Flip mode emittance analysis

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Overview

- Current status of refining the beam selection routines: Rejection Sampling
- Cooling performance recovery
- Brief recap of the initial analysis (no transmission cut imposed)
- Analysis with full transmission imposed: DATA VS MC. Results presented here for FULL LH2 and NO ABSORBER 6 mm, 140 MeV/c, FLIP mode
- Hybrid MC truth: first comparisons

Beam Selection: Rejection Sampling

- $P_{selection}(x)$ = *Norm * Target(x) / Parent (x)*

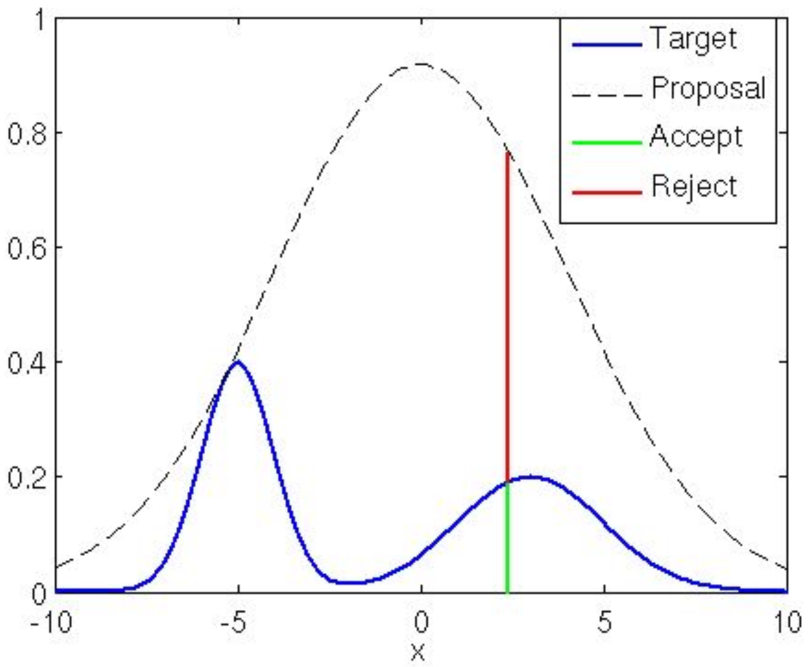
- Draw *u* from *U[0,1]*. If $u < P_{selection}(x)$ then accept event. Otherwise reject it.

- Normalisation calculation:

    - for a large number of times (10k) randomly draw a sample *x* from the target distribution and take the minimum of *Parent (x) / Target (x) (approximate)*

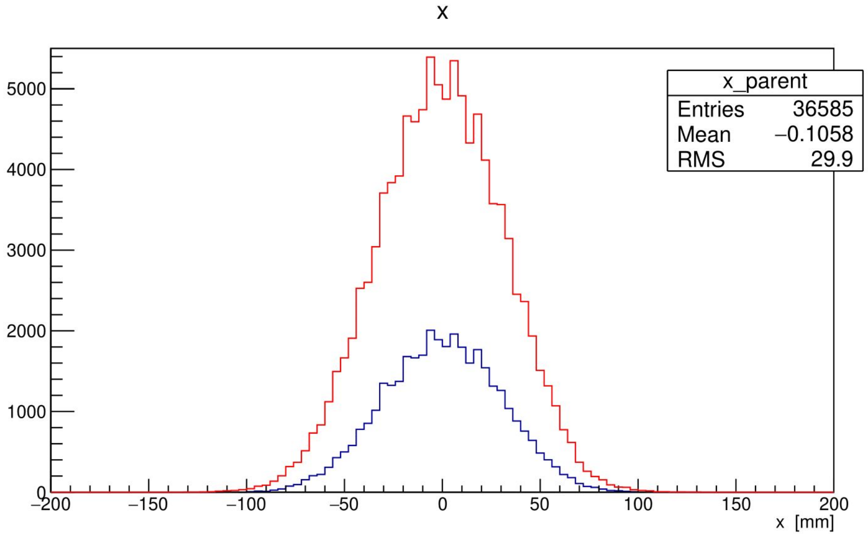
    - OR iterate through all parent beam events and use the minimum of *Parent (x) / Target (x) (more CPU intensive)*

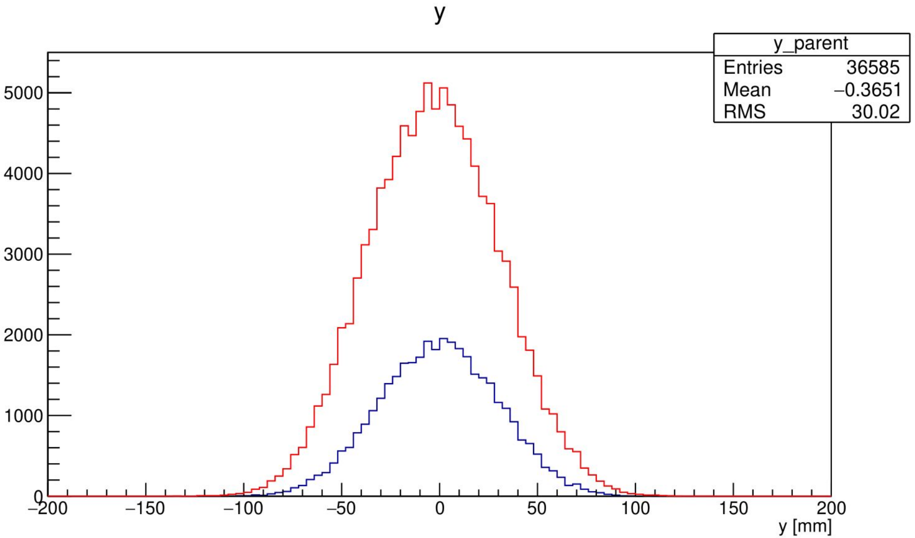
    - Normalisation ensures that $P_{selection}(x) <= 1$.



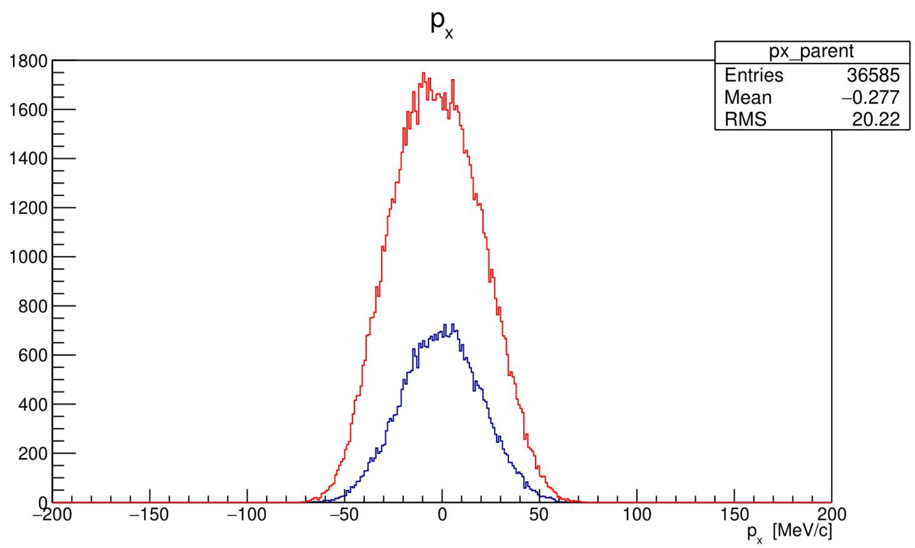
Parent VS Target (Full LH2 MC)

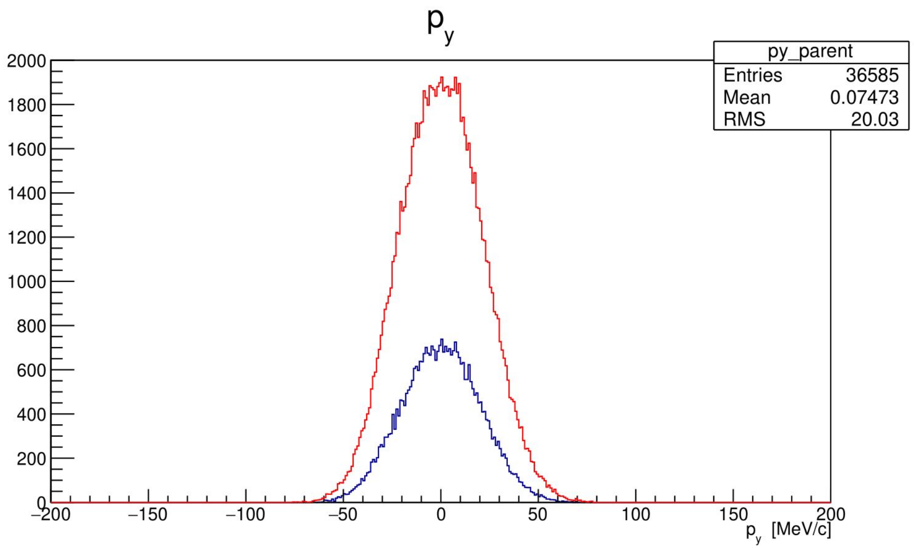
- RED - Parent; BLUE - Target
- ~ 4 mm emittance sampled target beam



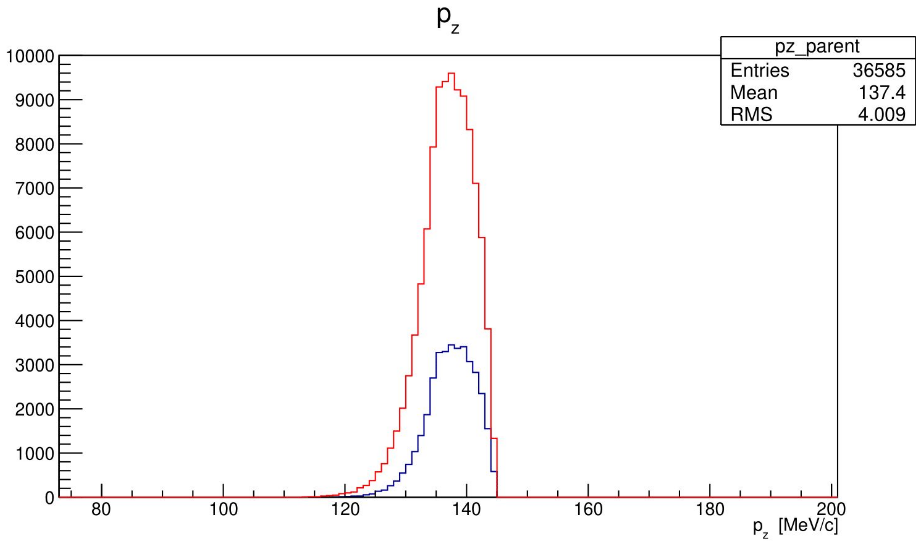


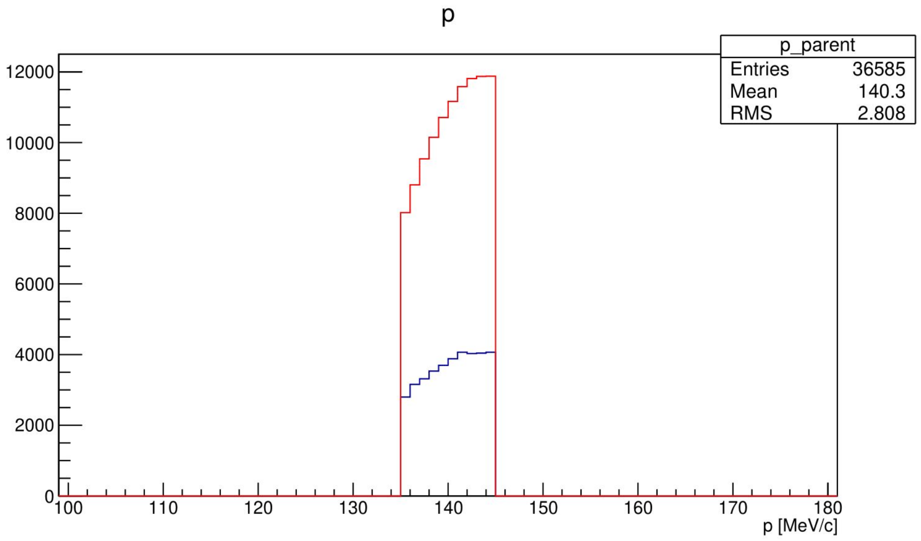
Parent VS Target (Full LH2 MC)





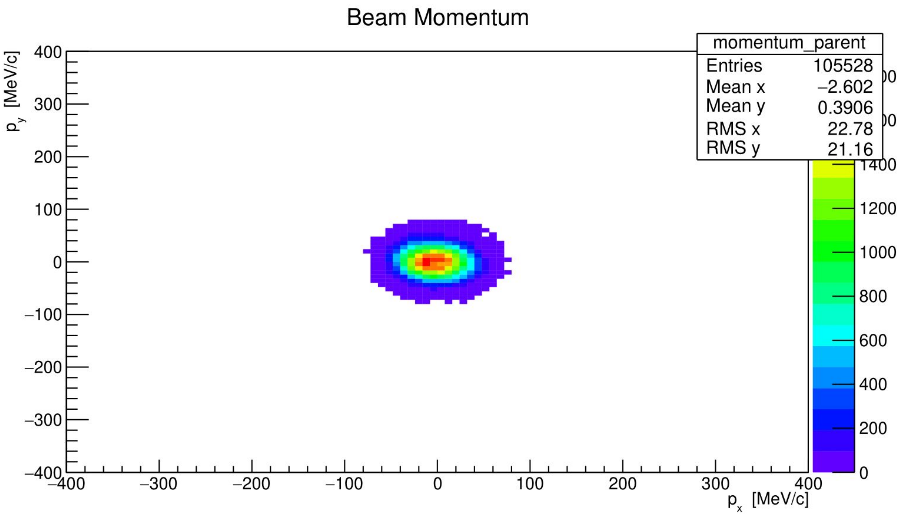
Parent VS Target (Full LH2 MC)



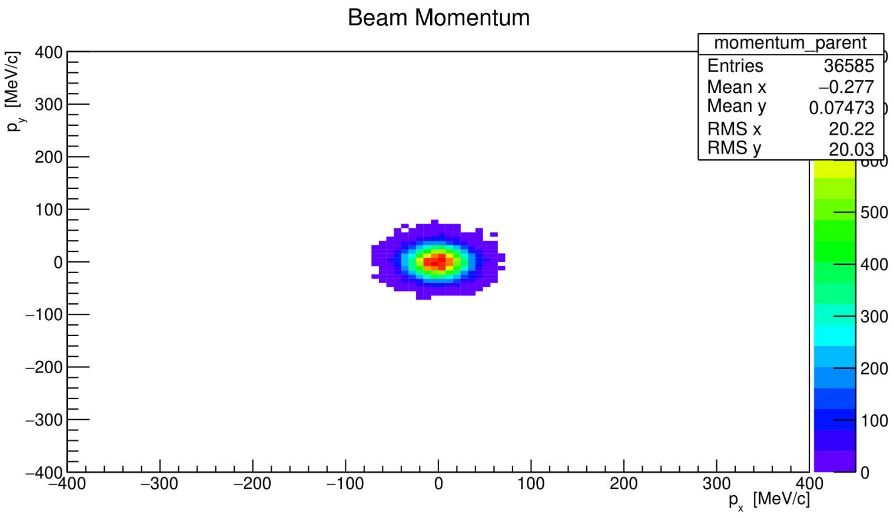


Parent VS Target (Full LH2 MC)

Parent

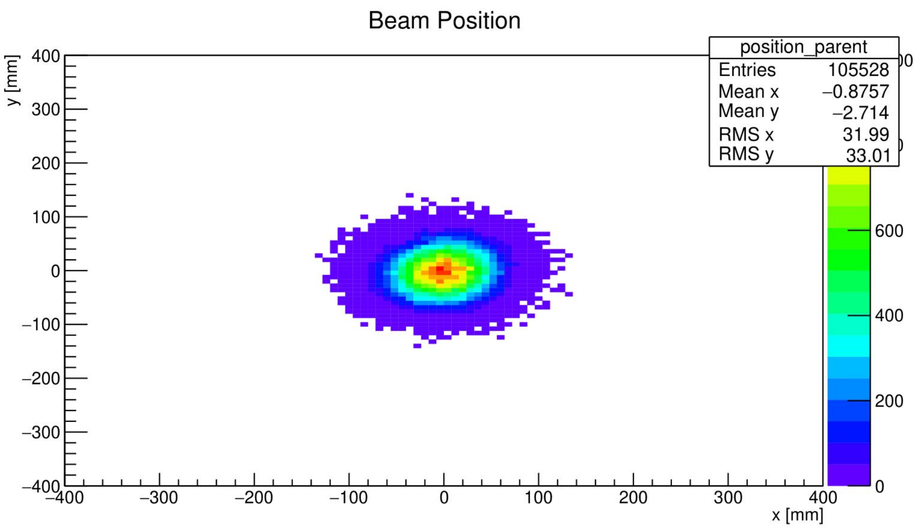


Target

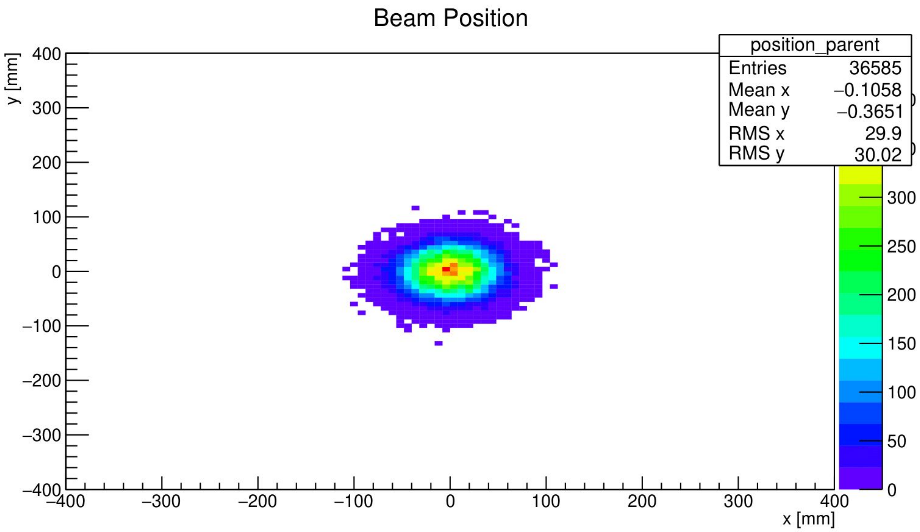


Parent VS Target (Full LH2 MC)

Parent

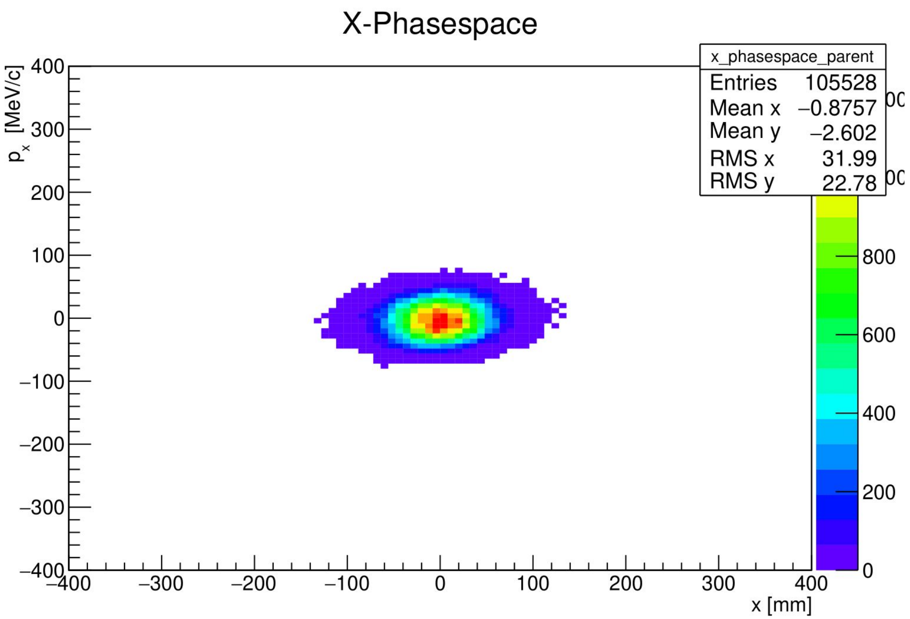


Target

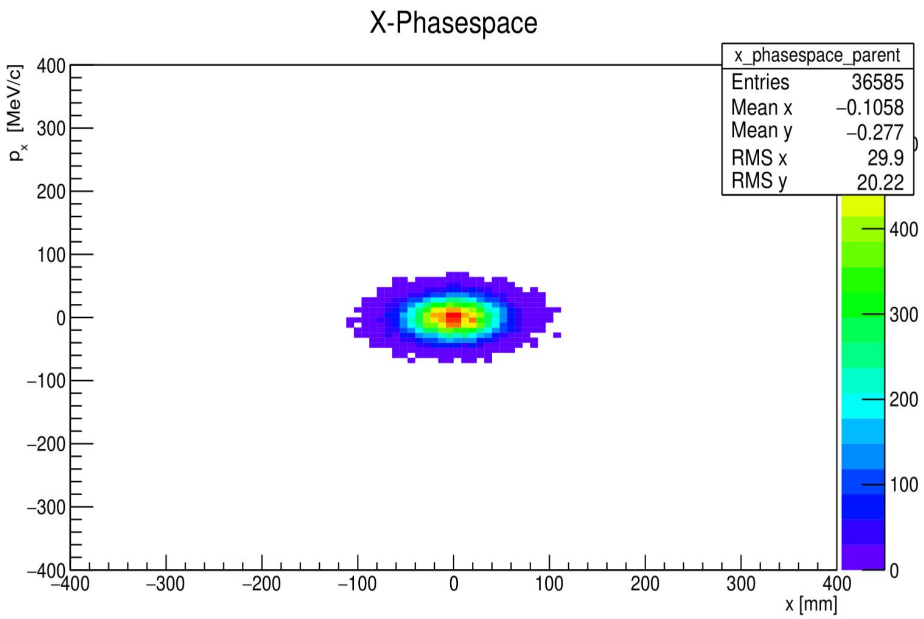


Parent VS Target (Full LH2 MC)

Parent

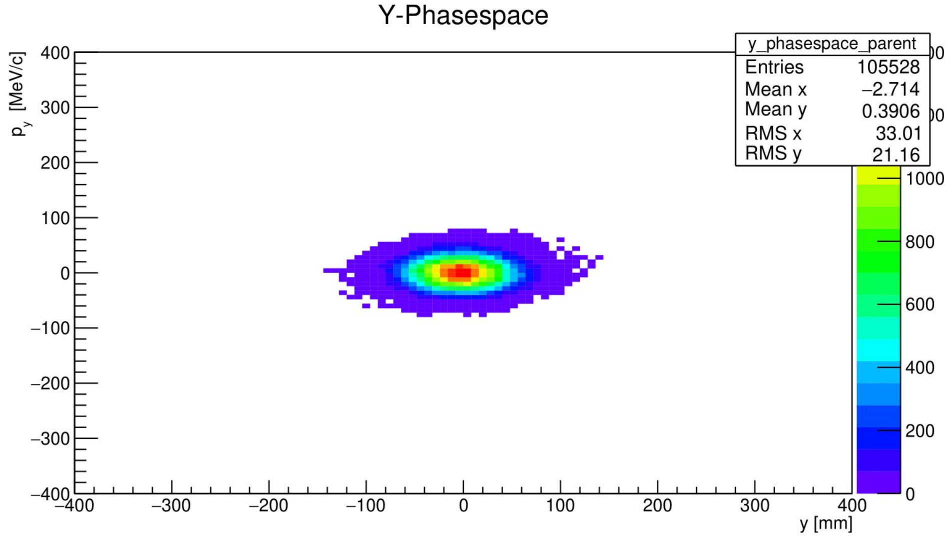


Target

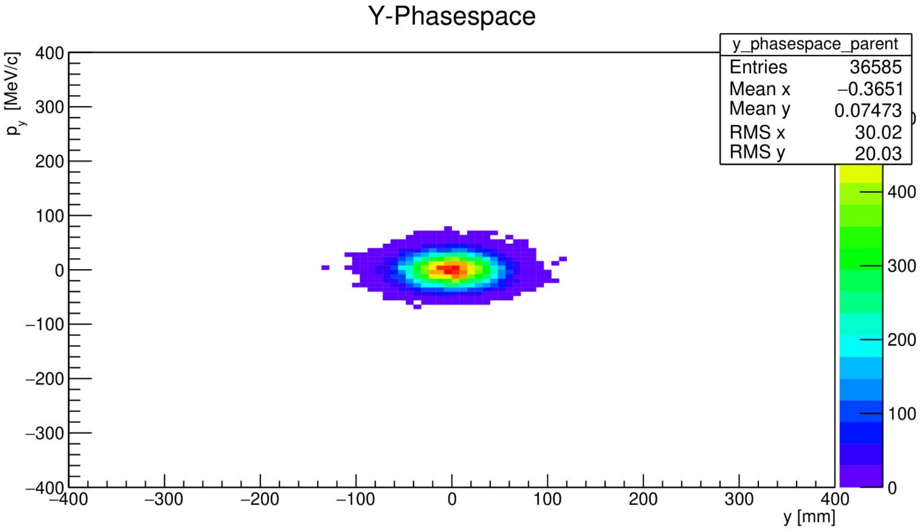


Parent VS Target (Full LH2 MC)

Parent



Target



Cooling performance comparison
Unmatched vs Matched/Improved Optics

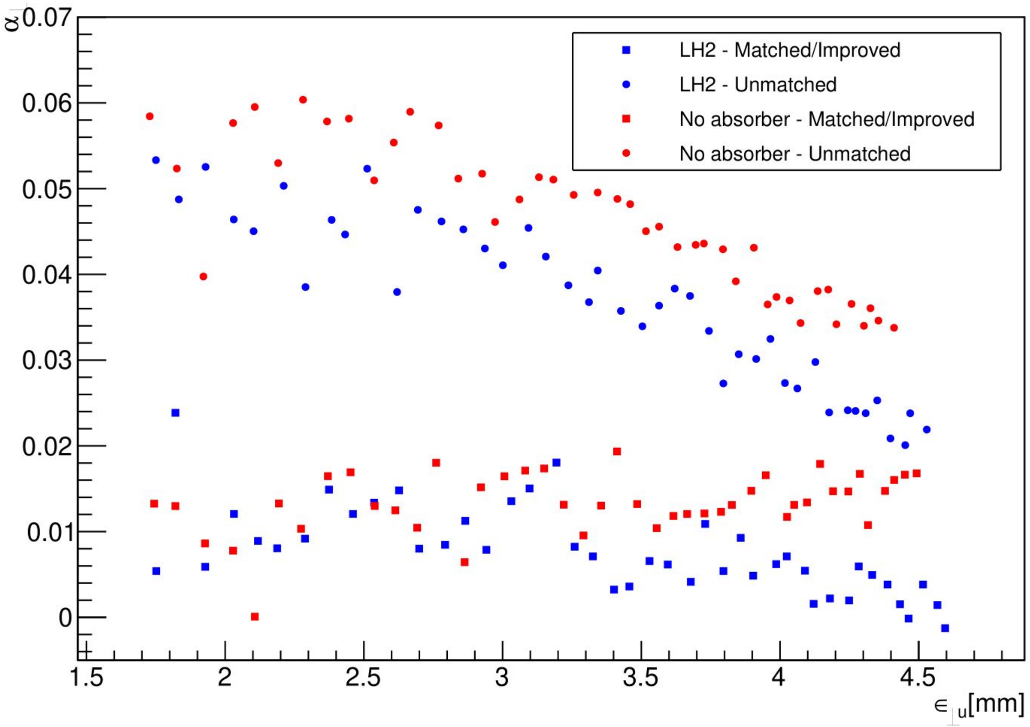
- Sampled a set of beams by requesting the same optics parameters as those of the parent beam (aim to preserve the original optics), but only varied the target emittance.

- Compared with a set of sampled beams with same targets emittances, but matched target optics parameters.

- Results presented in the form of relative emittance change between the two reference planes.

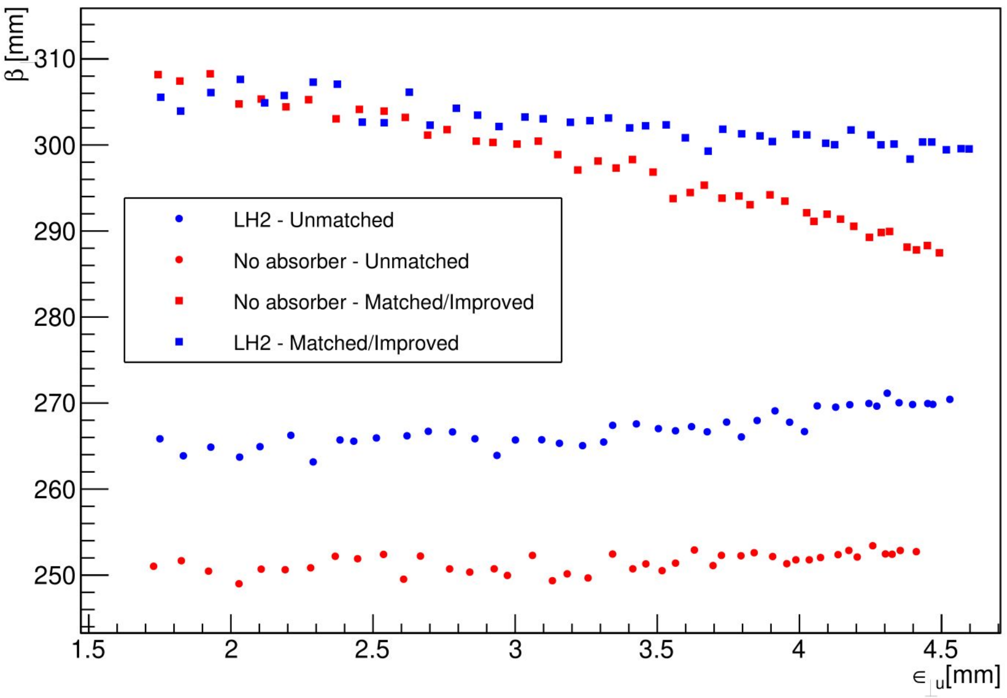
Target alpha TKU reference plane

- For the matched optics, α = 0.0 was requested
- For the unmatched optics, α = 0.04 (LH2) and α = 0.051 (No absorber) were requested



Target beta TKU reference plane

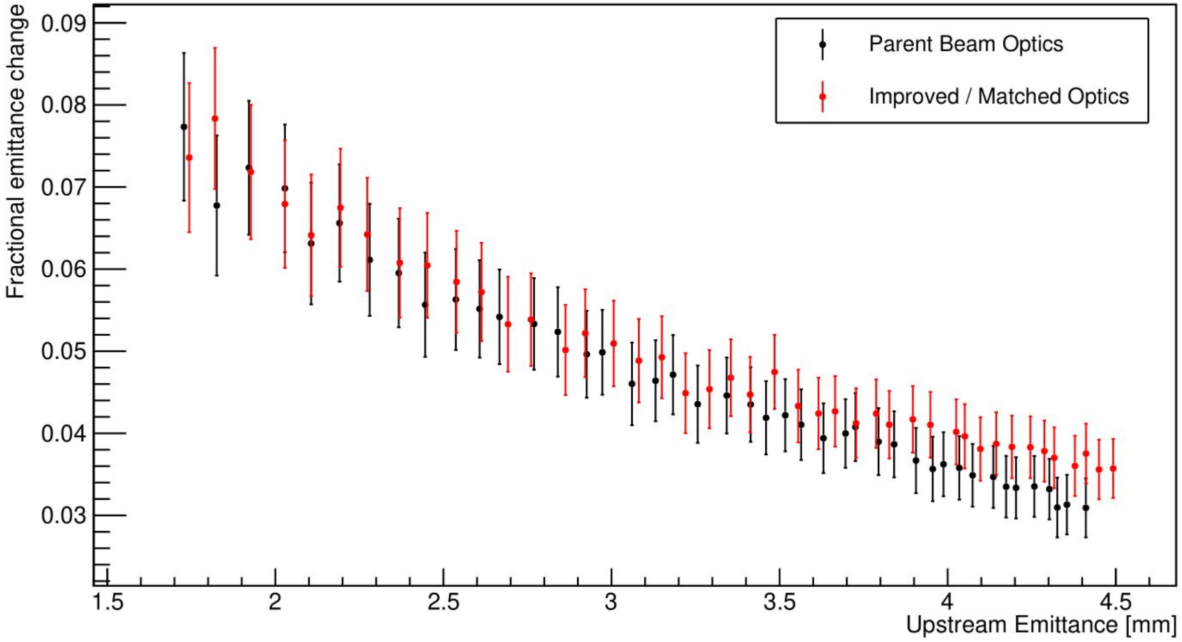
- For the matched optics, β = 310 mm was requested
- For the unmatched optics, β = 268 mm (LH2) and β = 252 mm (No absorber) were requested
- In the matched case, it can be observed that as the target emittance increases, beta converges towards the beta of the parent beam. As the target emittance approaches the parent emittance, the parent optics characterististics become noticeable



No absorber Data

Slightly more heating present in the matched optics sampled beams at higher emittances.

