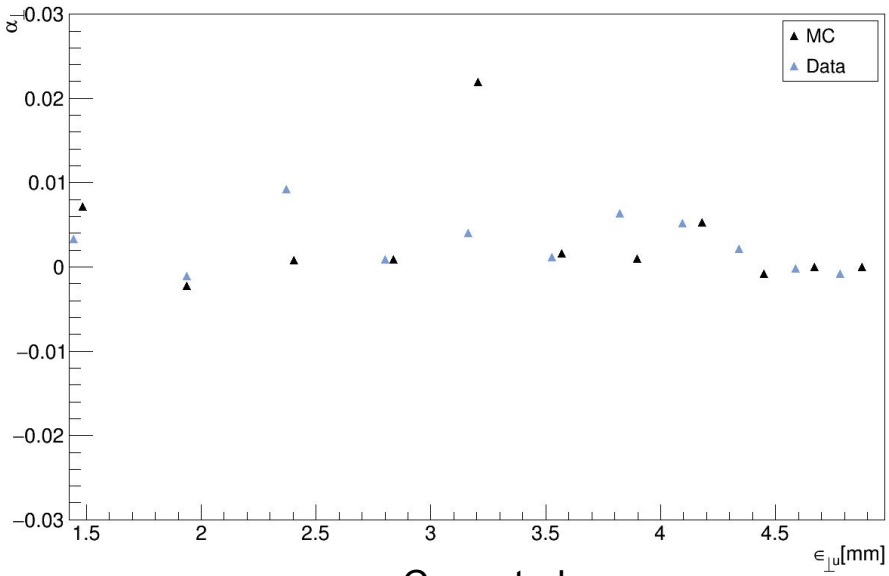
Momentum change

Apparent no momentum loss in MC, indicates reconstruction issues.
More momentum loss seen at higher emittances (data).

LiH: Optics corrections applied - Alpha



No correction



Corrected

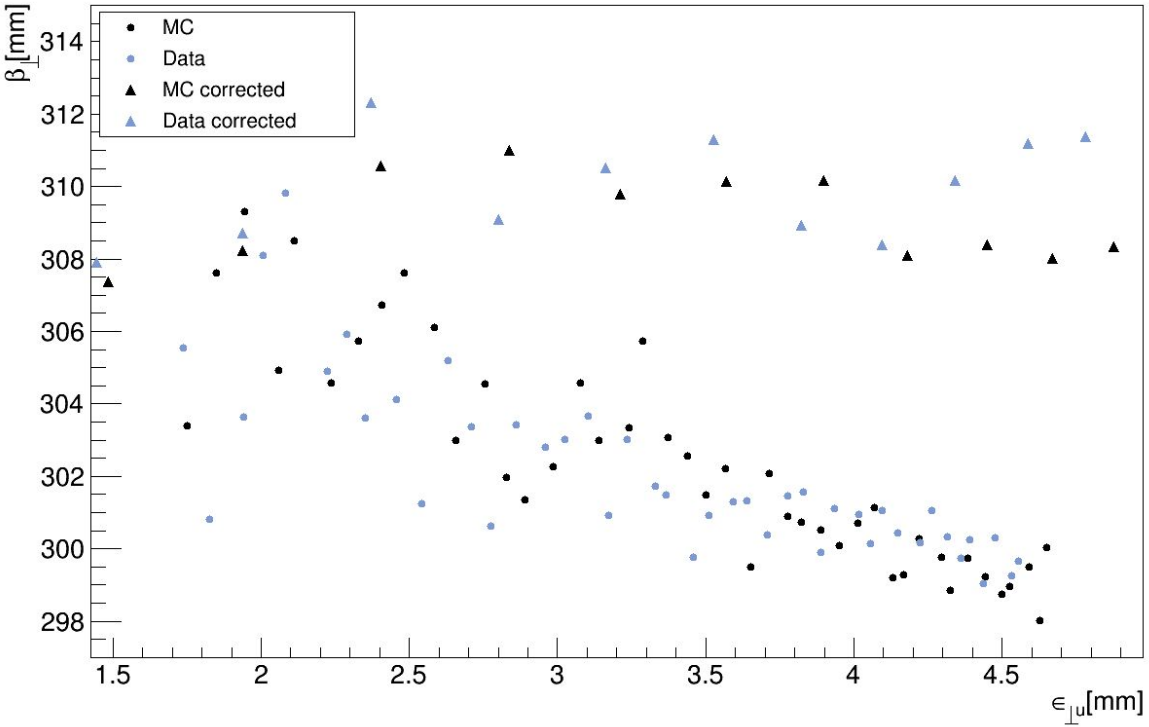
Improved agreement with the α = 0.0 target value

