

# 6D Cooling with Multivariate Density Estimators

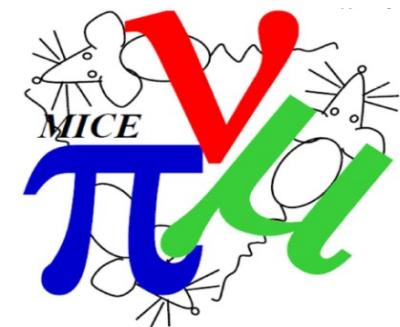


Tanaz A. Mohayai

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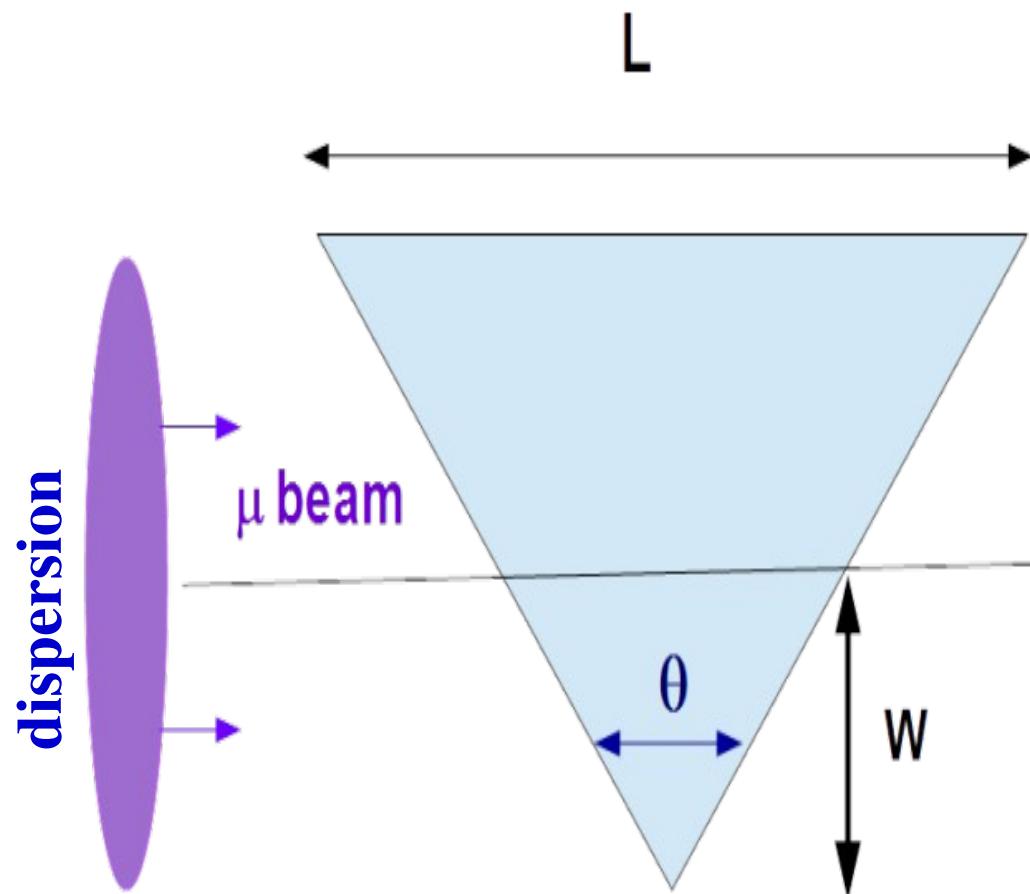
March 1, 2018

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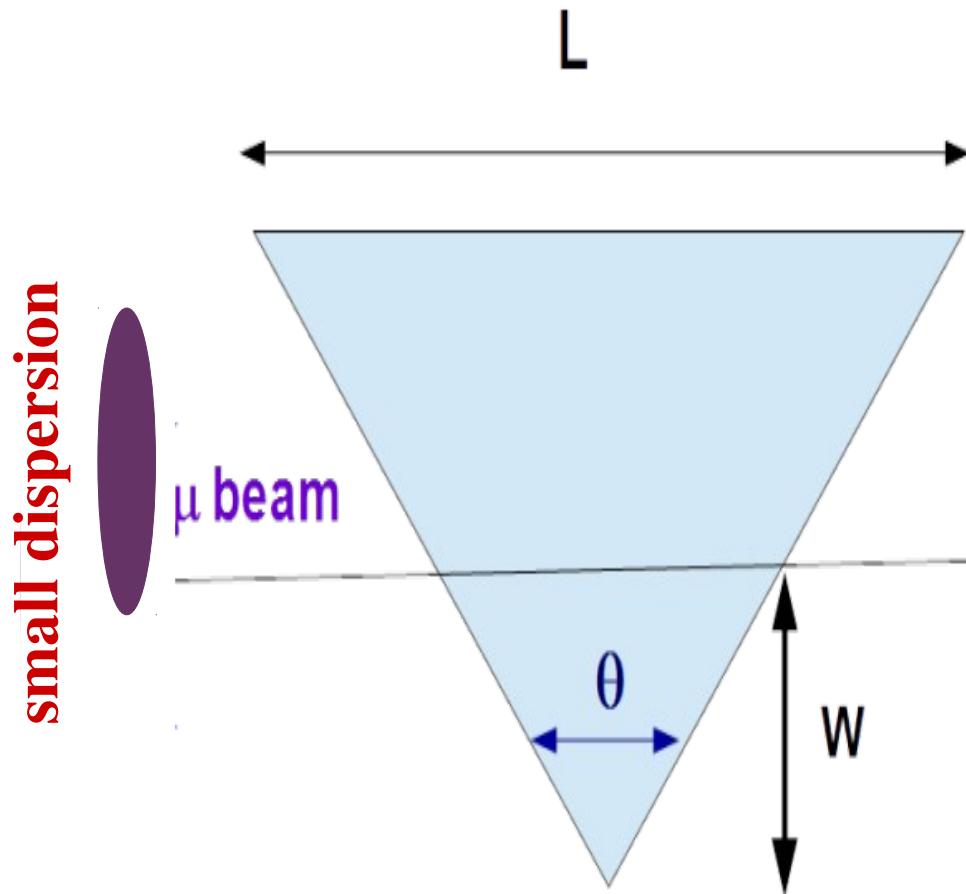
# Motivation

- Goal: use the kernel density estimator to demonstrate **emittance exchange**
- Exchange transverse and longitudinal emittance → transverse heating, longitudinal cooling
- Only possible if wedge data is re-weighted!



# Motivation

- Goal: use the kernel density estimator to demonstrate **reverse emittance exchange**
- Reverse of **emittance exchange** → transverse cooling, longitudinal heating
- Can be demonstrated without re-weighting of wedge data



# G4beamline Tracker to Tracker Simulation

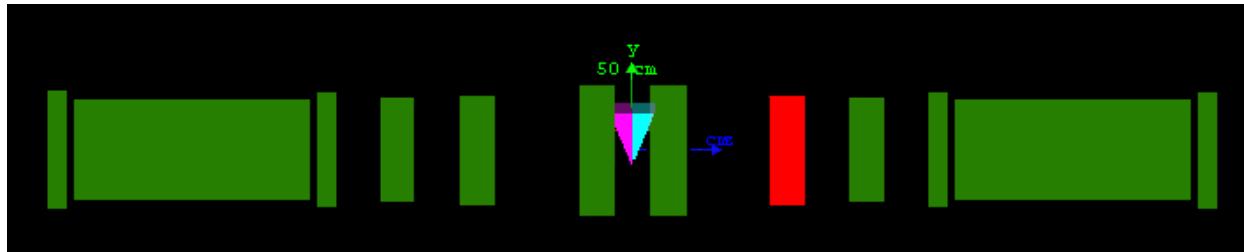
- Current data vs. MC comparison (MAUS wedge geometry under development):
  - ★ Take the reconstructed beam distribution at **TKU station 5**
  - ★ Add a Gaussian time distribution to it
  - ★ Pass it to G4beamline and simulate it from **TKU station 5** to **TKD station 5**
  - ★ Record the position and momentum coordinates at each tracker station with G4beamline “zntuples” (virtual planes with no widths) + calculate the core density and volume at each tracker station
  - ★ Compare the simulated core density and volume with the reconstructed core density and volume
  - ★ Without the re-weighting, the expected outcome is **reverse emittance exchange**.

# Data Specifications

- Cooling channel: 2017-02-7
- Beamline: 6-140
- 2017-2.7 cycle
- Run # 10541
- Density and volume measured in 6D, transverse, and longitudinal using the KDE technique
- **Note the generous P cut** →

| Parameters                        | Values     |
|-----------------------------------|------------|
| Transmission [%]                  | 77         |
| Cooling channel setting           | 2017-02-7  |
| Cooling channel field [T]         | 3 US, 2 DS |
| TOF0-TOF1 cut [ns]                | 28 – 32    |
| Single TOF spacepoint             | ✓          |
| Single track in TKU               | ✓          |
| Single track in TKD               | ✓          |
| $P_{\text{upstream}}$ cut [MeV/c] | 125 – 155  |
| Dy [mm]                           | 38         |
| $p_{\text{ref}}$ [MeV/c]          | 140        |

# Simulation Parameters

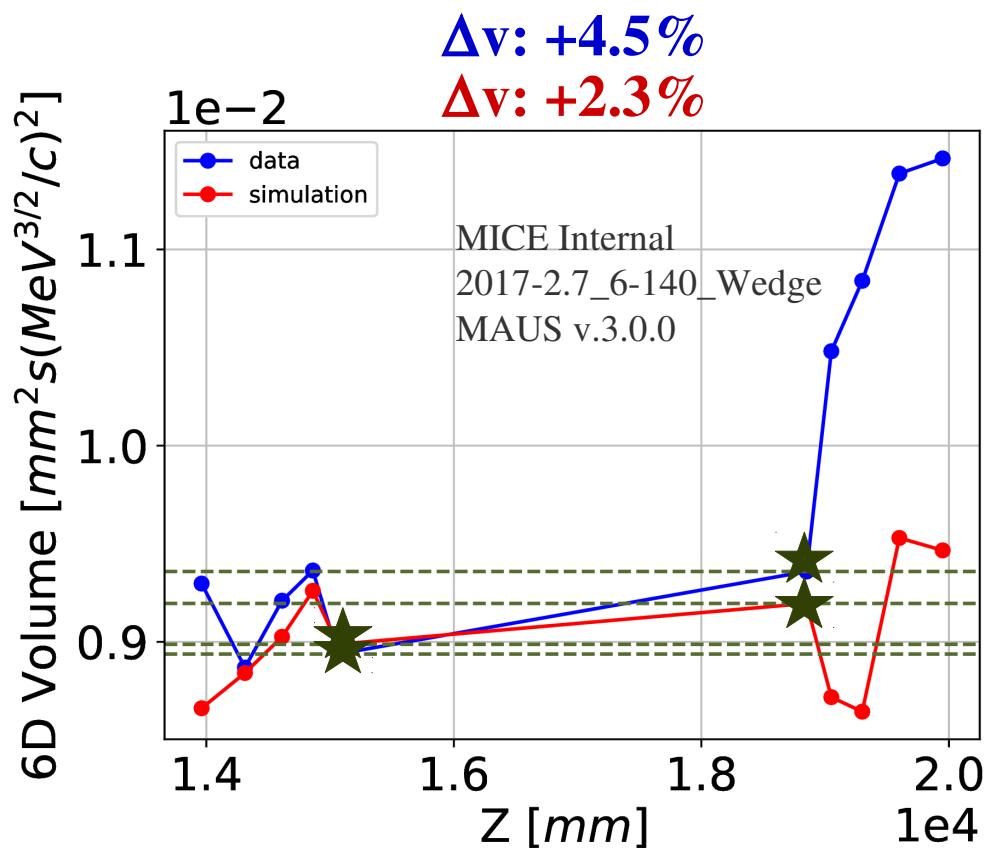
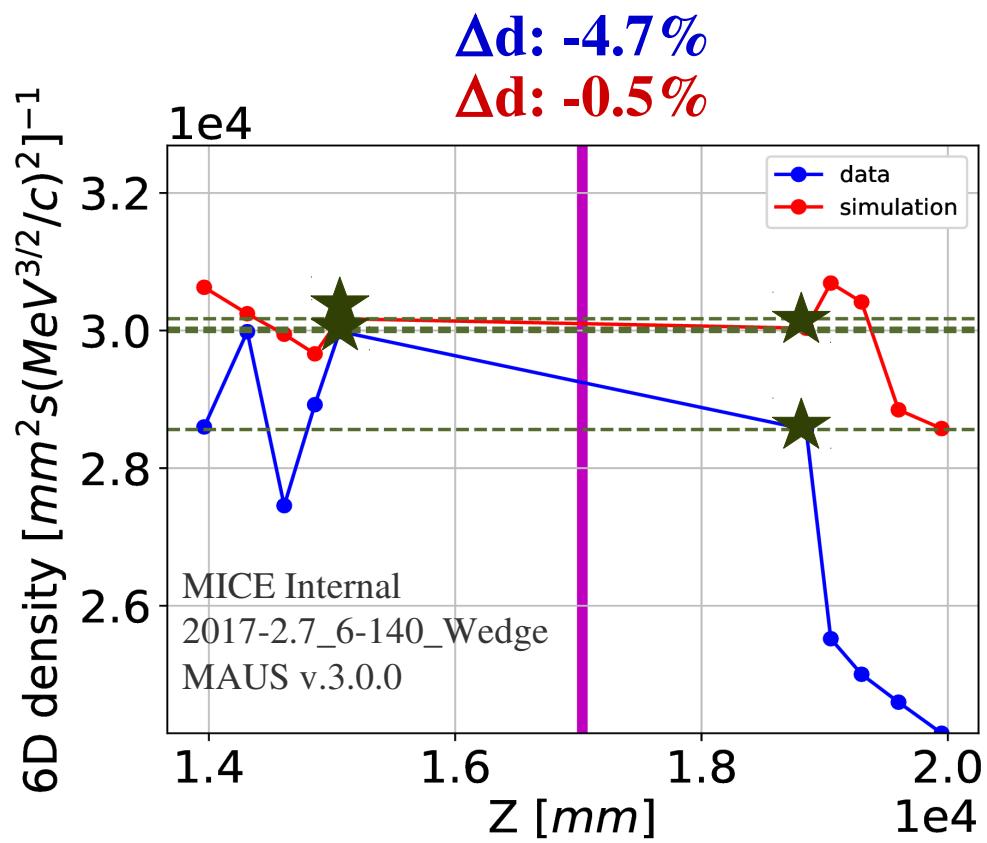


