# Muon Beam Dynamics in HFOFO Cooling Channel

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# Introduction

- Goal: HFOFO optimization using stochastic reference particle.
  - Implement a stochastic reference particle within G4beamline and validate against the nominal reference particle (stochastic disabled by default)
  - Run multiple simulations and summarize the ensemble to find the representative trajectory.
  - Use representative stochastic particle directly for HFOFO channel tuning and optimization eliminating the need for manual tuning.

# Implementation & Validation

- Stochastic reference particle is implemented in G4beamline with eventID -3 Slides
- Below table compares the average energy loss of beam and reference particles (with and without stochastic effects) through carbon and LiH absorbers.

| Average dE/dx (MeV/cm) | Reference particle | Beam, no stochastics | Beam, with stochastics | Stochastic reference particle | Bethe-bloch |
|---|---|---|---|---|---|
| 2.5 mm carbon absorber "tube" 200 MeV muon | 3.24 | 3.24 | 3.26 | 3.16 ± 1.17 | 3.29 |
| LiH wedge absorber HFOFO 200 MeV muon | 1.72 | 1.72 | 1.73 | 1.90 ± 0.49 | 1.73 |

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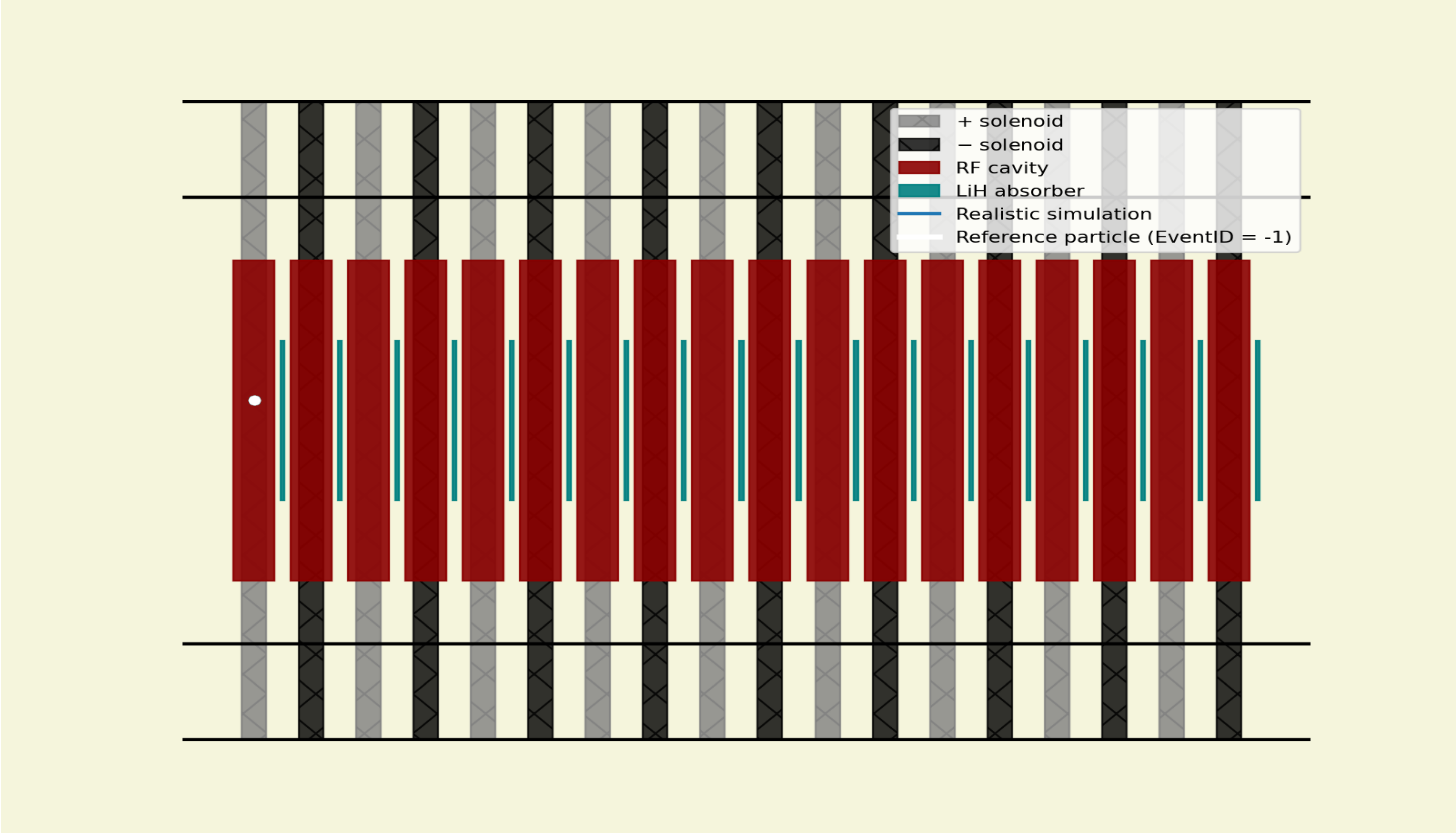
# Stochastic Reference Particle: Multiple Simulations