RHS plot: MC point at ϵ ~ 3.2 mm, wrong correction applied, one order of magnitude larger

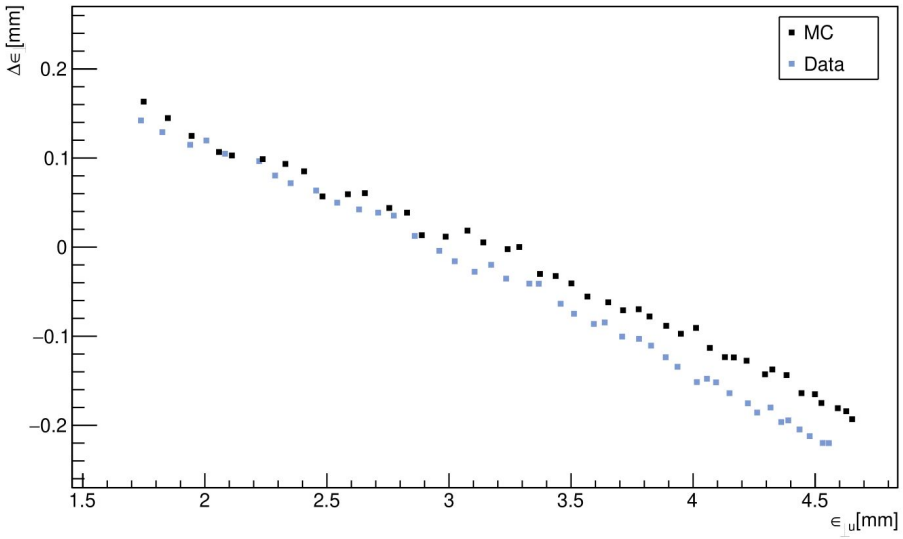
Beta

Improved agreement with the β = 310 mm target value

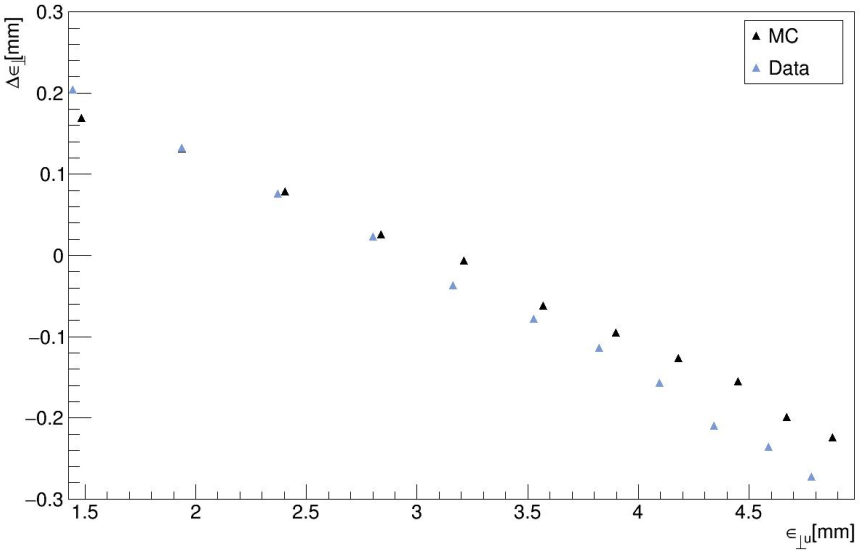
Still scope for improvement on Data / MC agreement