- MICE lattice based on recent survey
- Cooling channel: 2017-02-7
- Beamline: 6-140
- Density and volume measured in 6D, transverse, and longitudinal using KDE technique.

| Parameters                | Values     |
|---------------------------|------------|
| Transmission [%]          | 77         |
| Cooling channel setting   | 2017-02-7  |
| Cooling channel field [T] | 3 US, 2 DS |
| Wedge angle [°]           | 45         |
| Wedge on-axis length [mm] | 52         |
| $\epsilon_{\perp}$ [mm]   | 6          |
| Dy [mm]                   | 52         |
| $p_{\text{ref}}$ [MeV/c]  | 140        |

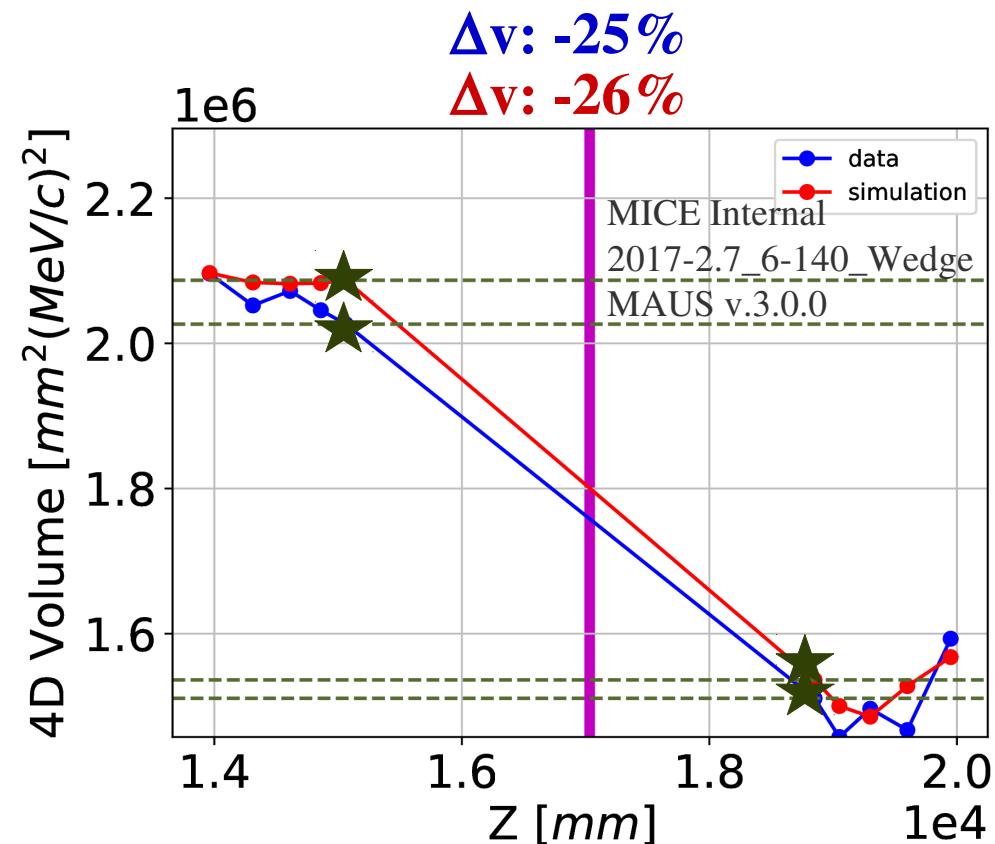
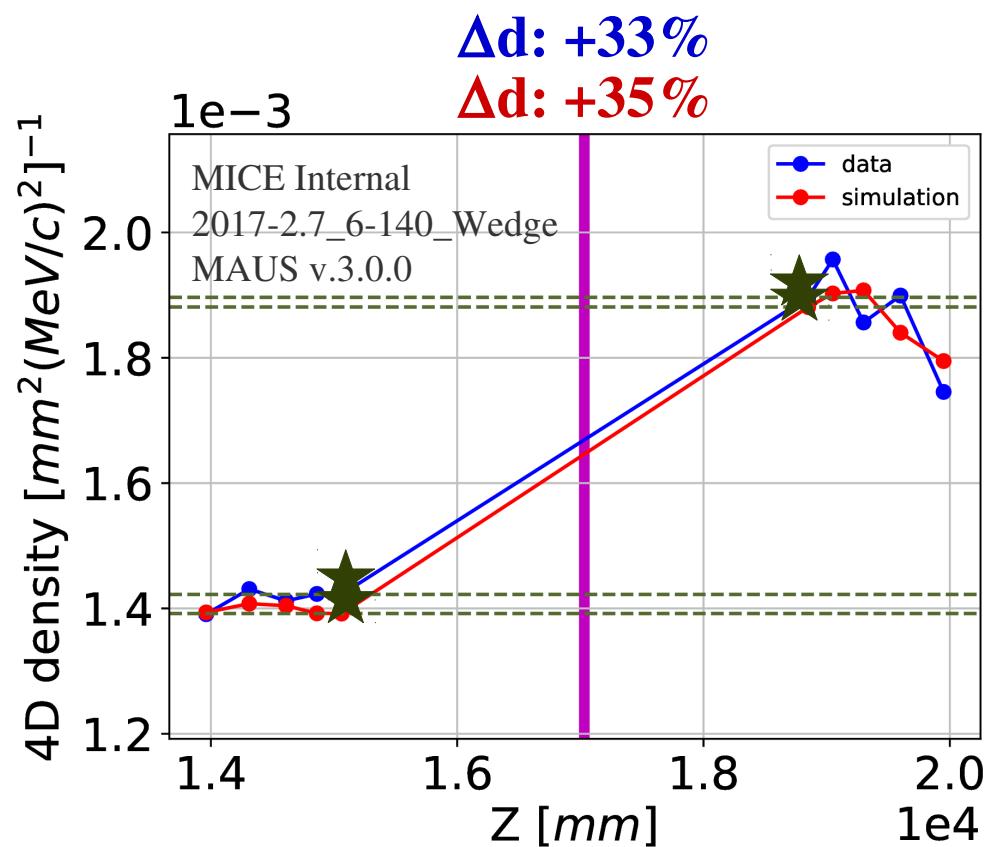
# Data vs. MC – 6D

- $\varepsilon_{\perp}$ : 6 mm;  $p_{\text{ref}}$ : 140 MeV/c
- 6D coordinates:  $\Delta t$ ,  $\Delta E$ ,  $x$ ,  $p_x$ ,  $y$ ,  $p_y$
- KDE-based density and volume of the 2<sup>nd</sup> percentile contour ( $\sim 1\sigma$  of 6D distribution)
- Density  $\downarrow$ , Volume  $\uparrow$ : 6D heating; expected for a beam with a small dispersion
- Features under investigation – possibly sample size related



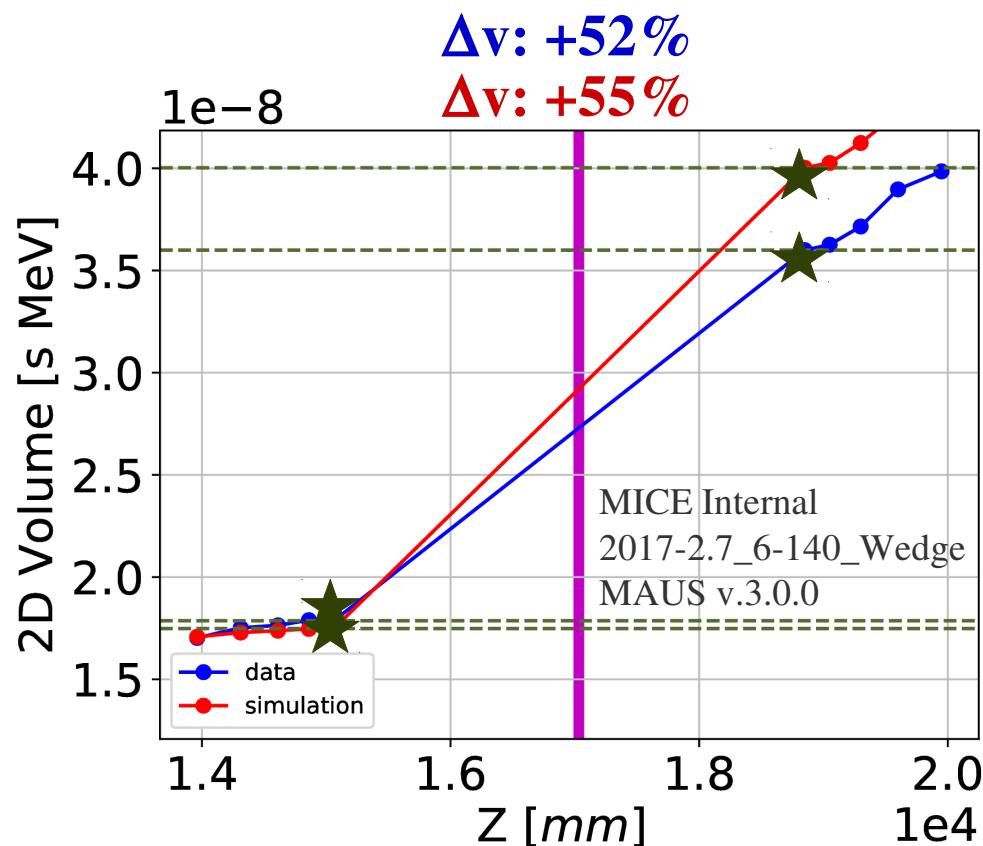
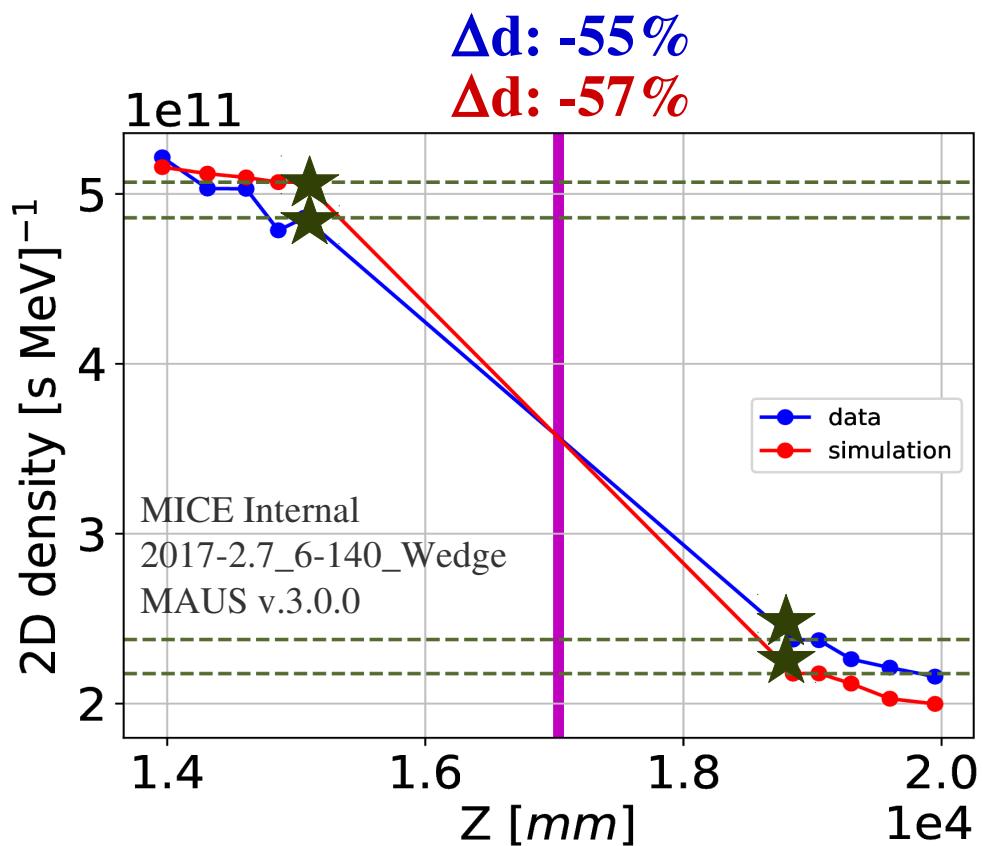
# Data vs. MC – 4D