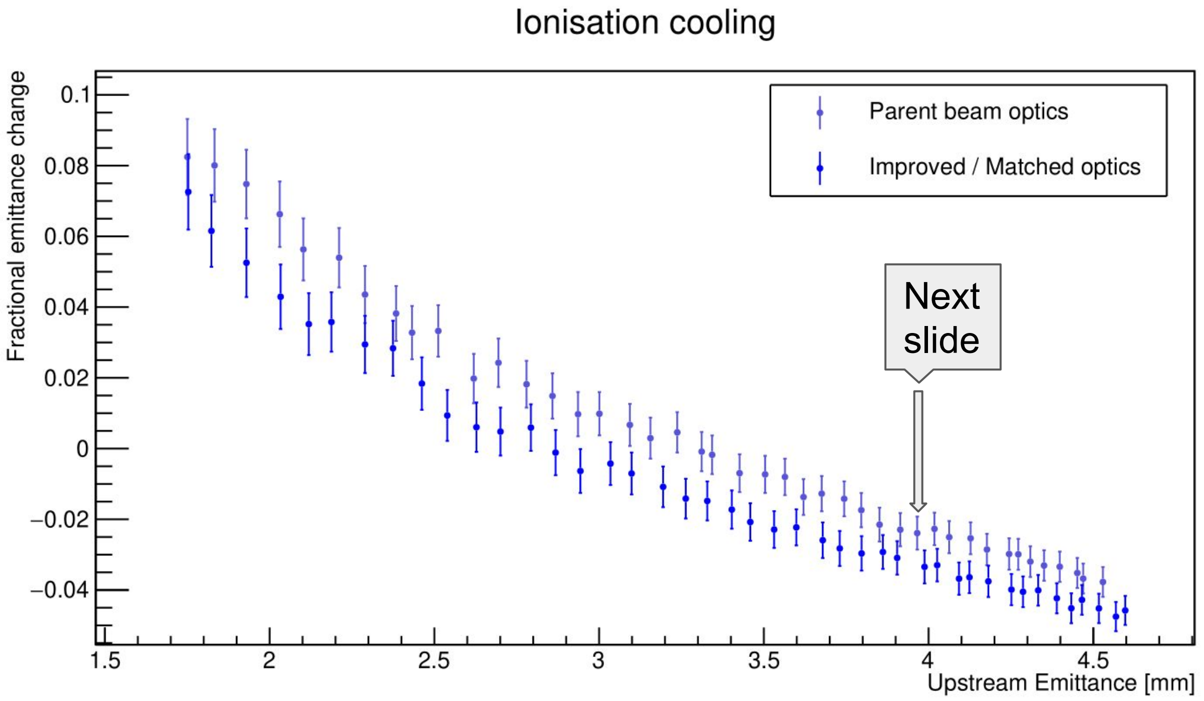
Need to study the optics between the trackers using hybrid MC.



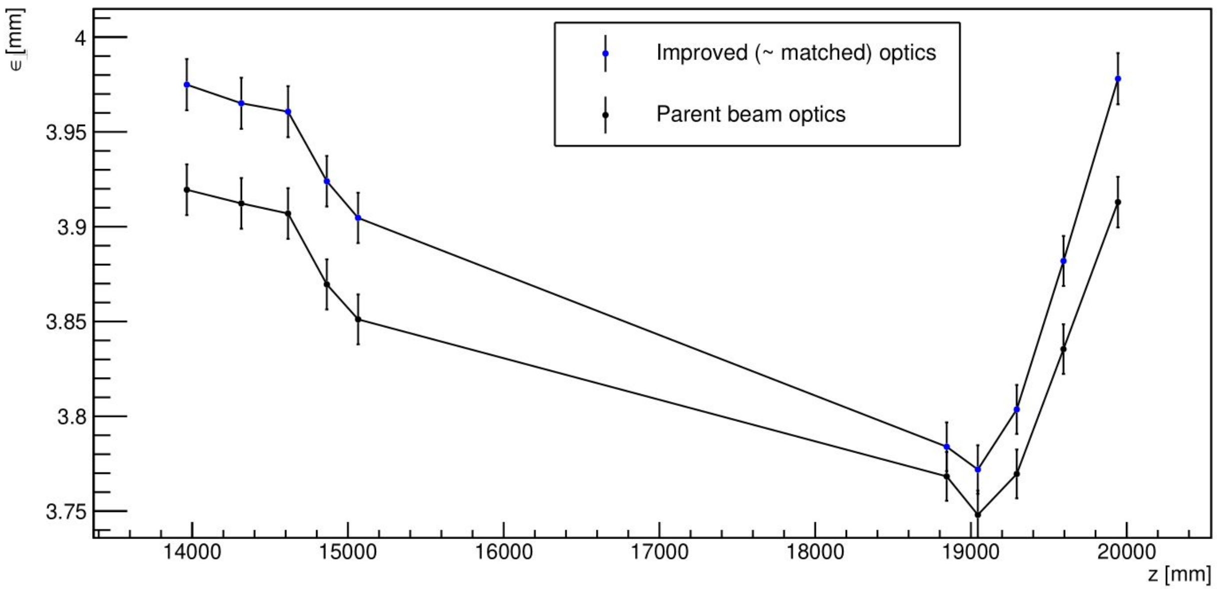
Full LH2 Data

Consistently more cooling seen in the sampled beams with improved optics.

This indicates that beta at the absorber is reduced, resulting in less MCS heating.



Greater emittance decrease observed for the beam with improved (~ matched) optics.



Analysis chain

- Parent beam: sample selection

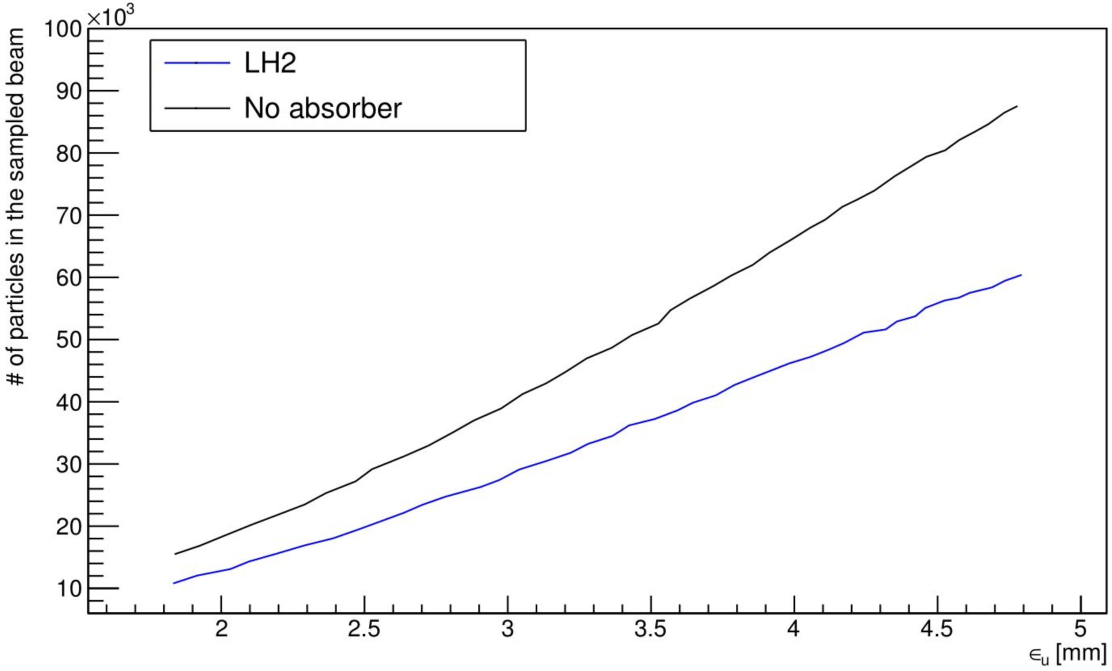
- Beam sampling from the upstream ensemble

- Perform emittance, amplitude analyses on the sampled beams

Parent Beam: Sample selection

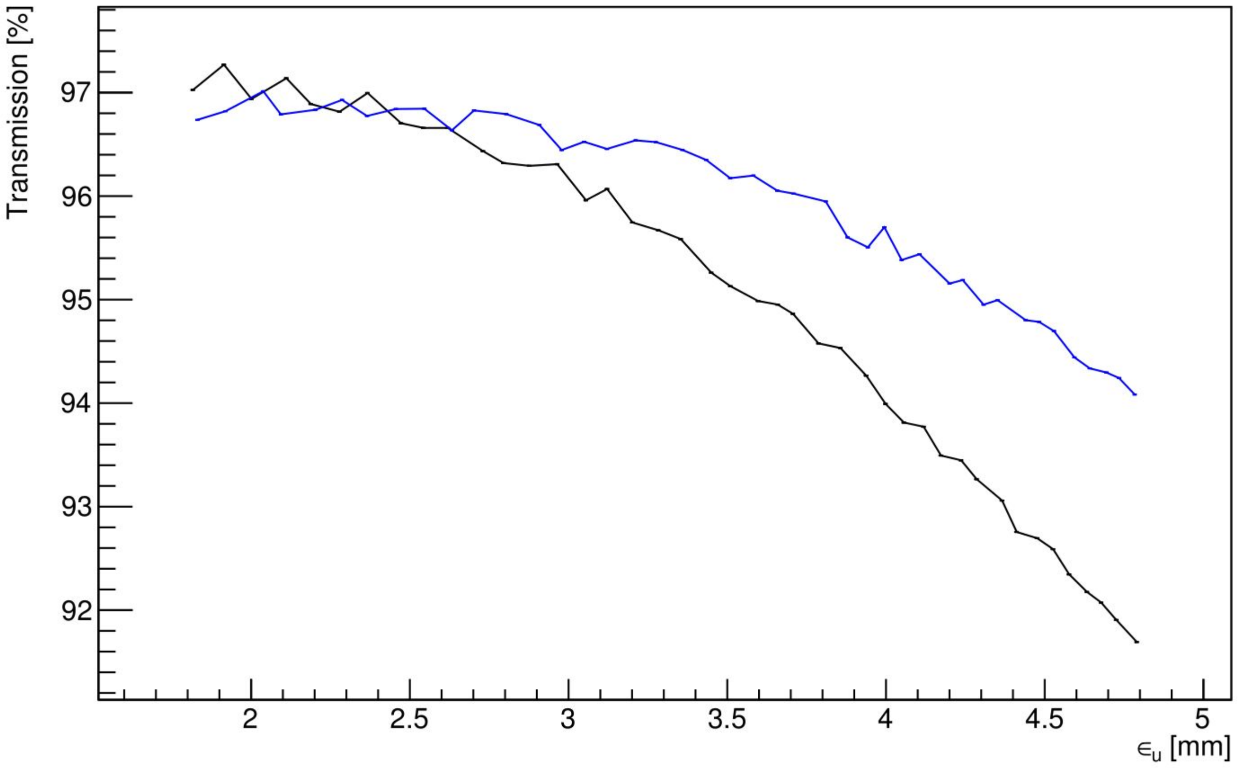
- Upstream
  - 1 SP in both TOF0 and TOF1
  - TOF01 consistent with muon peak
  - Banana plot cut
  - 135 MeV/c < Total momentum < 145 MeV/c
  - $\chi 2$ / ndf < 8
  - Diffuser radius cut: r < 90 mm
  - Fiducial cut: r < 150 mm
- Downstream
  - 90 MeV/c < Total momentum < 170 MeV/c
  - $\chi 2$ / ndf < 8
  - Fiducial cut: r < 150 mm
- **The particles cut downstream are considered as lost between TKU and TKD and thus contribute to the transmission loss (previously)**
- **Events not required to have 1 track in both trackers (previously)**

- Sampling routine is applied to the upstream ensemble
- Sampling parameters: α = 0.0, β = 310 mm, ϵ = [1.8, 6.0] mm, L = 1.1
- Show here is number of particles in the sampled (daughter) beams for both LH2 and No absorber cases



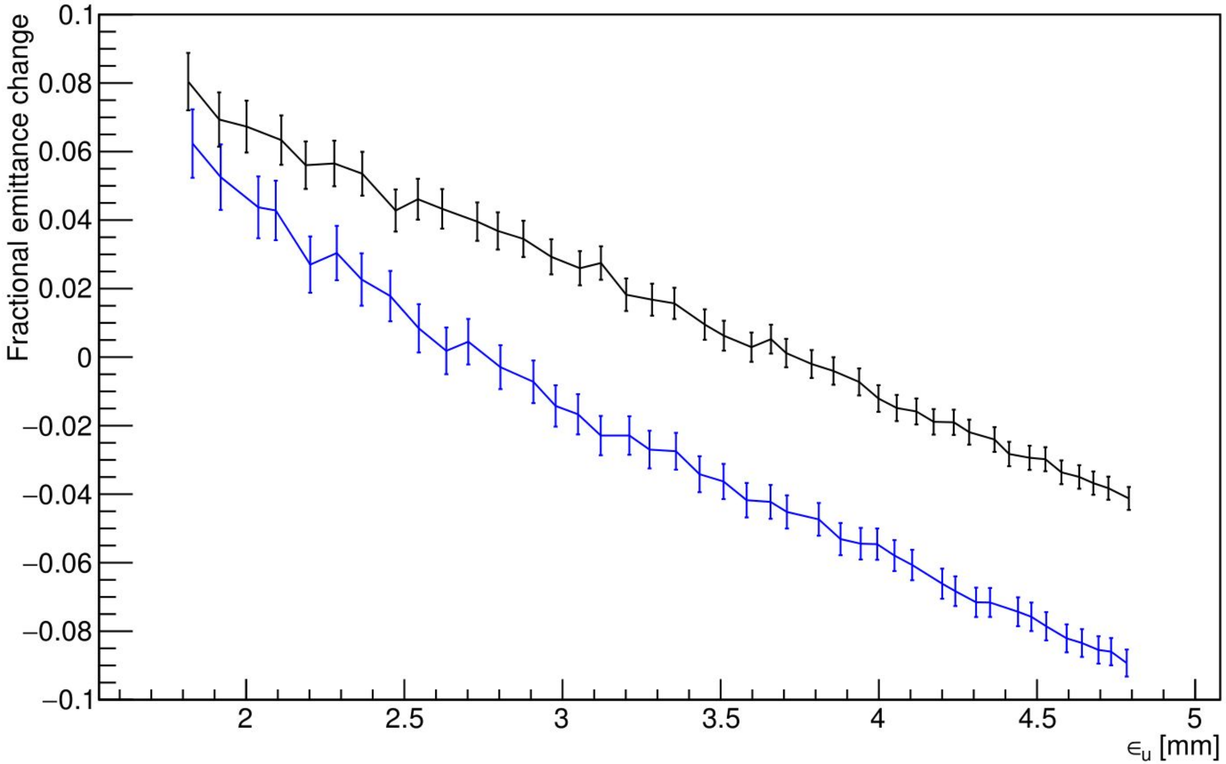
Transmission

- Blue - LH2
- Black - No absorber
- Calculated equilibrium emittance (for β ~ 540 mm) is ~ 2.4 mm
- Cooled beams present better transmission above the equilibrium emittance



Fractional emittance change

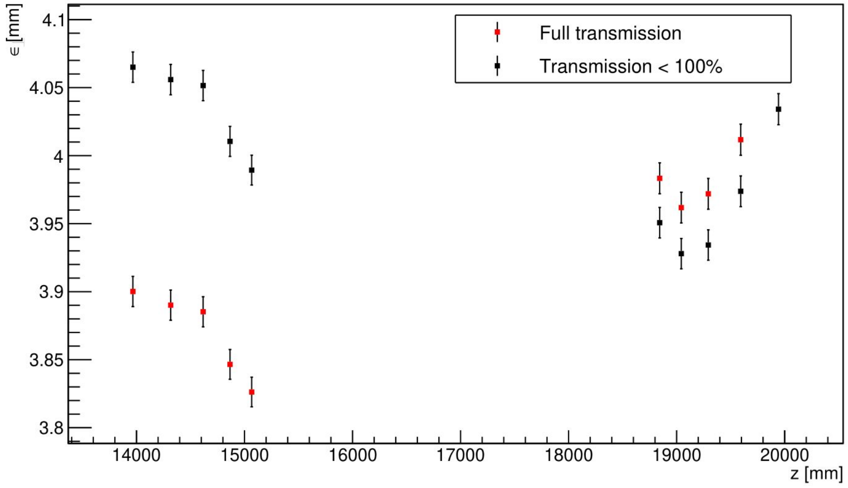
- Blue - LH2
- Black - No absorber
- Bias due to particle loss (we observe more cooling)



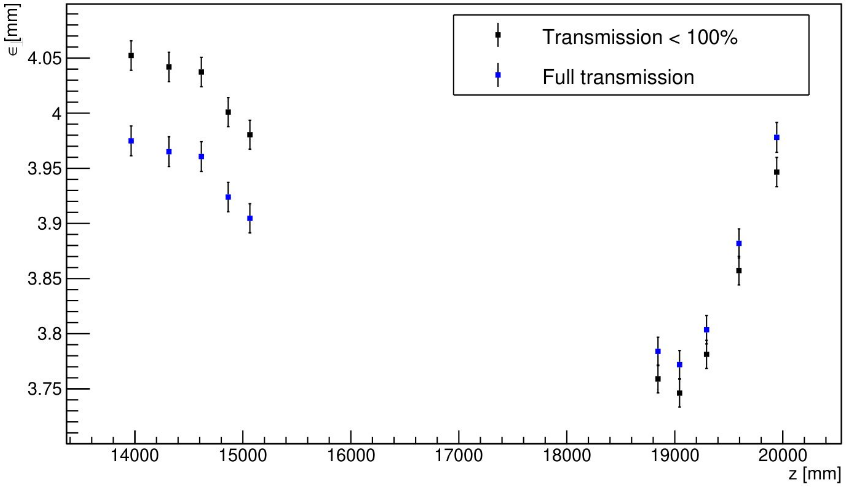
Full transmission

- Switched focus to a full transmission analysis
- **Only events that have 1 track in both trackers and that survive BOTH upstream and downstream cuts are kept**
- Bias due to particle loss removed. Now emittance is biased by removing the particles that were previously lost in the downstream section due to the presence of the absorber

Effect on reconstructed emittance



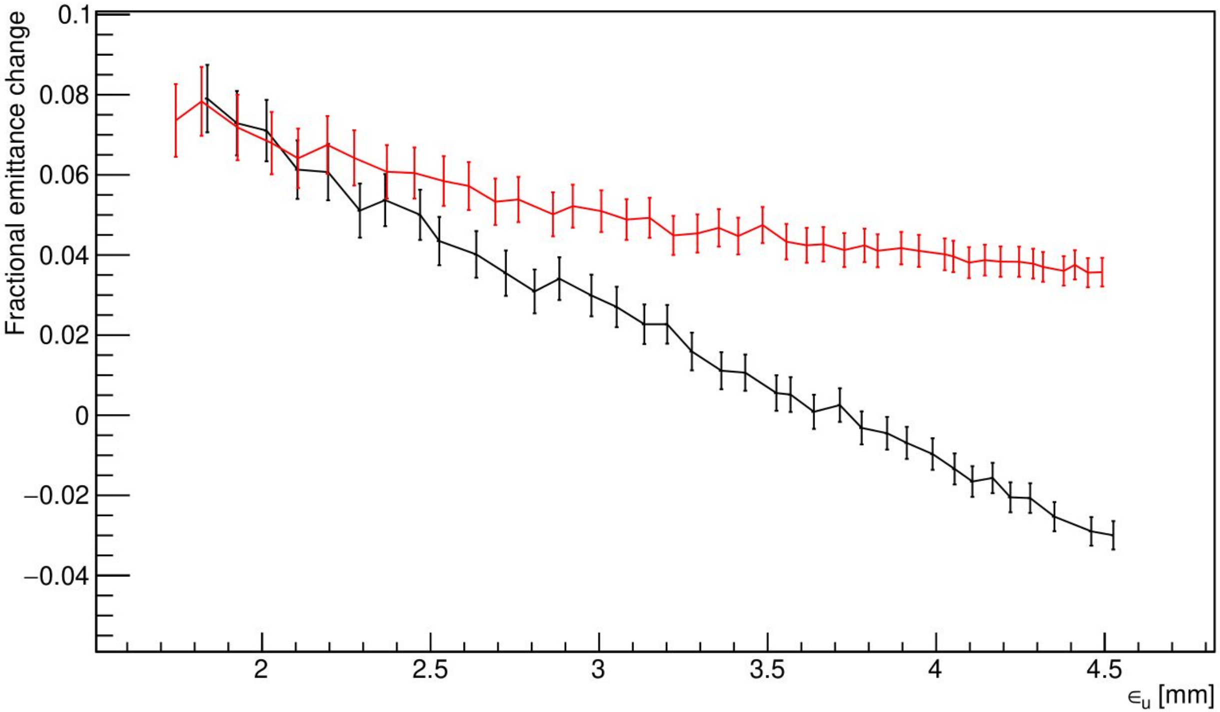
No absorber



LH2

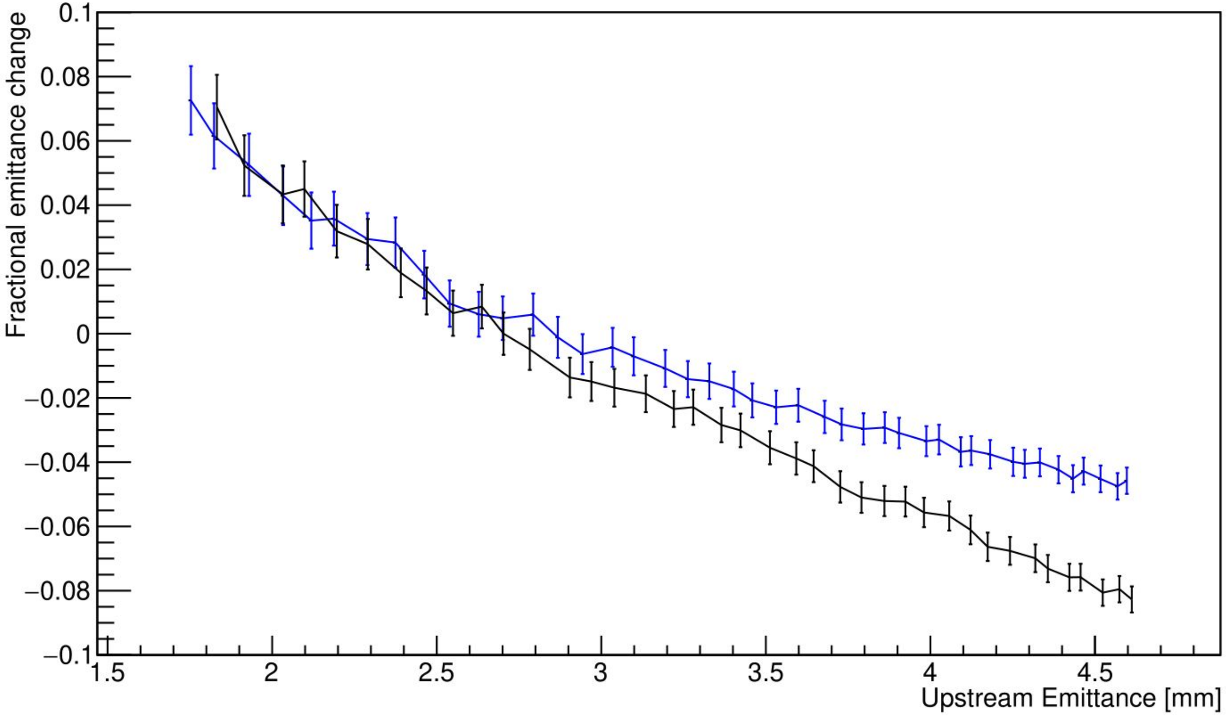
NO ABSORBER

- Black - limited transmission
- Red - 100% transmission; shows (optical) heating is present for all the beams



LH2

- Black - limited transmission
- Blue - 100% transmission



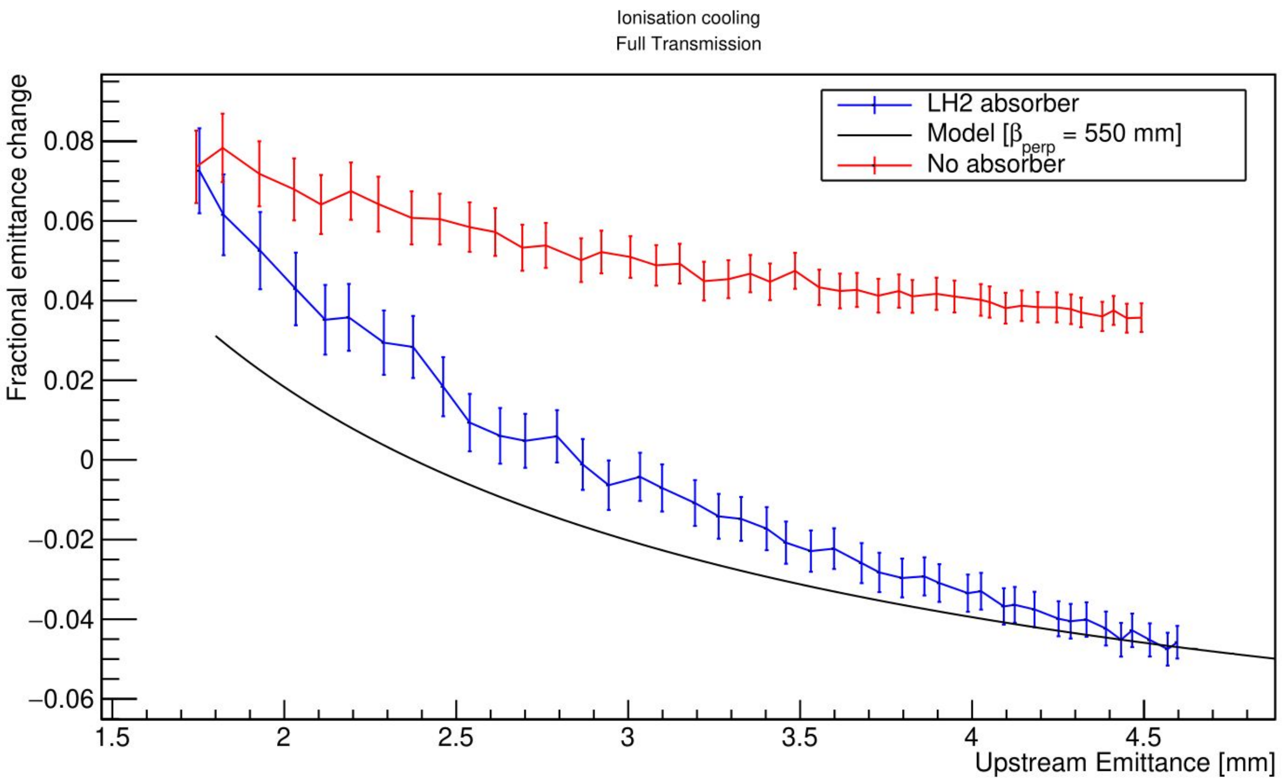
Full transmission - LH2 vs No Abs vs Theory

- Black line - Theoretical calculation

$$\frac{\Delta\epsilon}{\epsilon_u} = (1 - e^{-az})(\frac{\epsilon_{eqm}}{\epsilon_u} - 1)$$

where ***a*** is the cooling term in the cooling term in the cooling eqn. and ***z*** is the mean path length through the absorber

