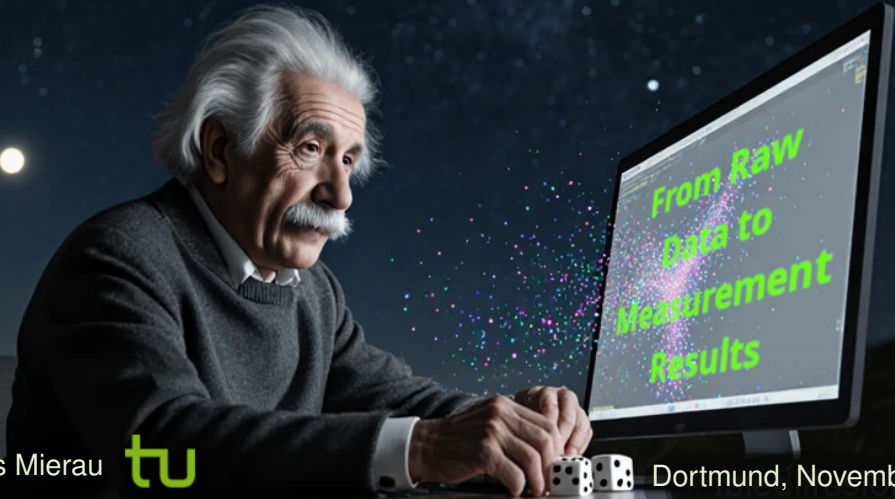


What is so special about Monte Carlo Simulations?



Prologue: The Logical Empiricism

theory

theoretical
vocabulary V_T

axioms and rules
of inferences

observation

observational logical vocabulary
vocabulary V_O

observation
statements

a non-logical term a has a meaning if
and only if a necessary and sufficient
condition for “ x is a ” in terms of obser-
vational vocabulary V_O is provided

Prologue: The Logical Empiricism

theory



observation

theoretical
vocabulary V_T



observational
vocabulary V_O

logical vocabulary

axioms and rules
of inferences

reduction
statements

observation
statements

$$V_T = \mathbf{A}^{-1} V_O$$

a non-logical term a has a meaning if and only if a necessary and sufficient condition for “ x is a ” in terms of observational vocabulary V_O is provided

Prologue: The Logical Empiricism

theory



observation

theoretical
vocabulary V_T



observational
vocabulary V_O

logical vocabulary

axioms and rules
of inferences

correspondence
rules

observation
statements

under condition k :

$$\mathbf{A}^{-1} V_O \rightarrow t_n$$

a non-logical term a has a meaning if and only if a necessary and sufficient condition for “ x is a ” in terms of observational vocabulary V_O is provided

The paradigm observer is not the man who sees and reports what all normal observers see and report, but the man who sees in familiar objects what no one else has seen before.

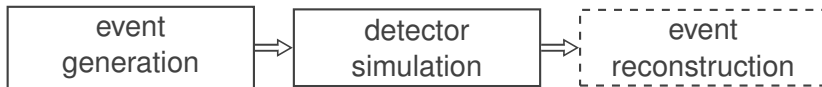
Norwood Hanson, *Patterns of Discovery* (1958)



Plan for the talk

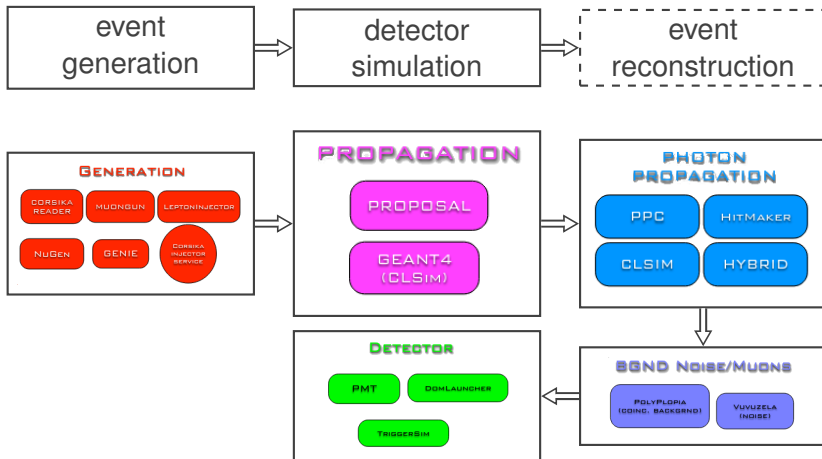
1. Philosophical discussion of computer simulations in high-energy physics
2. Differences in astroparticle physics and (maybe) overlooked aspects
3. Inference view vs. experiment view on Monte Carlo simulations
4. Consequences