# Stochastic Reference Particle: Ensemble Summary

- Mean: point-by-point (at each z) average of the ensemble

$$\langle \Delta \rangle(z) = \frac{1}{N} \sum_{i=1}^{N} \Delta_i(z)$$

$$\Delta_i(z) = q_i(z) - q_{\text{nom}}(z), \qquad i = 1, \ldots, N$$

Deviation from reference trajectory

- **Median: point-by-point (at each z) middle value of the ensemble.**

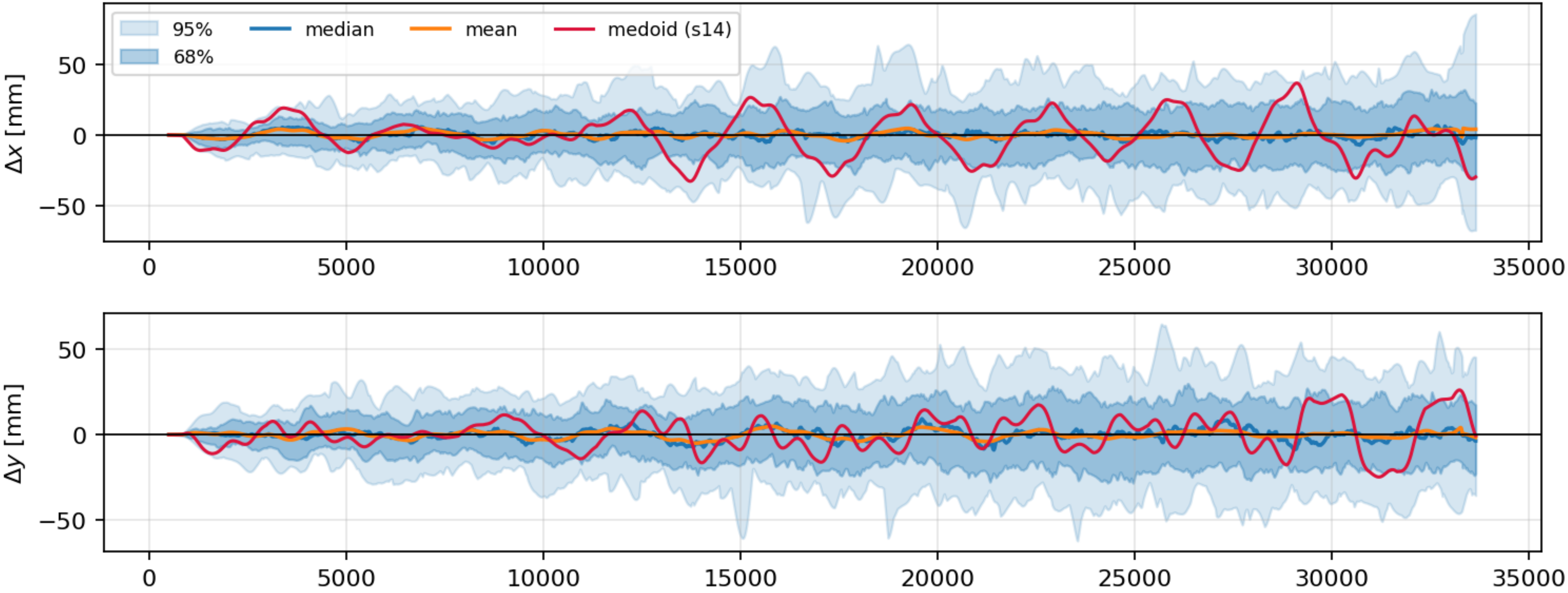
$$\operatorname{med} \Delta(z) = \begin{cases} \Delta_{\left(\frac{N+1}{2}\right)}(z), & N \text{ odd}, \\ \dfrac{\Delta_{\left(\frac{N}{2}\right)}(z) + \Delta_{\left(\frac{N}{2}+1\right)}(z)}{2}, & N \text{ even}. \end{cases}$$