- Equilibrium emittance expected at 2.4 mm; observed at ~2.85 mm

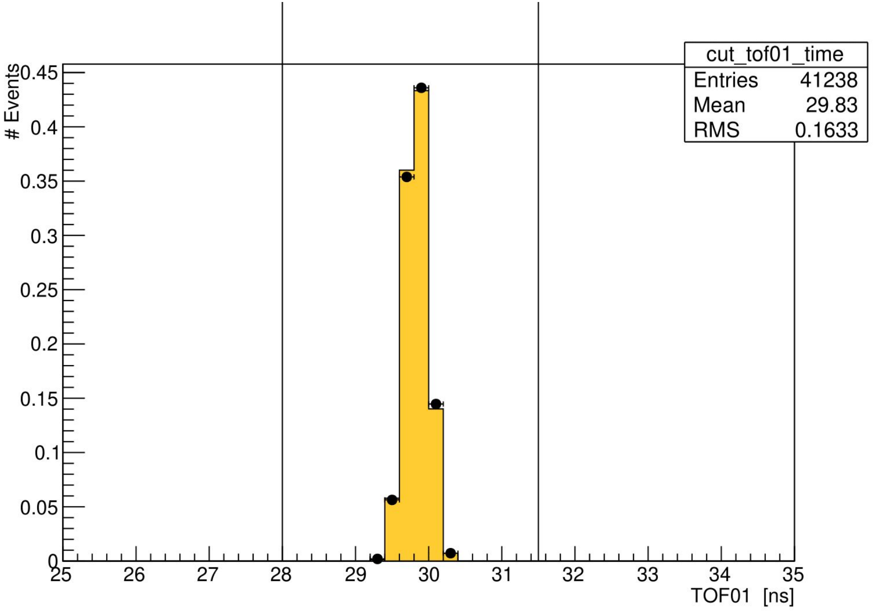


6mm Full LH2 & No absorber Data / MC comparison

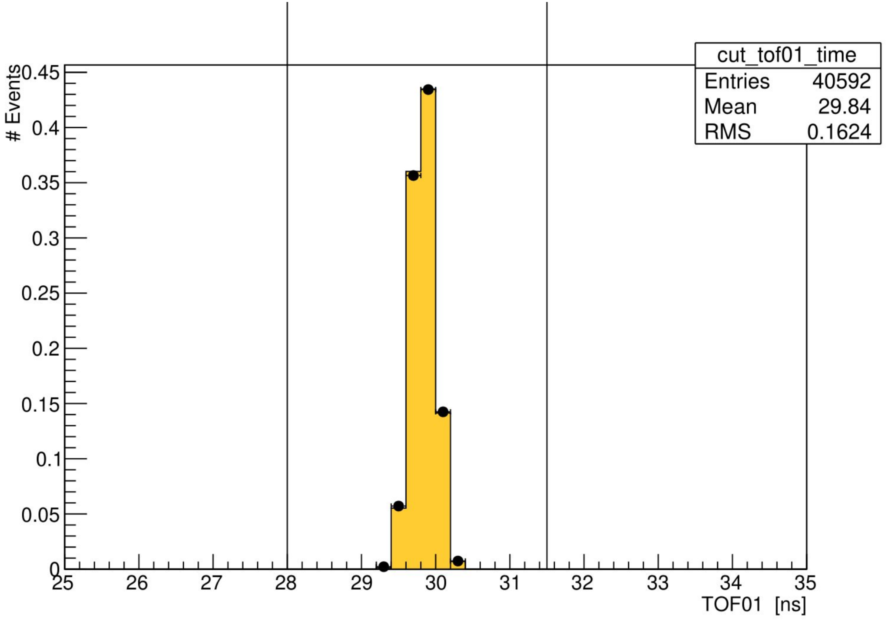
- Full Transmission Analysis
- Used Chris' MC
- Applied the beam sampling routine (Rejection Sampling) to the parent beam that survived the same set of cuts as the data