Emittance change



No correction

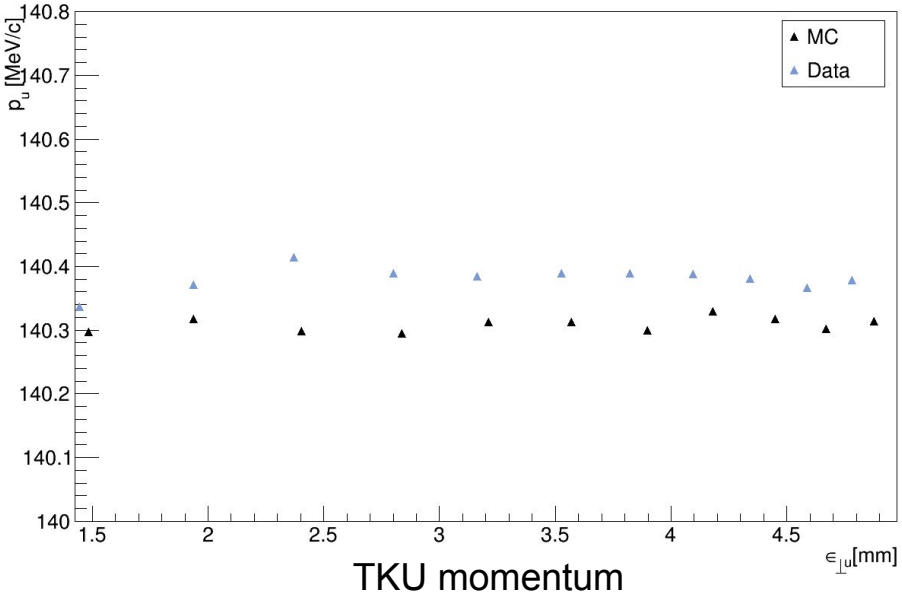


Corrected

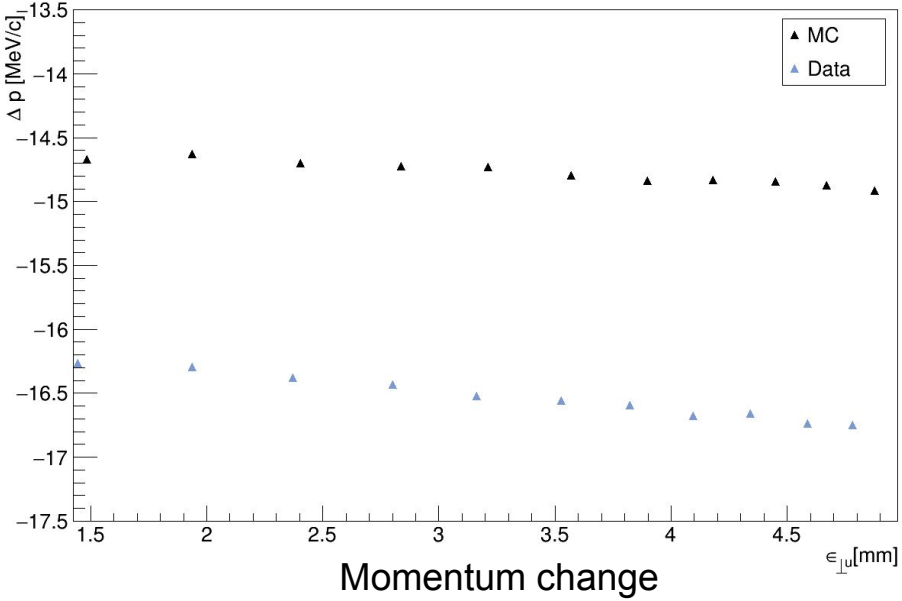
Discrepancy still present. The initial optics discrepancy at TKU ref plane does not explain the difference in emittance growth between Data and MC.

Slightly more cooling observed in corrected data at higher emittances.

Momentum (only corrected)



TKU momentum



Momentum change

Again, less momentum loss observed in MC.