- **Medoid: simulation closest to the ensemble center.**

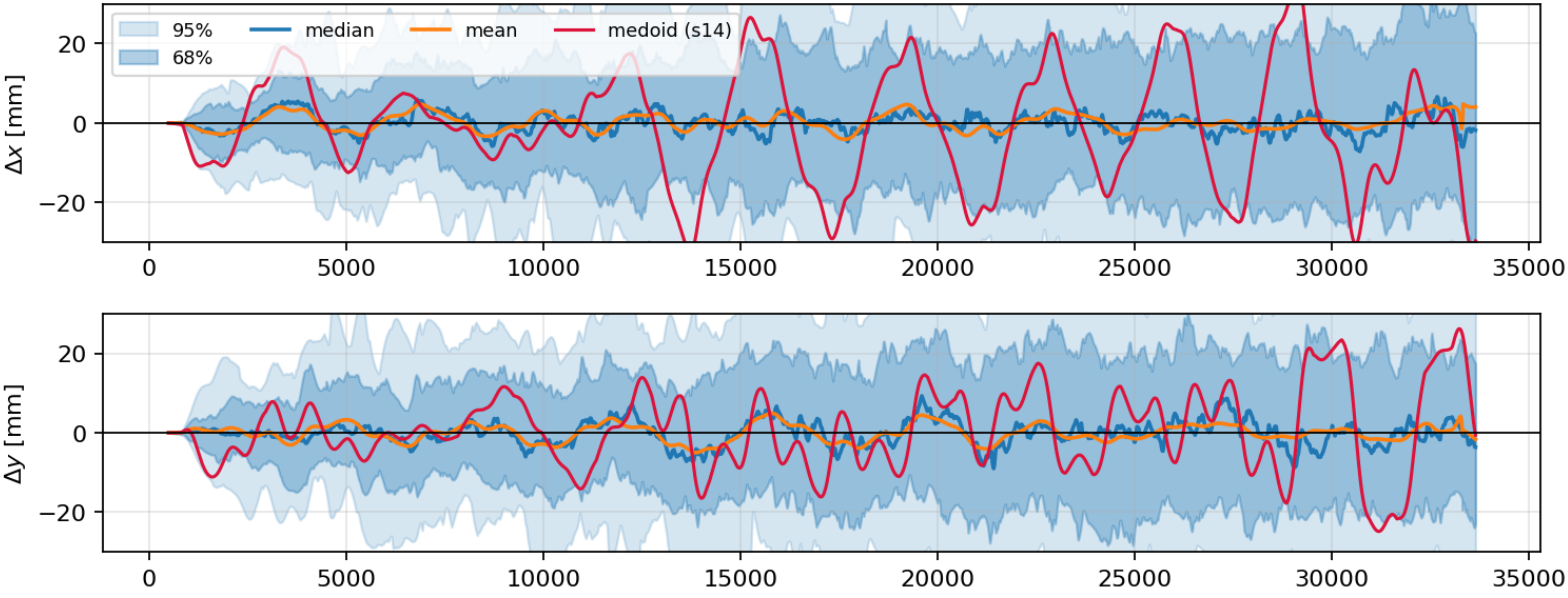
$$i_{\text{medoid}} = \arg\min_{i=1,\ldots,N} D_i$$

$$D_i = \sum_{k \in \mathcal{C}} w_k \sqrt{\left\langle \left( \frac{\Delta_i^k(z) - \operatorname{med} \Delta^k(z)}{\sigma_k} \right)^2 \right\rangle_z}$$