The simulation chain

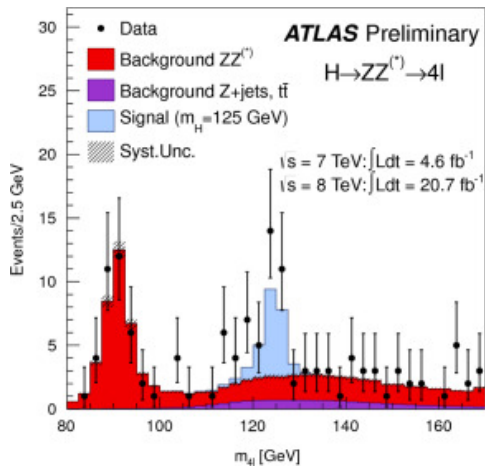


M. Massimi & W. Bhimji, *Computer simulations and experiments:
The case of the Higgs boson* (2015)

The simulation chain

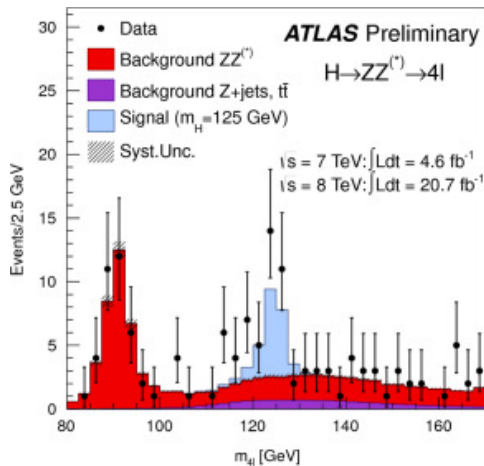


Monte Carlo simulations and the discovery of the Higgs boson

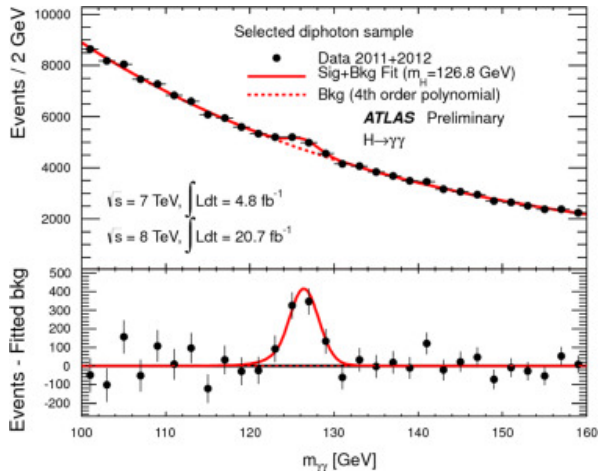


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Monte Carlo simulations and the discovery of the Higgs boson



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Were MCSs indispensable for the discovery of the Higgs boson?