Hybrid MC (Truth)

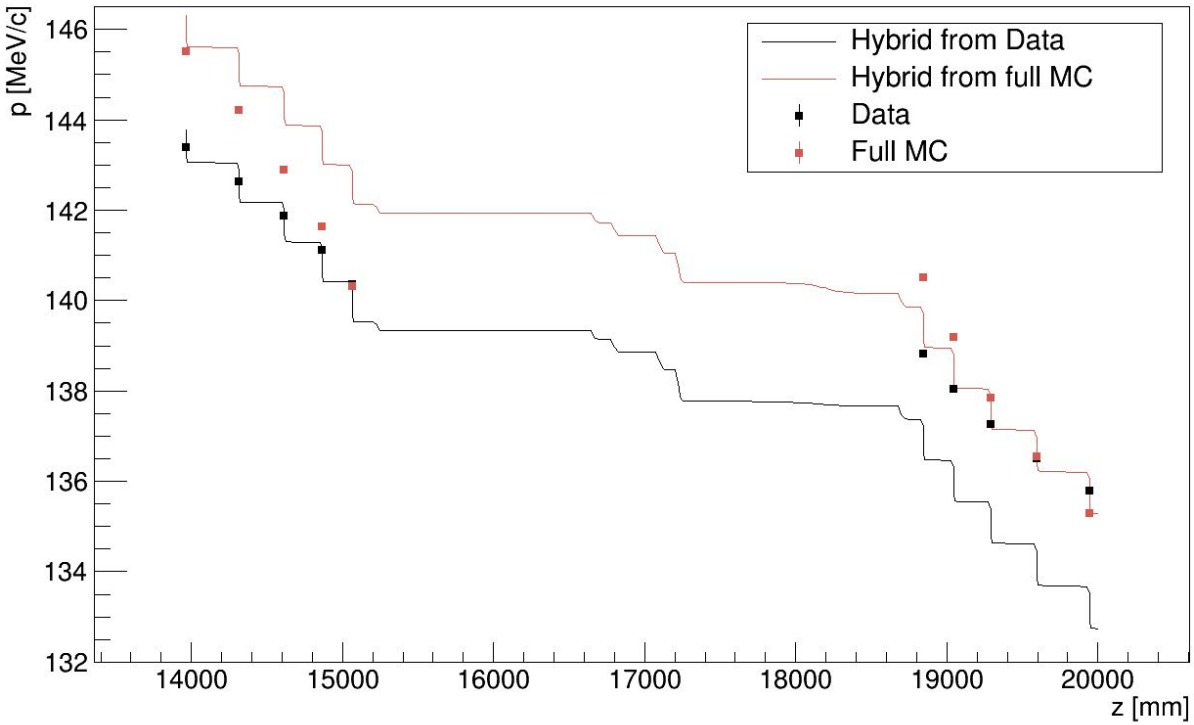
- Extracted Data and full MC parent beams at TKU5 and produced hybrid MC simulations
- Simulated 15k particles

Momentum

More energy/momentum loss at tracker stations observed in the full MC than in Data. However, while in Data the beam losses 1.6 MeV/c by passing through the vessel windows, there is no loss (0.2 MeV/c ‘gain’) in the full MC.

Also, the energy loss at *tracker stations* in the full MC is greater than the loss observed in the Hybrid MC. I am aware the glue density in the tracker stations was changed in the full MC -> are the trackers descriptions the same in CR’s full MC and my Hybrid MC? YES.