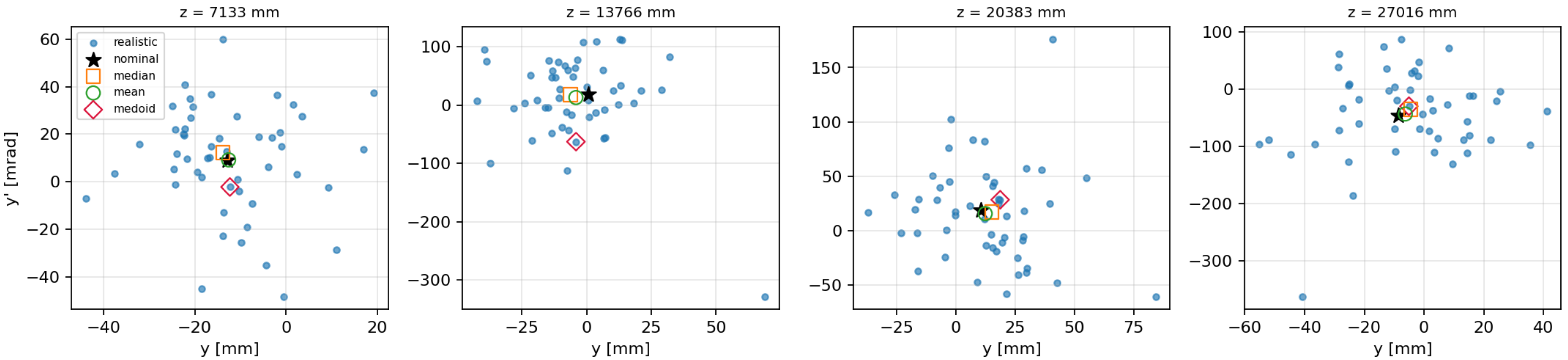
# Transverse Deviation



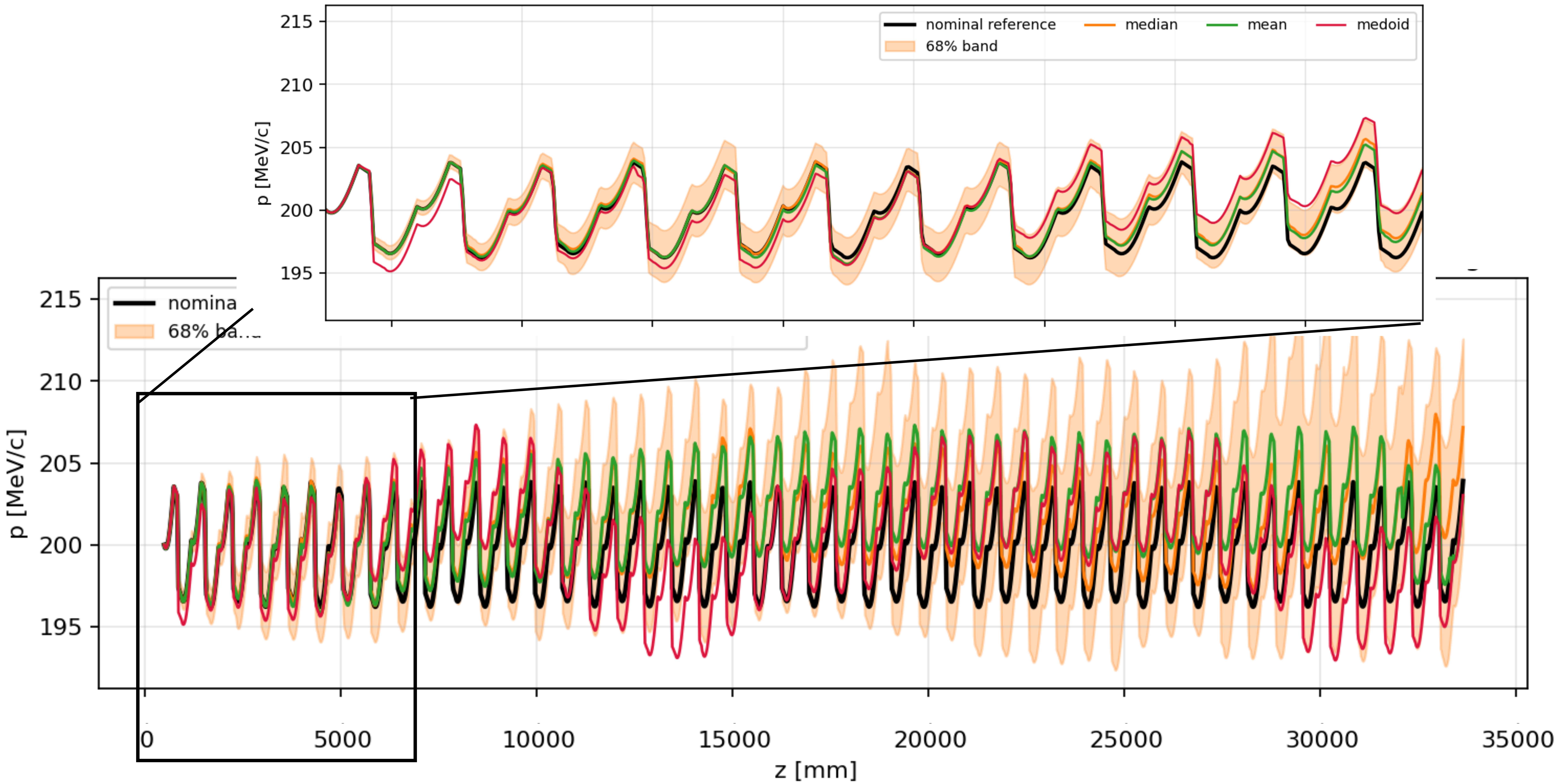
# Transverse Deviation



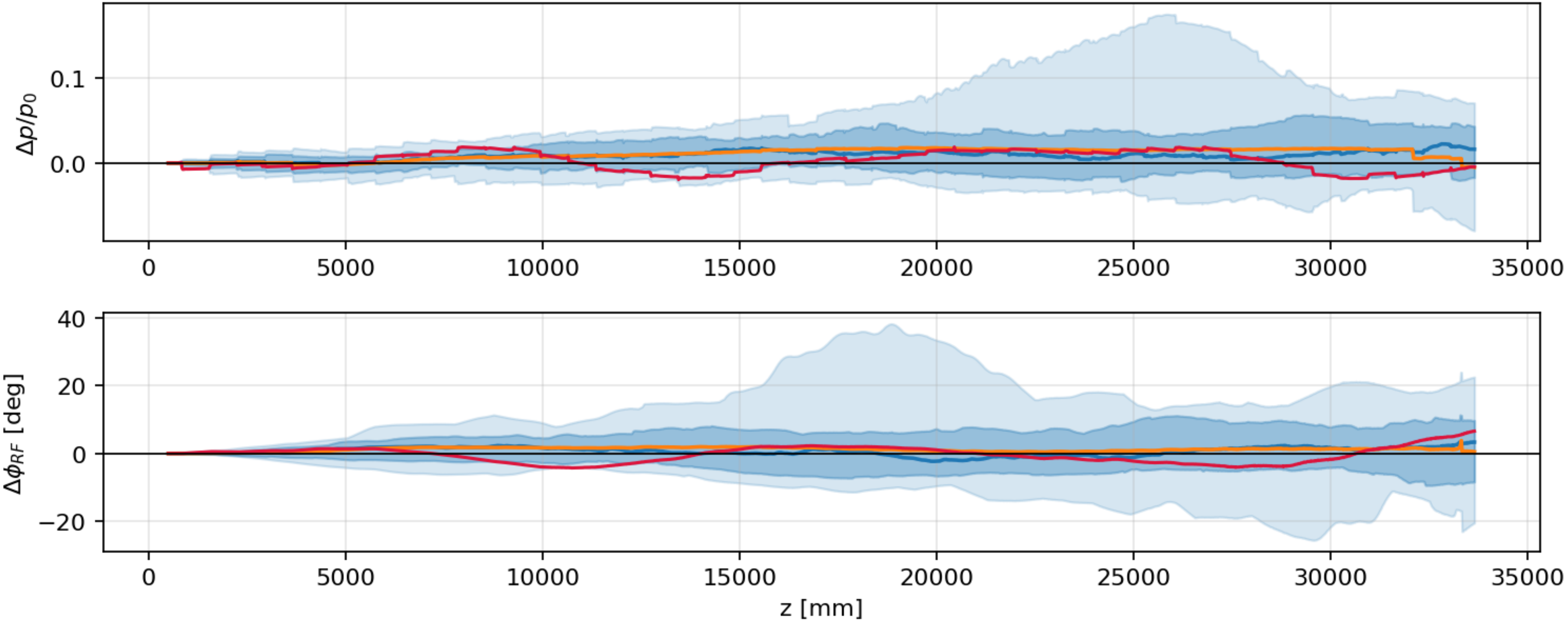