- $\epsilon_{\perp}$ : 6 mm;  $p_{\text{ref}}$ : 140 MeV/c
- 4D coordinates:  $x, p_x, y, p_y$
- KDE-based density and volume of the 9<sup>th</sup> percentile contour ( $\sim 1\sigma$  of 4D distribution)
- Density  $\uparrow$ , Volume  $\downarrow$ : transverse cooling



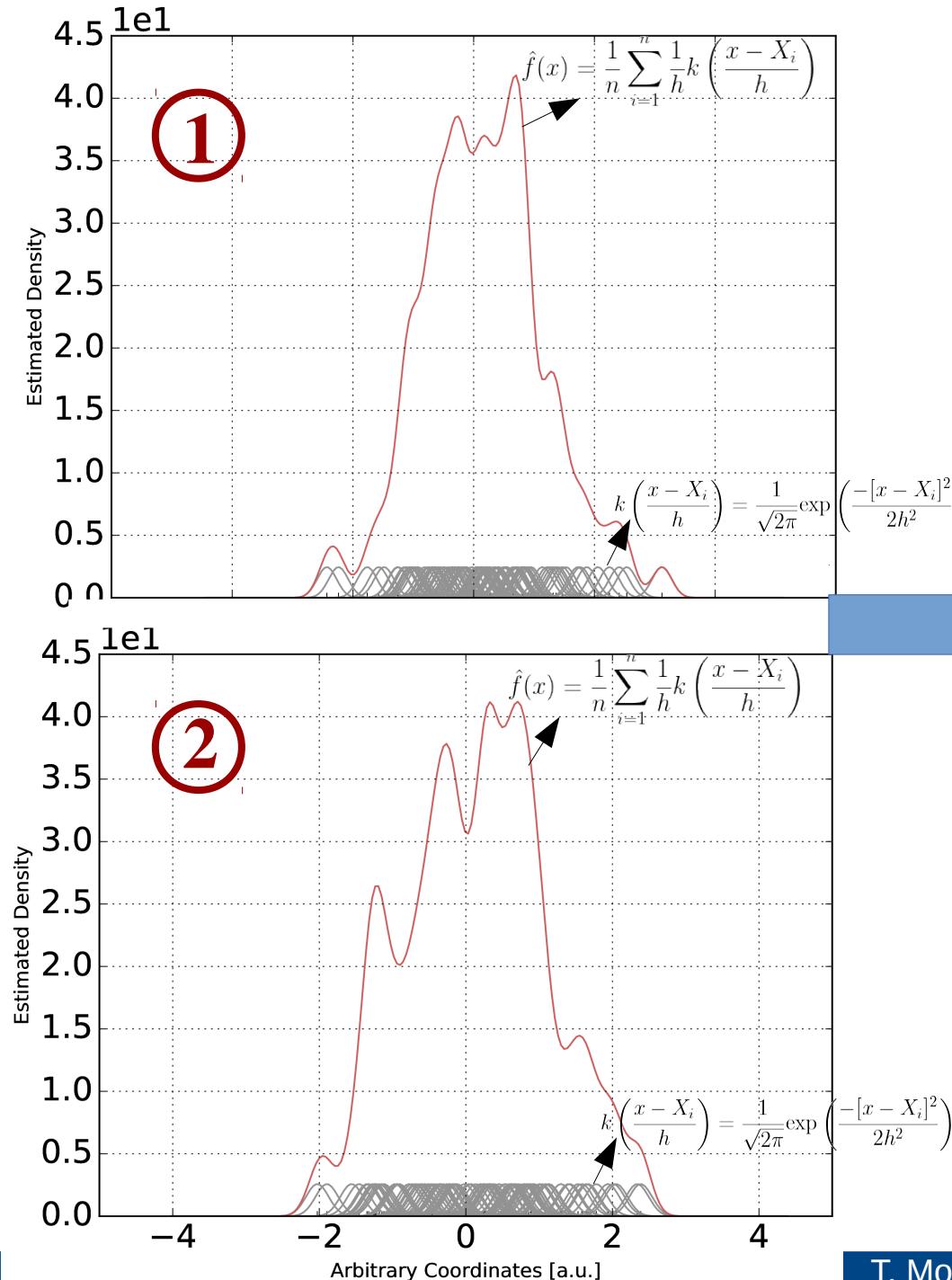
# Data vs. MC – 2D

- $\varepsilon_{\perp}$ : 6 mm;  $p_{\text{ref}}$ : 140 MeV/c
- 2D coordinates:  $\Delta t$ ,  $\Delta E$
- KDE-based density and volume of the 24<sup>th</sup> percentile contour ( $\sim 1\sigma$  of 2D distribution)
- Density  $\downarrow$ , Volume  $\uparrow$ : **reverse emittance exchange**

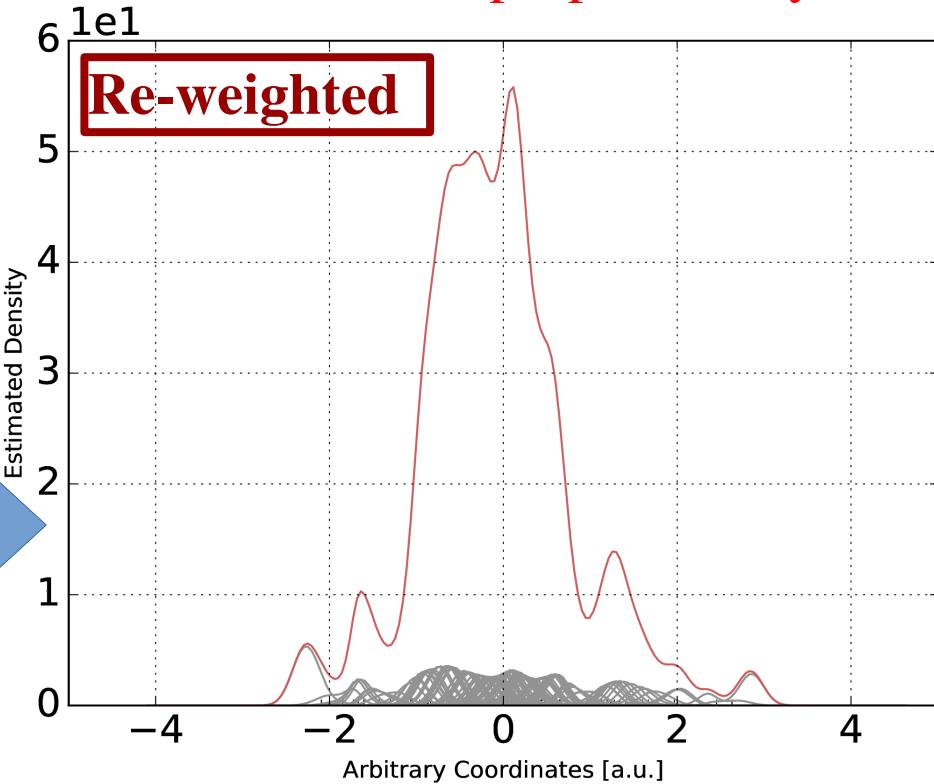


# **Now onto the re-weighting technique**

# How to re-weight kernel style



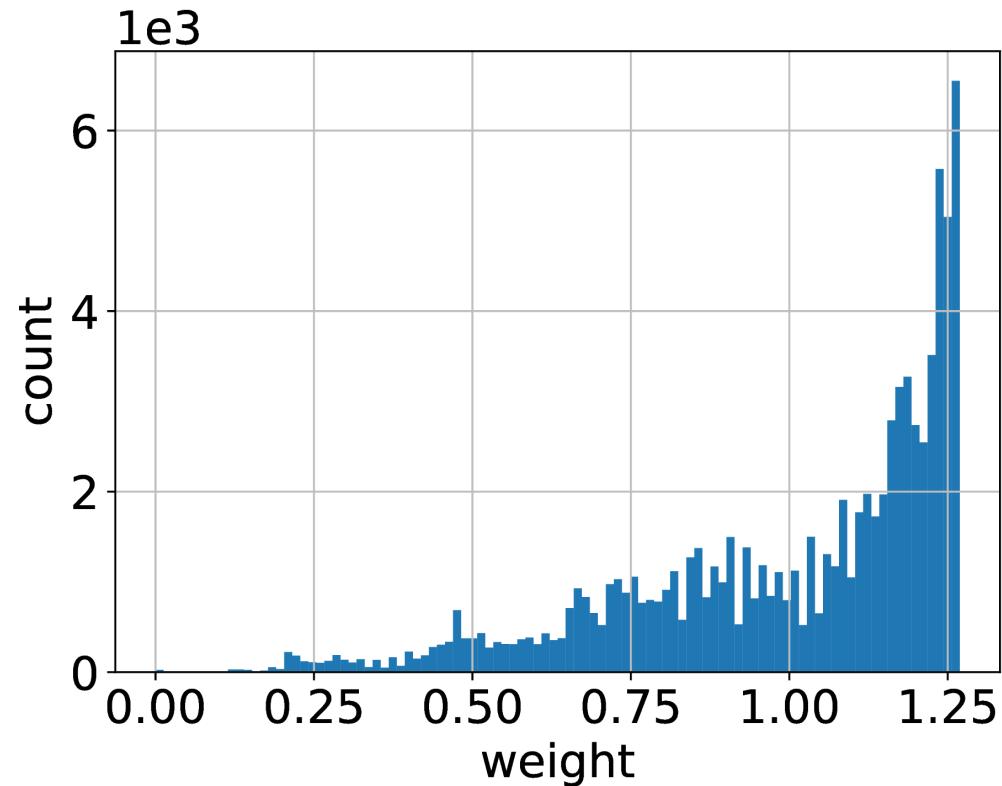
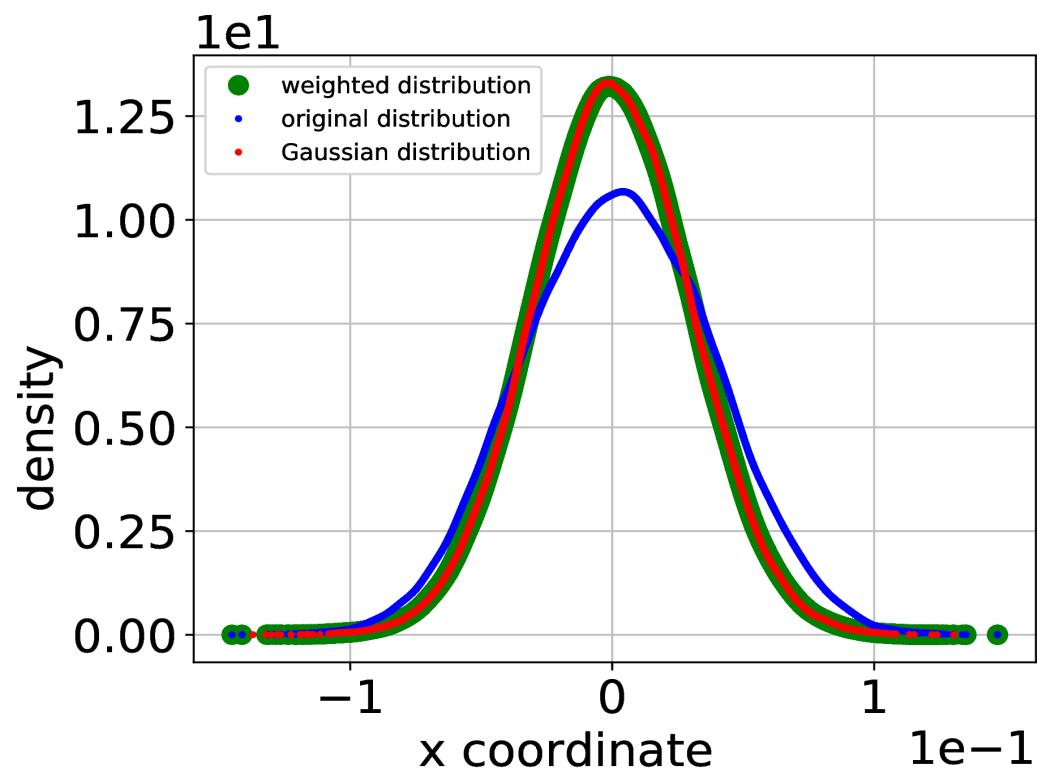
Disclaimer: a toy example, for illustration purposes only