Parent beams comparison

TOF01

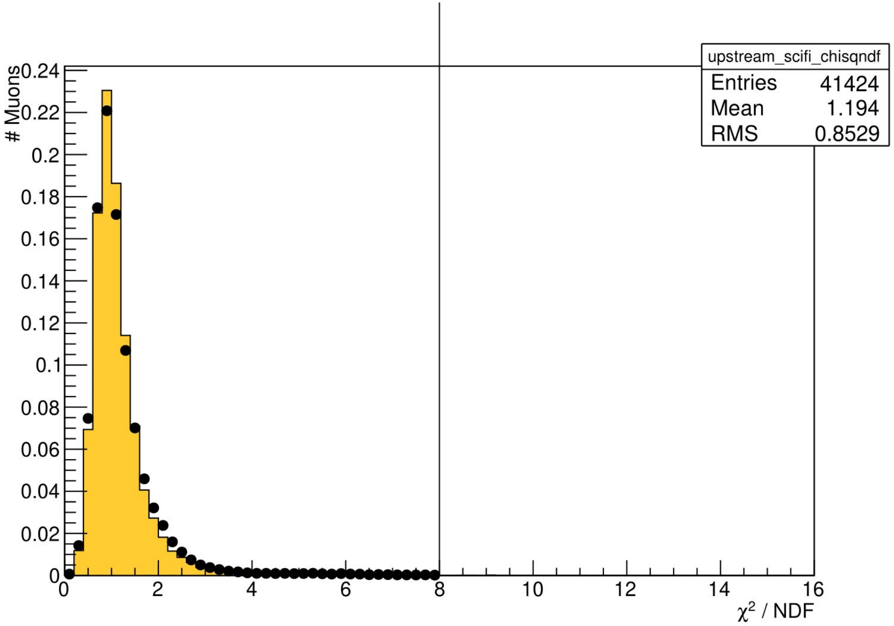


LH2

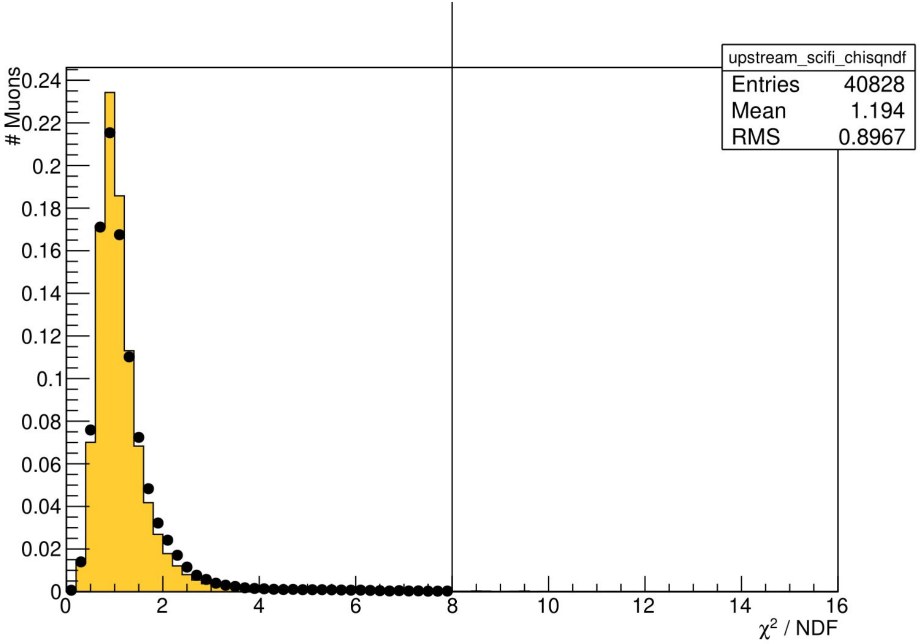


No absorber

TKU $\chi2$ / ndf

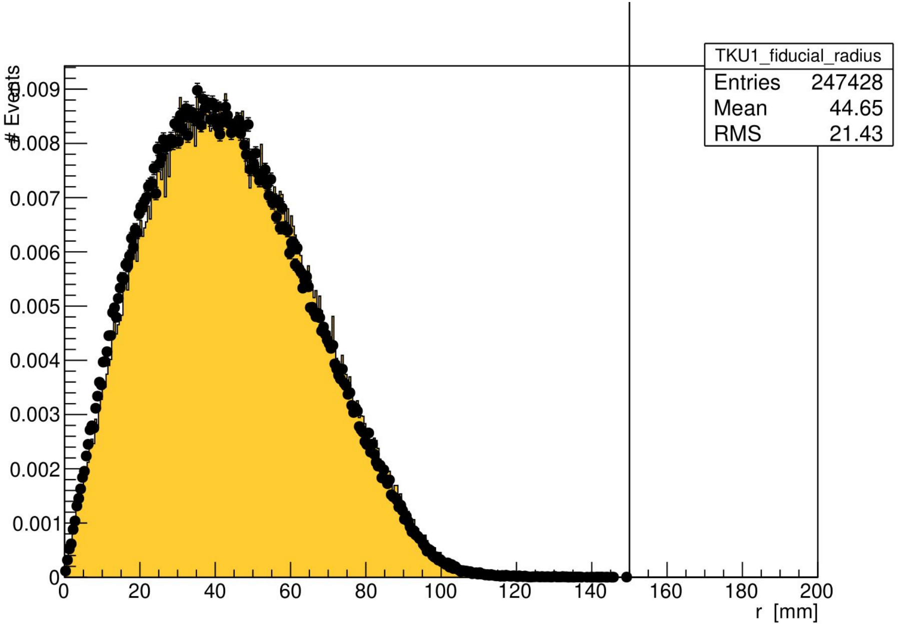


LH2

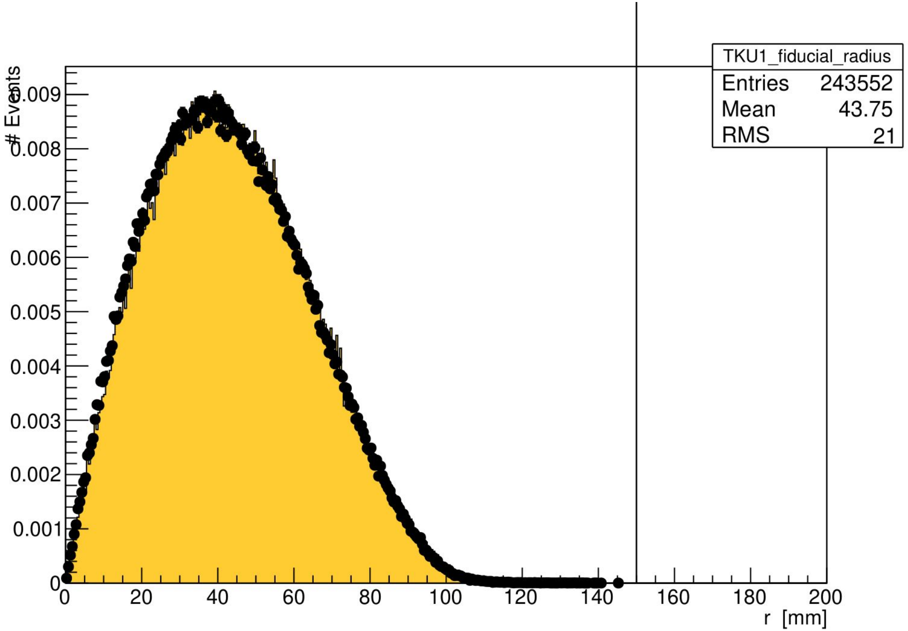


No absorber

TKU fiducial cut

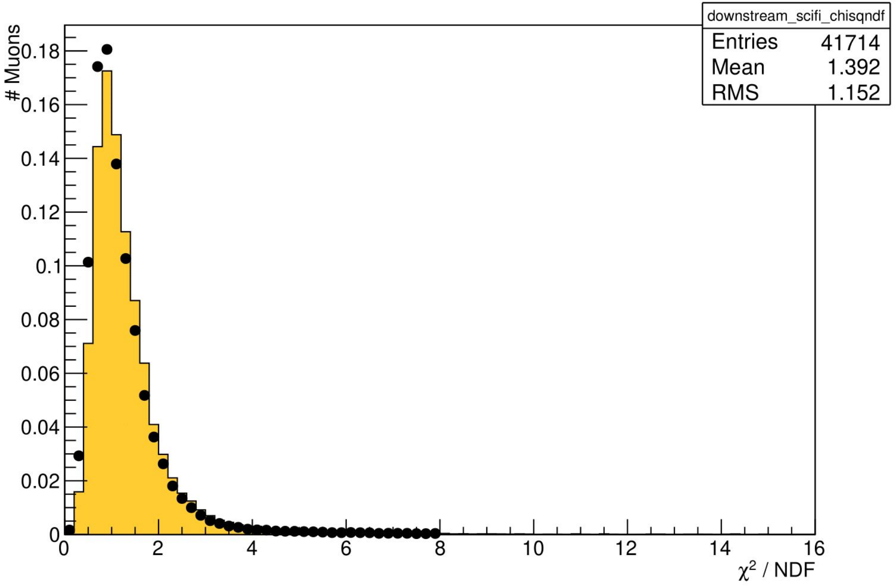


LH2

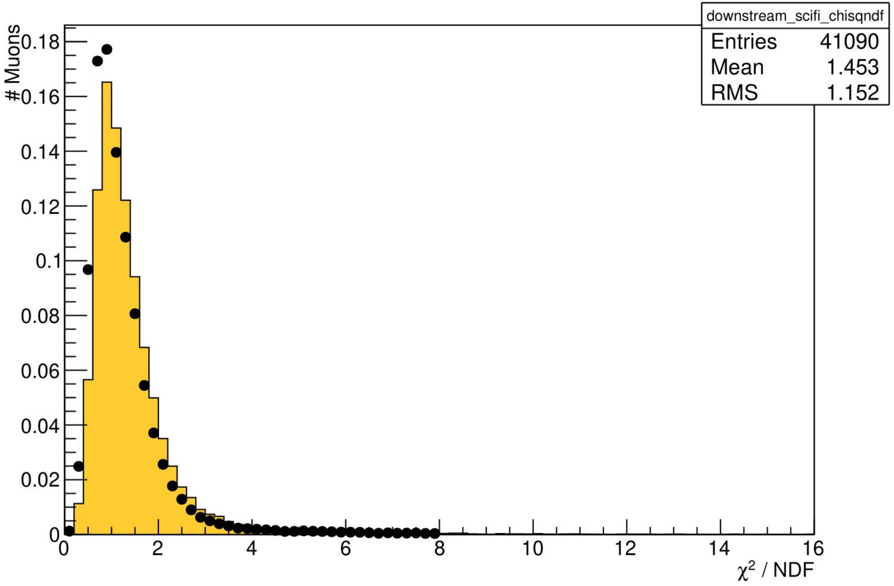


No absorber

TKD $\chi 2$ / ndf

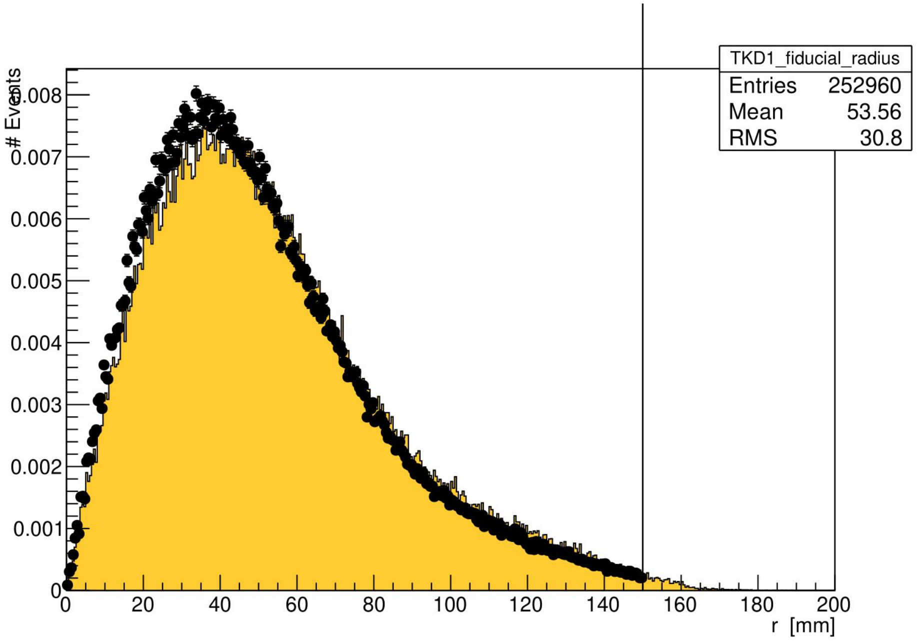


LH2

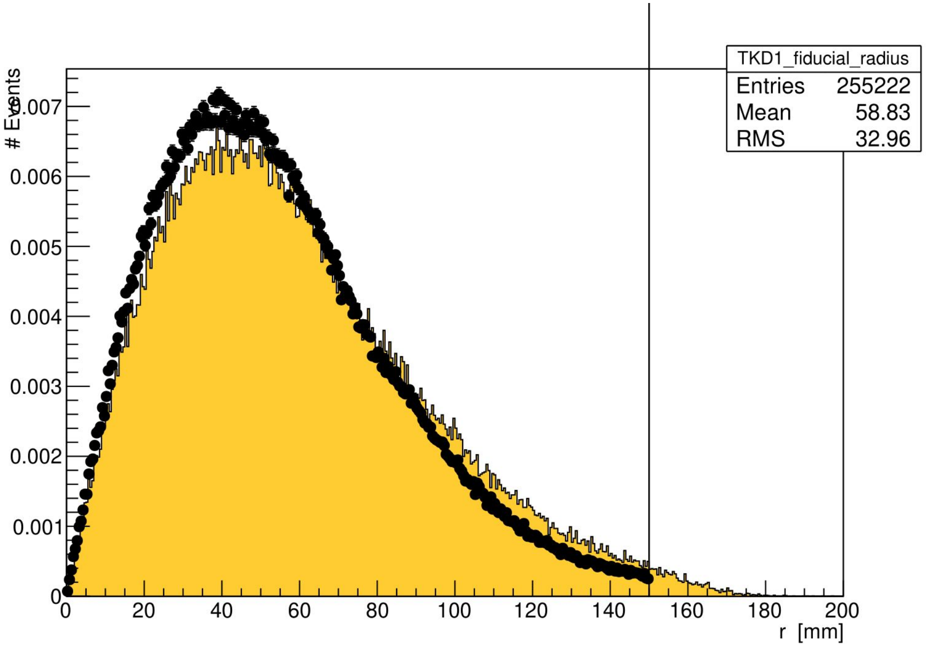


No absorber

TKD fiducial cut

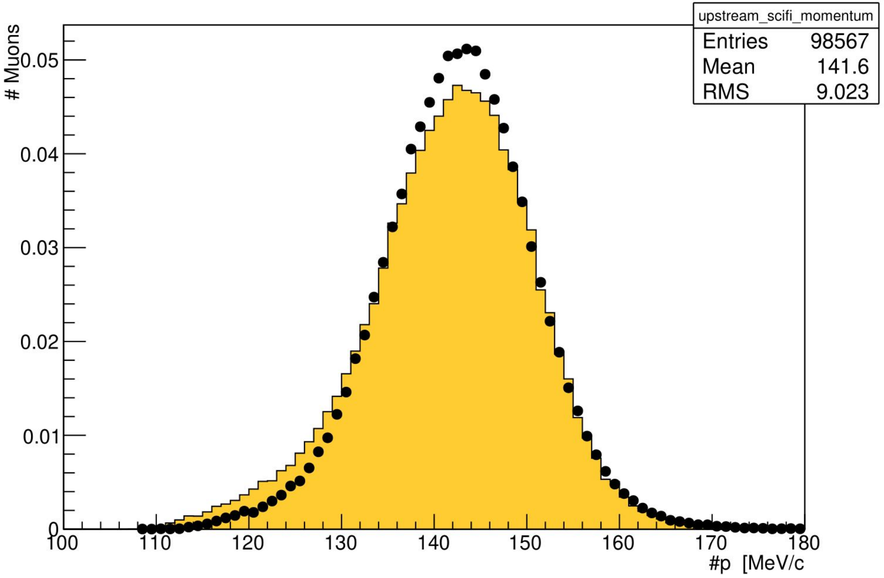


LH2

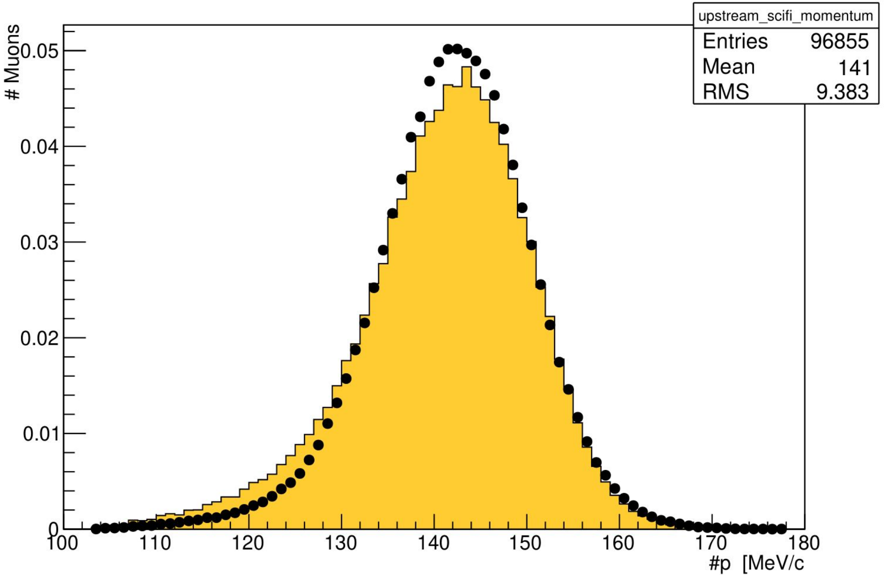


No absorber

TKU Momentum

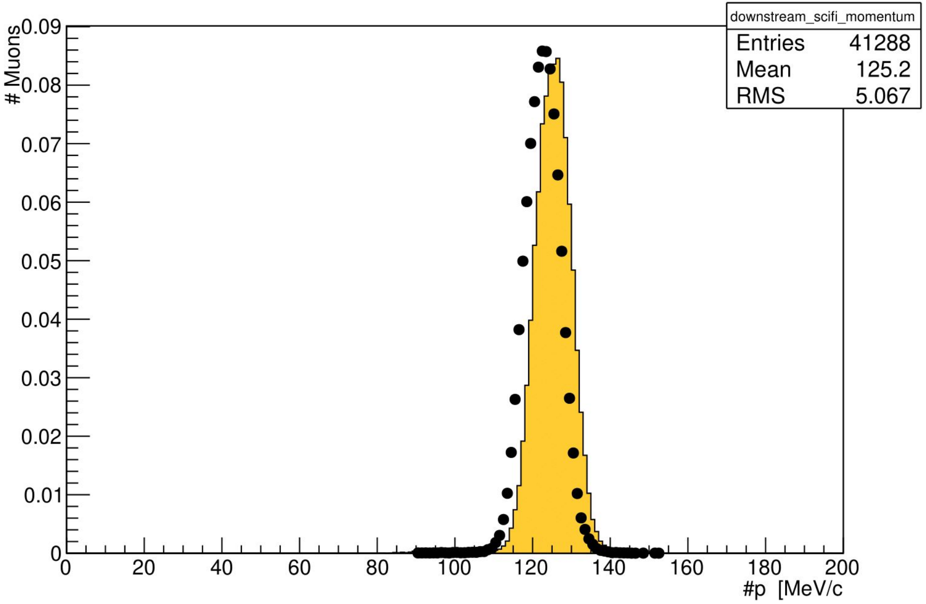


LH2

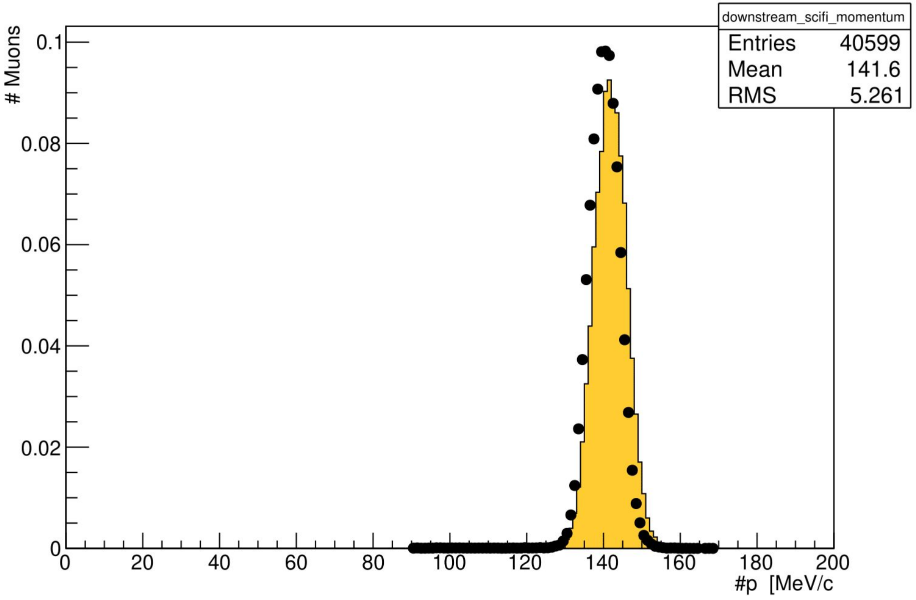


No absorber

TKD Momentum

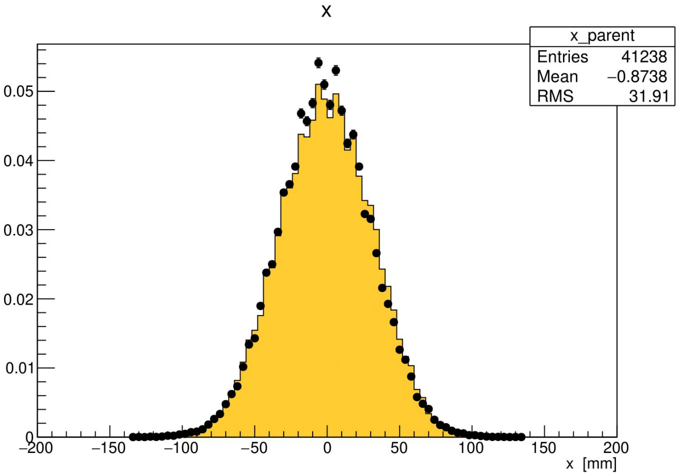


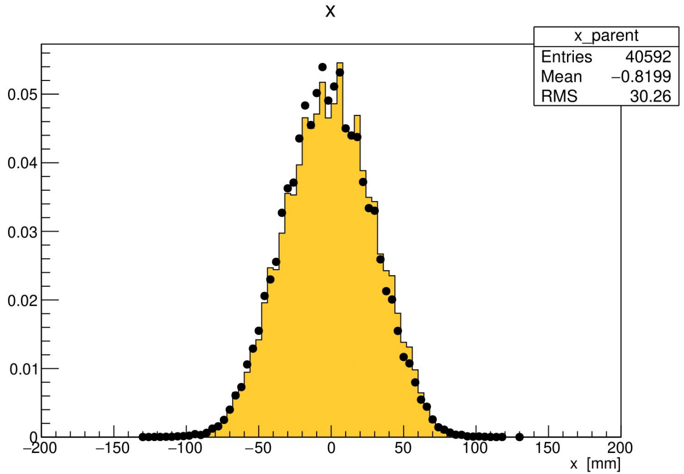
LH2



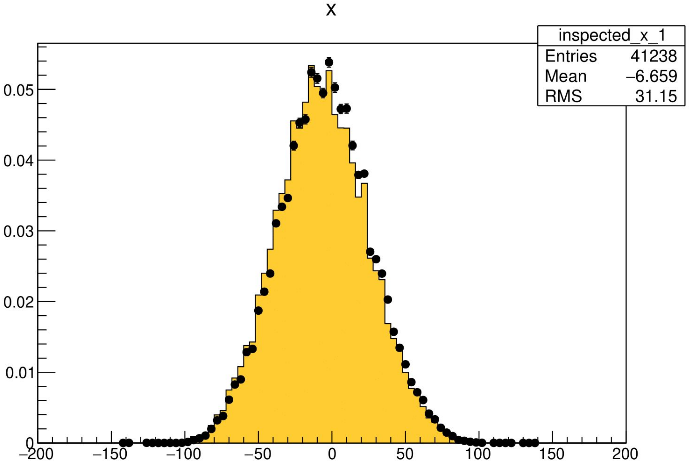
No absorber

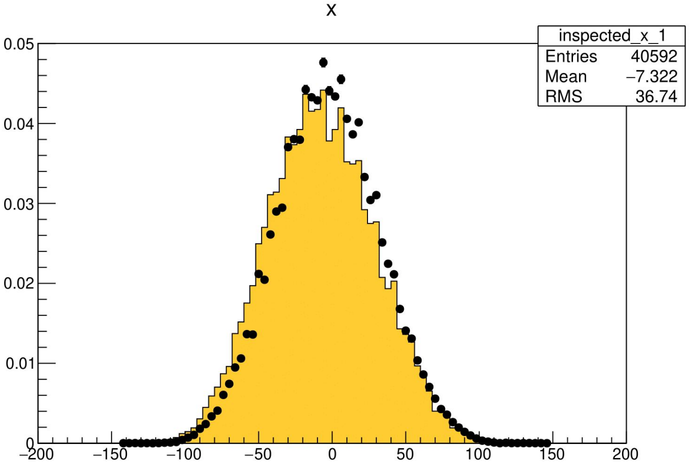
TKU





TKD

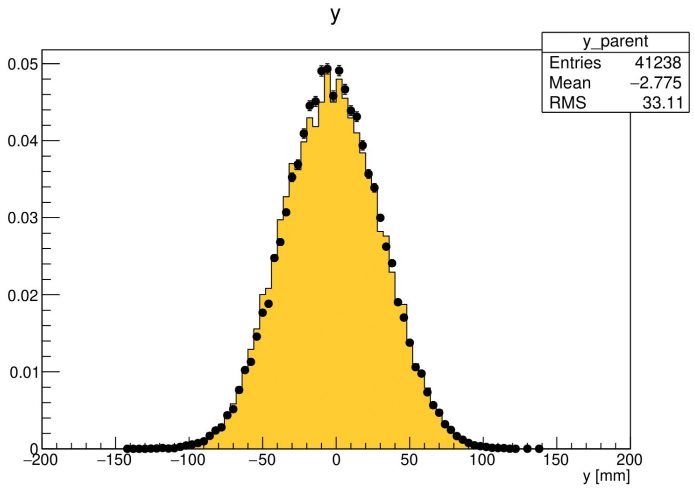


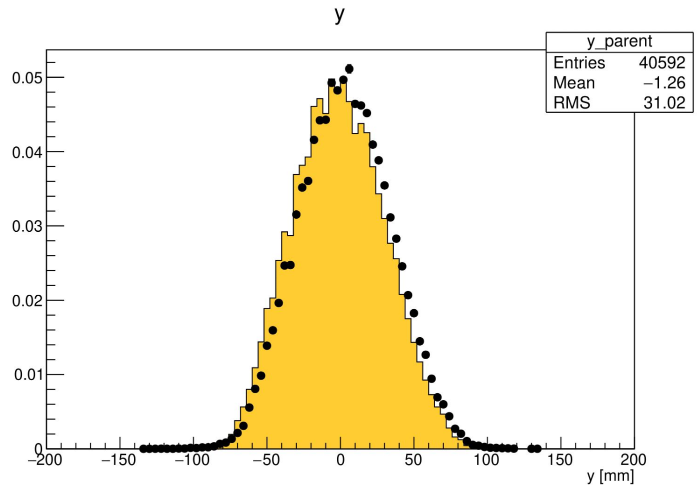


LH2

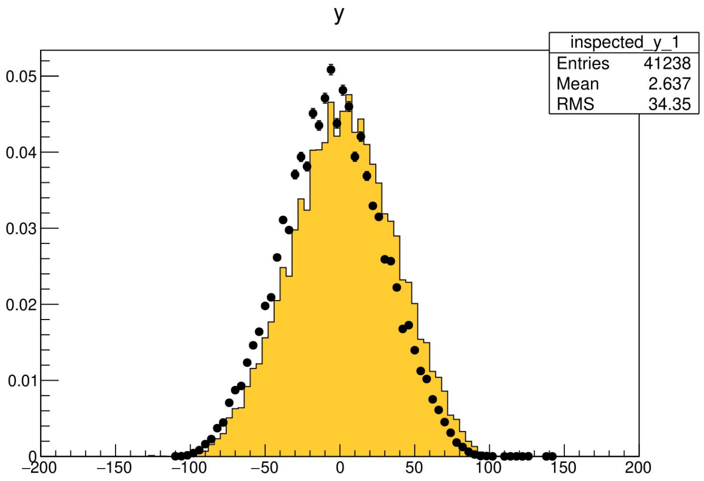
No absorber

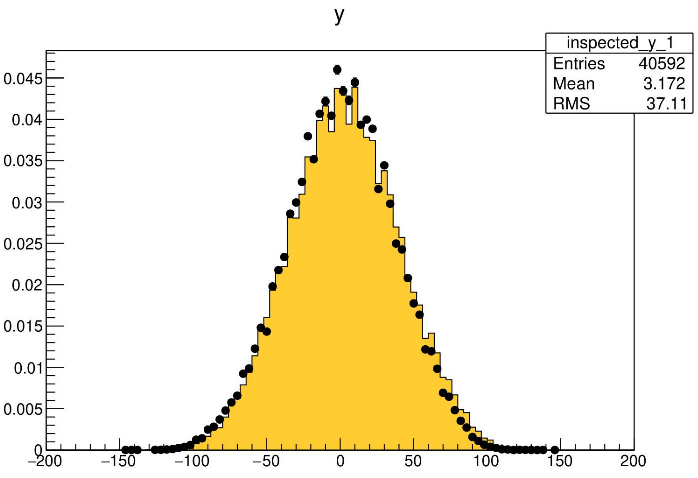
TKU





TKD



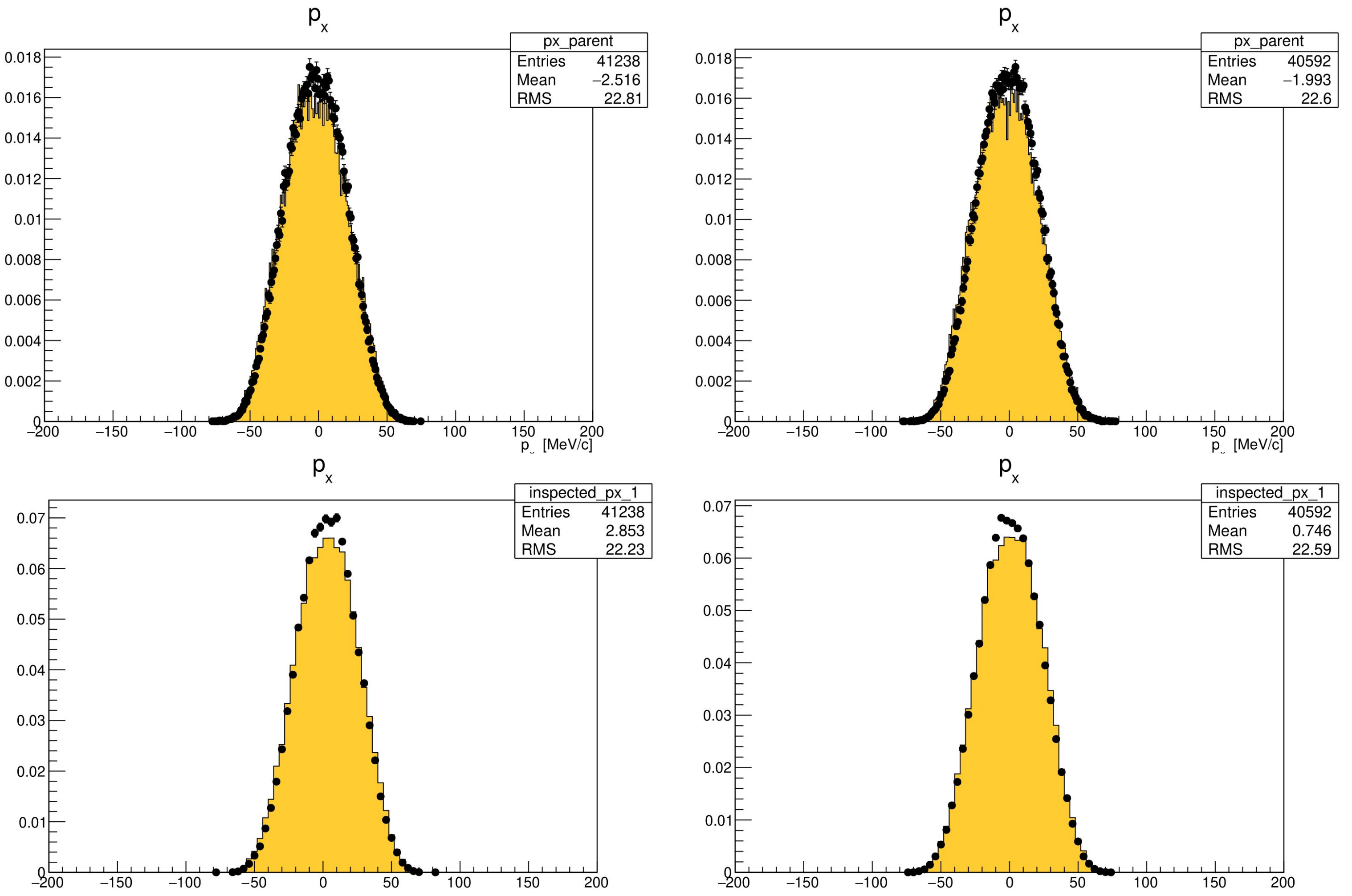


LH2

No absorber

TKU

TKD

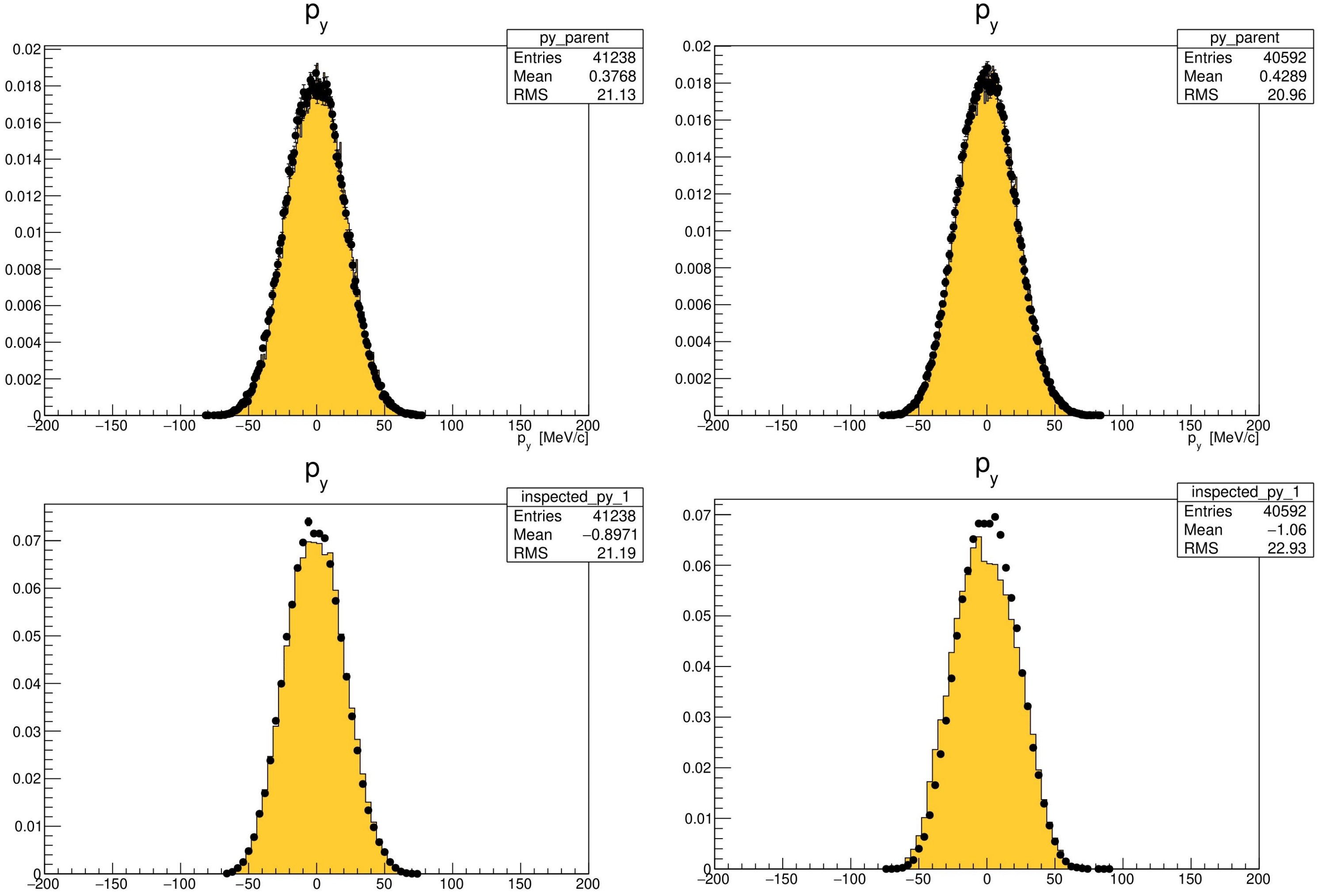


LH2

No absorber

TKU

TKD

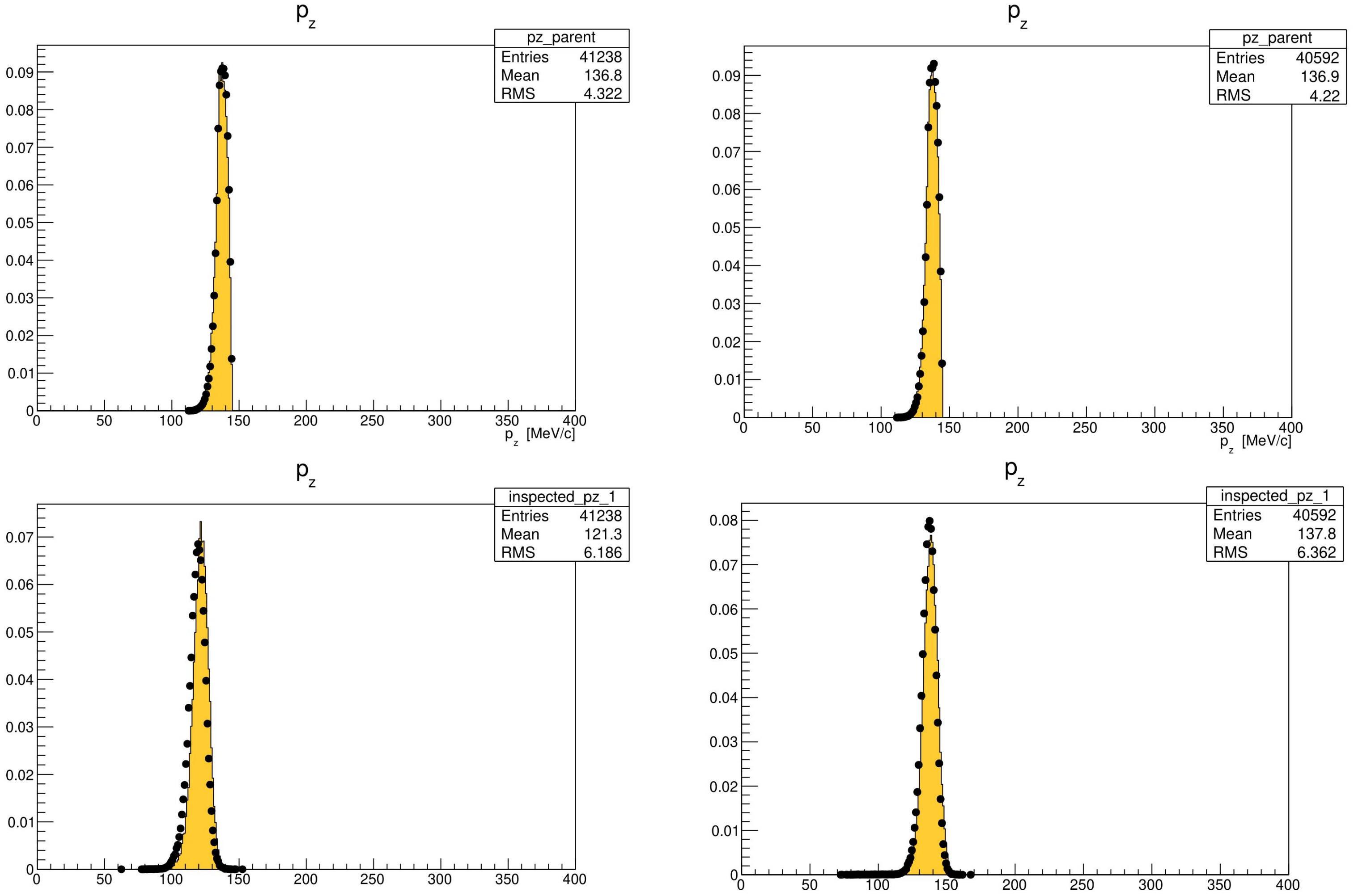


LH2

No absorber

TKU

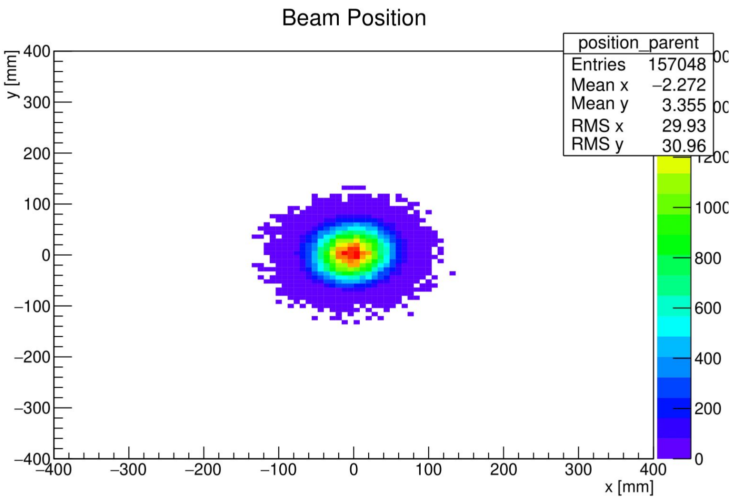
TKD

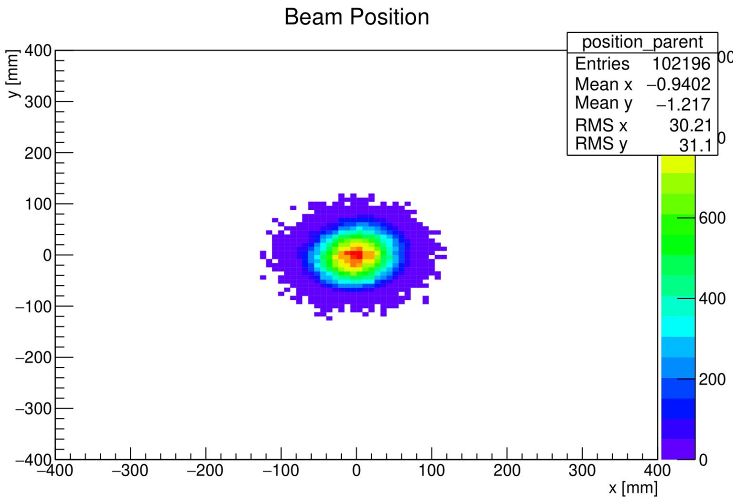


LH2

No absorber

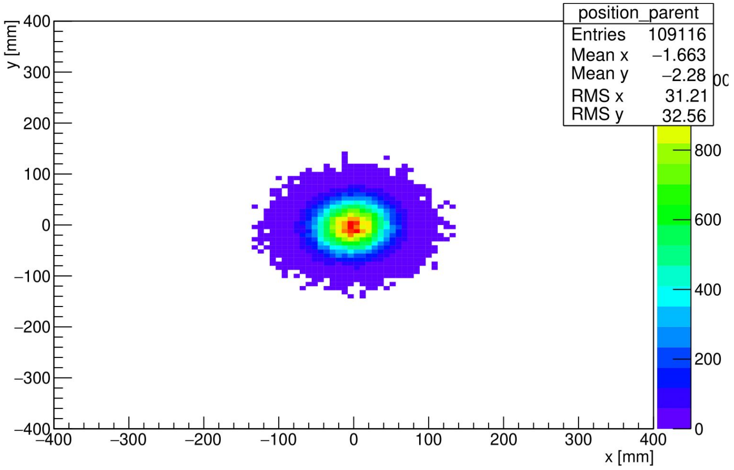
No absorber

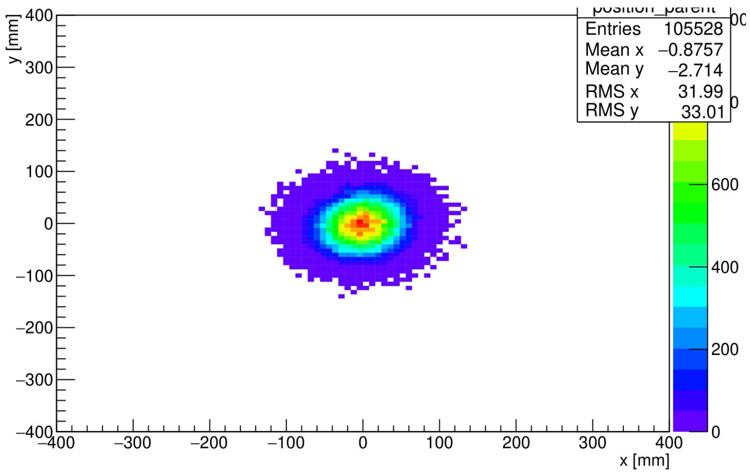




LH2

UPSTREAM





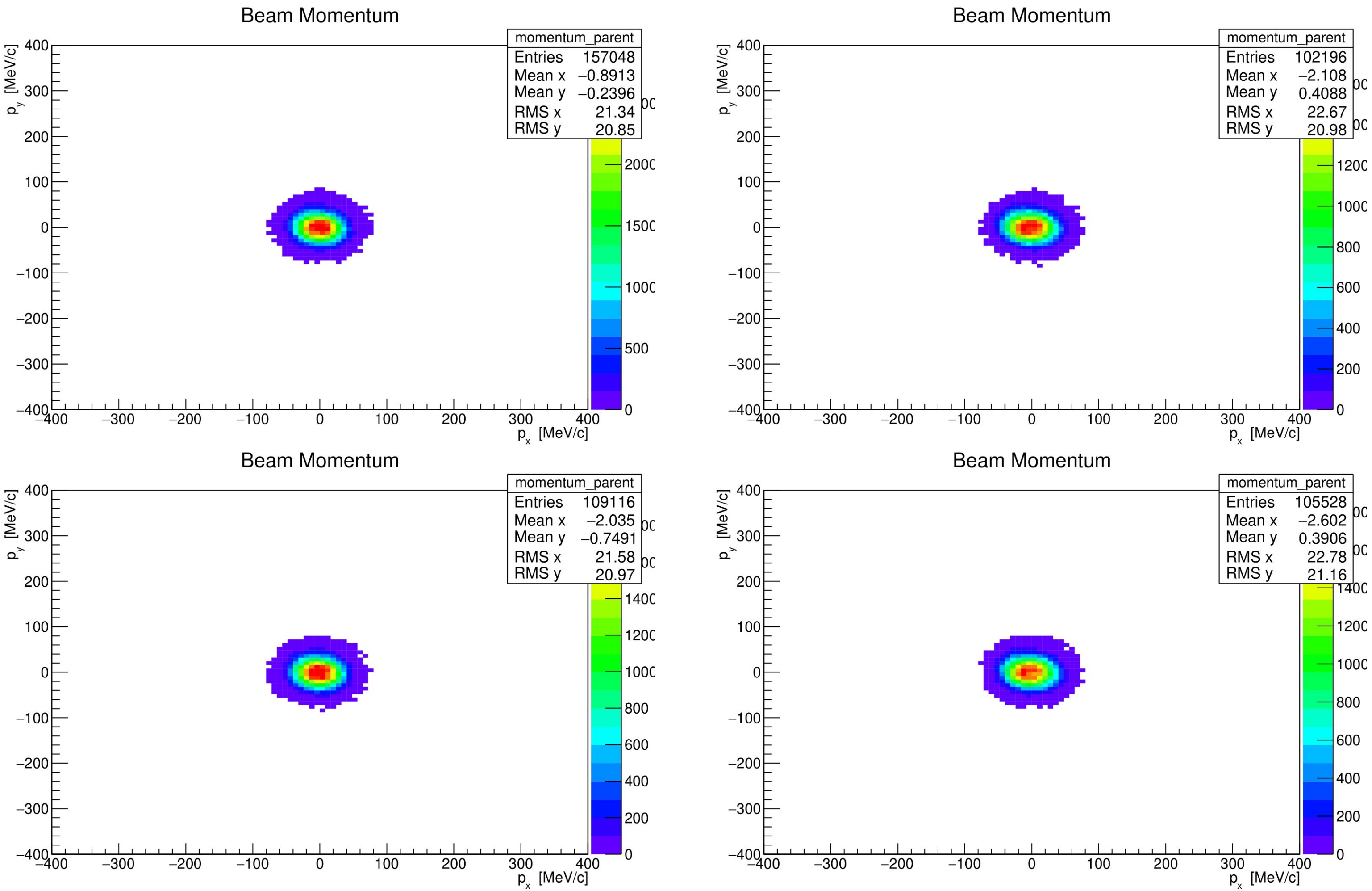
Data

MC

No absorber

LH2

DOWNSTREAM

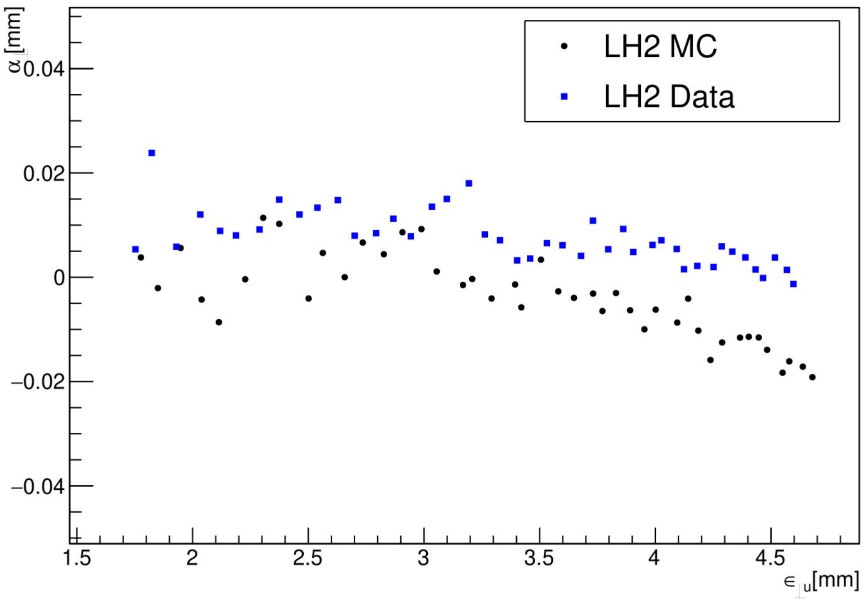


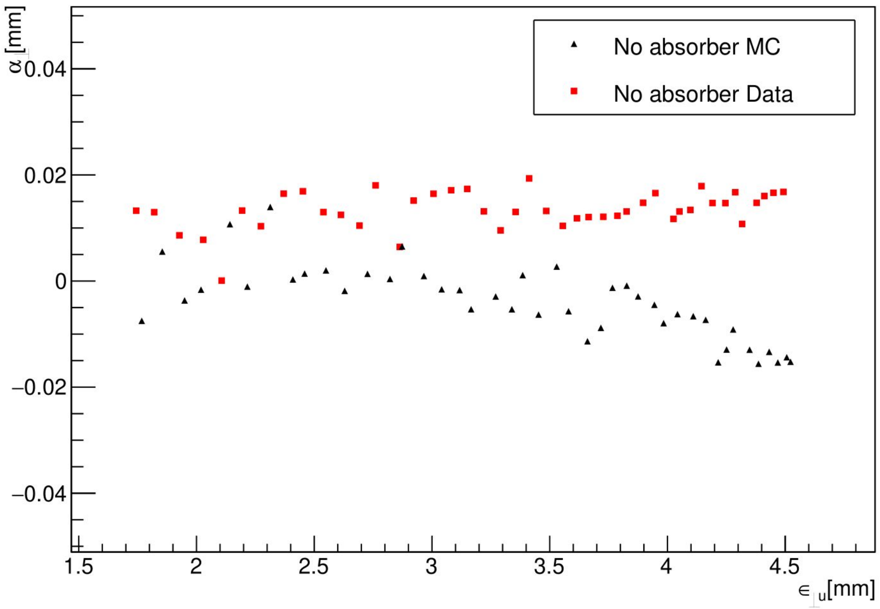
Data

MC

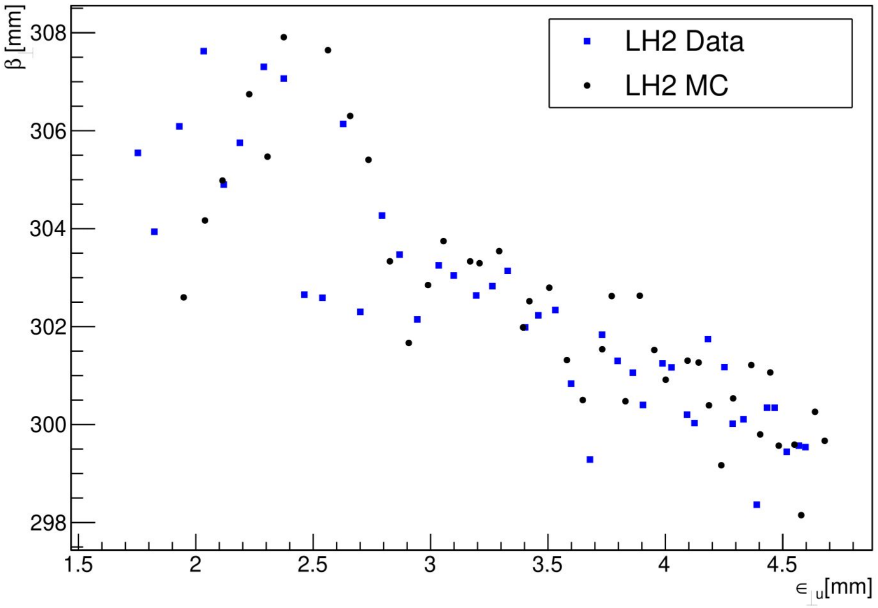
Beam selection

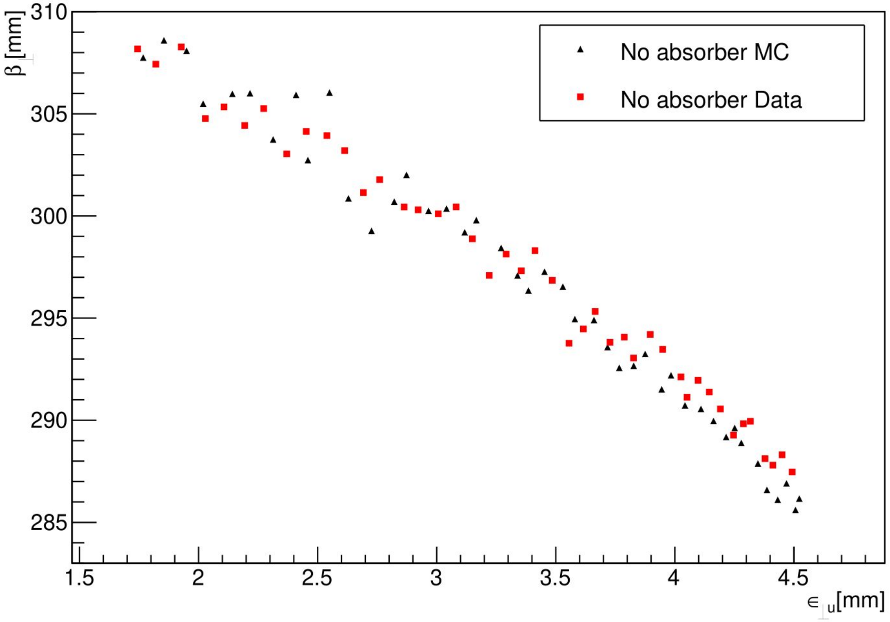
TKU reference plane: daugher beams alpha



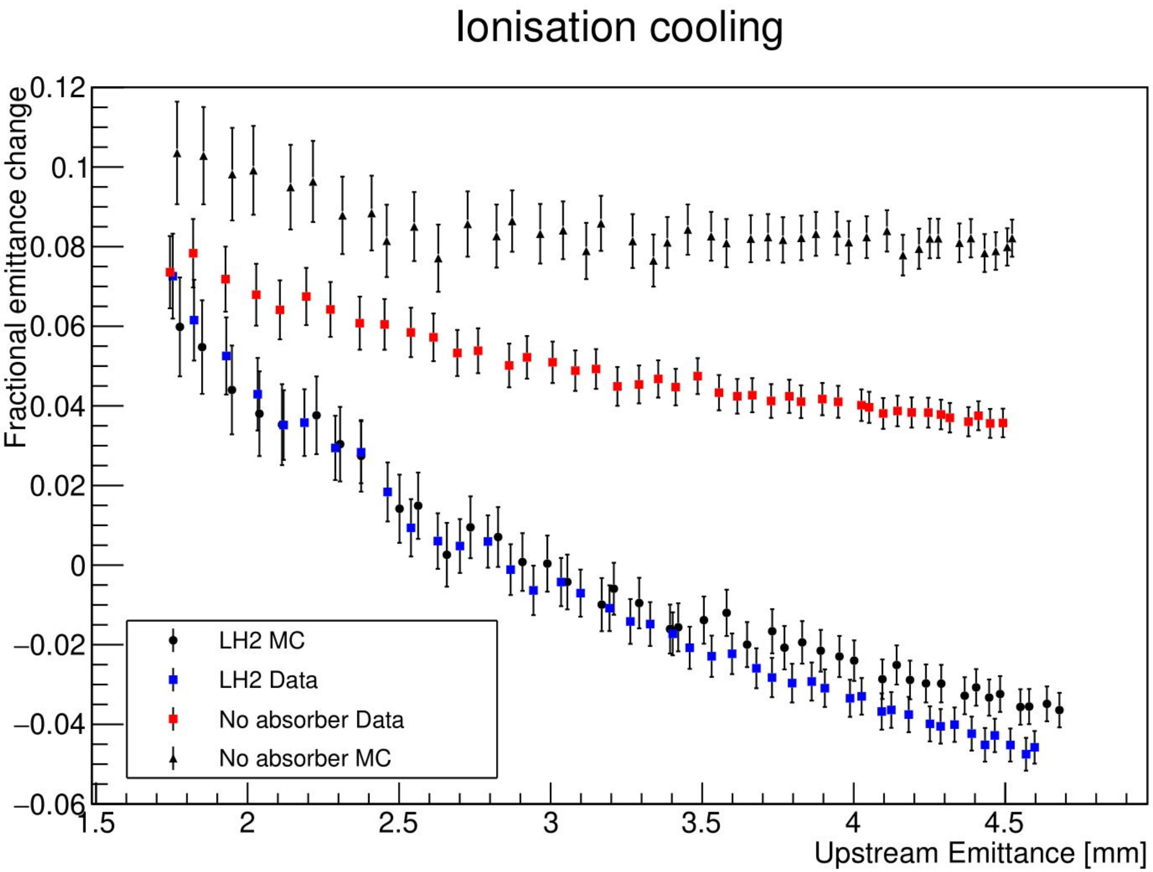


TKU reference plane: daughter beams beta





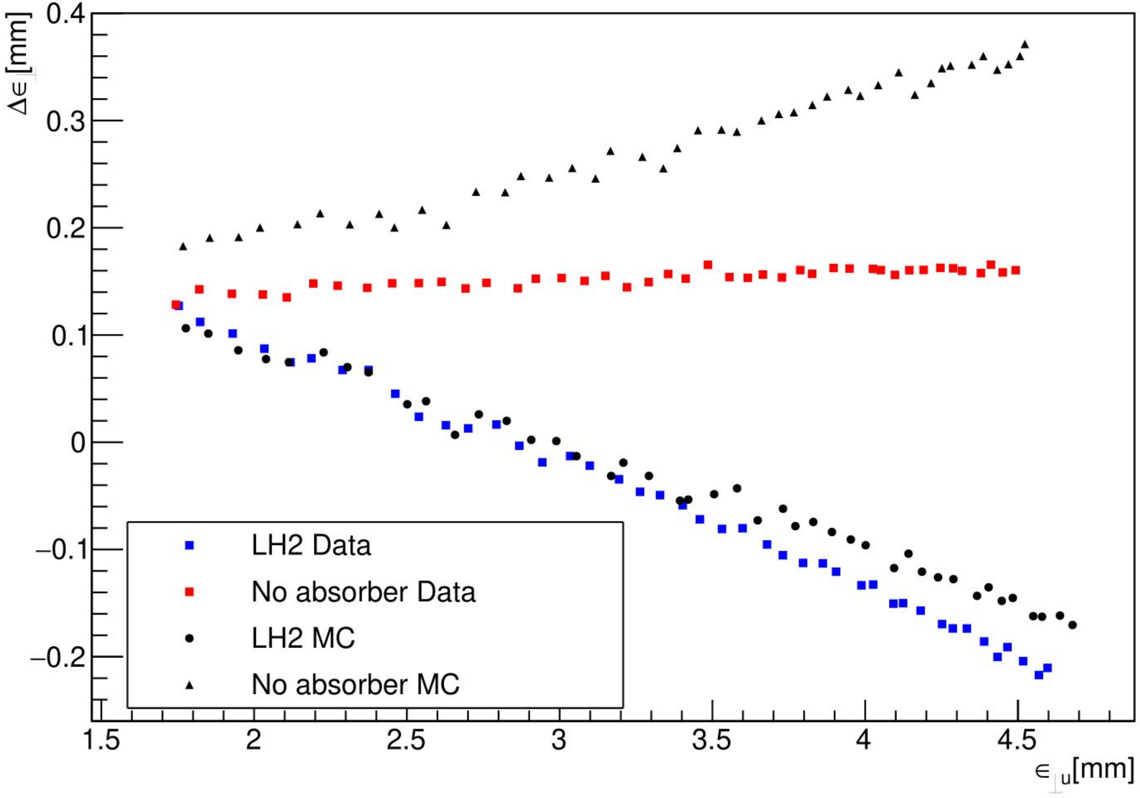
Relative emittance change



Above 3.5 mm, more cooling observed in data than MC. Consistent otherwise.