# Transverse Phase Space Snapshots



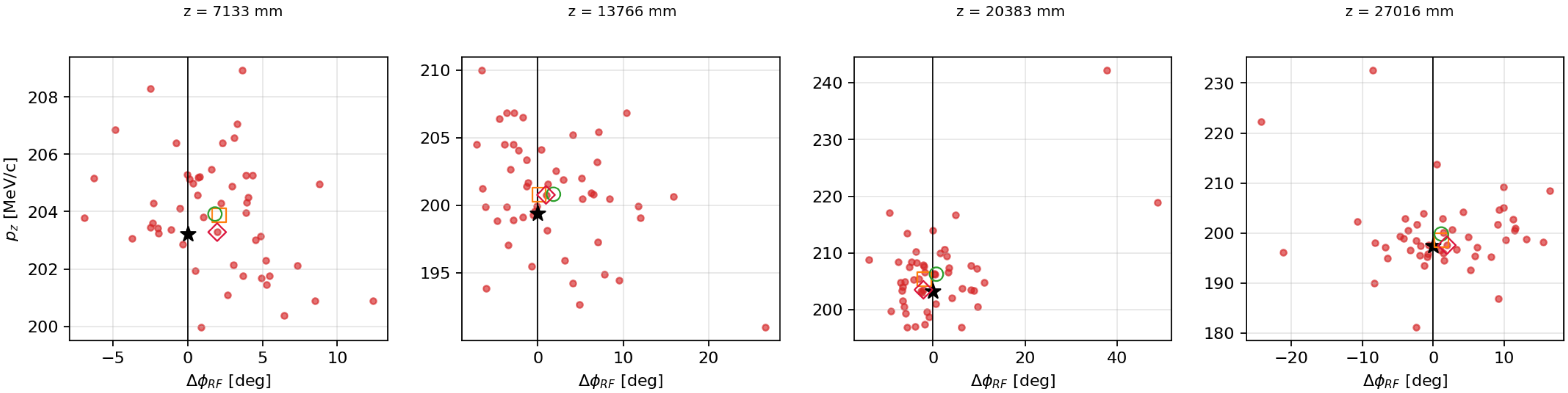
# Momentum Distribution



# Longitudinal Deviation



# Phase Space Snapshots



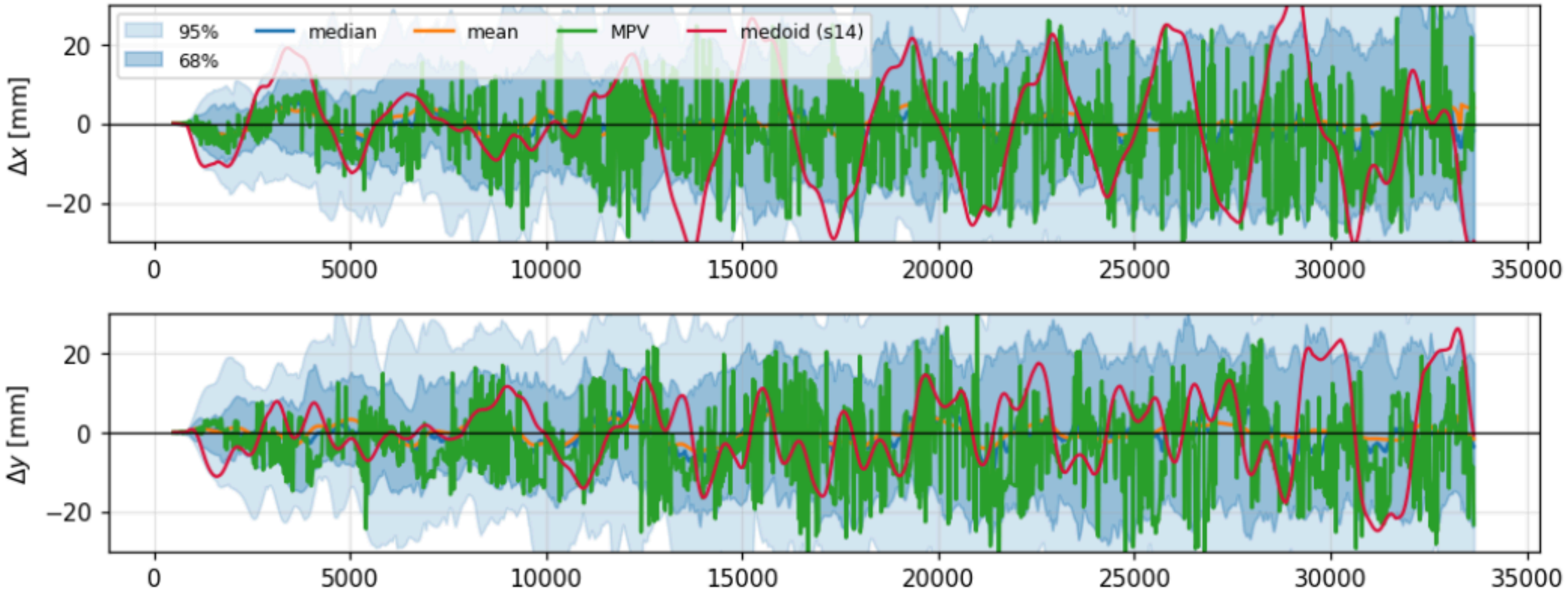
# Summary

- The ensemble mean could be used as a representative stochastic particle directly for HFOFO channel tuning and optimization eliminating the need for manual tuning