- ✓ “the discovery is logically and causally dependent on simulation”
M. Morrisson, *Reconstructing reality. Models, Mathematics, and Simulations* (2015)

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M. Massimi & W. Bhimji, *Computer simulations and experiments: The case of the Higgs boson*, (2015)
- ✗ “it would be possible to completely dispense with simulations for experiments conducted to date”
M. Krämer, G. Schiemanm & C. Zeitnitz, *Experimental high-energy physics without computer simulations* (2024)

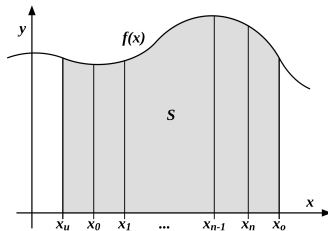
Experimental high-energy physics without computer simulations

- “The corresponding theoretical calculations [JM: of cross sections and decay probabilities] often use numerical methods, e.g., for solving complicated integrals, but can be carried out without computer simulations” (p. 39)
⇒ “allow an initial estimate of the requirements of an experiment for the Higgs discovery”
- “In practice, computer-based calculations are used in the planning, design, and operation of the accelerator. These are numerical calculations, but also model-based simulations. All these methods require only knowledge of well-established physics. Hence, there is no dependence on the physics questions to be addressed by the experiments. In addition, these simulations can be replaced by constructing more prototype components and by performing corresponding test measurements” (ibid.)
- “The discovery [...] requires a suitable detector. Designing the detector requires knowledge about the signatures of the expected physics processes. The signatures are provided by the respective theory” (ibid.)
- “[The] calibration is partially dependent on simulations. Again, known physics processes allow simulations to be replaced by data.” (p. 40)

Experimental high-energy physics without computer simulations

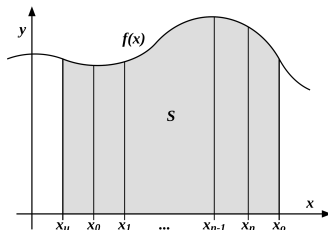
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Monte Carlo method vs. quadrature rule integration



- **Curse of dimensionality:** error bound of quadrature rule $\mathcal{O}(N^{-2/d})$
Monte Carlo integration $\mathcal{O}(N^{-1/2})$

Monte Carlo method vs. quadrature rule integration



- **Curse of dimensionality:** error bound of quadrature rule $\mathcal{O}(N^{-2/d})$
Monte Carlo integration $\mathcal{O}(N^{-1/2})$
- Actual advantage: for event reconstruction, we don't want mean values but probability densities

Fredholmification of the Logical Empiricism

$$g(\underline{y}) = \int_c^d A(\underline{y}, \underline{x}) f(\underline{x}) d\underline{x} + b(\underline{y})$$

$\underline{y}$ set of measurable quantities ($\sim$ observation terms)

$\underline{x}$ set of theoretical quantities ($\sim$ theoretical terms)

$g(\underline{y})$ measured probability density (relative frequencies of observations)

$b(\underline{y})$ background

$f(\underline{x})$ theoretical frequency distribution

$A(\underline{y}, \underline{x})$ design function (inverse correspondence rules)

Fredholmification of the Logical Empiricism

$$\tilde{g}(\underline{y}) = \int_c^d A(\underline{y}, \underline{x}) f(\underline{x}) d\underline{x}$$

$\underline{y}$ set of measurable quantities ($\sim$ observation terms)

$\underline{x}$ set of theoretical quantities ($\sim$ theoretical terms)

$\tilde{g}(\underline{y})$ probability density of the signal (measurement minus background)

$f(\underline{x})$ theoretical frequency distribution

$A(\underline{y}, \underline{x})$ design function (inverse correspondence rules)

Fredholmification of the Logical Empiricism

$$f(\underline{x}) = \mathbf{A}^{-1}(\underline{y}, \underline{x}) \tilde{g}(\underline{y})$$

$\underline{y}$ set of measurable quantities ($\sim$ observation terms)

$\underline{x}$ set of theoretical quantities ($\sim$ theoretical terms)

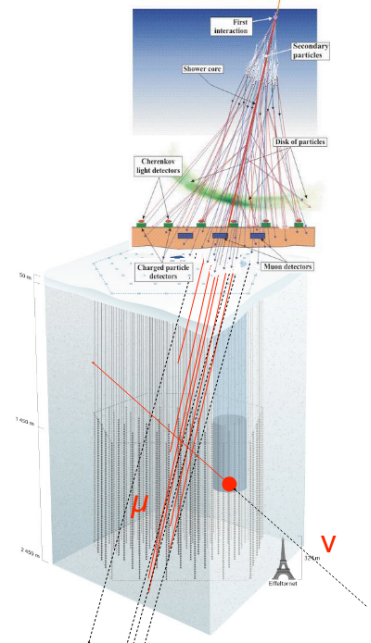
$\tilde{g}(\underline{y})$ probability density of the signal (measurement minus background)