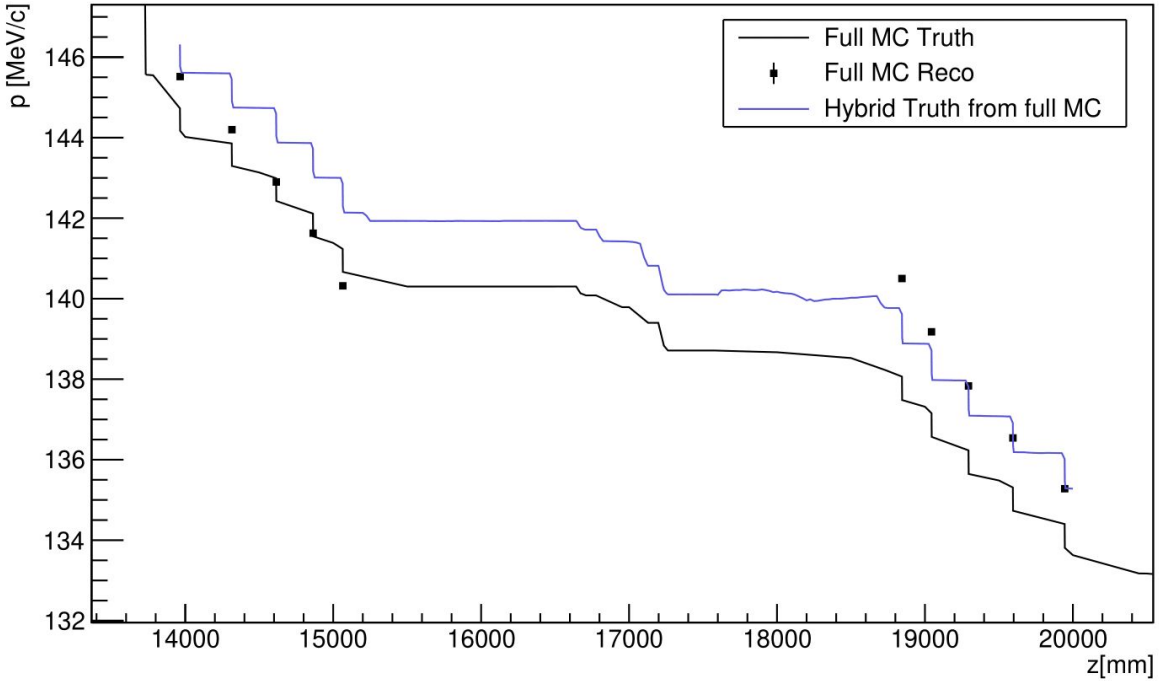
Also, the Hybrid MC observes the presence of the vessel.



Full MC: Momentum Update

Same momentum loss observed in Full MC Truth and Hybrid Truth -> geometry descriptions consistent between the two