- ★ Re-weight distribution **2** to match **1**
- via the kernels (instead of re-weighting the coordinates or the density)

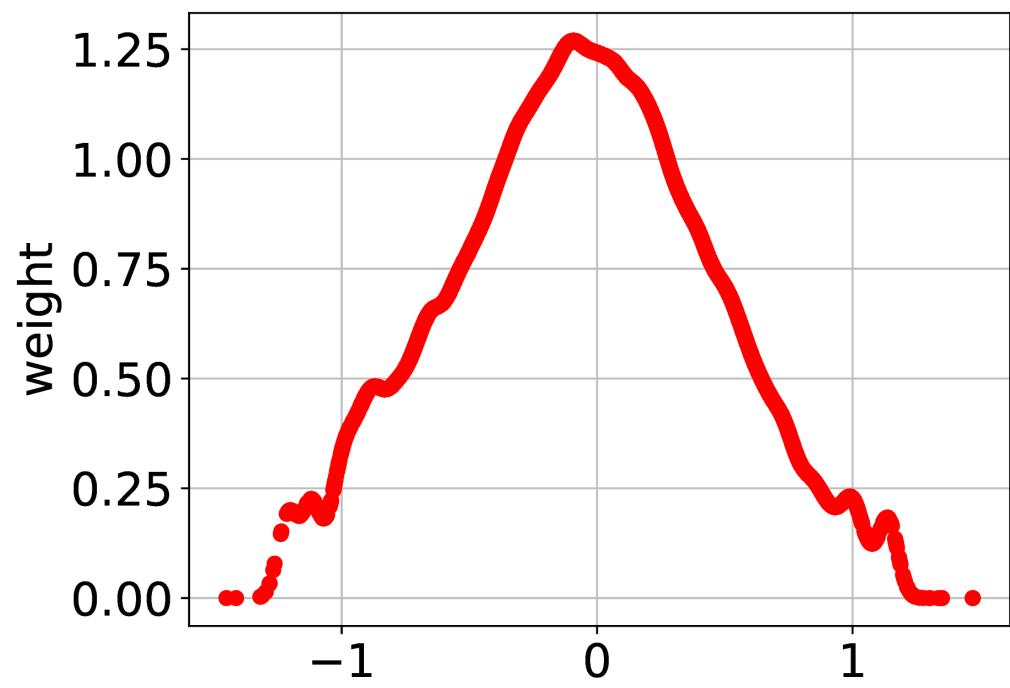
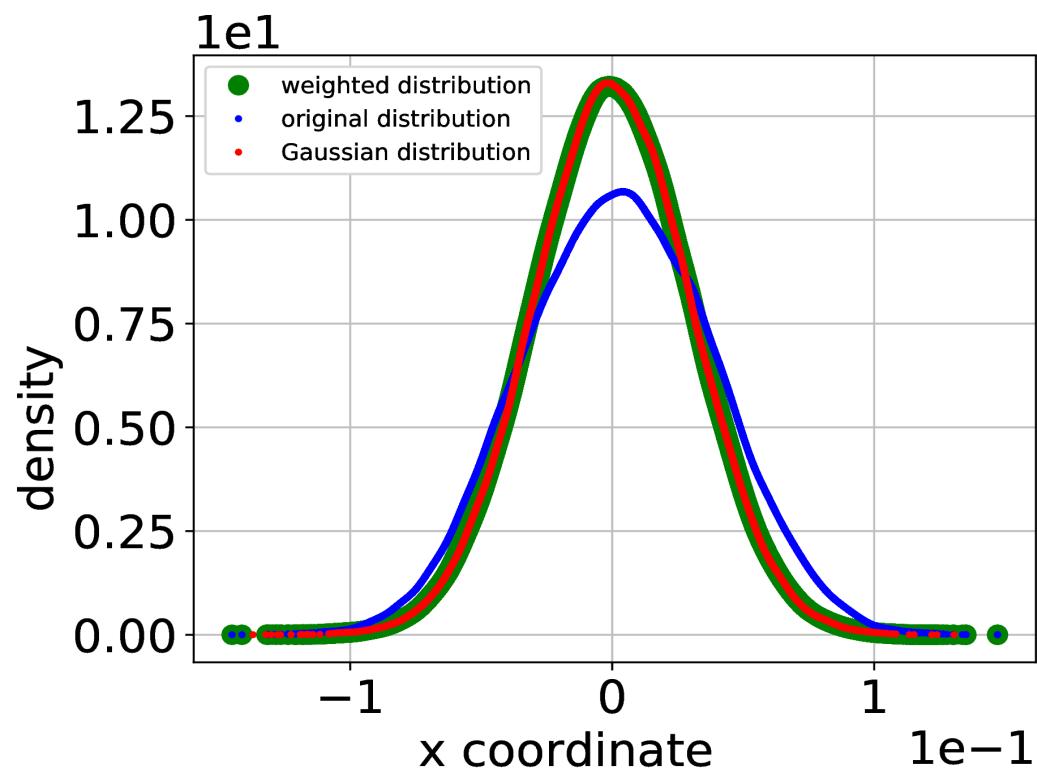
# Re-weighting with KDE – 1D Test

- **Original distribution:** TKU station 5 x coordinates. **Target distribution:** 1D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels to match the height of the target distribution



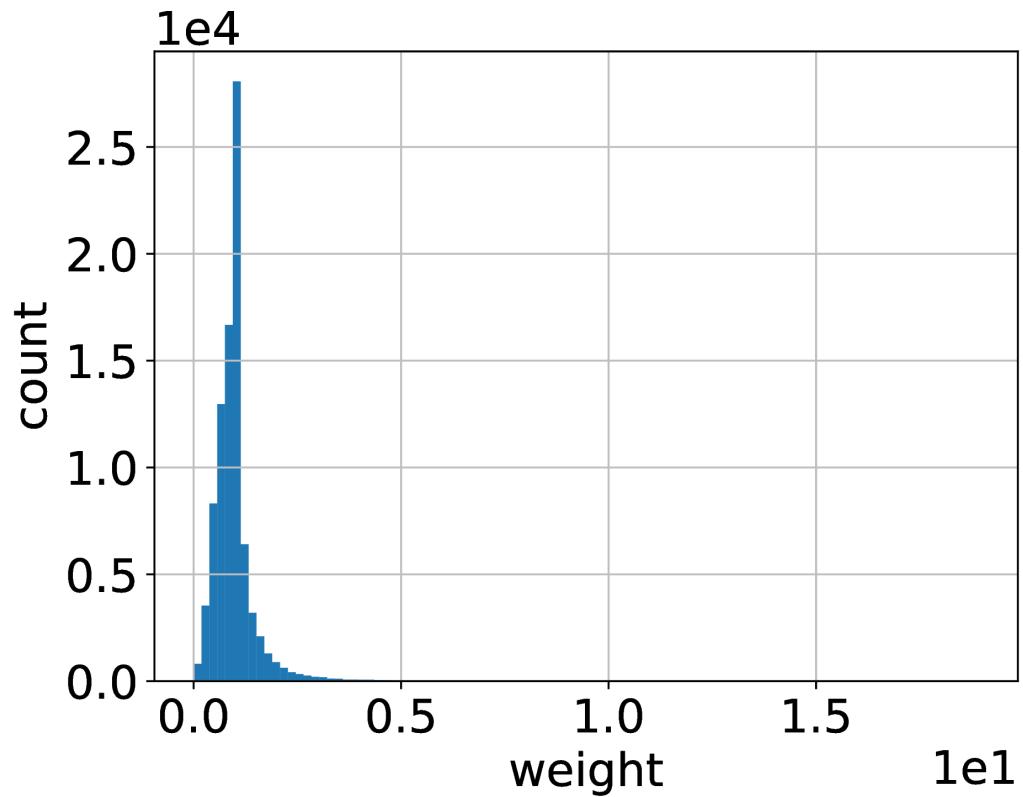
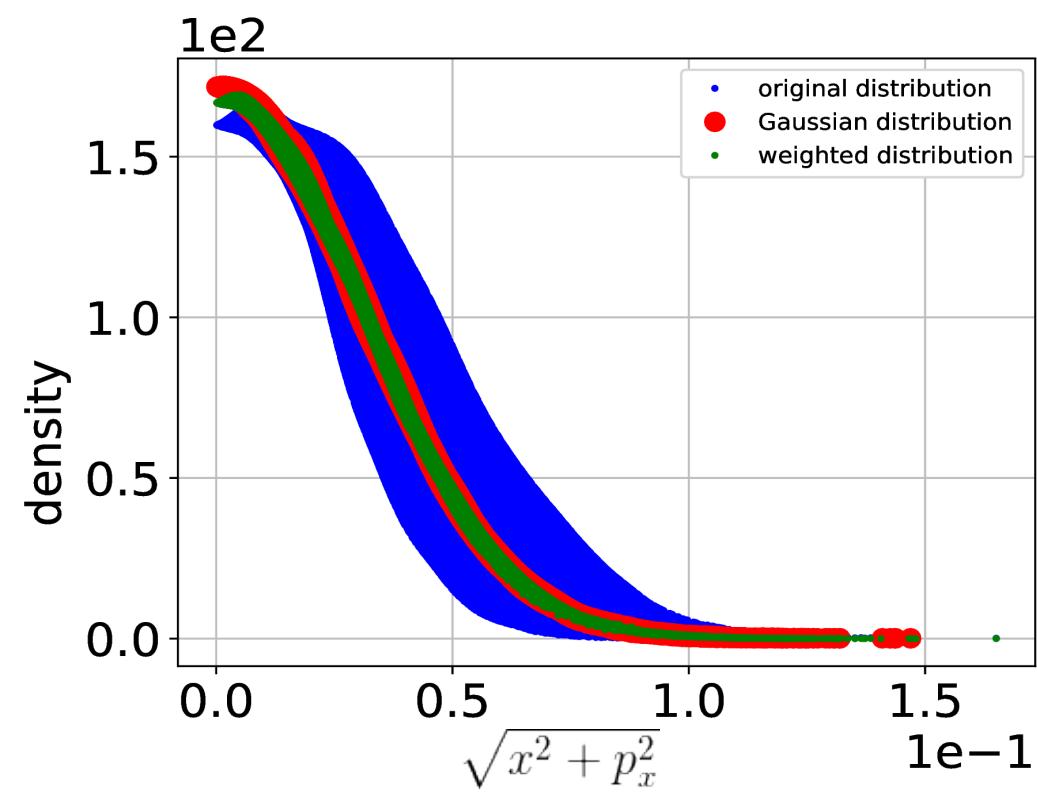
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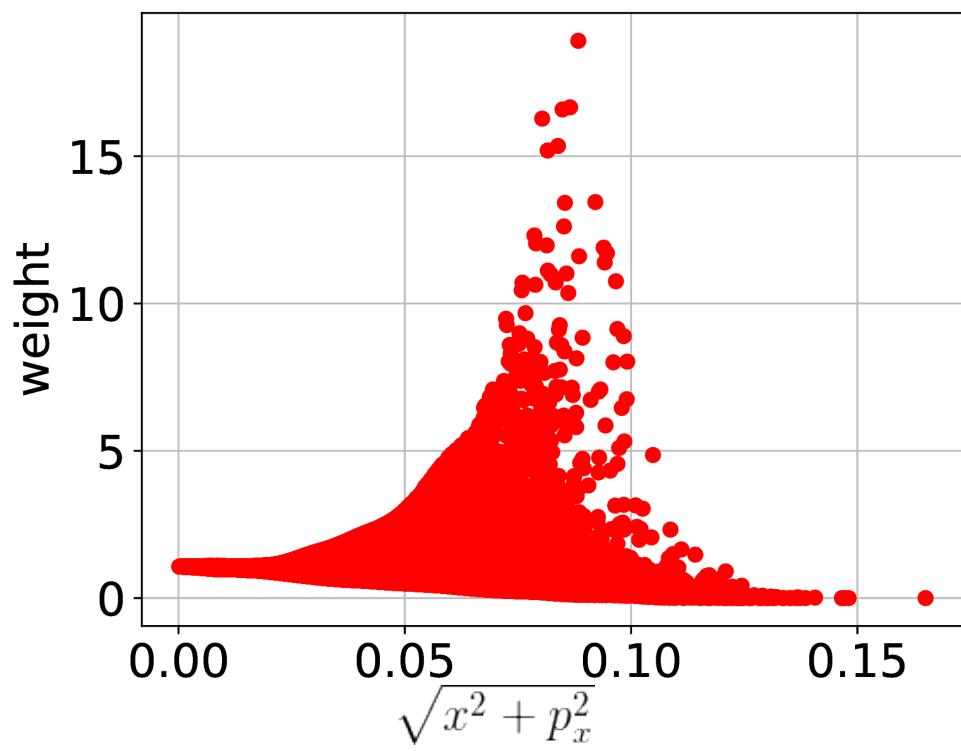
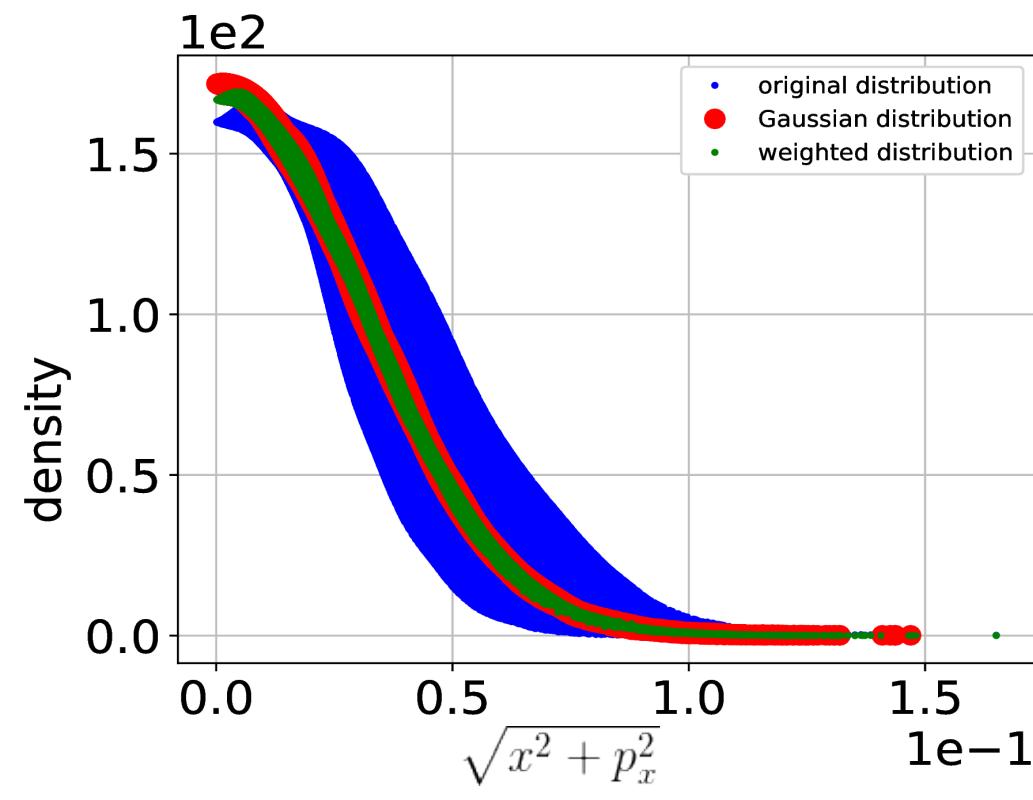
# Re-weighting with KDE – 2D Test