In the No absorber case, consistently more heating seen in MC. Apparent cause are tail events that are pulling the emittance downstream. Need to double check.

Absolute emittance change



No absorber - in data, heating slightly dependent on emittance. Correlation stronger in MC. Possible cause could be the difference in optics at the upstream -> enhanced exposure to non-linear effects.

LH2 - discrepancy between data and MC occurs for beams with emittance above 3.5 mm. Needs digging.

Hybrid MC (truth) studies required.

Emittance change via core Amplitude Mobility

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 follows:

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

This can then be used to calculate the relative emittance change as follows:

$$\Delta\epsilon_{\perp rel} = \sqrt{(f^u/f^d)} - 1$$

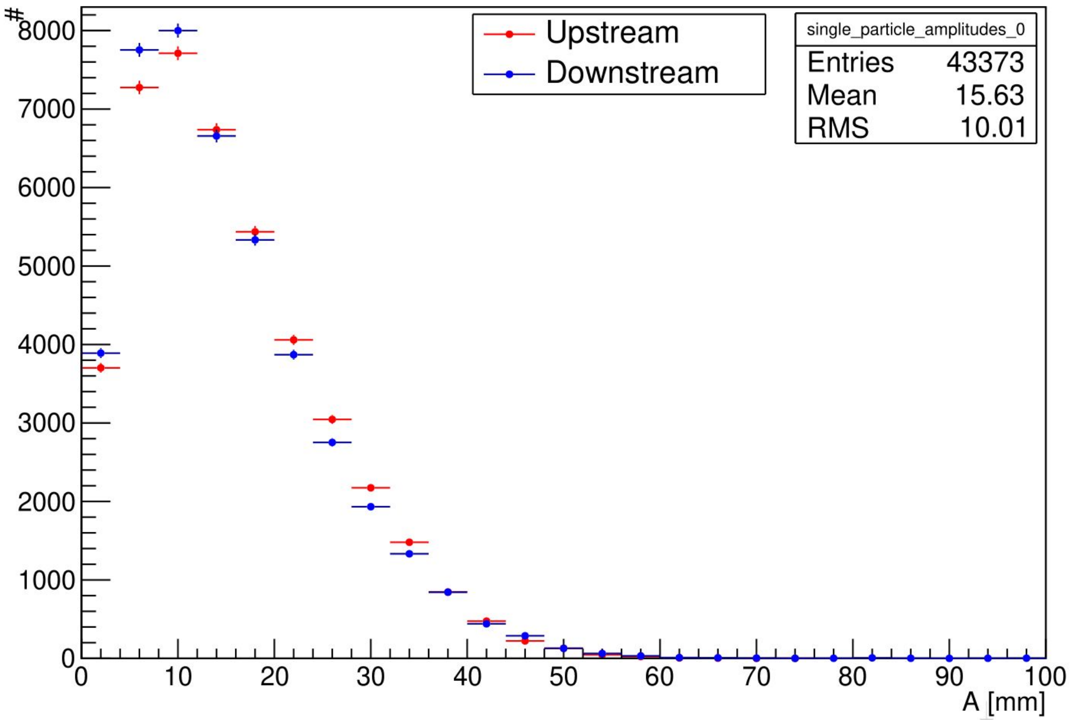
Amplitude distributions - LH2 Data

~ 4 mm emittance sampled beam

Amplitude bin size is 4 mm

Net migration into the core of the beam is observed

NOTE: here amplitudes calculated using the full ensamble covariance matrix

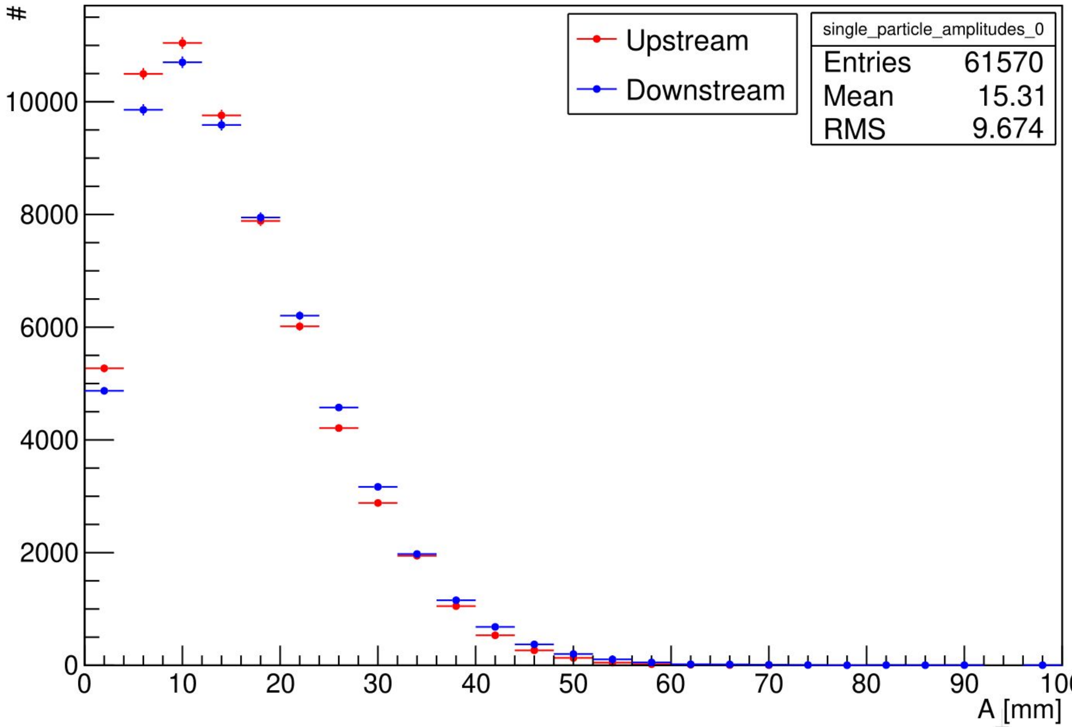


Amplitude distributions - No absorber Data

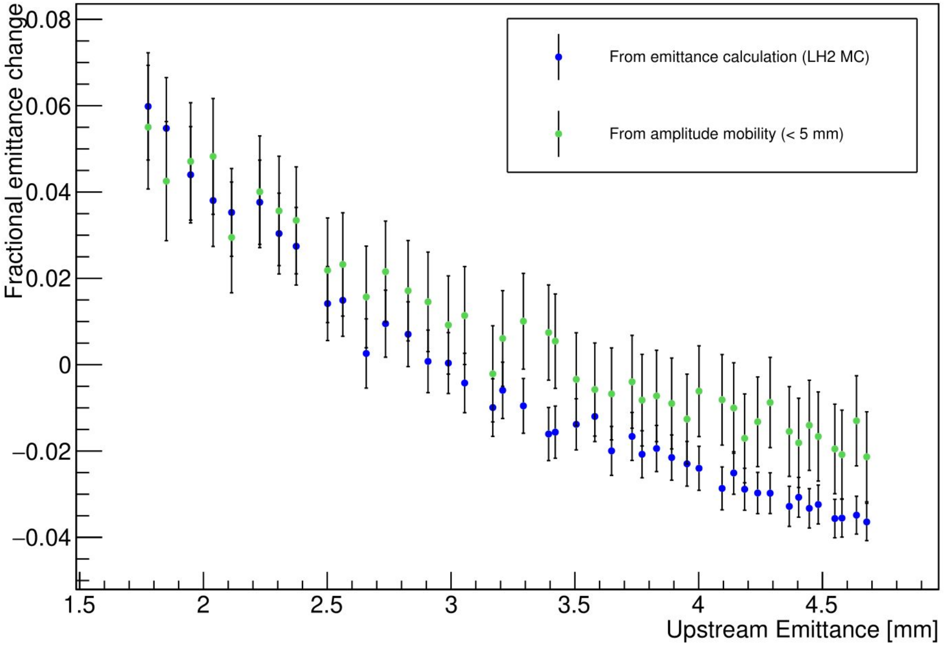
~ 4 mm emittance sampled beam

Amplitude bin size is 4 mm

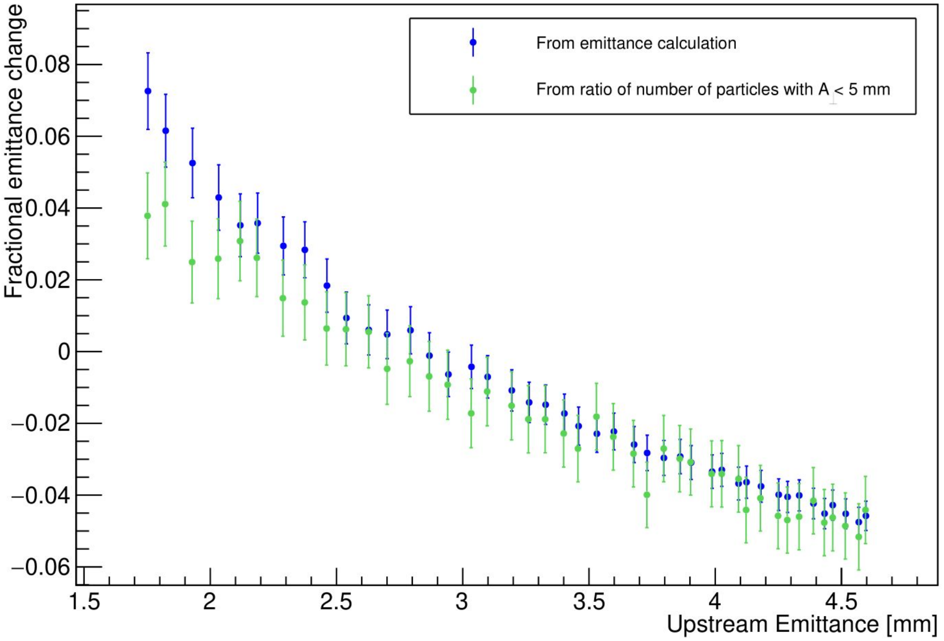
Net migration out of the beam core is observed