Biased reconstruction

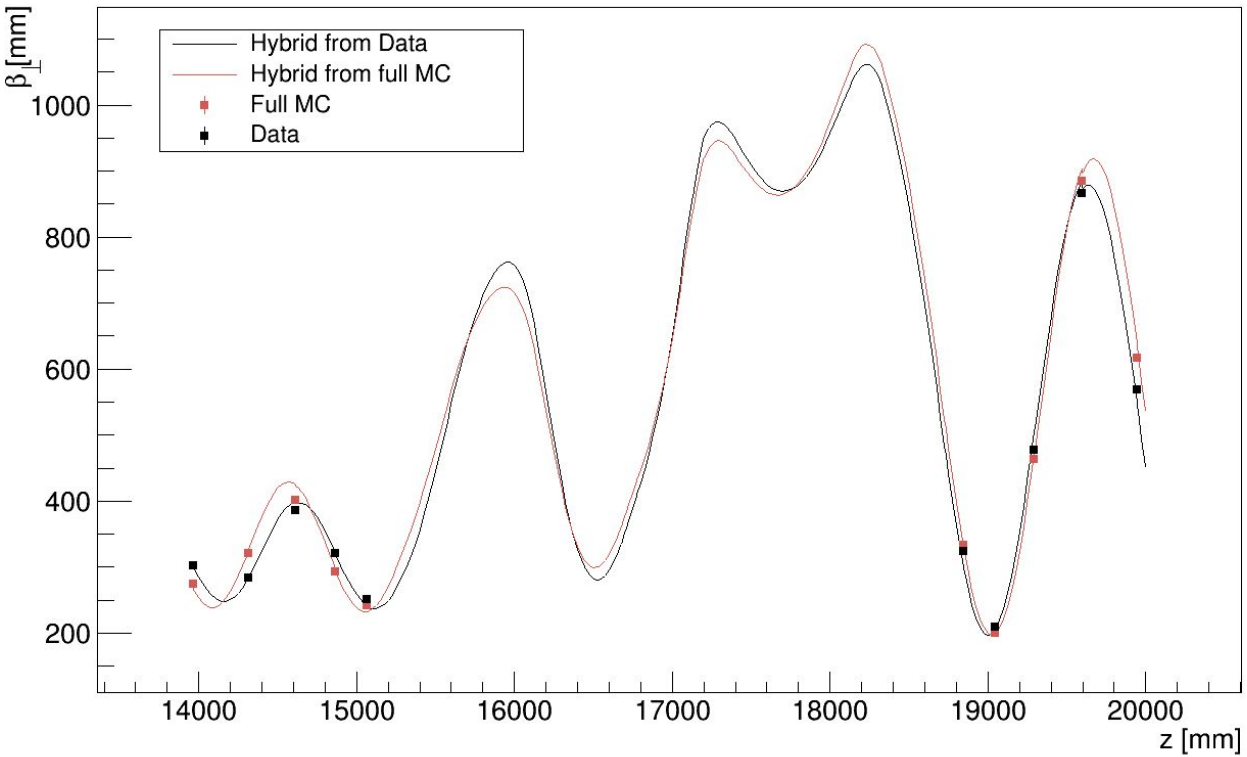


Job List

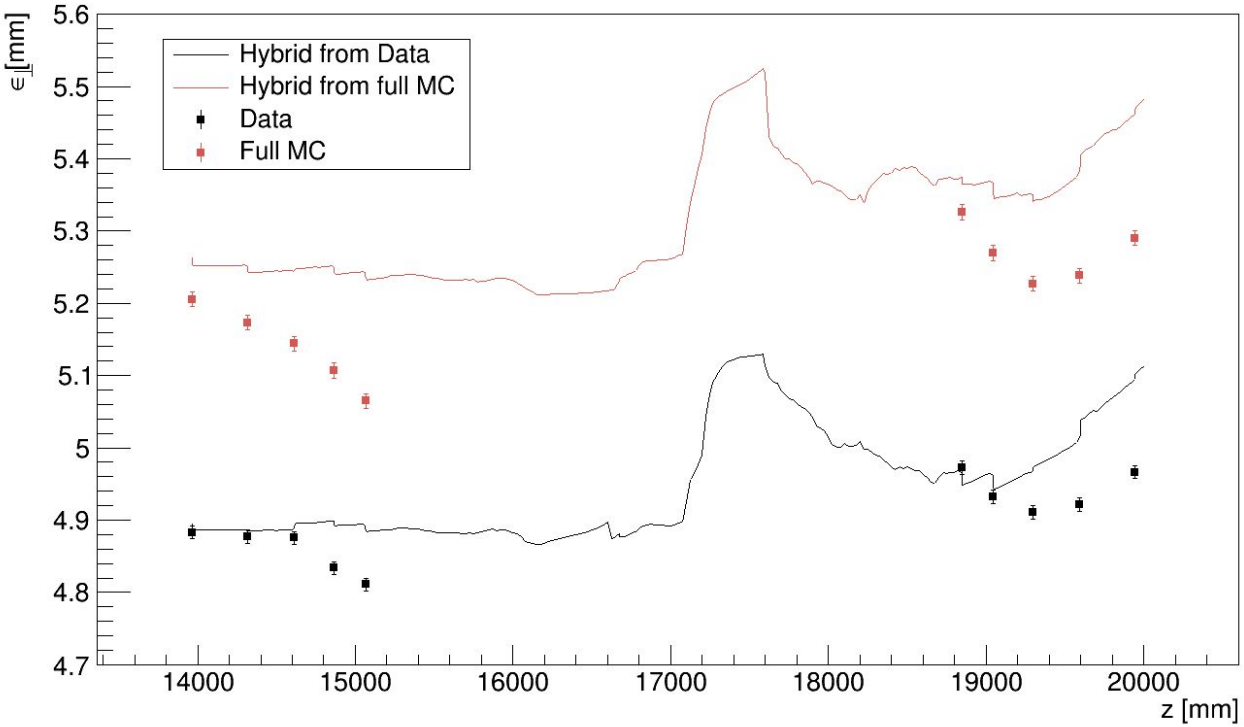
- Apply corrected optics sampling to all the analyses
- Attempt to apply alternative normalization procedure for higher statistics in the sampled beams
- DATA MC disagreement
  - look into momentum reconstruction disagreement
  - produce new MC