- **Original distribution:** TKU station 5 x, px coordinates. **Target distribution:** 2D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels



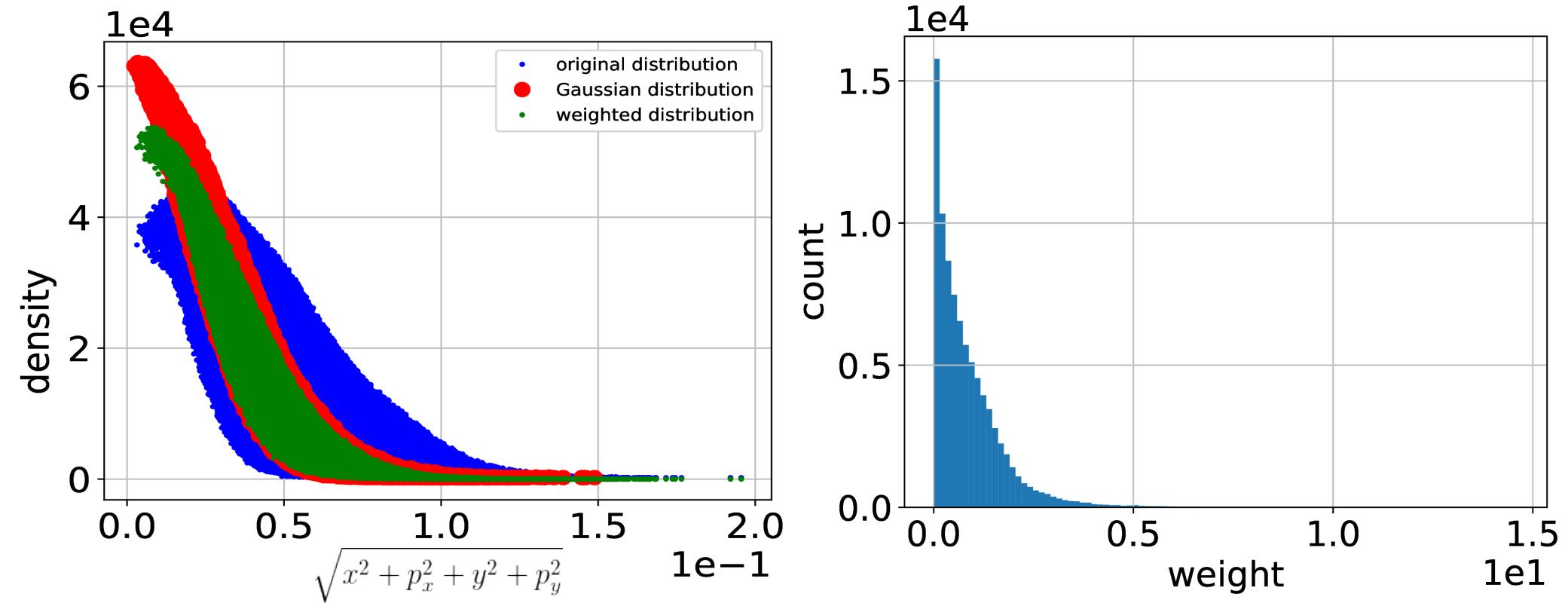
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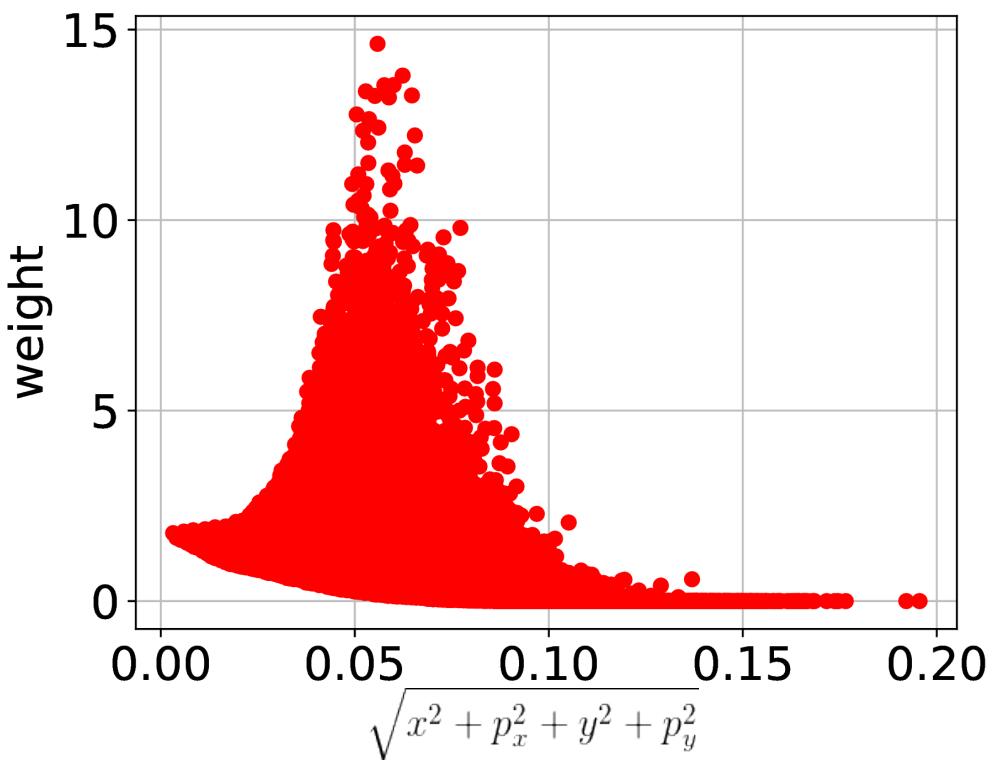
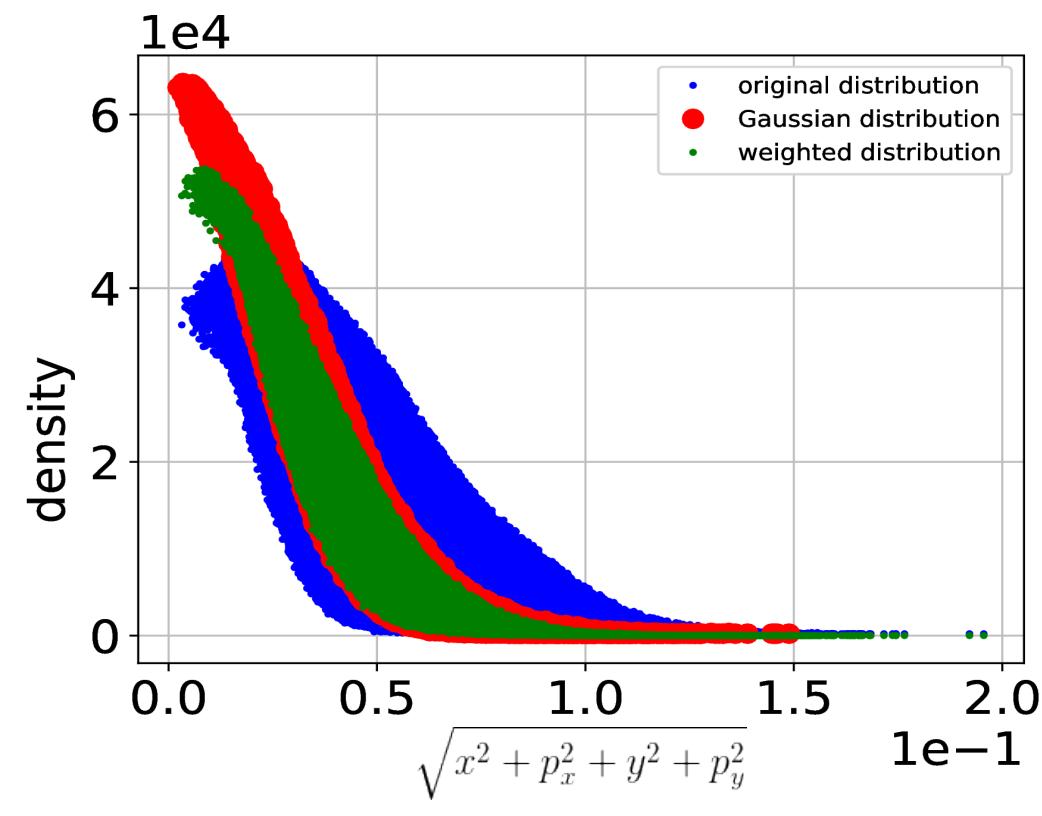
# Re-weighting with KDE – 4D Test

- **Original distribution:** TKU station 5 x, px, y, py coordinates. **Target distribution:** 4D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels



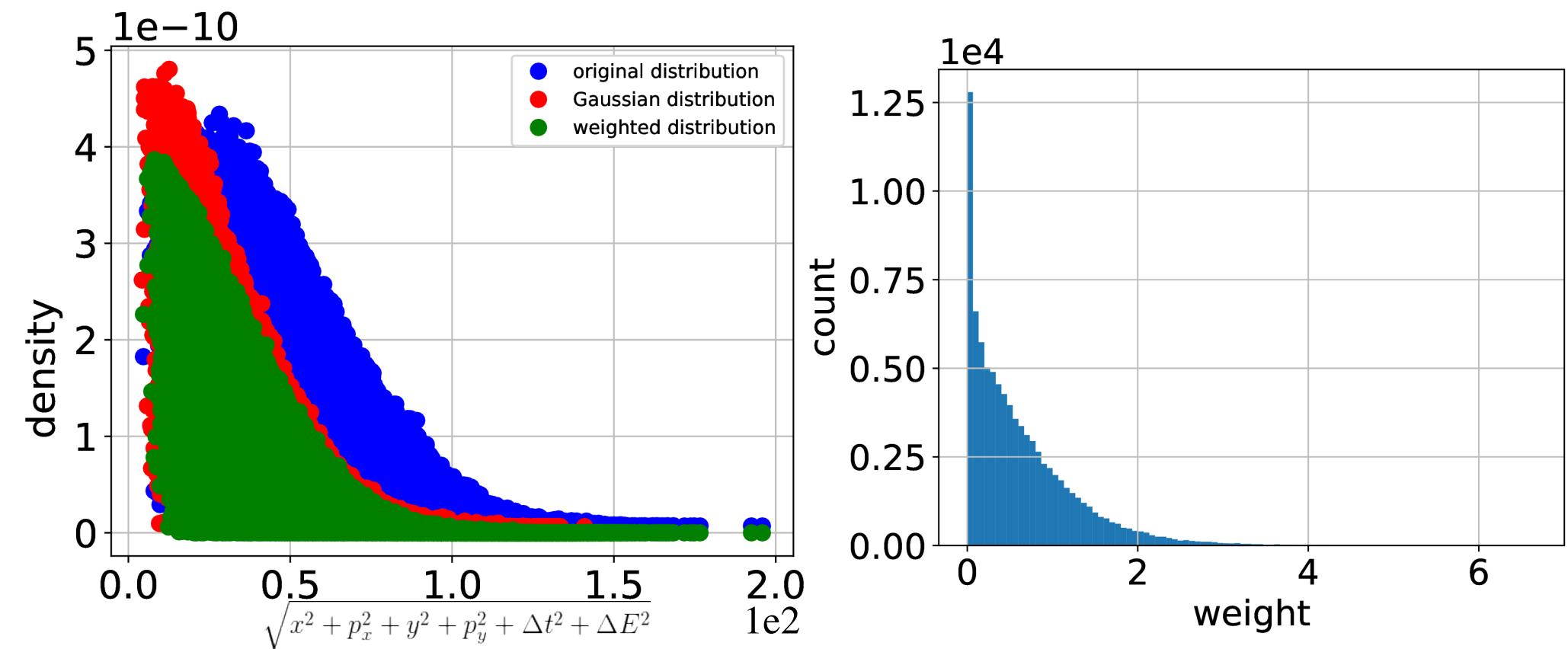
# Re-weighting with KDE – 4D Test

- **Original distribution:** TKU station 5 x, px, y, py coordinates. **Target distribution:** 4D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels



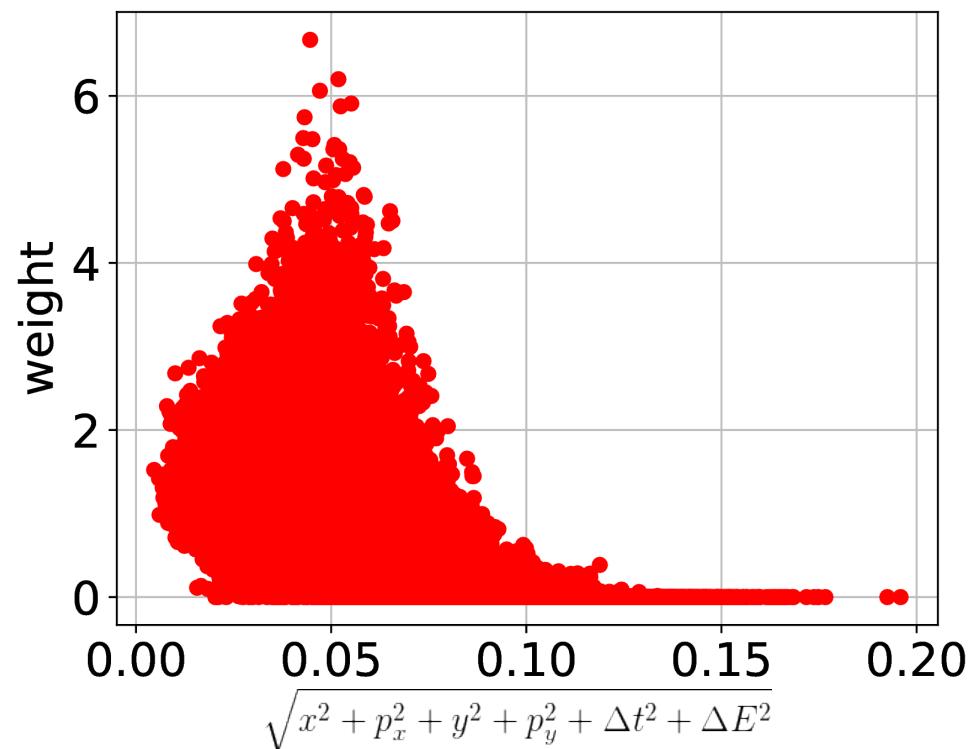
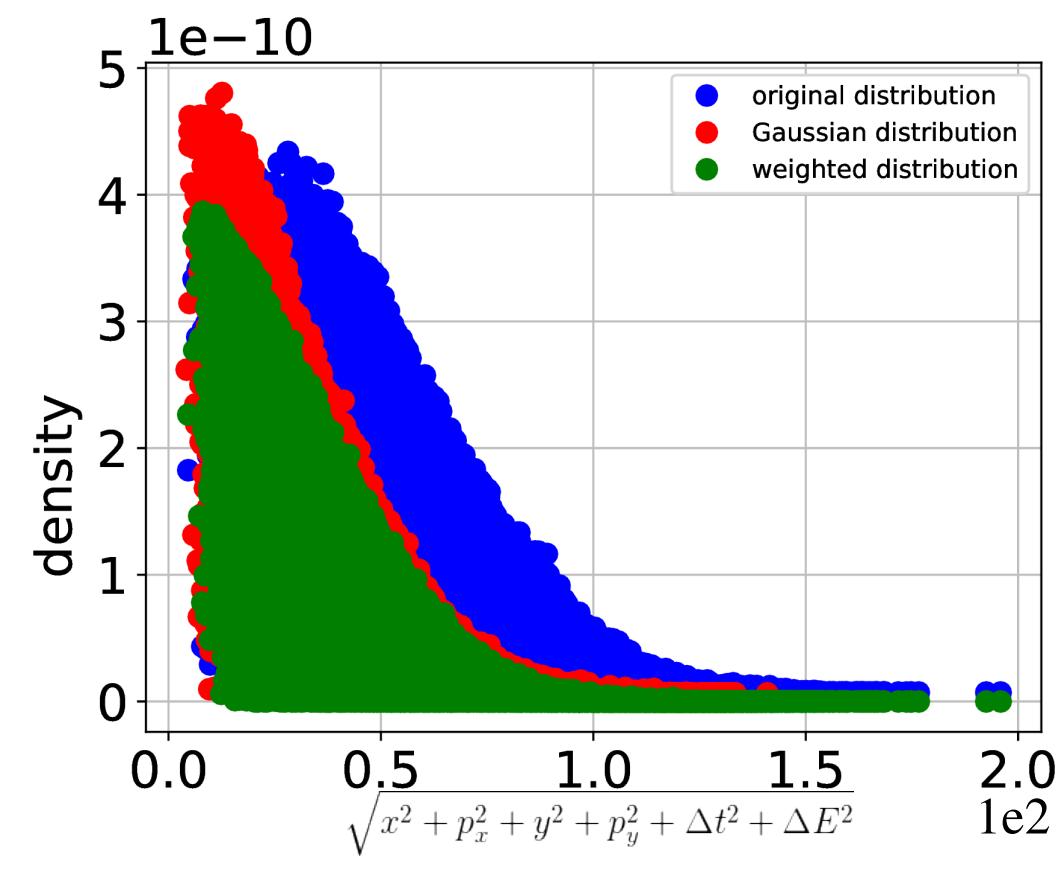
# Re-weighting with KDE – 6D Test

- **Original distribution:** TKU station 5 x, px, y, py, Δt, ΔE coordinates. **Target distribution:** 6D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels



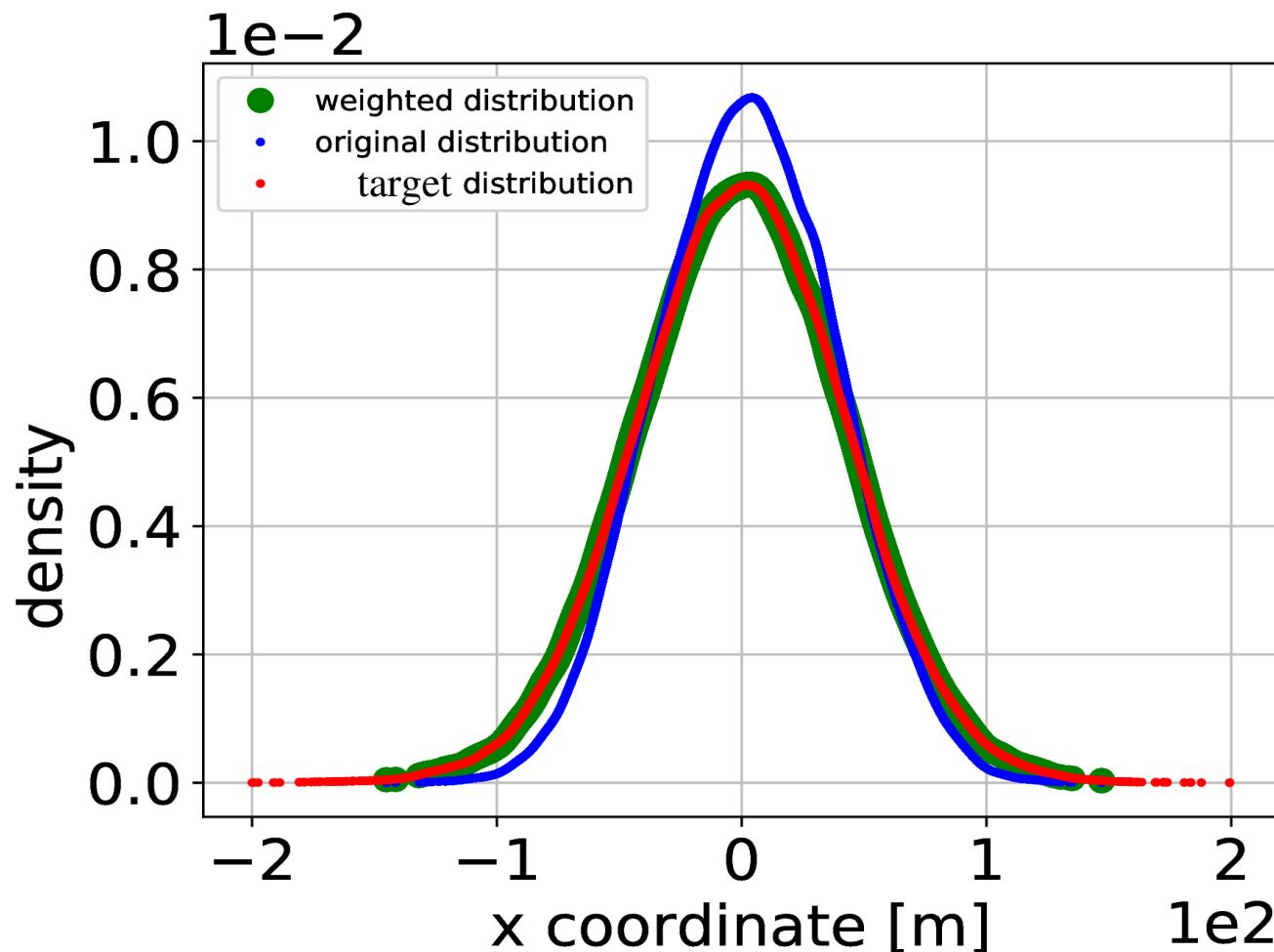
# Re-weighting with KDE – 6D Test

- **Original distribution:** TKU station 5 x, px, y, py, Δt, ΔE coordinates. **Target distribution:** 6D Gaussian distribution. **Weighted distribution:** a distribution with re-weighted kernels