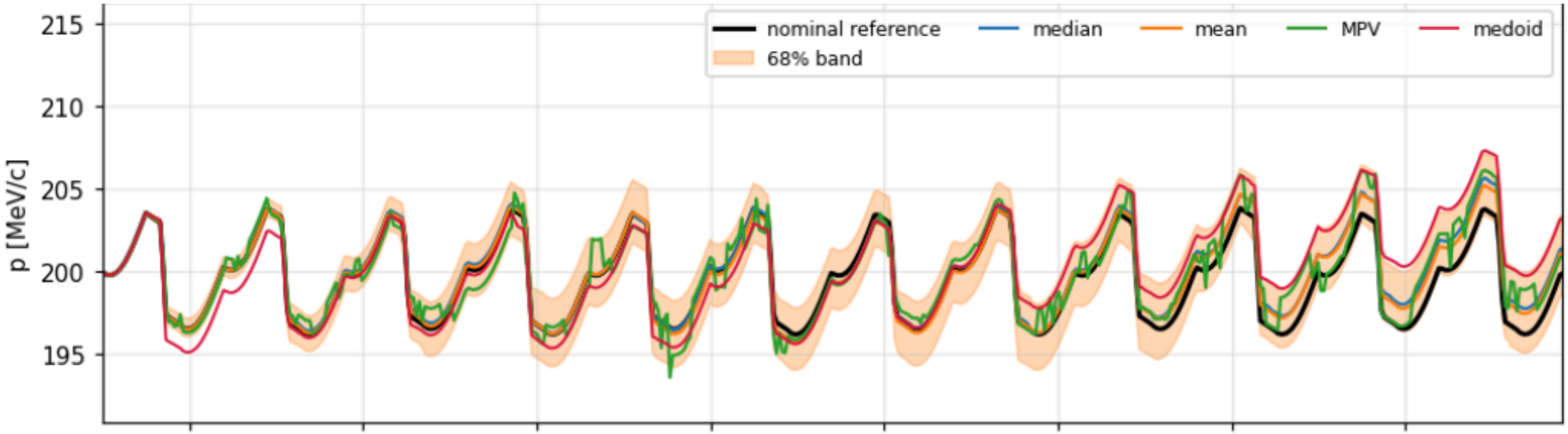
- The next step is implementation within G4beamline.