Backup

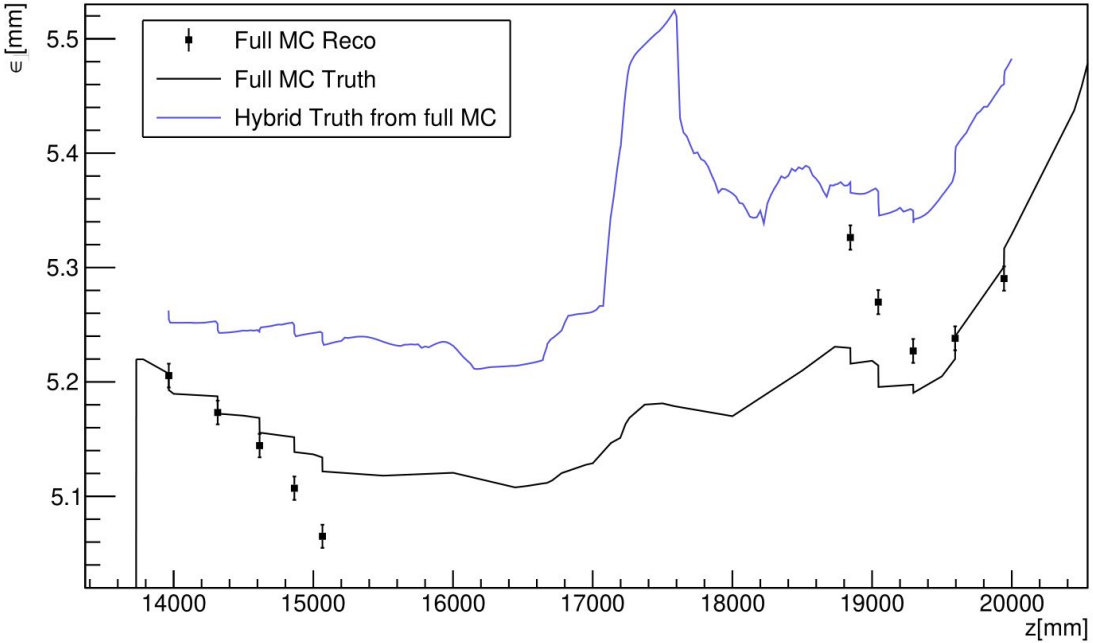
Betatron function



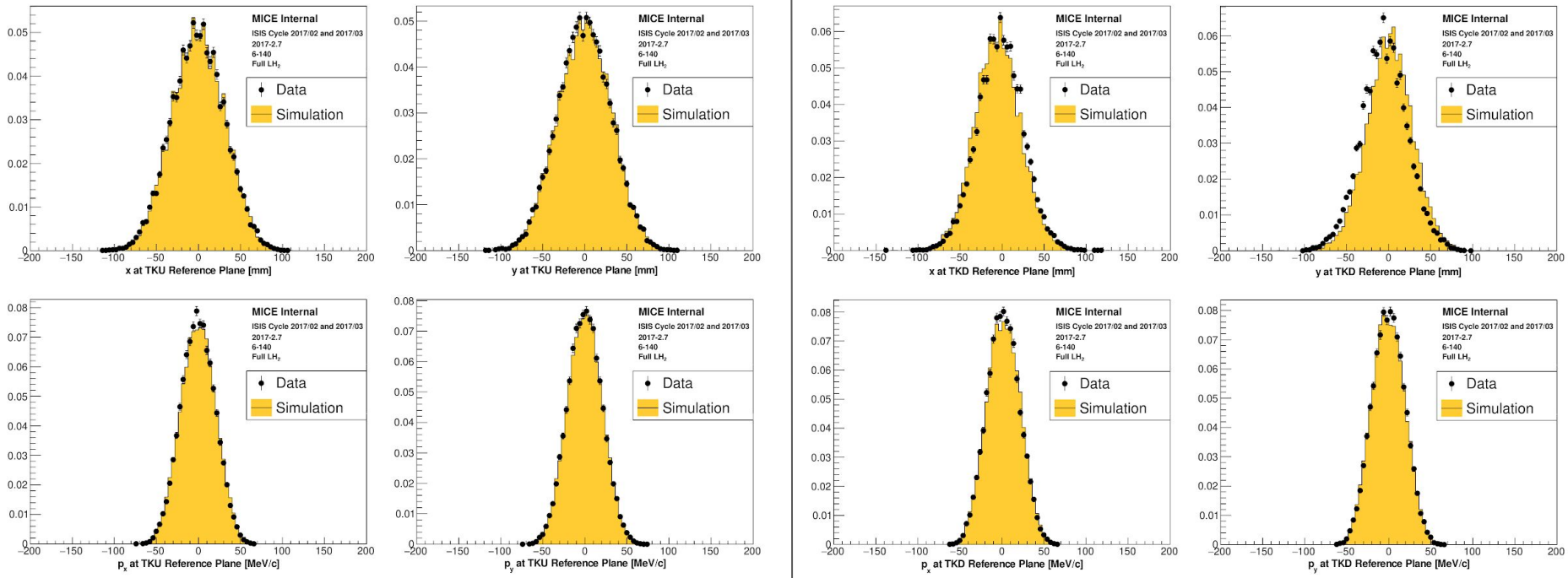
Emittance including particle losses in Hybrid MC