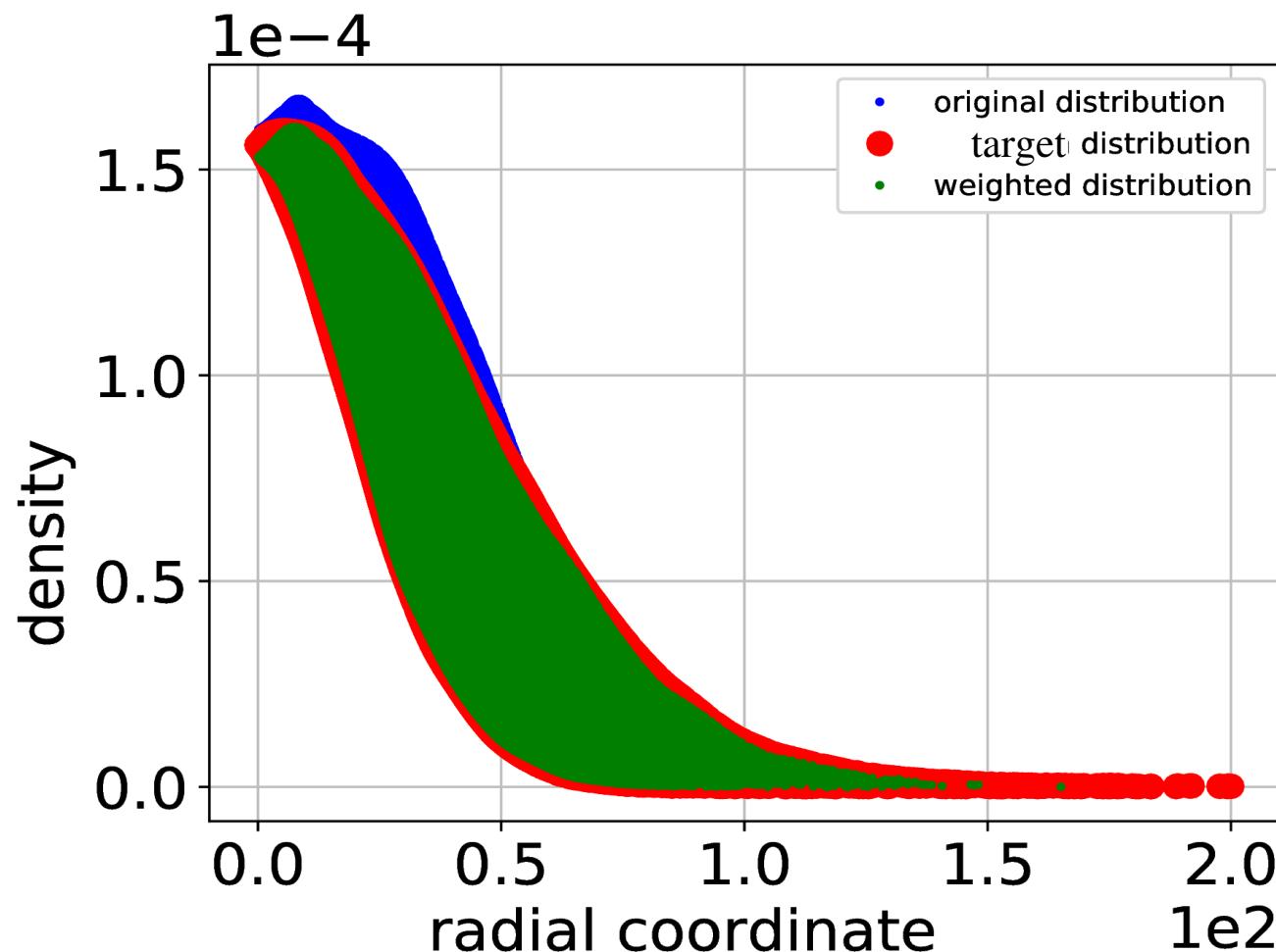
# Re-weighting – 1D Test with Dispersion

- **Original distribution:** TKU station 5 x coordinates. **Target distribution:** 1D dispersive beam distribution. **Weighted distribution:** a distribution with re-weighted kernels



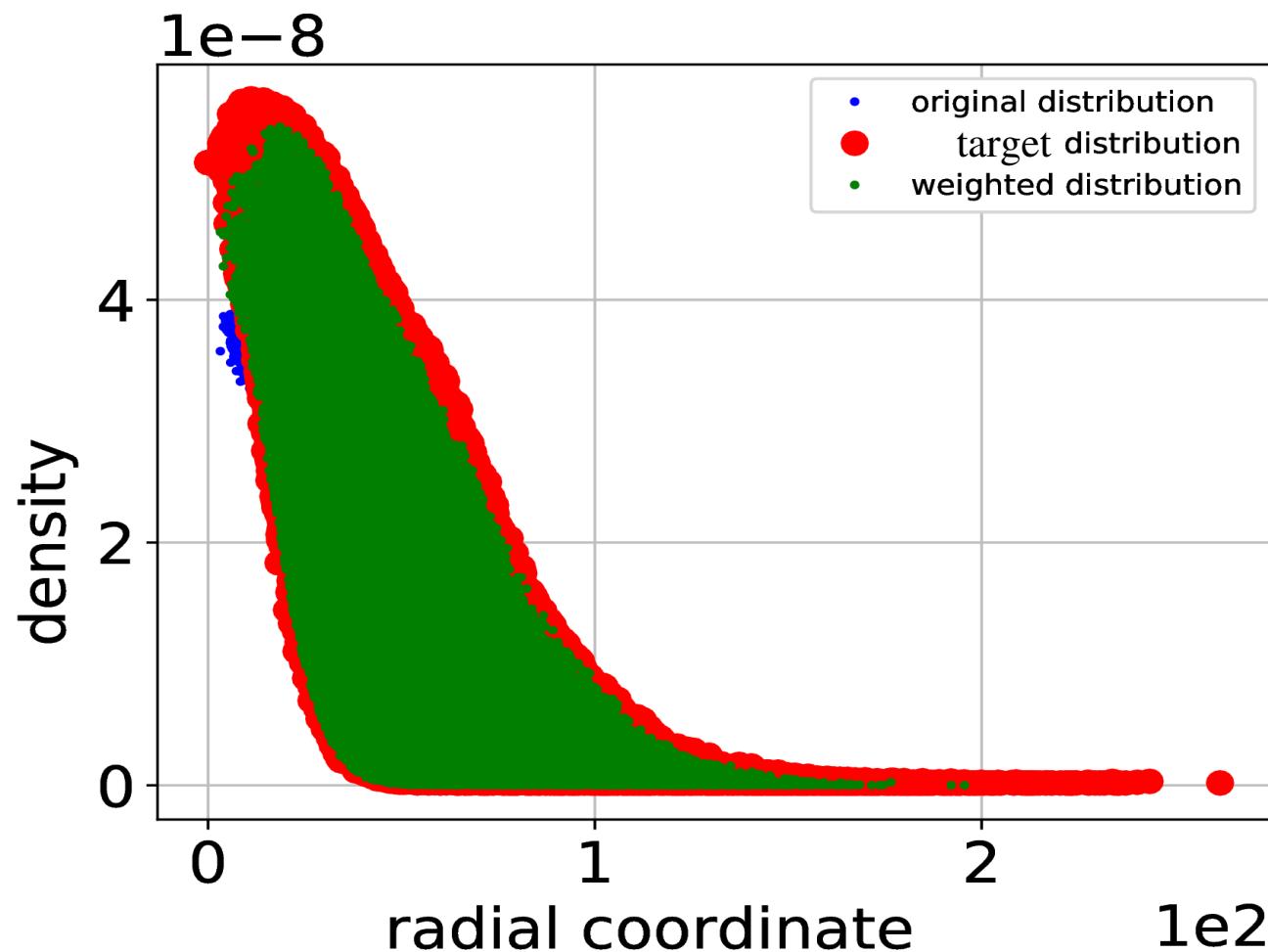
# Re-weighting – 2D Test with Dispersion

- **Original distribution:** TKU station 5 x, px coordinates. **Target distribution:** 2D dispersive beam distribution. **Weighted distribution:** a distribution with re-weighted kernels



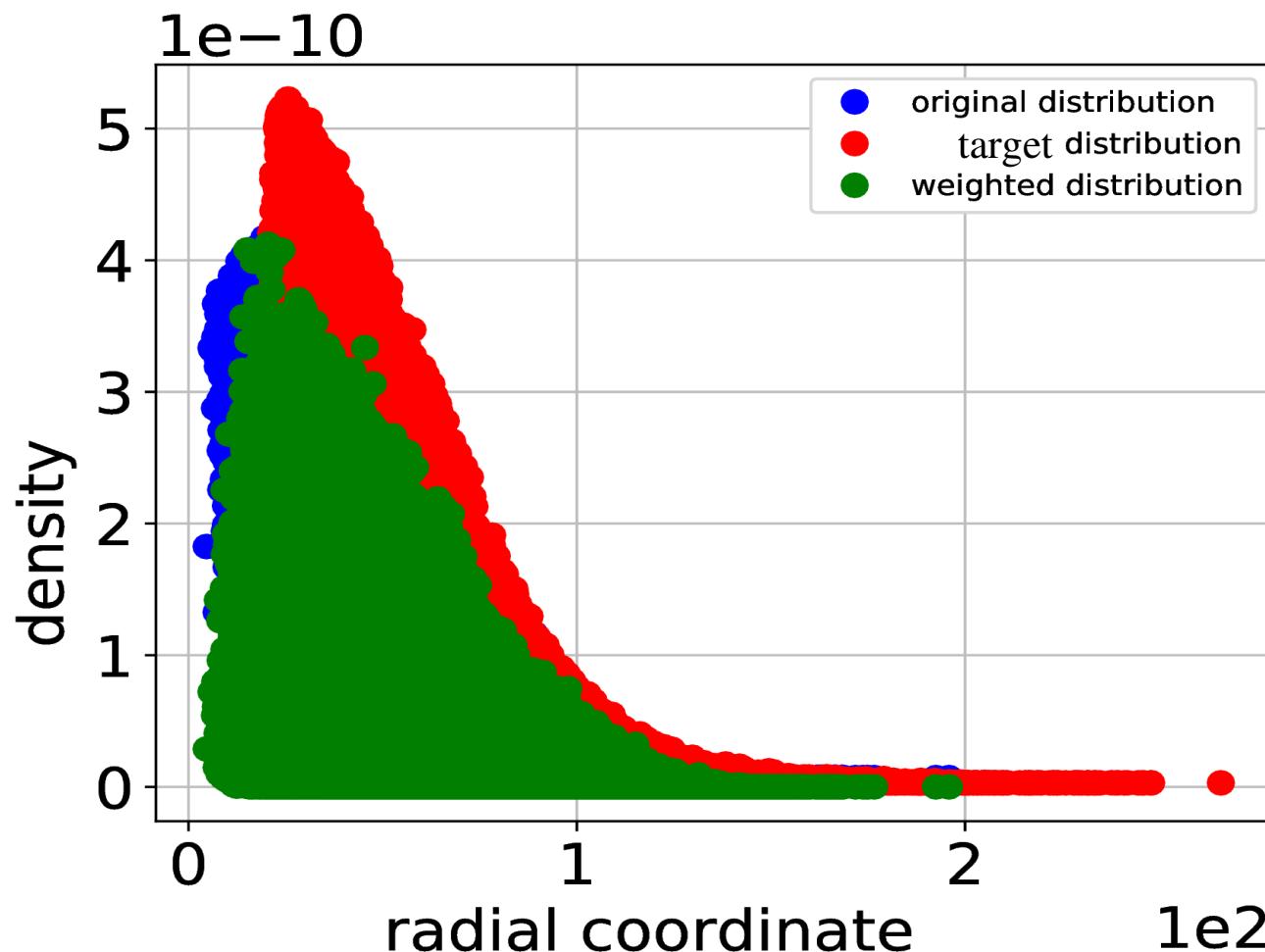
# Re-weighting – 4D Test with Dispersion

- **Original distribution:** TKU station 5 x, px, y, py coordinates. **Target distribution:** 4D dispersive beam distribution. **Weighted distribution:** a distribution with re-weighted kernels



# Re-weighting – 6D Test with Dispersion

- **Original distribution:** TKU station 5 x, px, y, py,  $\Delta t$ ,  $\Delta E$  coordinates. **Target distribution:** 6D dispersive beam distribution. **Weighted distribution:** a distribution with re-weighted kernels