5 mm amplitude bins

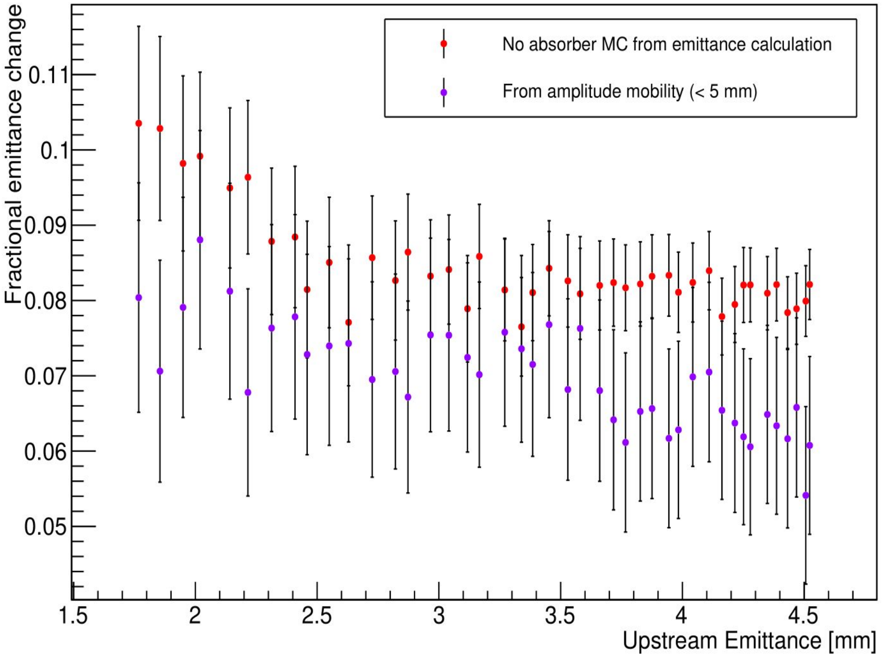


LH2 - MC

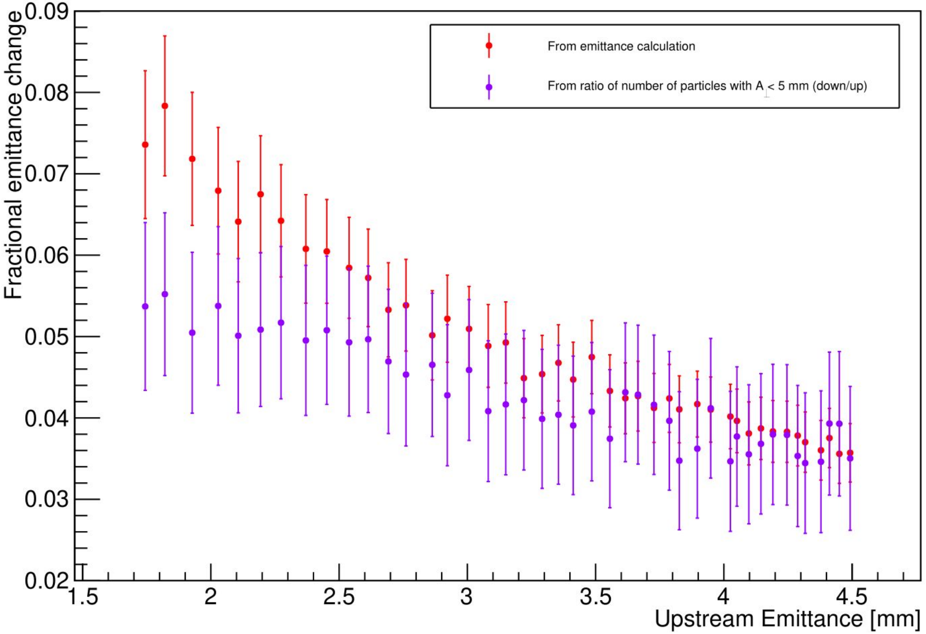


LH2 - Data

5 mm amplitude bins

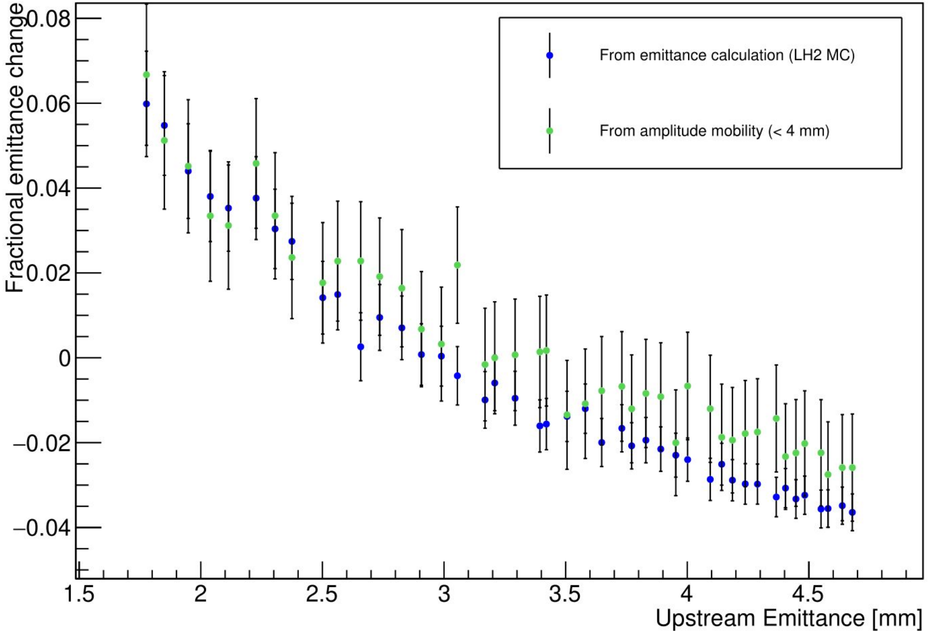


No absorber - MC

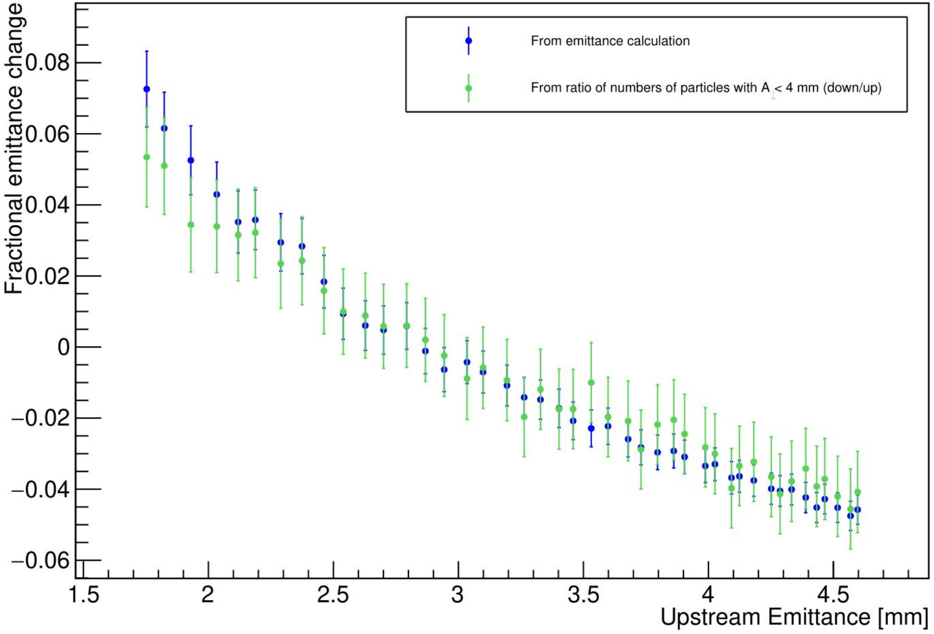


No absorber - Data

4 mm amplitude bins

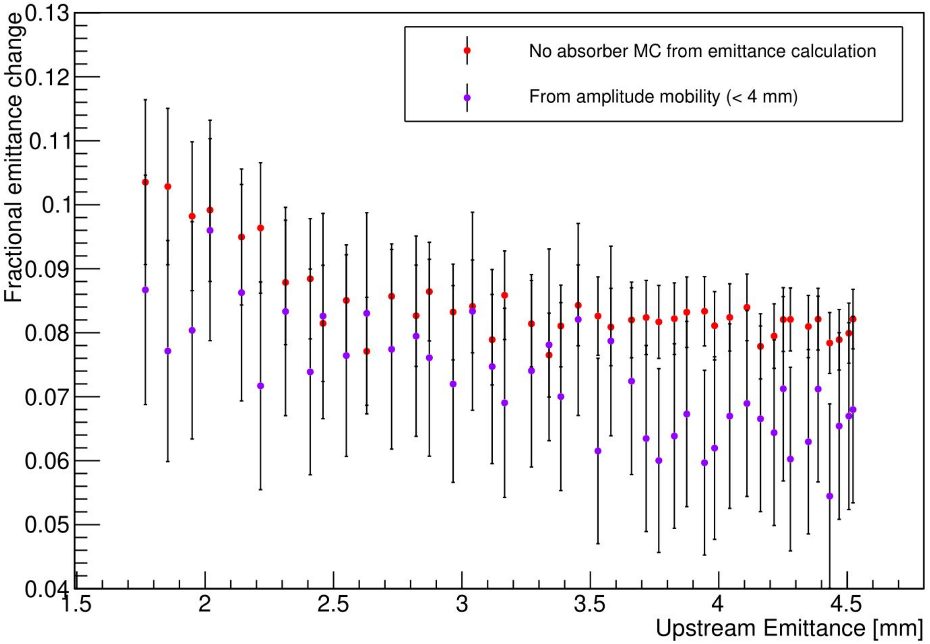


LH2 - MC

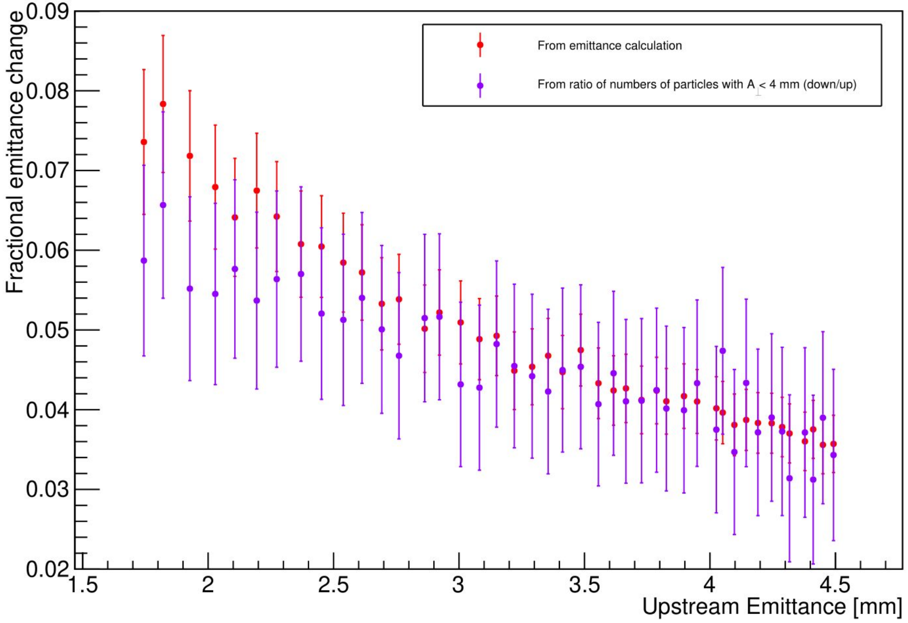


LH2 - Data

4 mm amplitude bins

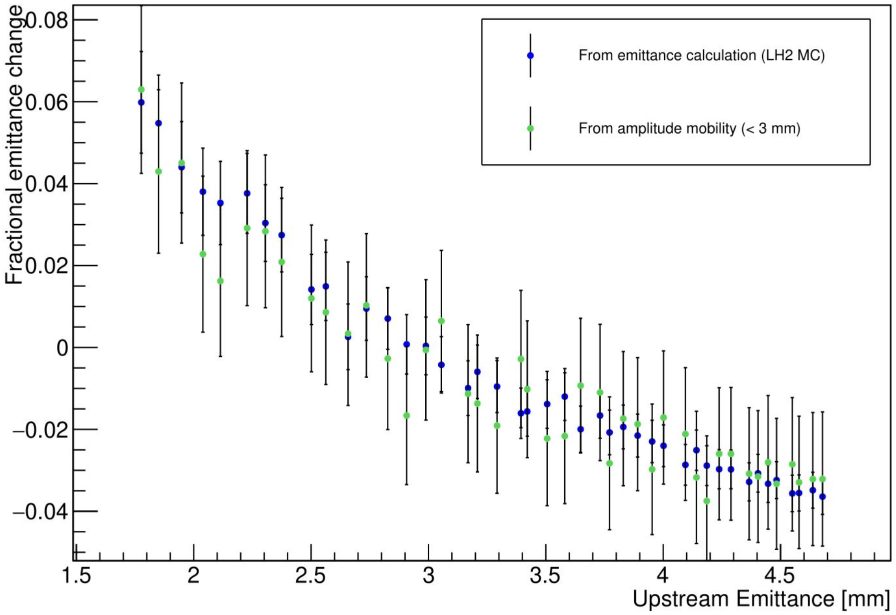


No absorber - MC

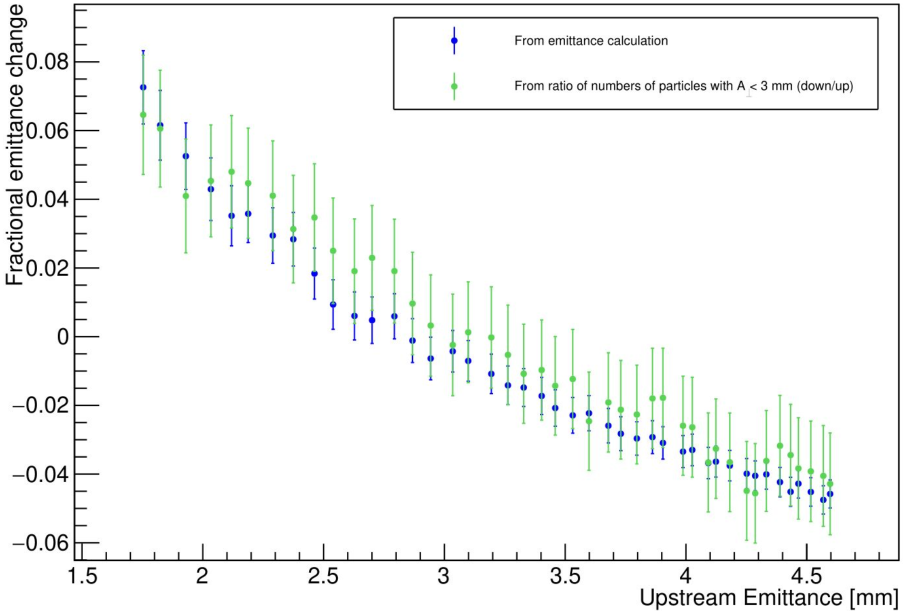


No absorber - Data

3 mm amplitude bins

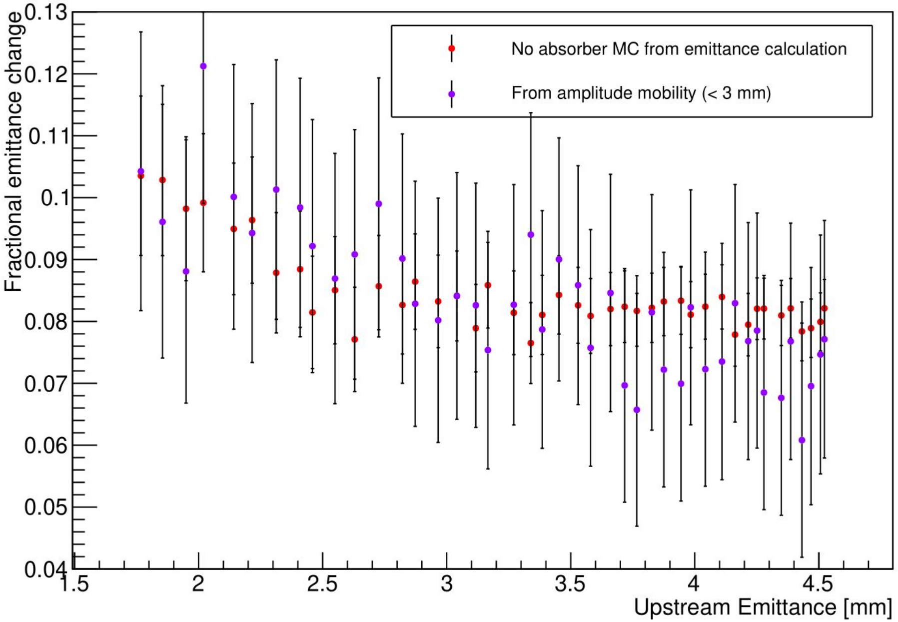


LH2 - MC

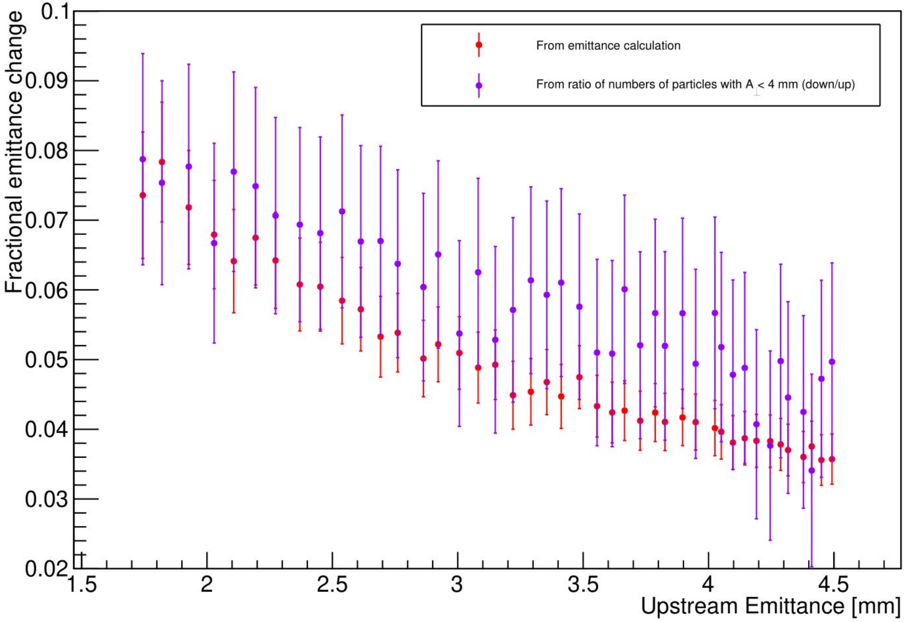


LH2 - Data

3 mm amplitude bins



No absorber - MC



No absorber - Data

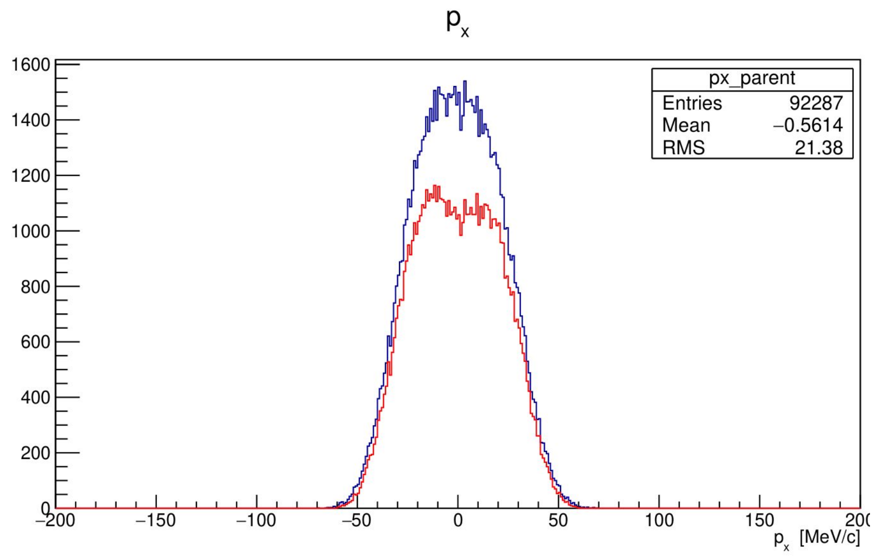
Hybrid MC

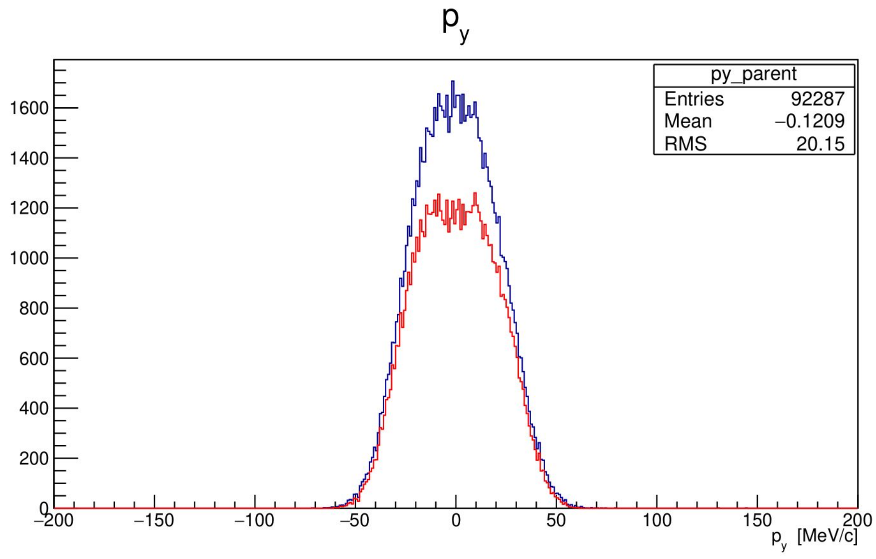
Production procedure

- Extract data parent beam at the most upstream tracker plane of station 5 in TKU (transverse phase-space coordinates + p_z, TOF0, TOF1)
- Time-of-flight information needed for the low-P_T patch
- KDE is used to form a pdf from which the new hybrid beams are sampled
- TOF0,1 spacepoints info is generated by looking at (p_z, TOF) distributions of the input beam and assuming a gaussian distribution of the TOF at each (slice of) p_z

Low-P_T hole

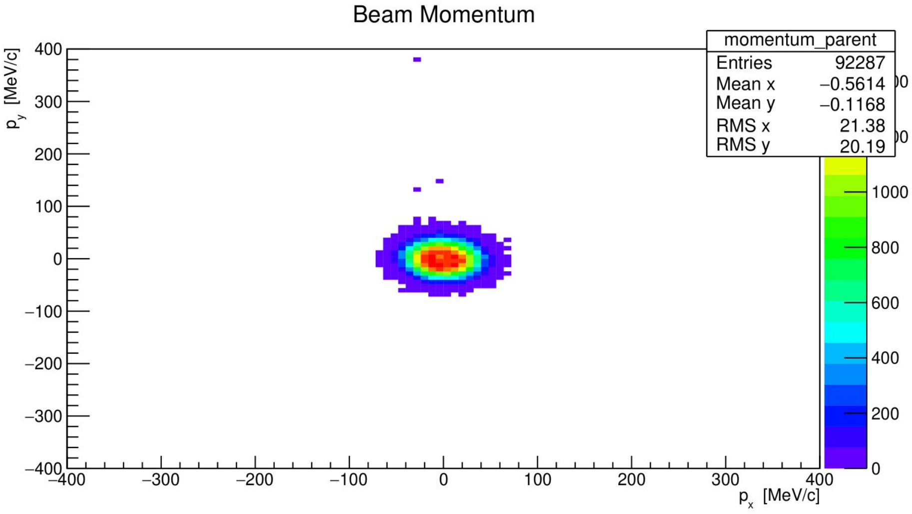
- after applying the [135,145] MeV/c upstream momentum cut to the hybrid MC beams, the low-P_T shows up

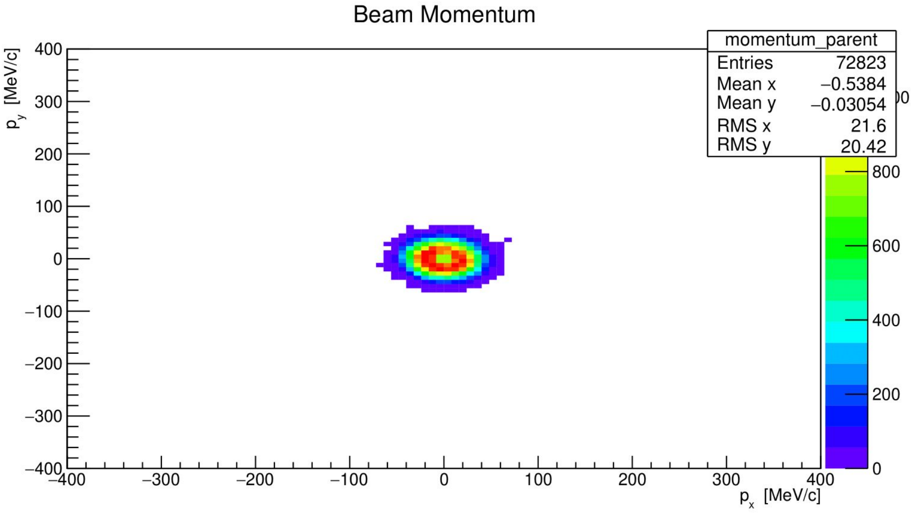




Low-P_T hole

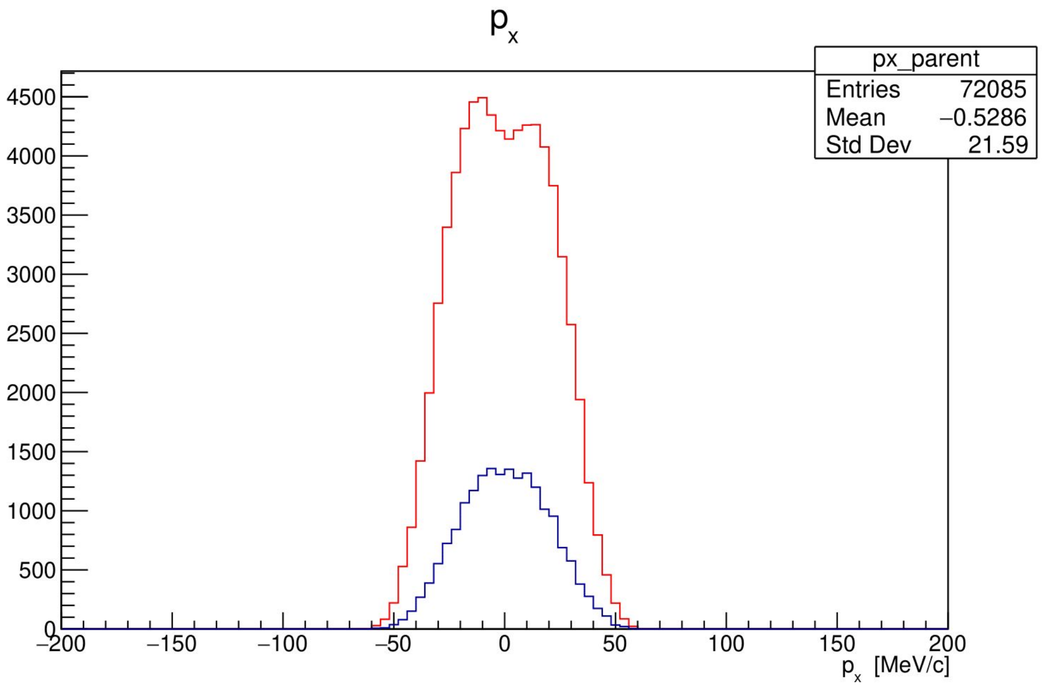
- after applying the [135,145] MeV/c upstream momentum cut to the hybrid MC beams, the low-P_T shows up (RHS plot)



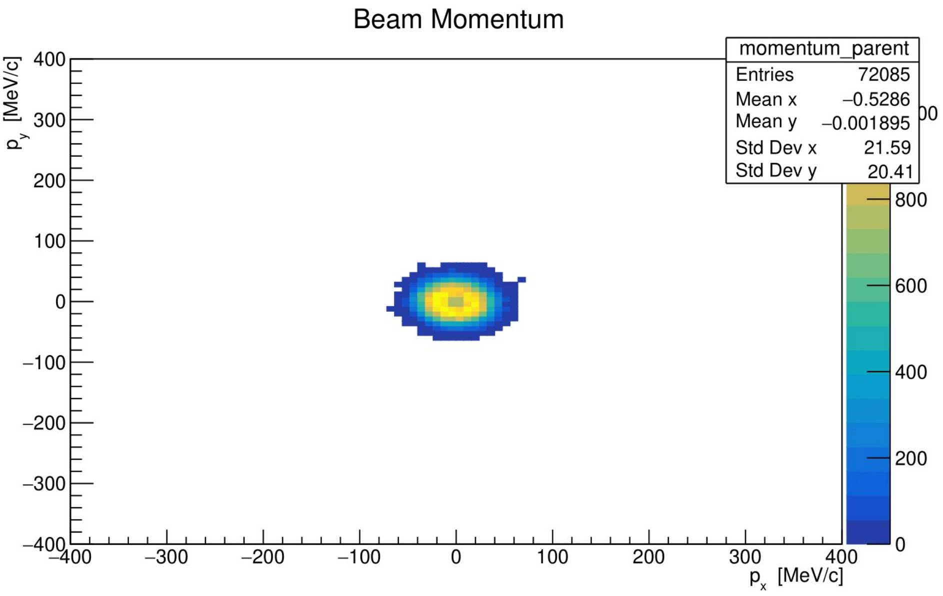


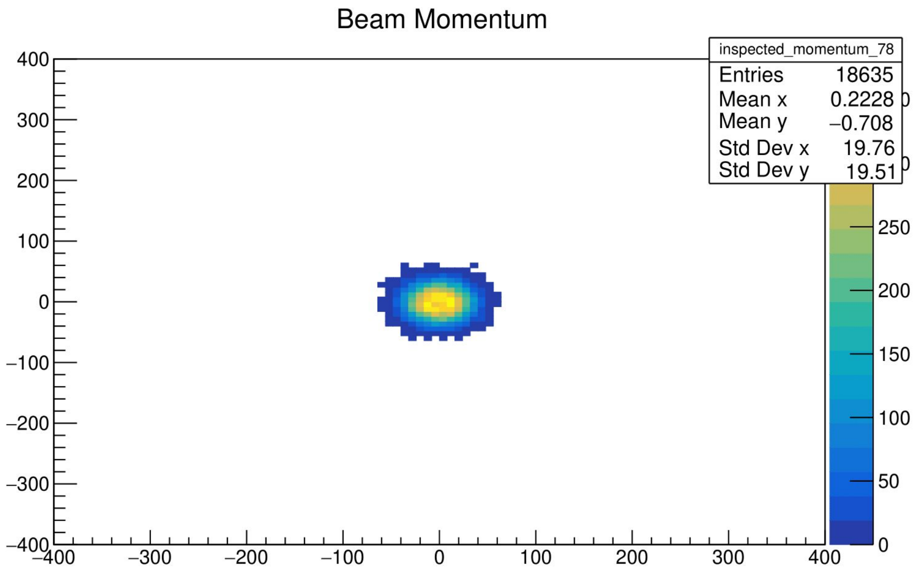
Low-P_T hole

- Beam selection mitigates the issue.
- Here the selected daughter beam has a target emittance of 4.6 mm and an actual emittance of ~ 4 mm
- Further investigation required still



Low-P_T hole





Parent

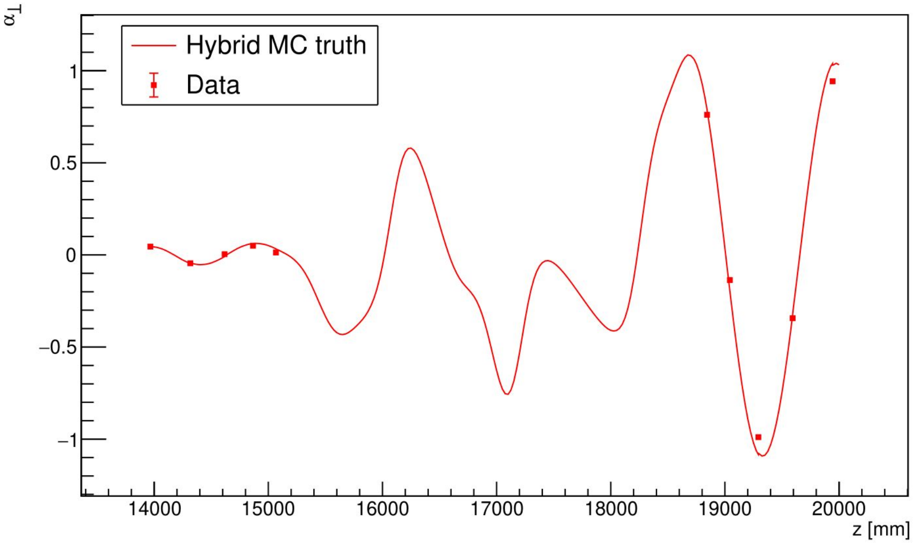
Daughter

Hybrid MC comparisons

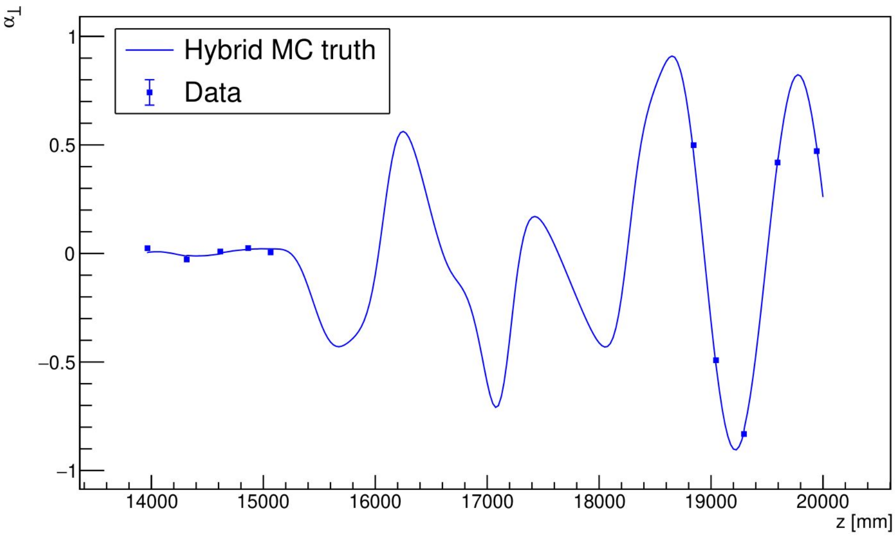
- preliminary comparisons with hybrid MC truth

- compared Data and Hybrid MC daughter beams that have a sampled emittance of ~ 4 mm

Alpha

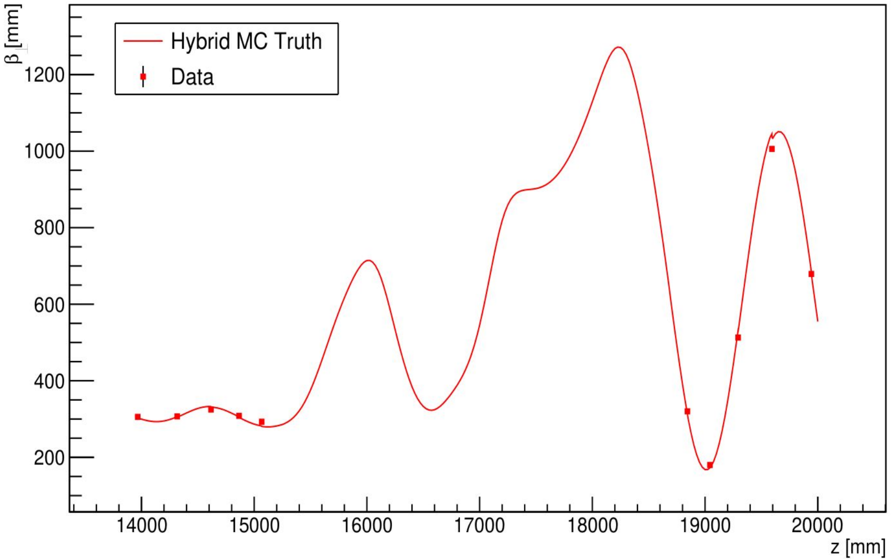


No absorber

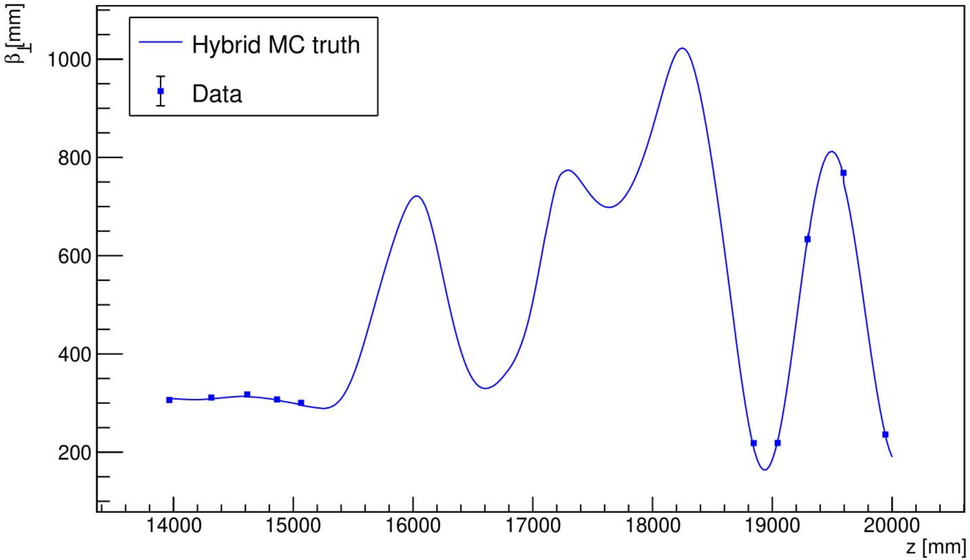


LH2

Beta

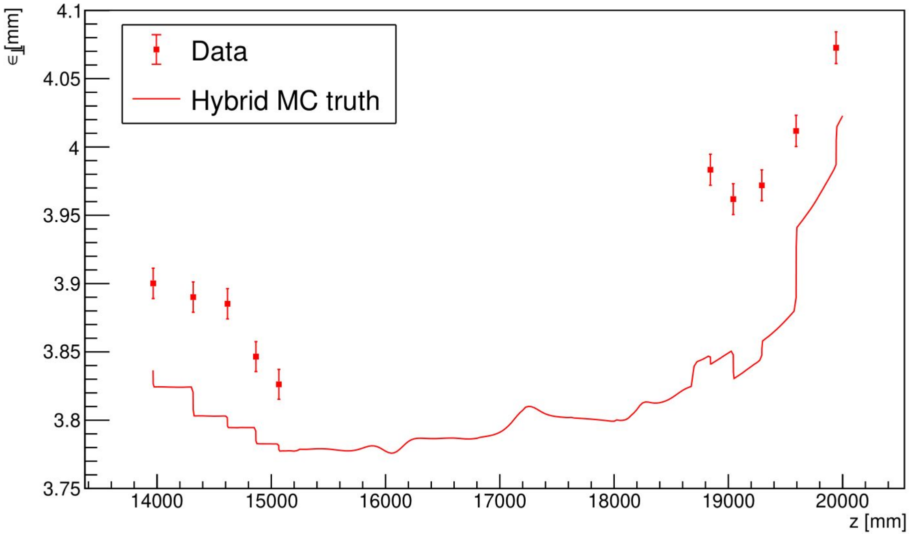


No absorber

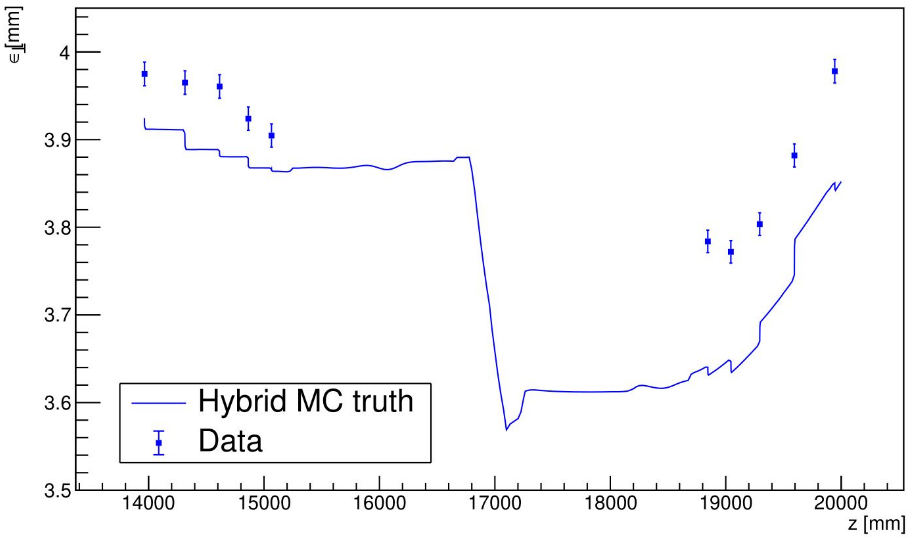


LH2

Emittance

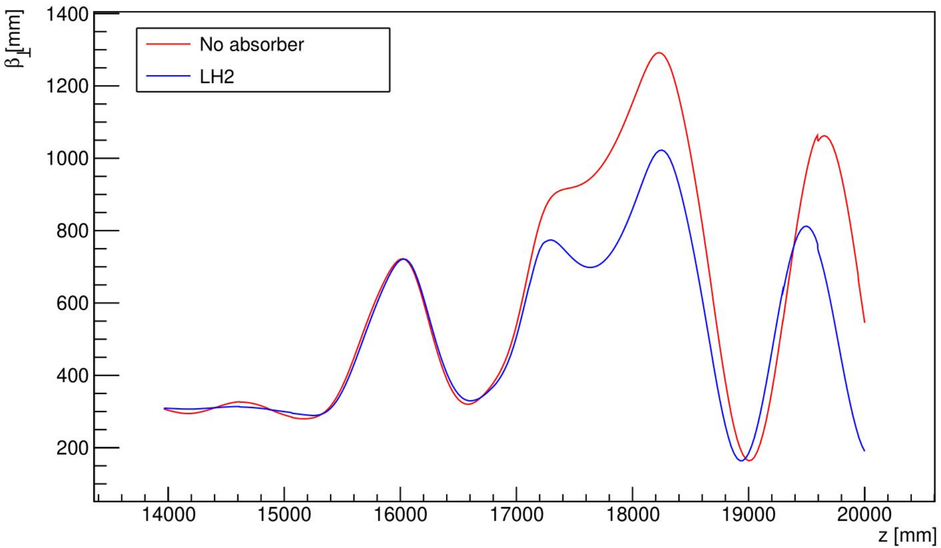


No absorber

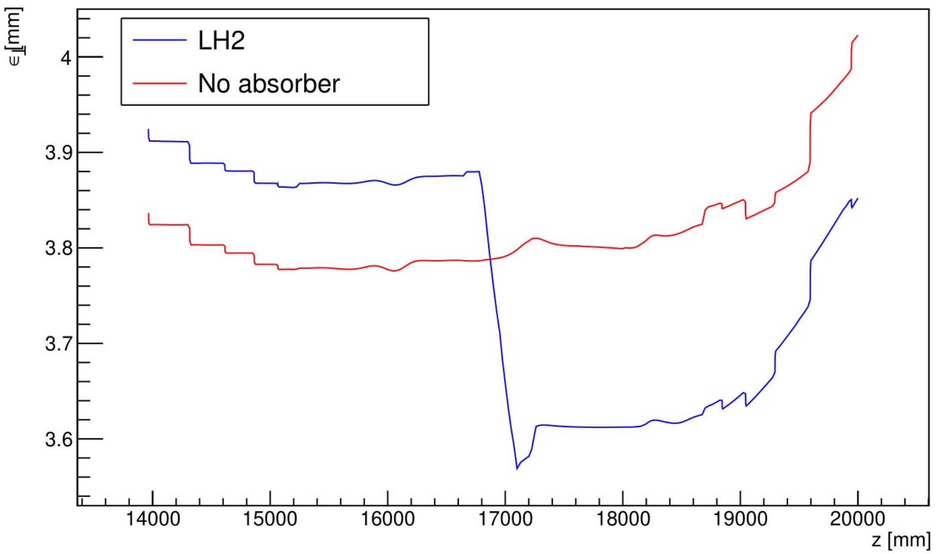


LH2

Hybrid MC truth: LH2 vs No absorber

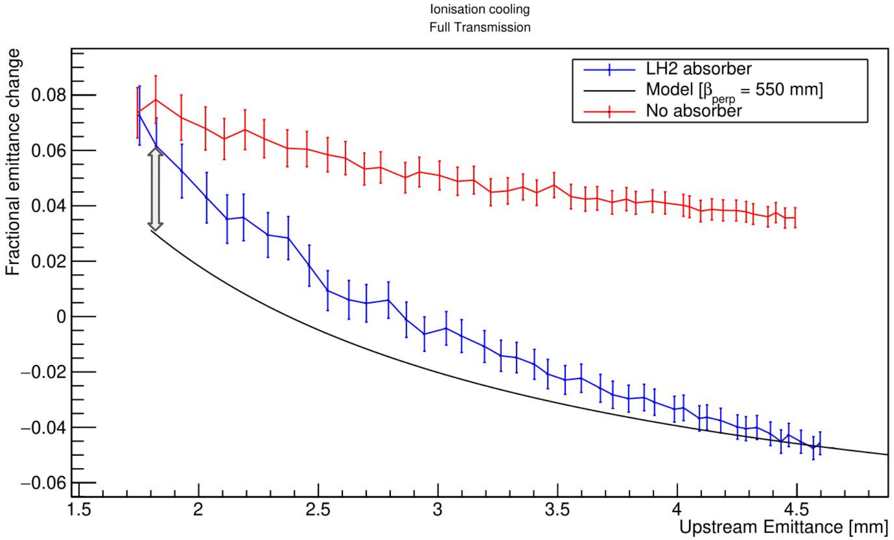


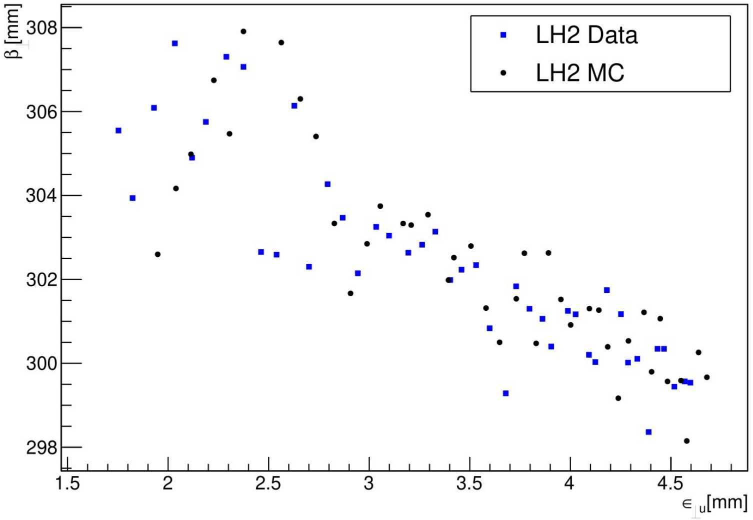
Beta



Emittance

Hybrid studies preview



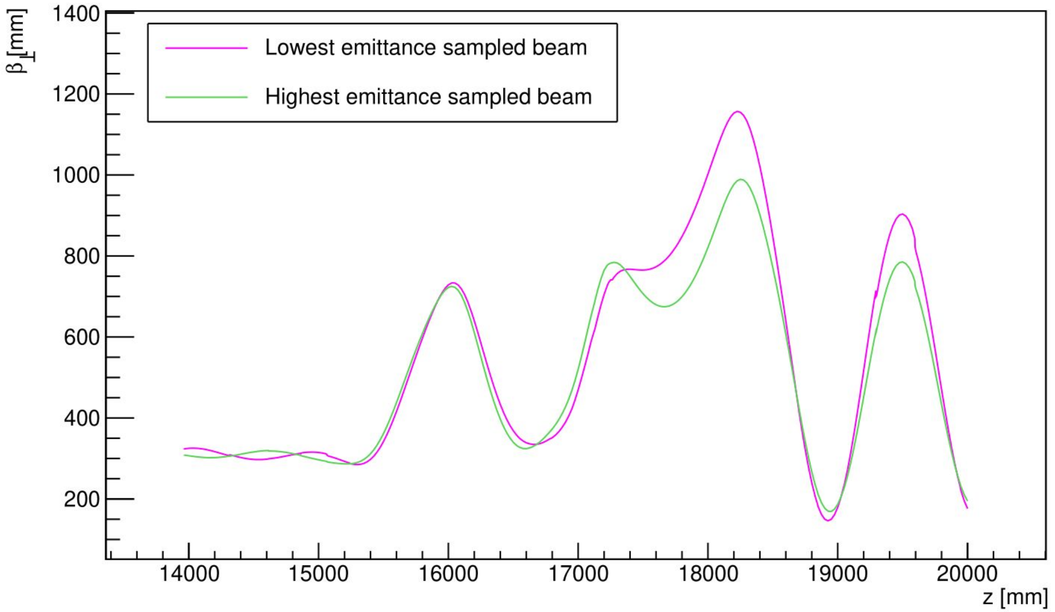


- observed more heating than expected from theoretical model for the beams with upstream emittance at the lower side of the range
- supected to be caused by the varying optics between those beams

Beta evolution for the lowest and highest emittance beams. Differences both at the absorber and in the region before the downstream tracker where heating occurs.