Full MC: Emittance Update

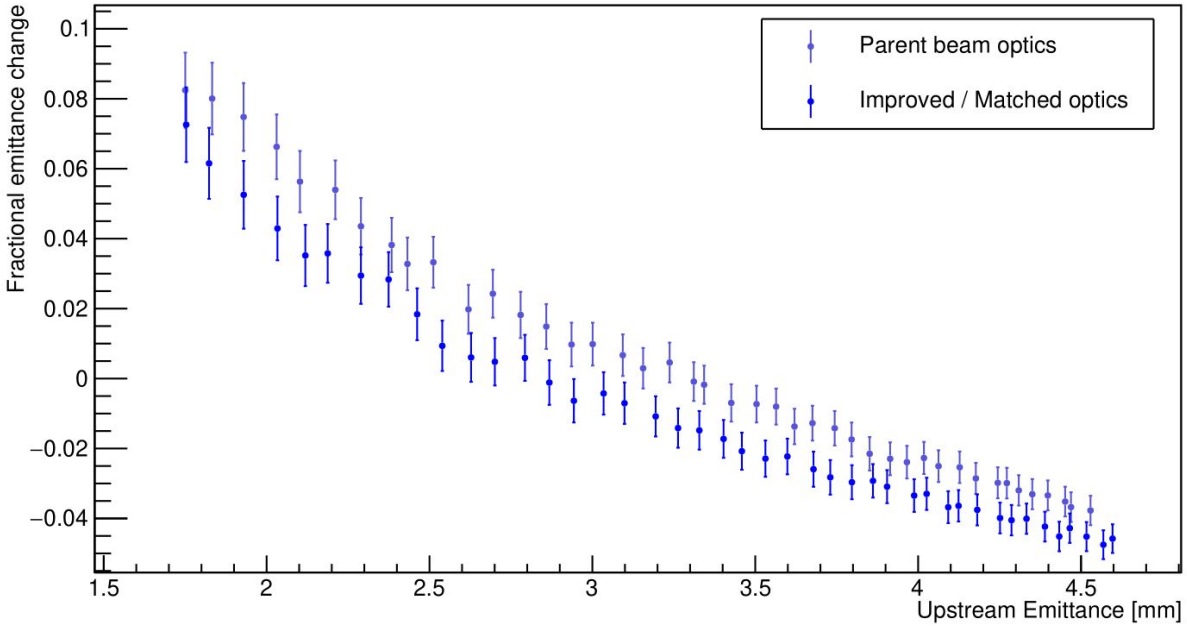


Transverse phase-space plots



UPSTREAM → DOWNSTREAM

(~ 4 mm emittance sampled beam)


Fractional emittance change
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
1.5
2
2.5
3
3.5
4
4.5
Upstream Emittance [mm]
Parent beam optics
Improved / Matched optics