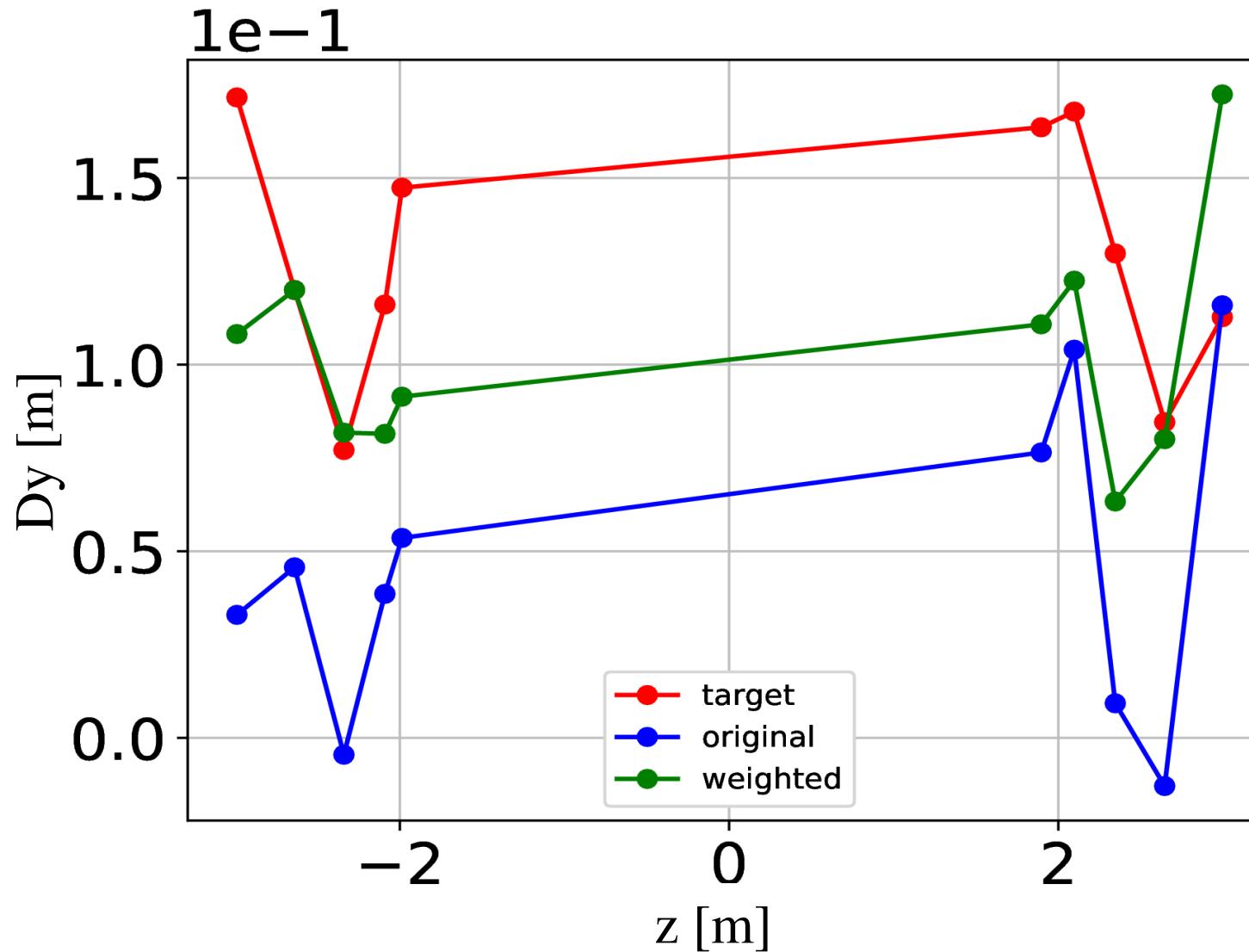


# Re-weighting in MC and Data

- Re-weighting routine in MC and data:
  - ★ Take the reconstructed beam distribution at **TKU station 5** as the **original** distribution
  - ★ Take the **TKU station 5** beam with the desired dispersion at the absorber as the **target** distribution
  - ★ Find the weights associated with each muon in the two **TKU station 5** distributions
    - ▶ Each muon has a weight associated with it
    - ▶ Propagate the weights:
      - Each muon traversing the channel always has the same weight
      - ▶ Find the density associated with the said muon at each tracker station or zntuple, then scale its kernel by the weight

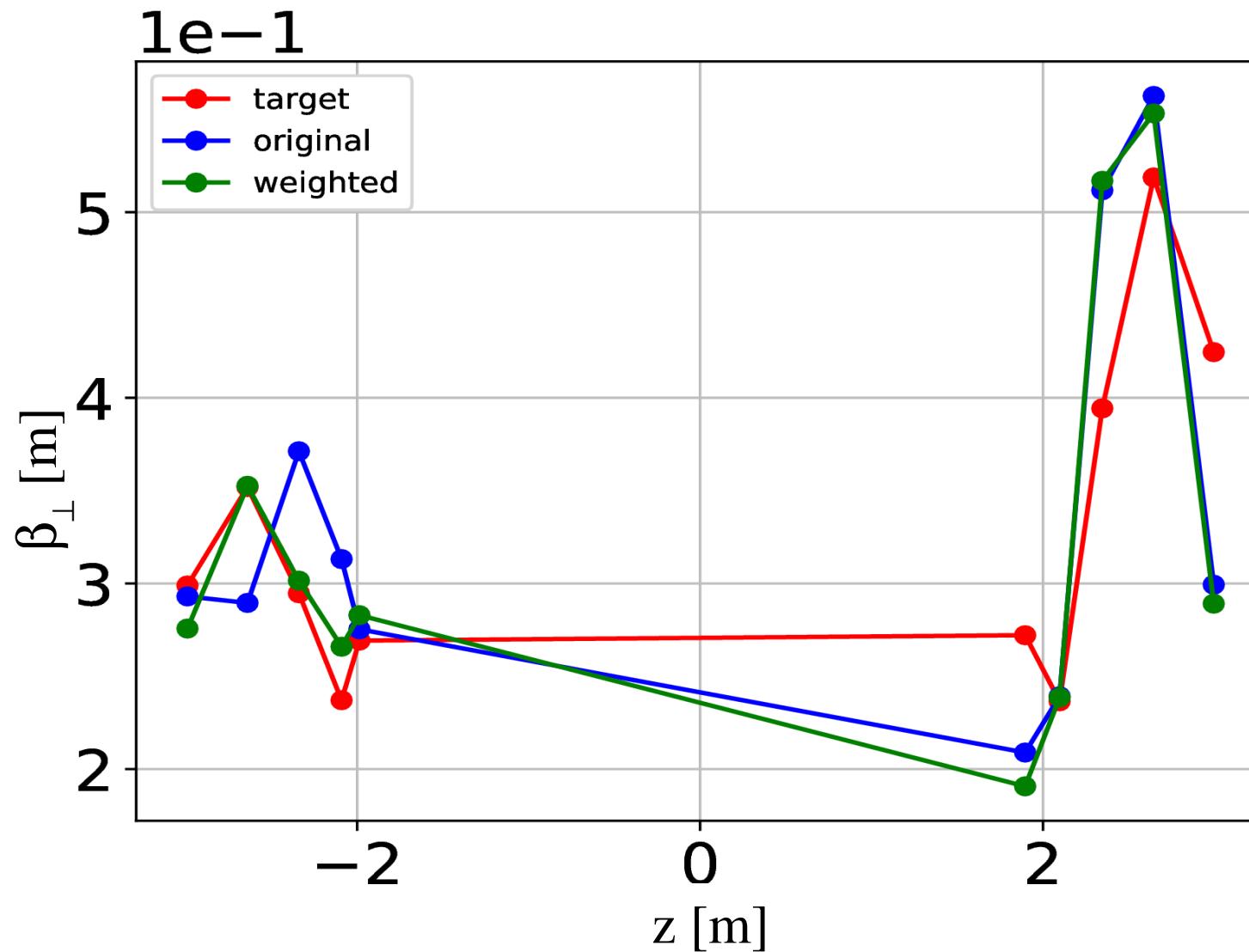
# MC Weighted vs. Original – Dispersion

- First things first: dispersion with the re-weighting approach in MC



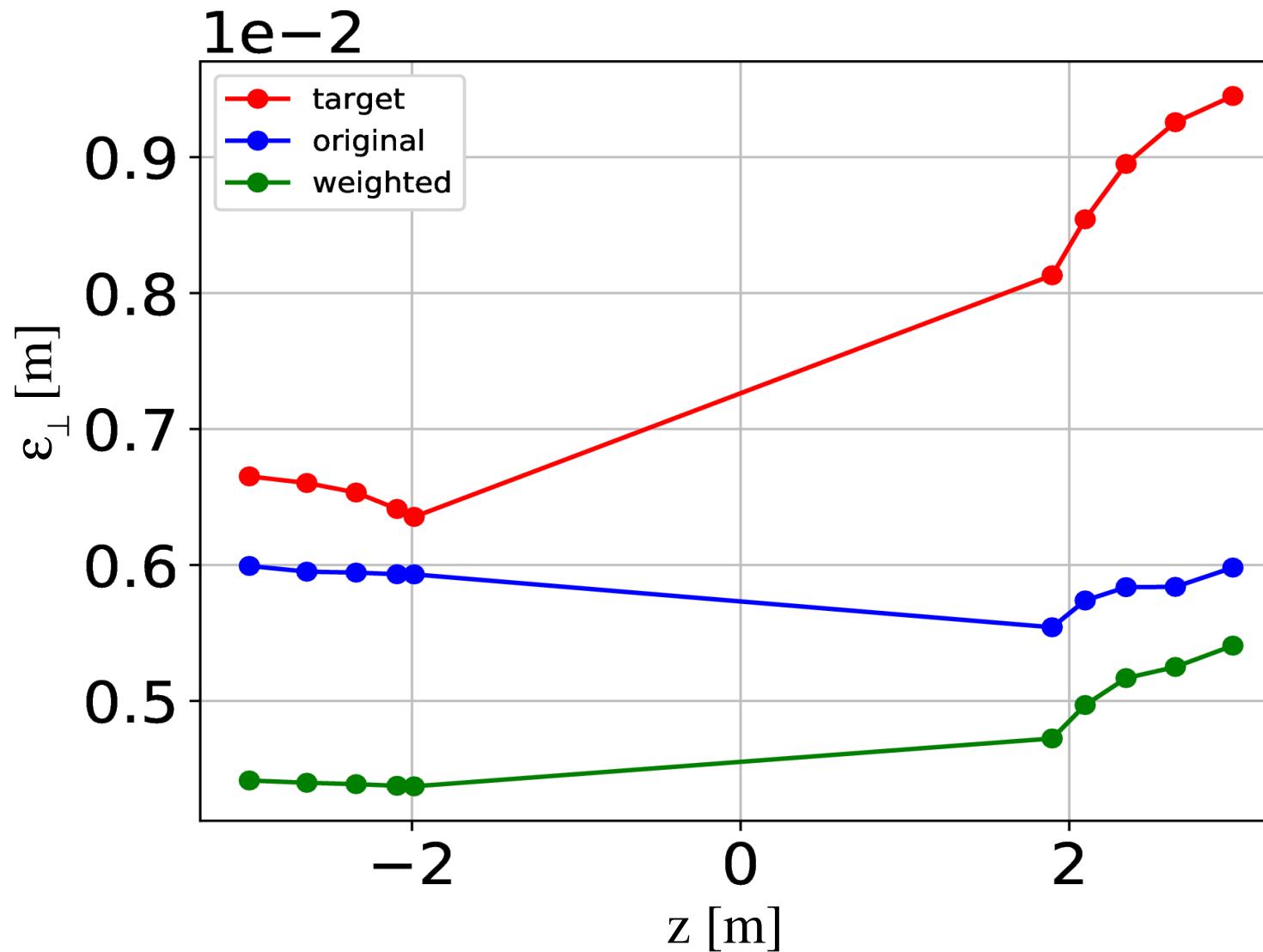
# MC Weighted vs. Original – Beta Function

- Beta function stability ✓



# MC Weighted vs. Original – Transverse $\epsilon$

- Reminder: **target** distribution has dispersion, **original** does not

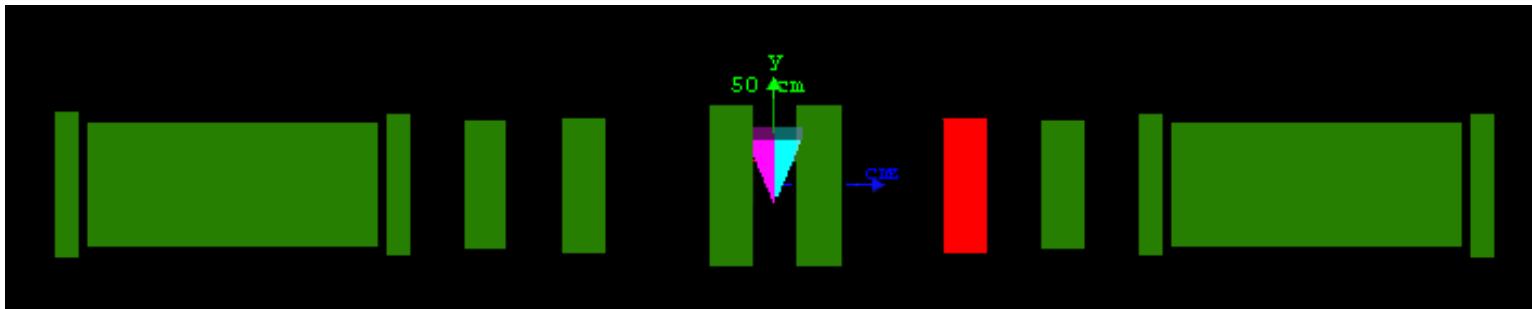


# Conclusion, Next Steps

- Reverse emittance exchange has been observed
- Wedge G4beamline geometry is undergoing further improvements
- Re-weighter routine:
  - ★ Capable of extension to 6D
  - ★ Tends to display under-estimation at the core (under investigation)
  - ★ Capable of reviving the desired dispersion in the beam
  - ★ 6D and longitudinal cooling on the way – resolving on-going issue with dispersion preservation all the way to TKU station 5
  - ★ Application to data in progress
- Full emittance exchange demonstration on the way. Stay tuned!

# Additional Slide/s

# 2017-02-7 Magnet Setting Details



| Coil Name | Values [A] |
|-----------|------------|
| US-ECE    | 205        |
| US-M2     | 168        |
| US-M1     | 191        |
| FCU       | 129        |
| DS-ECE    | -144       |
| DS-M2     | -195       |
| DS-M1     | 0          |
| FCD       | -129       |