5.1 Heisenberg Uncertainty Principle

The standard HUP arises from the non-commutative nature of quantum operators. For position ($\hat{x}$) and momentum ($\hat{p}$), it is expressed as:

$$\Delta x \Delta p \geq \frac{\hbar}{2},$$

where:

- Δx and Δp represent the standard deviations (uncertainties) in position and momentum, respectively.
- $\hbar$ is the reduced Planck constant.

This inequality reflects the intrinsic quantum mechanical limit on measurement precision, arising directly from the commutation relation:[13]

$$[\hat{x}, \hat{p}] = i\hbar.$$