Lower MCS heating at the absorber for the lowest emittance beam. However, more non-linear optics heating between the absorber and TKD. Results in overall more heating.

Next to investigate correlations between beta and emittance heating at points of interest in the CC.



Summary

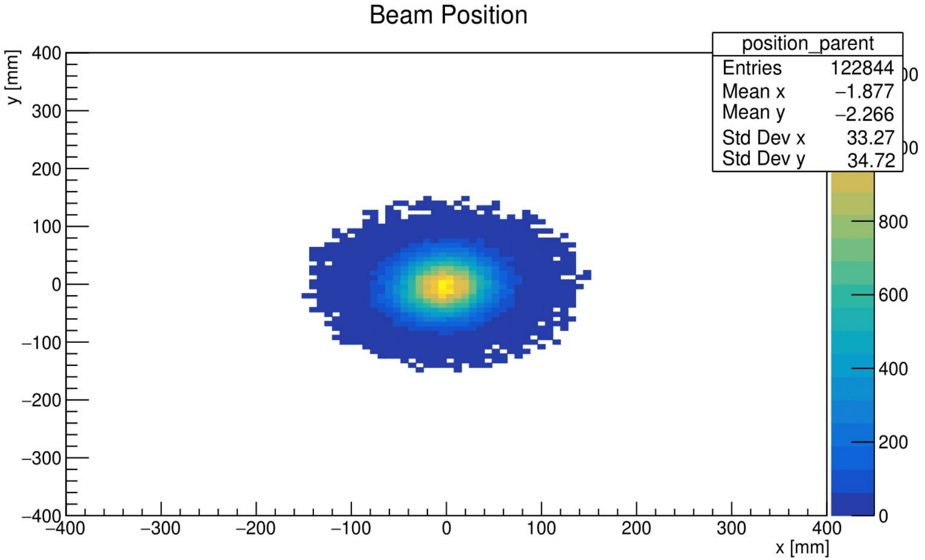
- compared the performance of matched vs unmatched beam optics : cooling is improved. This is probably due to a reduction of beta at the absorber, rather than optical heating suppression
- DATA / MC comparison: partially good agreement of cooling; In the absence of an absorber, complete disagreement. Enhanced tails develop in MC -> more heating
- Emittance calculation from amplitude. Needs further work.
- next steps:
  - hybrid MC production - track down the low-P_T hole
  - Use hybrid MC to study beam optics between trackers
  - Improve amplitude calculation - implement Chris R algorithm
  - MC production - increase stats; tidy up comparison plots (cuts, phase space etc)
  - Look into 4, 10 mm beams

BACK UP

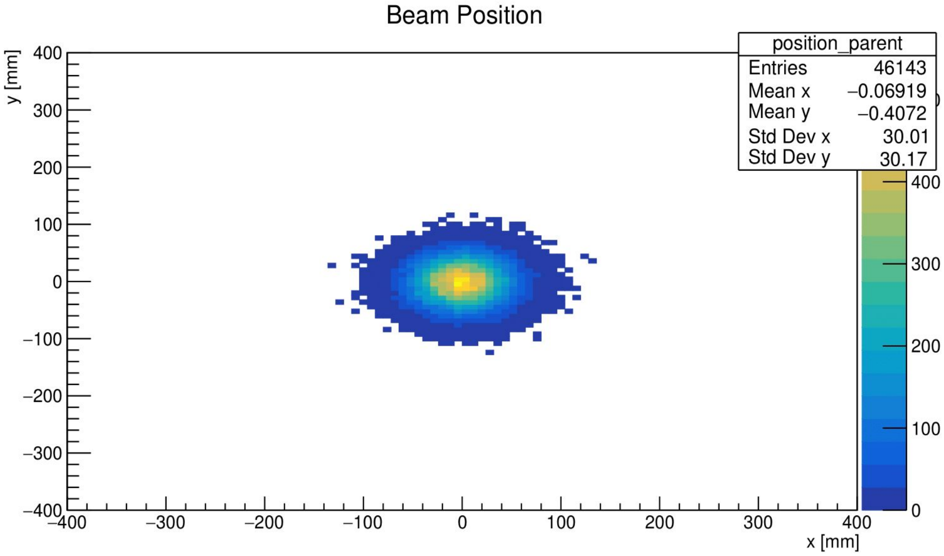
Beam Sampling

- Sampling routine is applied to the upstream ensemble
- Sampling parameters: α = 0.0, β = 310 mm, ϵ = [1.8, 6.0] mm, L = 1.1
- Phase-space plots shown for target emittance of 4.6 mm, LH2

Parent

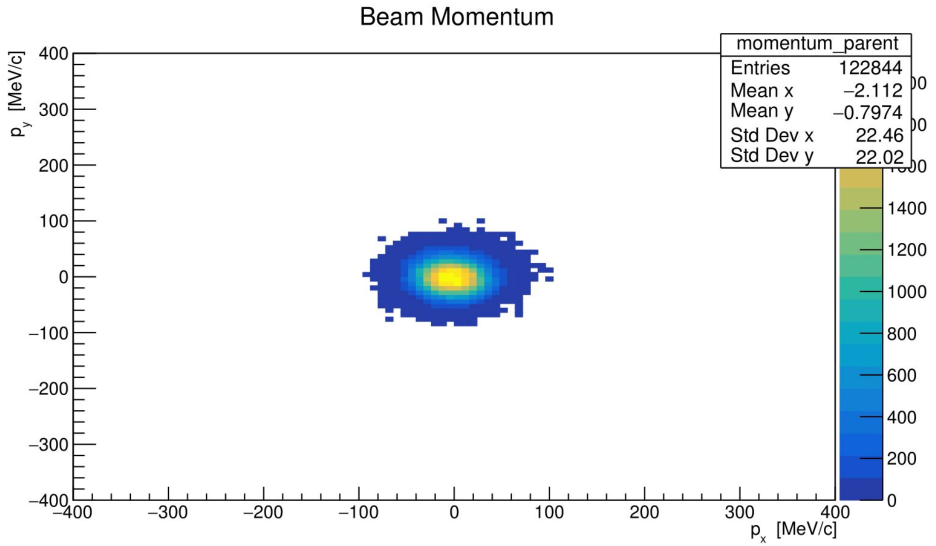


Daughter

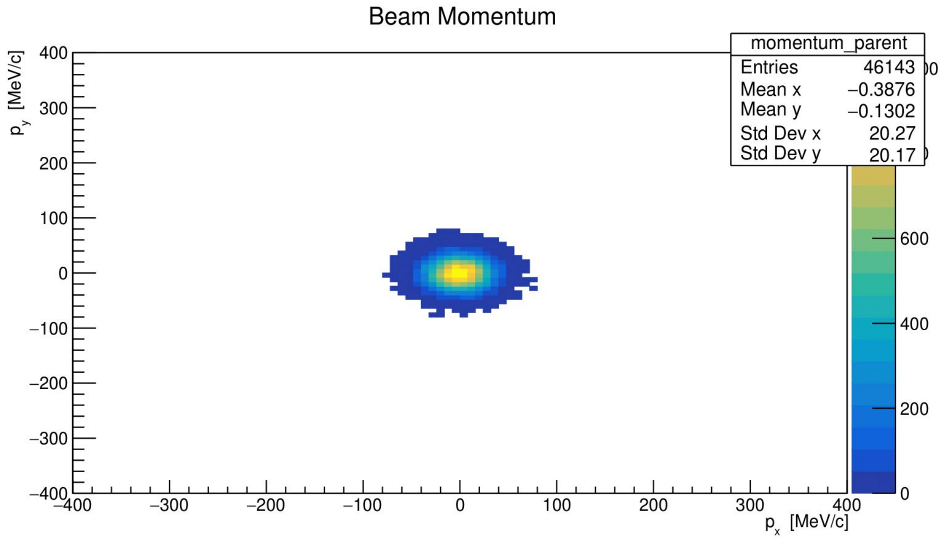


Imperial College London

Parent



Daughter

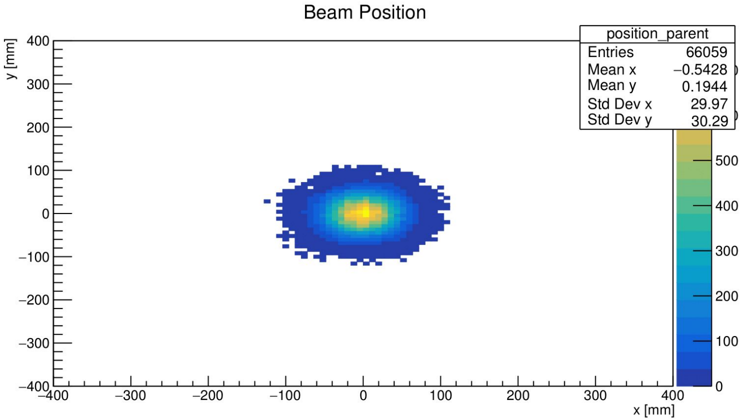


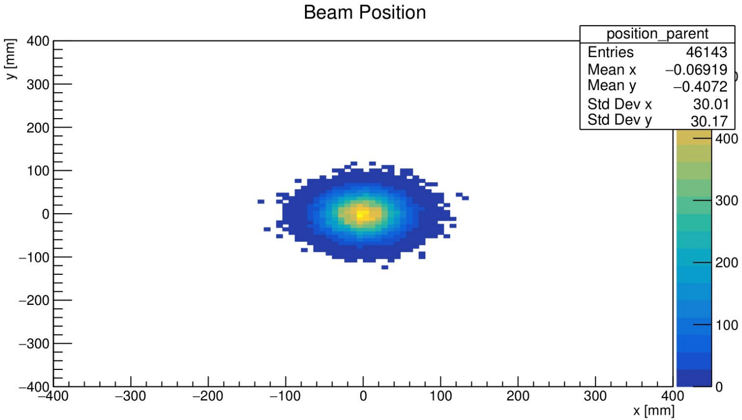
Sampled Beam Evolution - xy

NO ABSORBER

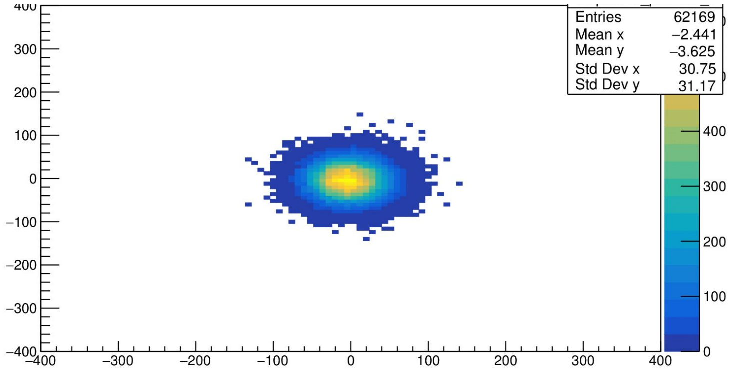
LH2

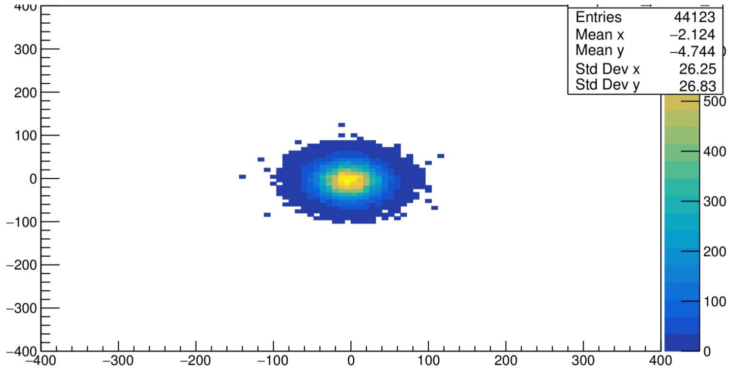
Upstream





Downstream



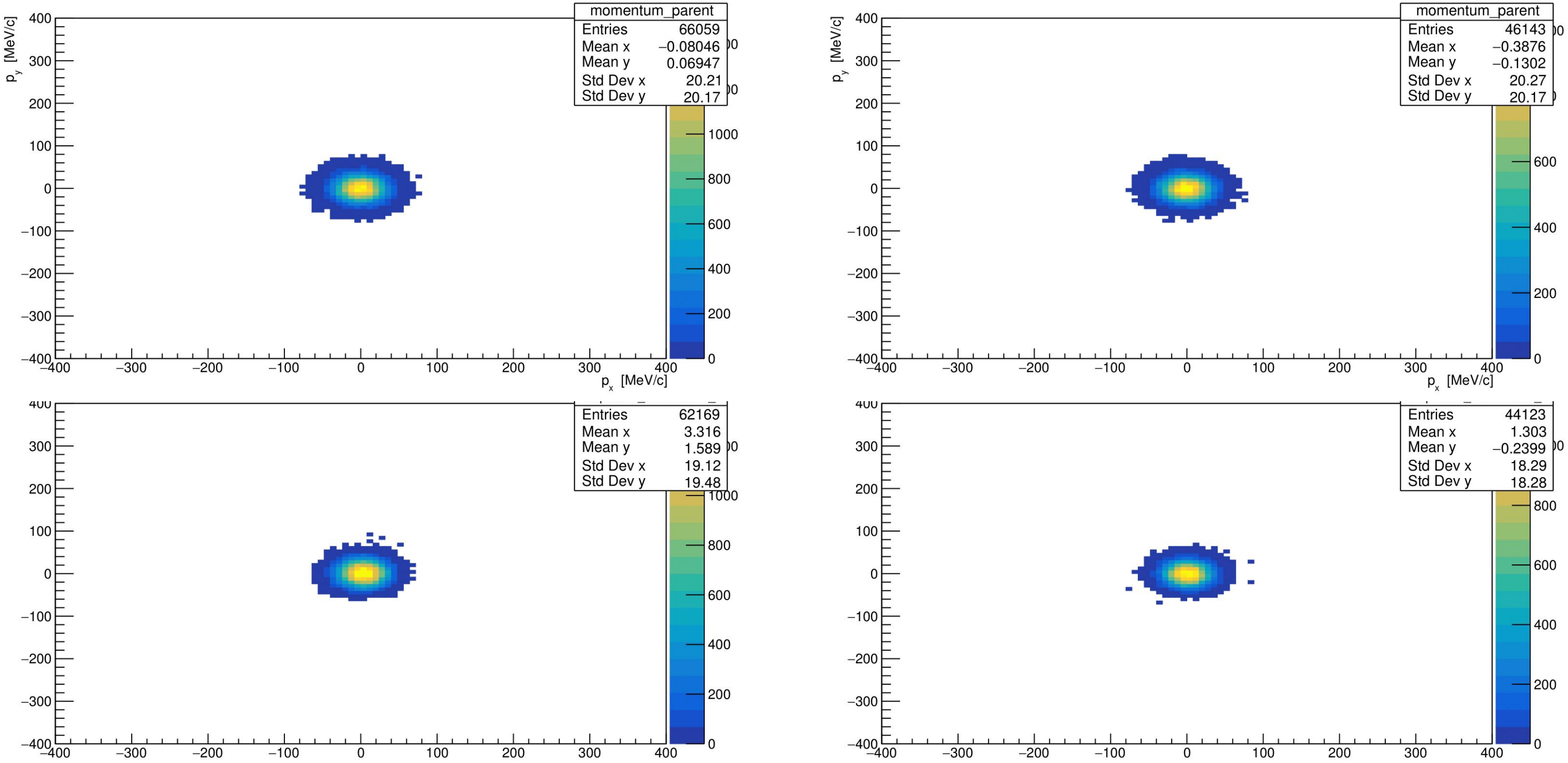


Sampled Beam Evolution - PxPy

NO ABSORBER | LH2

Upstream

Downstream



FULL TRANSMISSION ANALYSIS

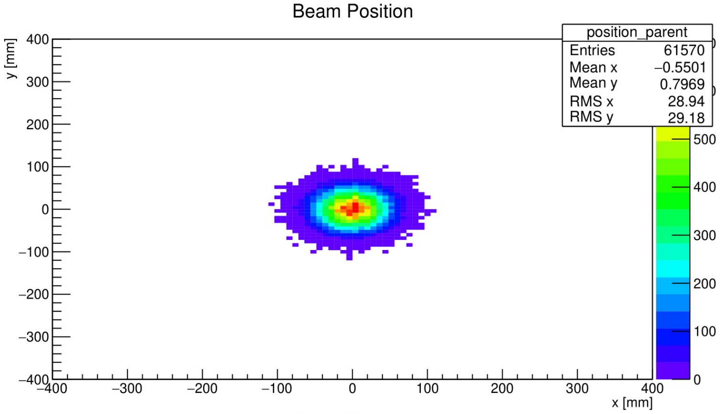
(Only events that have one track upstream and downstream are kept)

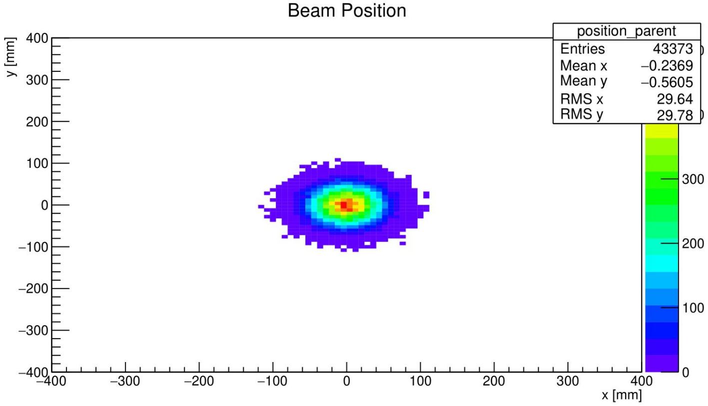
Sampled Beam Evolution - xy

NO ABSORBER

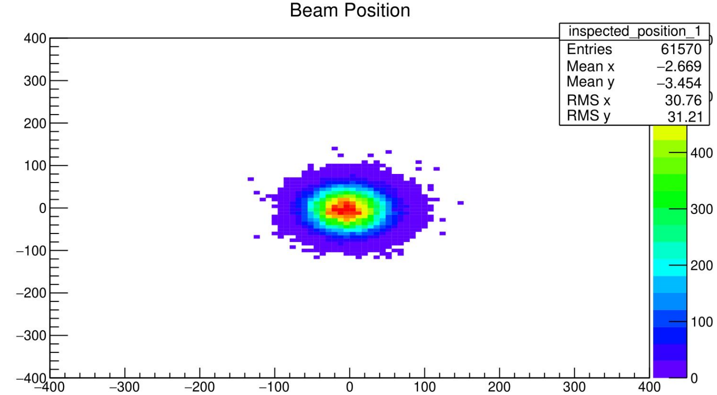
LH2

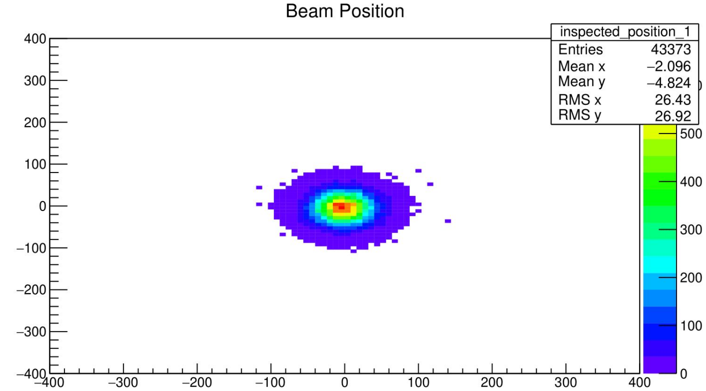
Upstream



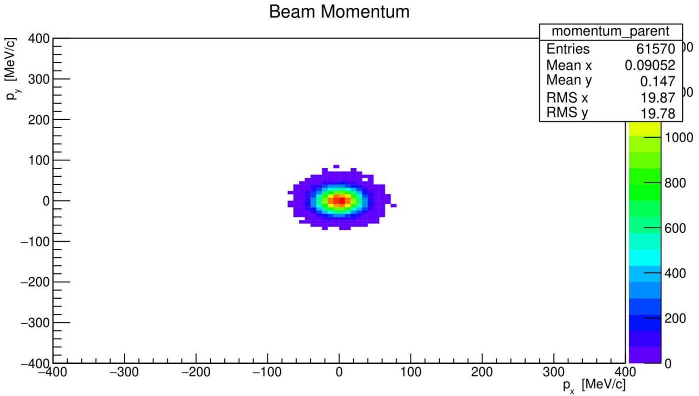
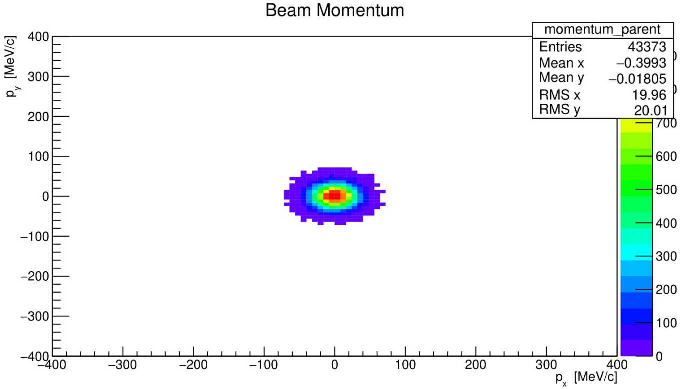
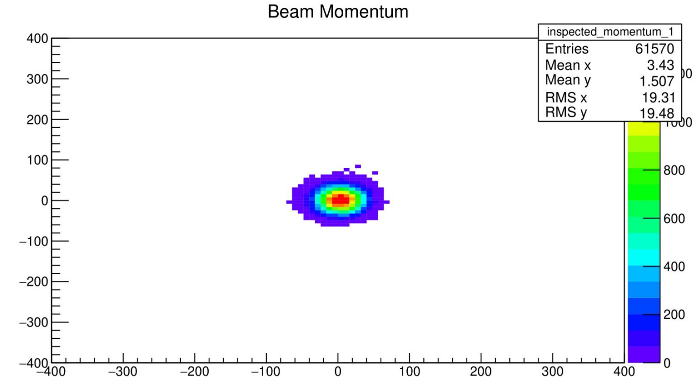
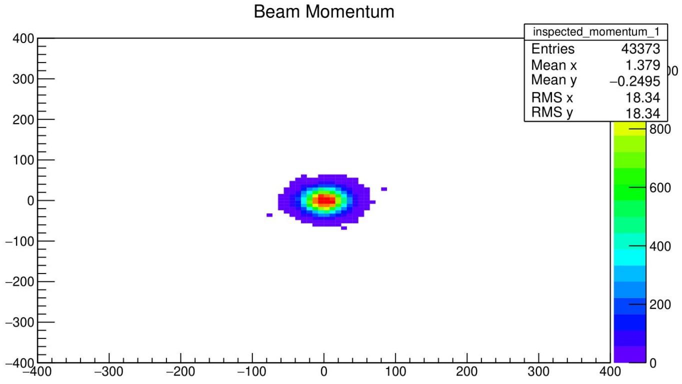


Downstream





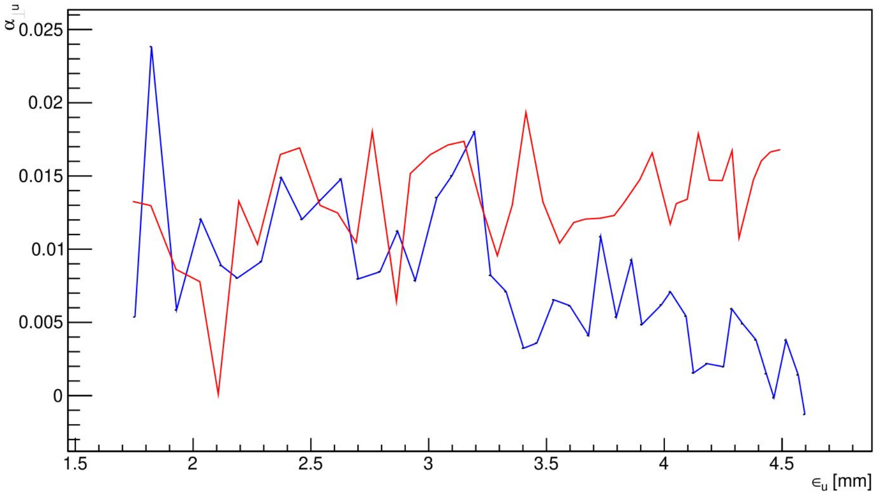
Sampled Beam Evolution - PxPy

	NO ABSORBER	LH2
Upstream		
Downstream		

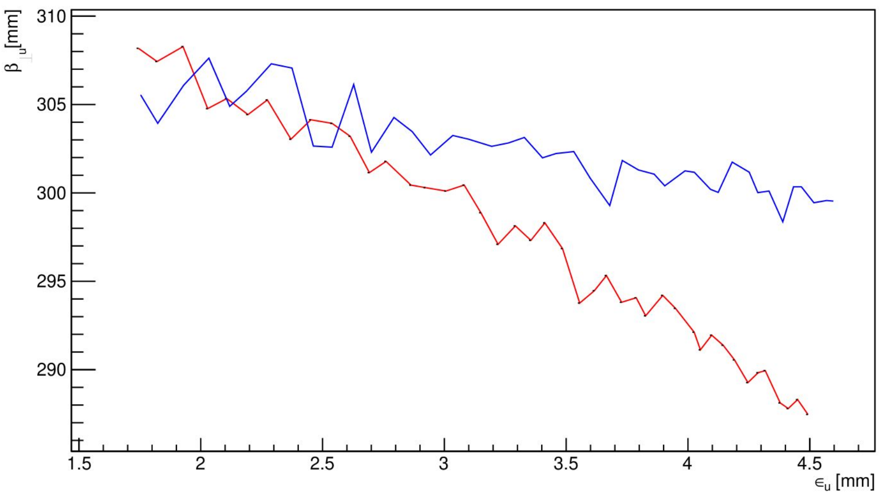
Optics at the upstream reference plane

RED - no absorber, BLUE - LH2

Alpha



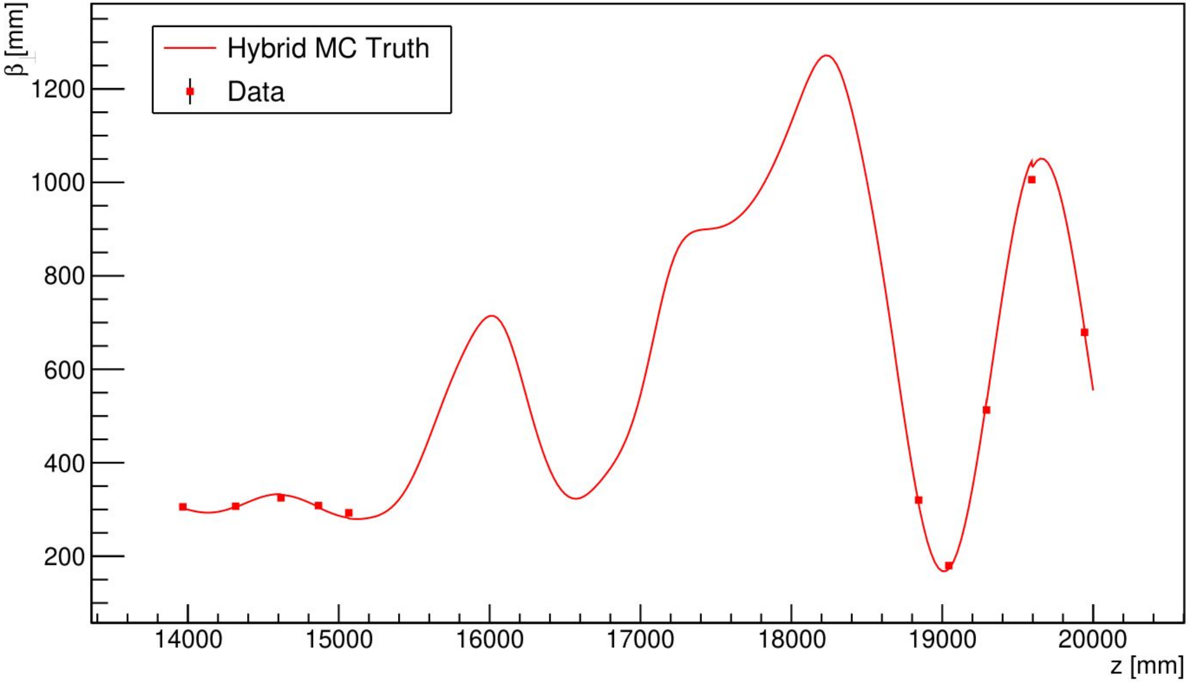
Beta



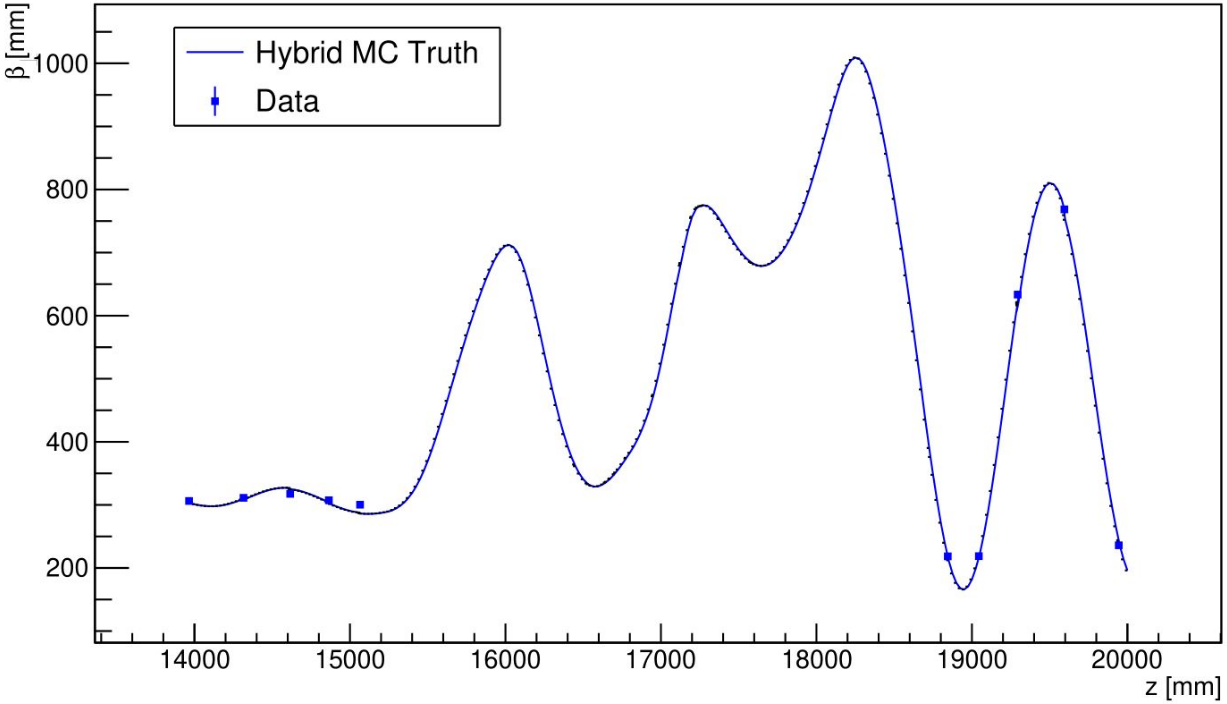
Hybrid MC comparisons

- preliminary comparisons with hybrid MC truth
- however, p_T hole at low transverse momenta is present; the current hybrid MC production routine does not include the TOF Tracker patch

