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An exact framework for uncertainty quantification in Monte Carlo simulation

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Uncertainty Quantification (UQ) addresses the issue of predicting non-statistical errors affecting the results of Monte Carlo simulations, deriving from uncertainties in the physics data and models they embed. In HEP it is relevant to particle transport in detectors, as well as to event generators.

We summarize recent developments, which have established the mathematical ground of an exact framework for UQ calculation. This study assessed that in the case of a single uncertainty and under wide hypotheses a simple general relation exists, which relates the probability density function (PDF) of the input to Monte Carlo simulation, and of the output it produces. This result has been empirically verified in a conceptually simplified Monte Carlo simulation environment.

In this contribution we address the problem of extending this approach to the multi-variate case. A typical scenario in this context consists of predicting the dependence of simulation results on input cross section tabulations. We show that for a wide class of probability distributions of the input unknowns it is possible to determine analytically the expected output PDF for any required observable, both in the case of independent variations and in the case of linear correlations among the input variables. This class includes normal distributions, flat (and in general finite interval distributions), and all the Levy stable distributions - a four parameter family of heavy-tailed distributions, which includes the Breit-Wigner one.

For all these distributions it is possible to evaluate exactly the confidence intervals for the physical observables of experimental interest produced by the Monte Carlo simulation.

This is a powerful environment to perform UQ in many physical cases of interest to HEP and low energy nuclear physics experiments.

We present the mathematical methods for uncertainty quantification and some applications to relevant use cases.

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