$f(\underline{x})$ theoretical frequency distribution

$\mathbf{A}^{-1}(\underline{y}, \underline{x})$ inverse design function (correspondence rules)

The case of astroparticle physics

- A large number of unknown factors that are practically impossible to determine, **A** has to bridge a long distance of unknown processes
- Signal to background ratio much lower than in ATLAS case



Argument view vs. experiment view

argument view “Monte Carlo simulations [JM: are merely] a sequence of inferences no different from an ordinary derivation”
(C. Beisbart & J. D. Norton, *Why Monte Carlo Simulations Are Inferences and Not Experiments*, 2012)

Argument view vs. experiment view

argument view “Monte Carlo simulations [JM: are merely] a sequence of inferences no different from an ordinary derivation”

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experiment view “Computer simulations are *surrogate experiments*, executed consciously on the wrong kind of system, because findings on that (surrogate) system can be *mapped* to the target system, and because the surrogate can be *handled* in a way that the target cannot.”

(F. Boge, *Why computer simulations are not inferences, and in what sense they are experiments*, 2019)

Against Monte Carlo simulation as surrogate (for) experiments

- Synthetic data from Monte Carlo simulations contains complete information on the passed interactions and all physical parameters of the involved particles.
- ⇒ Synthetic data is fundamentally different from empirical data.
- In APP practice, synthetic data is not used as substitute for empirical data.

Objections against Monte Carlo simulations as theoretical activity (1)

1. “Something like intervention is crucial for experiments and for many simulations.”
(C. Beisbart, *Are computer simulations experiments? And if not, how are they related to each other?*, p. 197)
 - There are no interventions in Monte Carlo simulations as described
2. “CSs produce outputs that take a similar form as do data from experiments, at least if the outputs and data are suitably processed.” (ibid.)
 - synthetic data is fundamentally different from experimental data (cf. last slide)
3. “Both experiments and CSs have results in the sense that they can show something. Scientists can obtain information about a system by experimenting on it or by simulating it.” (p. 198)
 - show_{ex} = measure, derive from measurements $\neq$ show_{MCS} = predict, infer from theory

Objections against Monte Carlo simulations as theoretical activity (2)

4. “The results of both experiments and CSs can often not be foreseen.” (ibid.)
 - true
5. “The epistemologies of experiments and CSs share important similarities in that scientists use similar strategies when they use the outputs of experiments and simulations to justify certain claims. This is a consequence of the similarities 1 and 2 given above.” (ibid.)
 - inaccurate description for Monte Carlo simulations in APP and HEP (cf. objections 2 and 3)

What is so special about Monte Carlo simulations?

...or what is the argument in the argument view?

P_1 A Monte Carlo simulation of a sample of N particles with initial values $f(\underline{x})$, resulted in the detector image $g(\underline{y})$.

P_2 convergence criterion for MC for sample size N

C A measurement of particles with physical properties $f(\underline{x})$ will probably result in the measurement $g(\underline{y})$.

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P' The design function $A(\underline{y}, \underline{x})$ can be inverted.

C' A measurement of $g'(\underline{y}')$ is probably caused by a particles with physical properties $f'(\underline{x}') = Ag'(\underline{y}')$.

Conclusion

1. Monte Carlo simulations are indispensable for contemporary astroparticle physics.
2. Monte Carlo simulations are a method of prediction based on theoretical knowledge. They do not provide any empirical evidence beyond that.
3. The inference view on Monte Carlo simulations is useful for highlighting the specific role of Monte Carlo simulations in contemporary physics practice – which is a novel form of theoretical inference of probabilistic nature.