Beta - No absorber

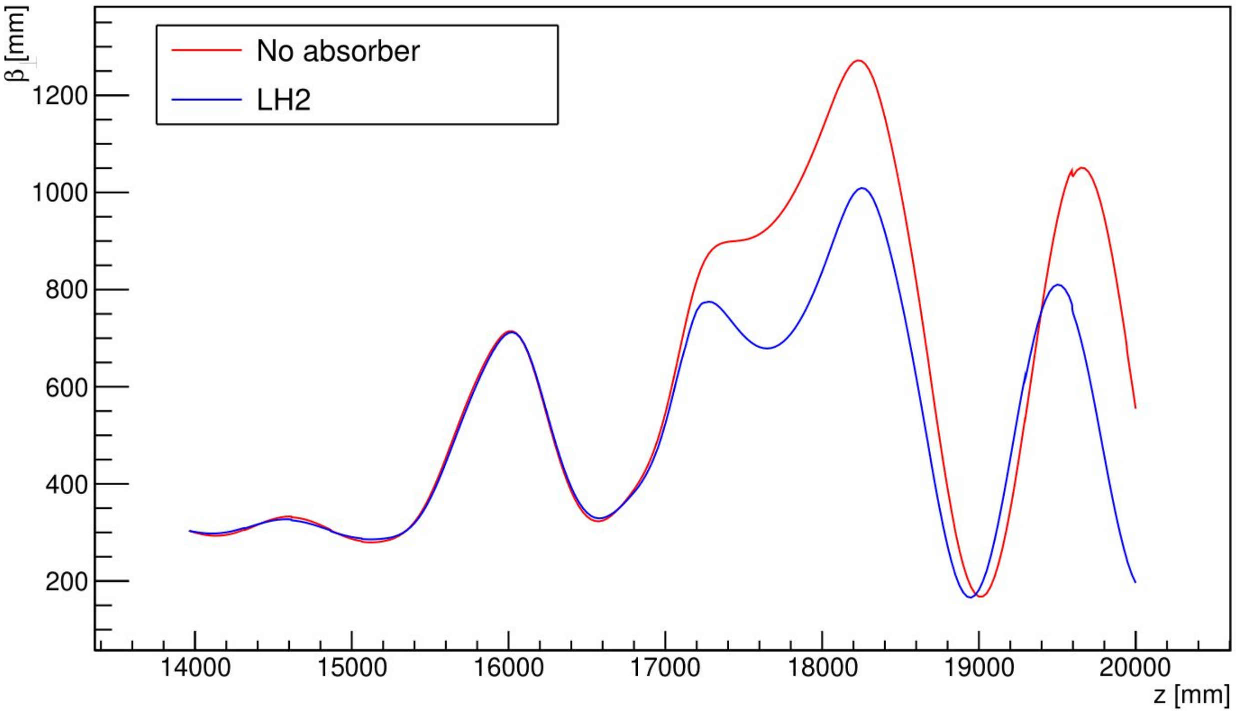


Beta - LH2

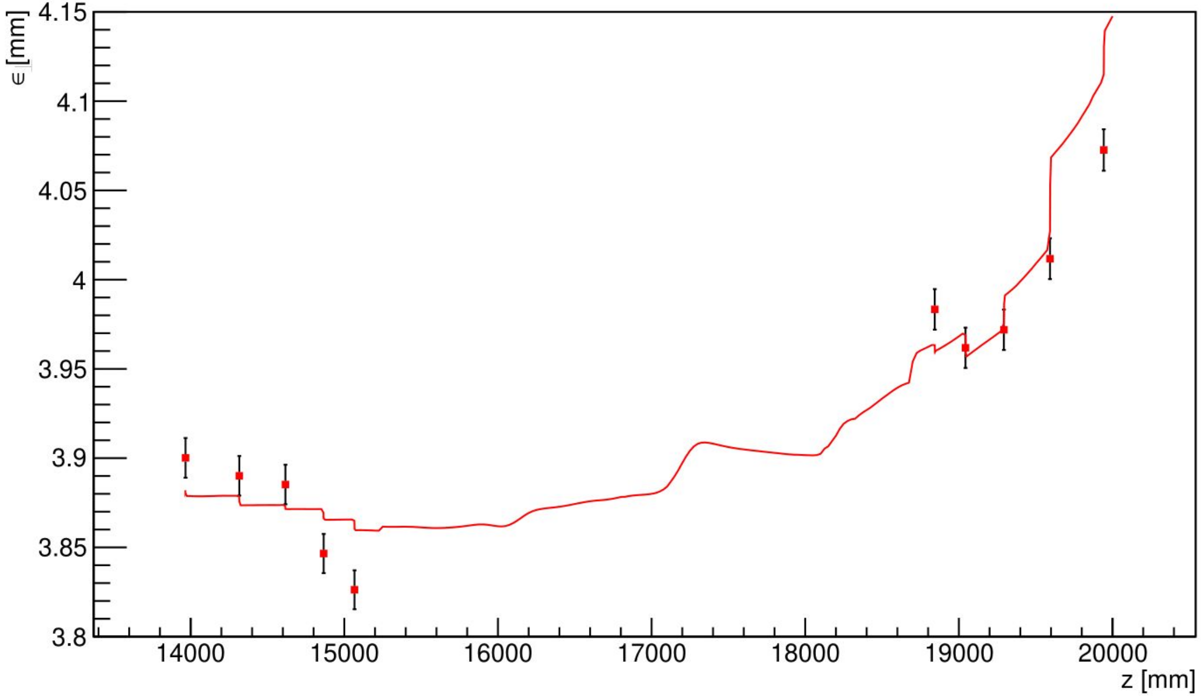


Hybrid MC Truth
Data
β [mm]
1000
800
600
400
200
14000
15000
16000
17000
18000
19000
20000
z [mm]

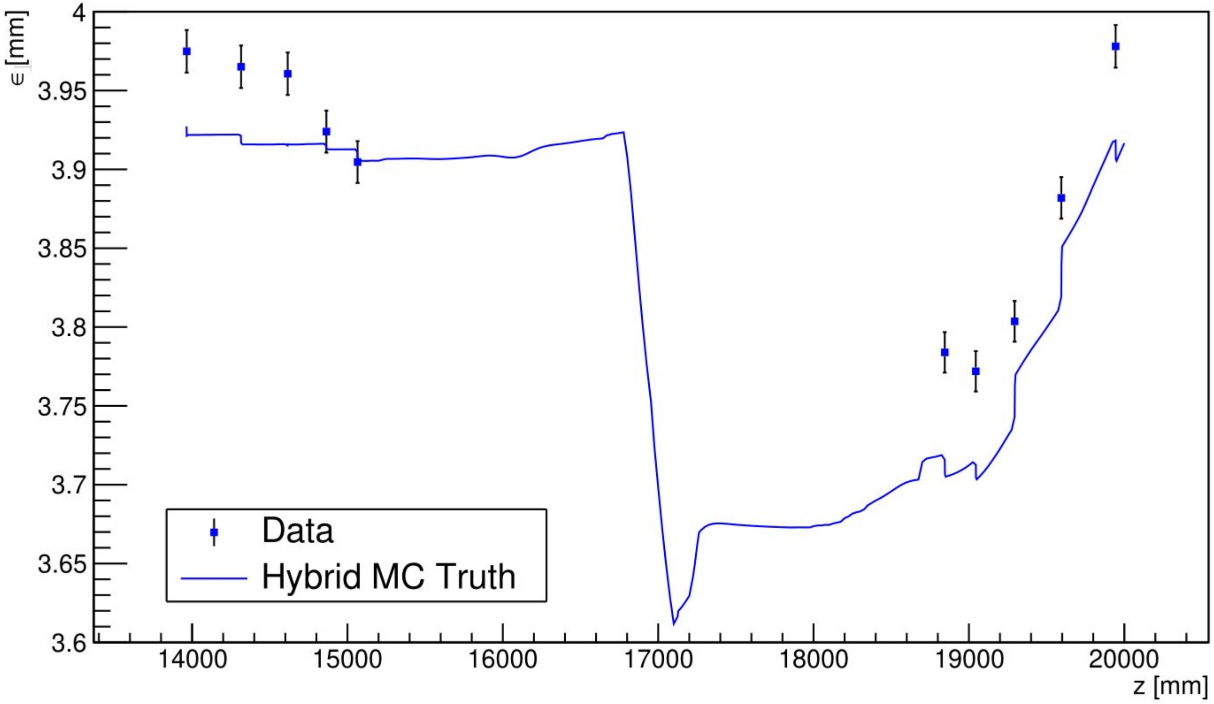
Beta - No absorber VS LH2 (truth)



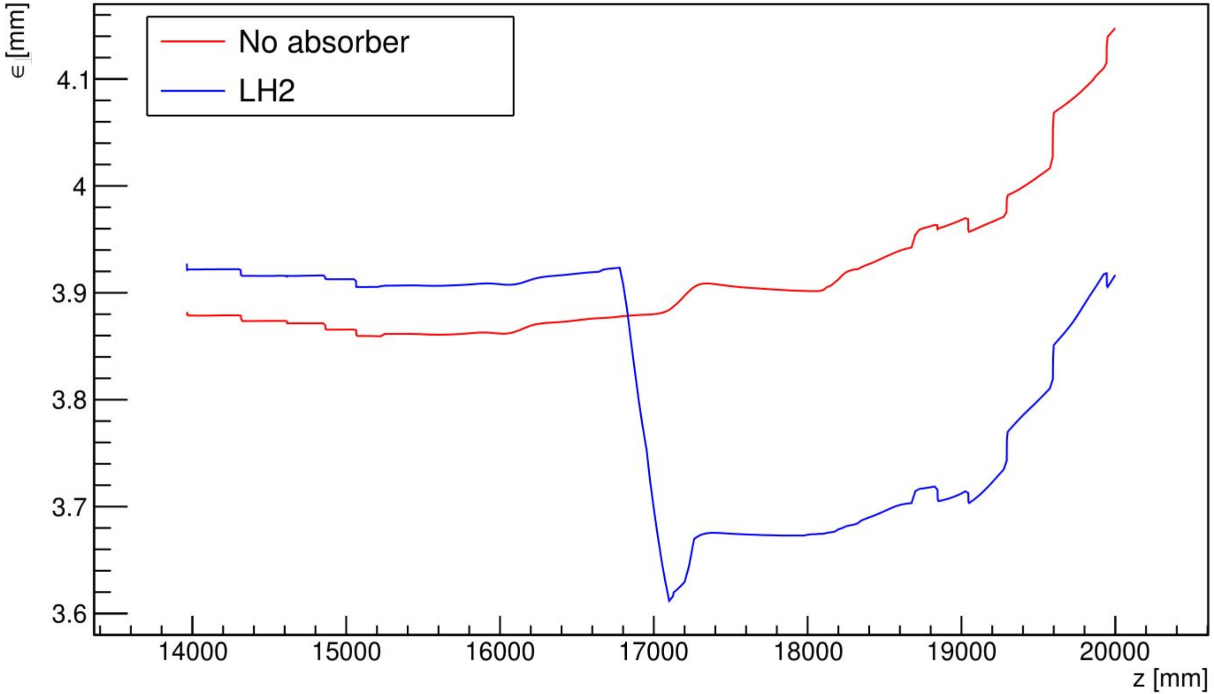
Emittance - No absorber



Emittance - LH2



Emittance - No absorber VS LH2 (truth)



Summary

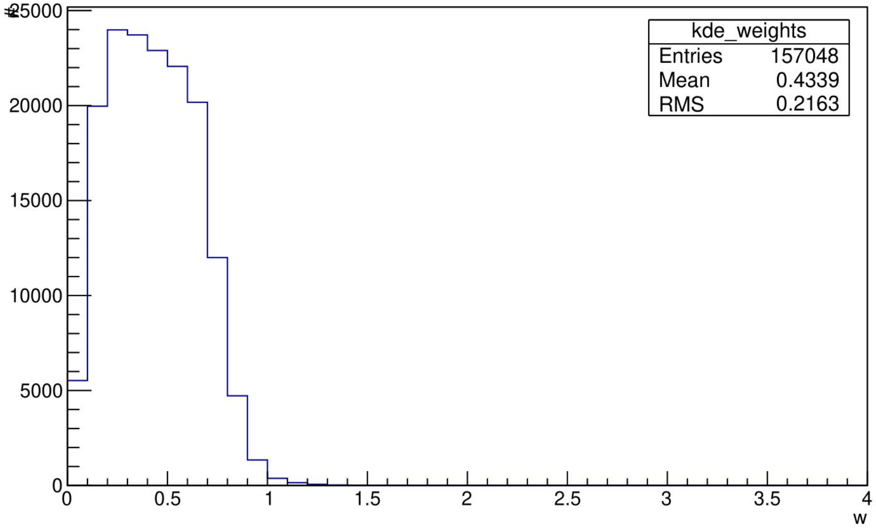
- the full transmission requirement removed the emittance change bias due to particle loss
- there is still optical heating dependence on initial emittance
- Good optics agreement bewteen data and MC truth; emittance not completely understood (low transverse momentum hole)
- next steps:
  - study optical heating as function of optics and initial emittance (both for no absorber and absorber case)
  - hybrid MC production - needs TOF Tracker combined fit
  - MC production
  - improve beam selection: MCMC Hastings-Metropolis sampling?

Rejection Sampling: Limitations

- Method suffers from the curse of dimensionality. As the number of dimensions increases the rate of rejection increases and algorithm becomes inefficient.

- Rate of rejection (~ normalisation) is also affected if the target distribution has heavier tails than the parent. In this case the normalisation and thus the rate of acceptance → 0. One such case would be when the emittance of the target is similar to the parent emittance.

- However, this is not observed. Instead, in such cases the normalisation is actually not small enough and the probability of selection for some events > 1. Will need to further dig into the normalisation calculation.
- Currently the normalisation calculation takes 10k iterations, seemingly not enough to estimate the normalisation accurately.
- However, method works well at target emittances smaller than the parent emittance.



An alternative (?): (Indpendent) Metropolis Markov Chain MC

Essentially a random walk through the parent distribution phase-space and accepts events into the target distribution according to the following algorithm:

- Draw a first sample from the parent distribution. Then for all the particles in the parent distribution proceed as follows:
    - Randomly draw another particle (proposal). Calculate the acceptance coefficient as follows:

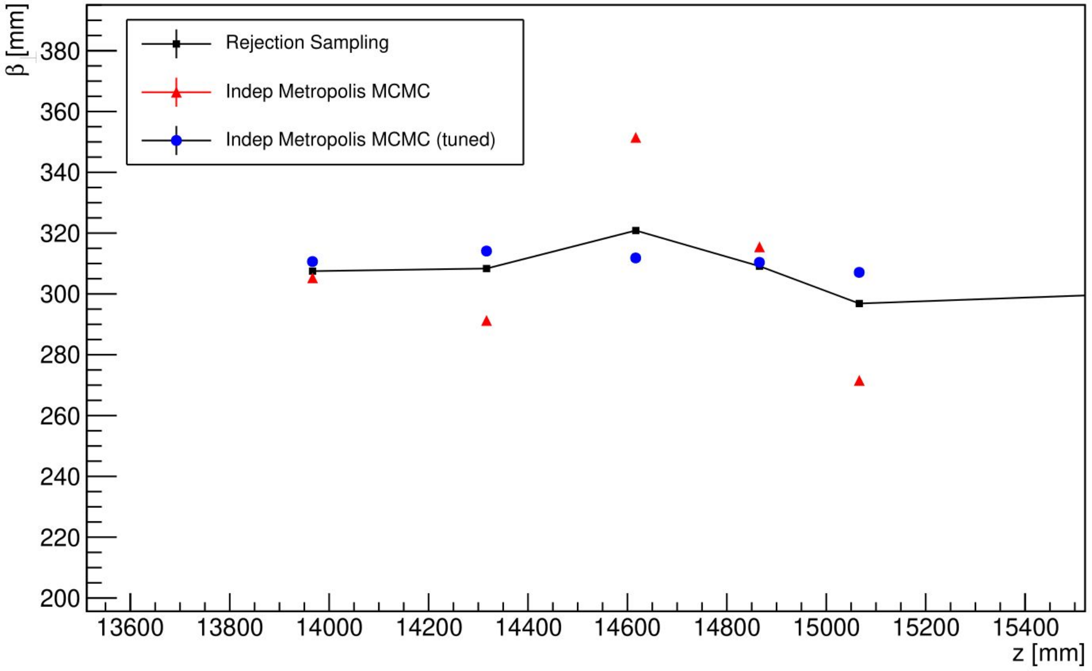
$$a = min(1, \frac{P_{target}(proposal)}{P_{target}(current)} \frac{P_{parent}(current)}{P_{parent}(proposal)})$$

- Draw *u* from *U[0,1]*. If *u* < *a* then accept event and update *current* = *proposal*. Otherwise reject it and keep *current* state the same.

- So far this algorithm does not seem to match the performance of Rejection Sampling, unless fiddled with / tuned (draw u from U[0.5, 1))

Sampled Beams Beta Comparison (TKU)

- All the sampled beams have a 4 mm target emittance, 310 mm target beta
- In terms of matching, the standard MCMC algorithm performs worse than Rejection Sampling, as oscillations are observed
- The tuned version of the MCMC however, shows better matched optics than RS.
- However, the same improvement is not observed for beams with 2, 3, 5 mm target emittance.



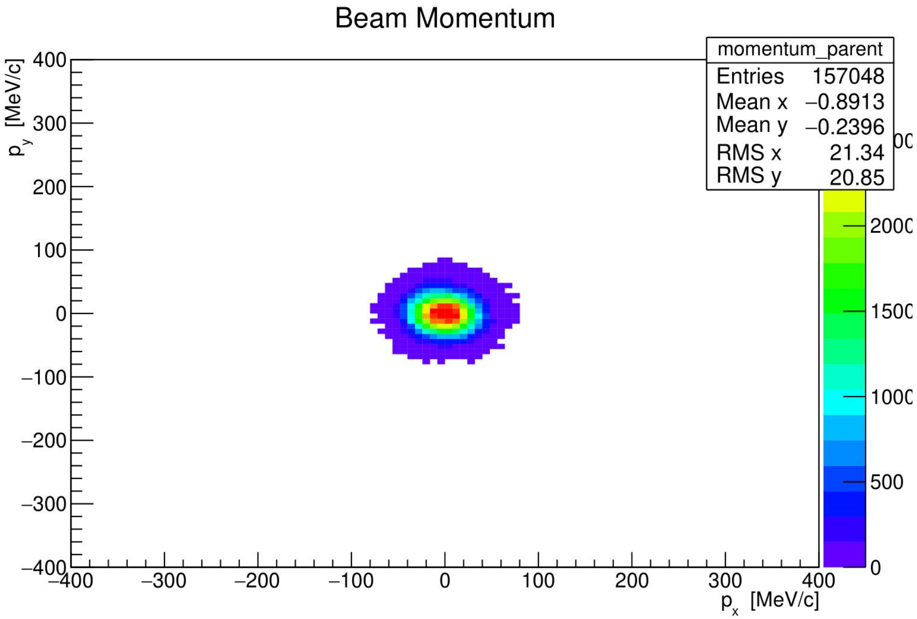
MCMC: Parent VS Target

- Overall, the particular Metropolis MCMC algorithm employed here has a better acceptance rate than Rejection Sampling, but this costs in terms of matching performance.

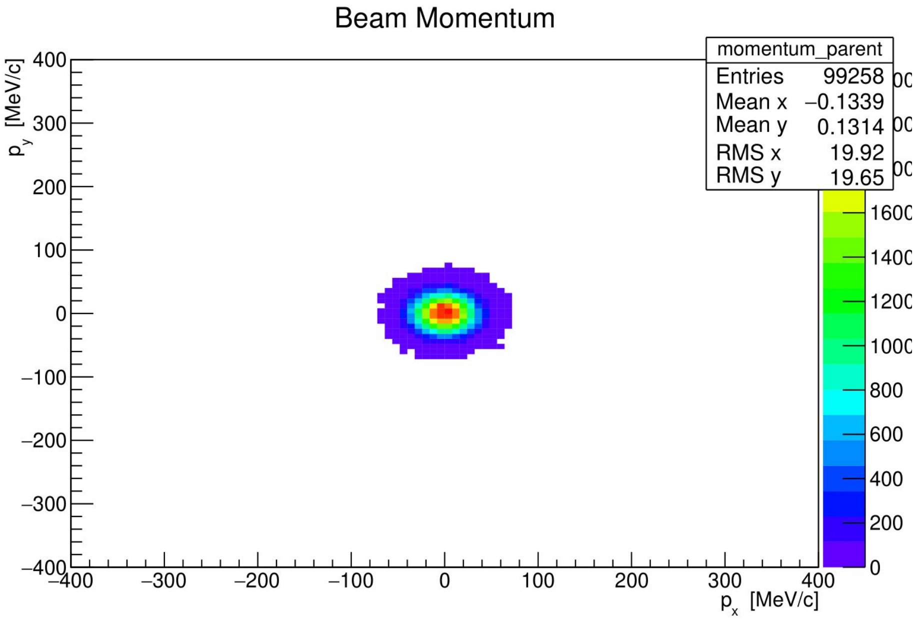
- Next two slides - Parent / Target comparisons using No absorber data. The target has ~ 4 mm emittance.

Parent VS Target (No absorber Data)

Parent

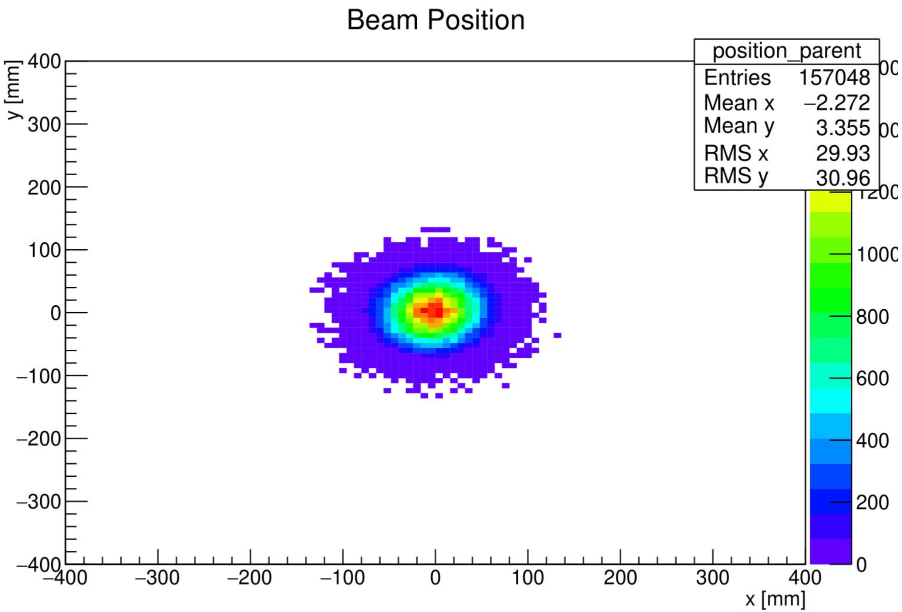


Target

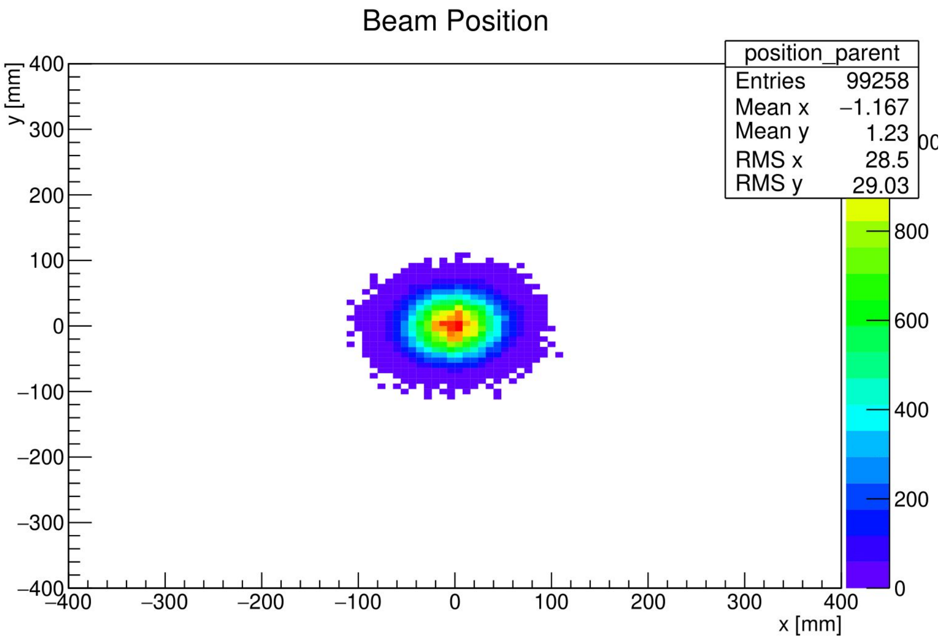


Parent VS Target (No absorber Data)

Parent



Target



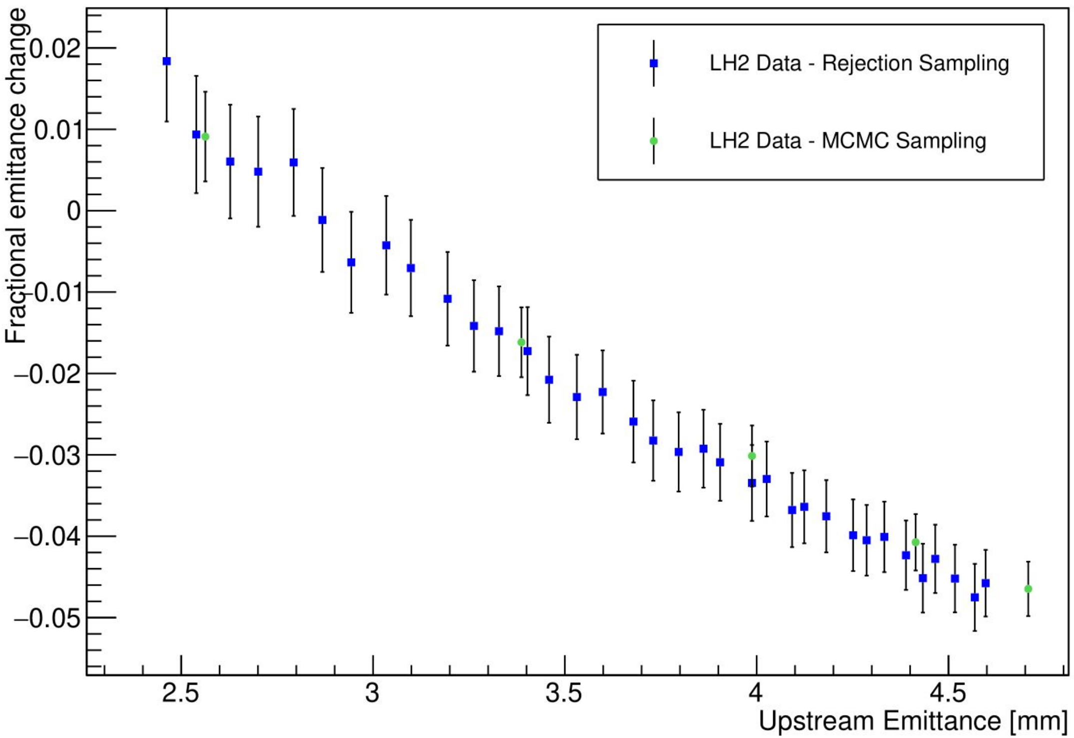
MCMC Sampling Cooling Performance

Cooling performance similar to the one obtained via Rejection Sampling at target emittances below < 3.5 mm.

At target emittances above ~ 4 mm, performance not as good (however, still better than the case of unmatched optics).

Next to consider the Random-Walk Metropolis algorithm.

Ionisation cooling



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