# Back-up

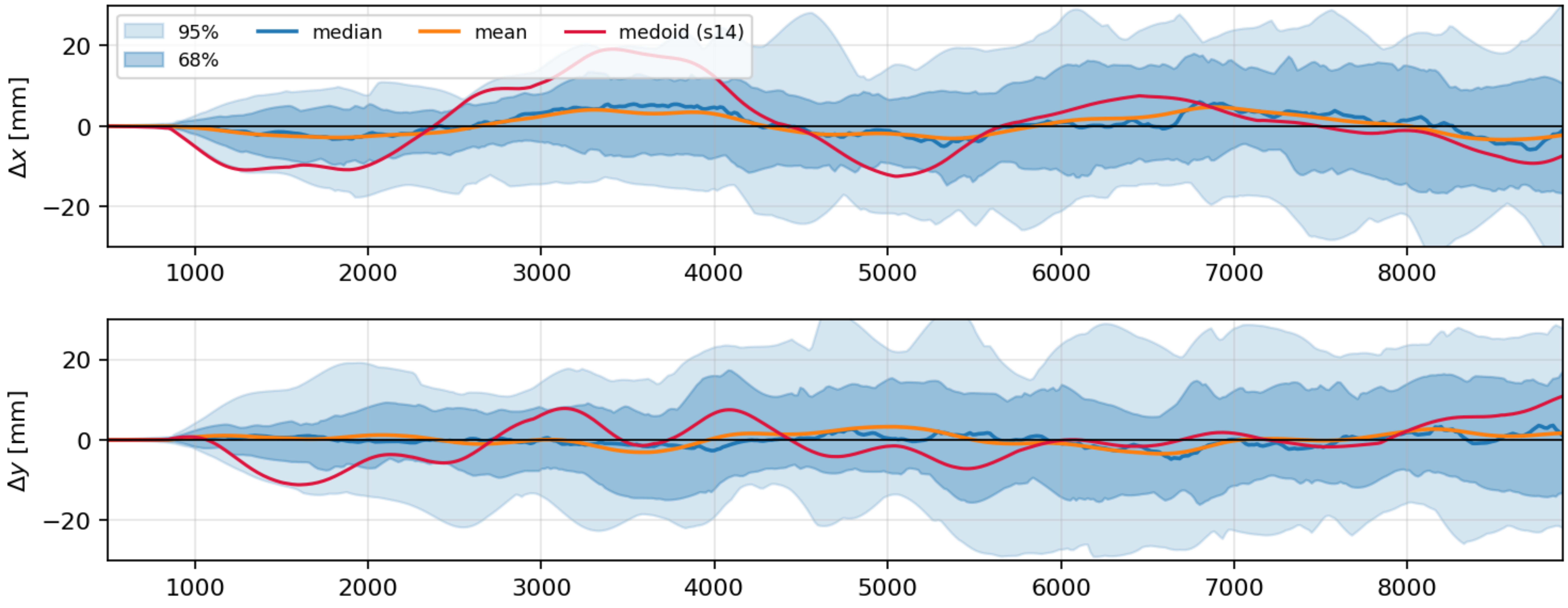
# Transverse Phase Space



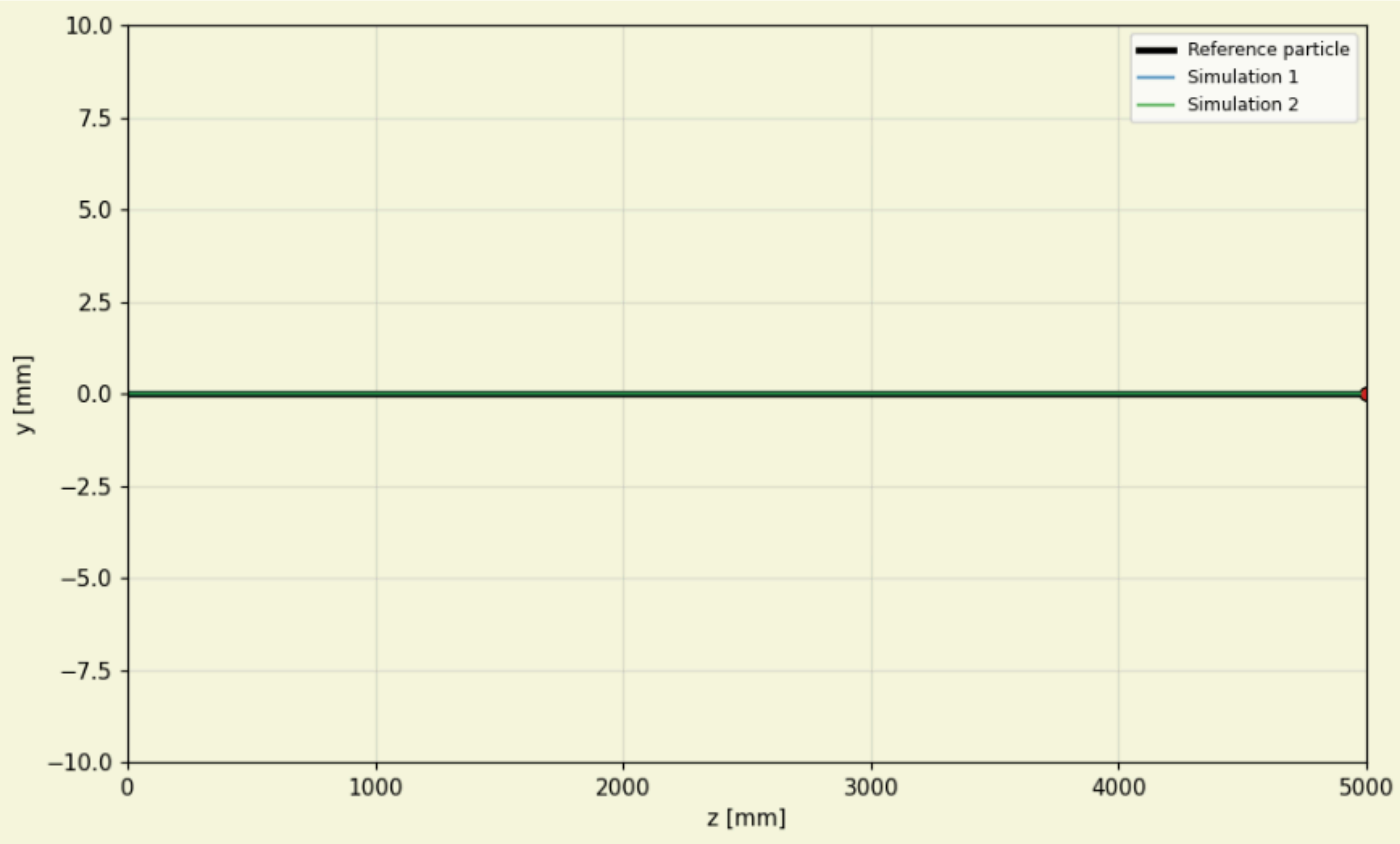
# Longitudinal Momentum



# Transverse Phase Space



# Closure test




- Reference and realistic reference particles through vacuum: Every realistic sample must be identical to the nominal reference.