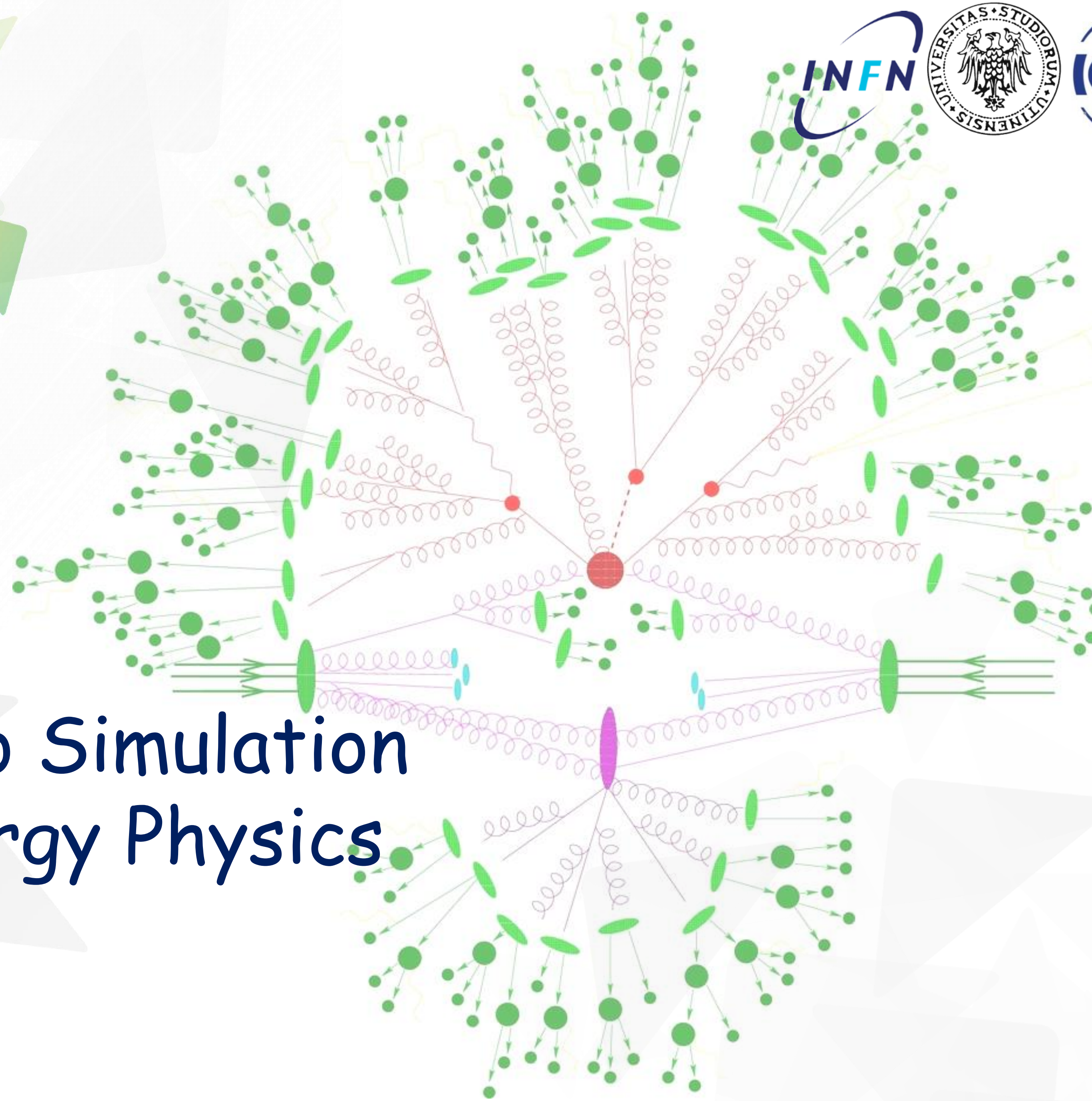

Monte Carlo Simulation in High Energy Physics

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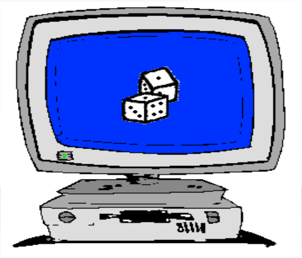
with inputs by M. Pinamonti

The Concept of Probability

- Many processes in nature have uncertain outcomes.
- A *random process is a process* that can be reproduced, to some extent, within some given boundary and initial conditions, but whose outcome is uncertain.
- For example, quantum mechanics phenomena have intrinsic randomness.
- *Probability* is a measurement of how *favored one of the possible outcomes of such a random* process is compared with any of the other possible outcomes.



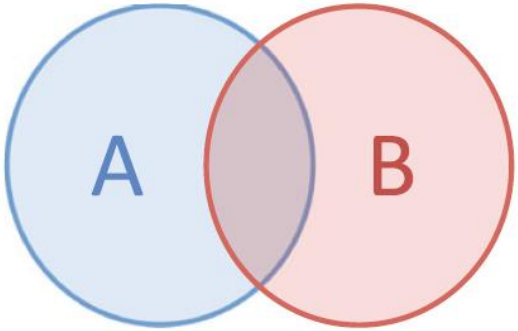
The Meaning of Probability: 2 approaches

- *Frequentist probability is defined as the fraction of the number of occurrences* of an event of interest over the total number of possible events in a repeatable experiment, in the *limit of very large number of experiments.*

- *Bayesian probability measures someone's degree of belief that a statement, and it makes u*se of an extension of the Bayes theorem: the probability of an event *A given the condition that the event B has occurred is given by:*

$$P(A|B) = \frac{P(A \cap B)}{P(B)} .$$

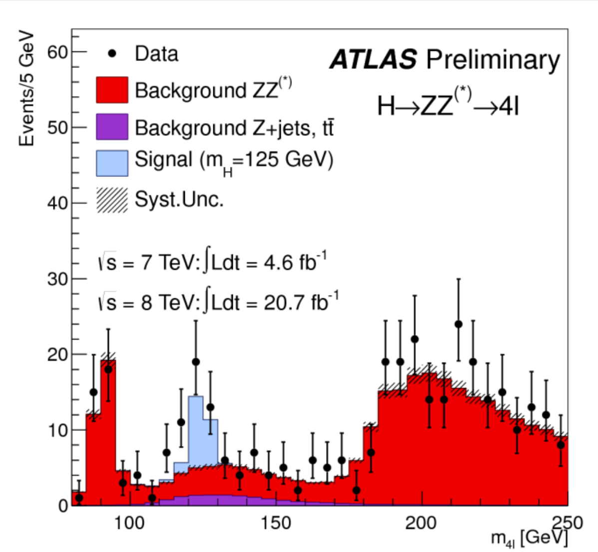
- The conditional probability is equal to the area of the intersection divided by the area if B



A Word on Simulation

- What a (computer) simulation does:
  - Applies mathematical methods to the analysis of complex, real-world problems
  - Predicts what might happen depending on various actions/scenarios
- Use simulations when
  - Doing the actual experiments is not possible
  - The cost in money, time, or danger of the actual experiment is prohibitive (e.g. nuclear reactors)
  - The system does not exist yet (e.g. an airplane)
  - Various alternatives are examined (e.g. hurricane predictions)

Why we need and have so much data at LHC?



What we are looking for is very rare:
in 1.80 x 10^{15} collisions we found only
30 Higgs events decaying into 4 leptons

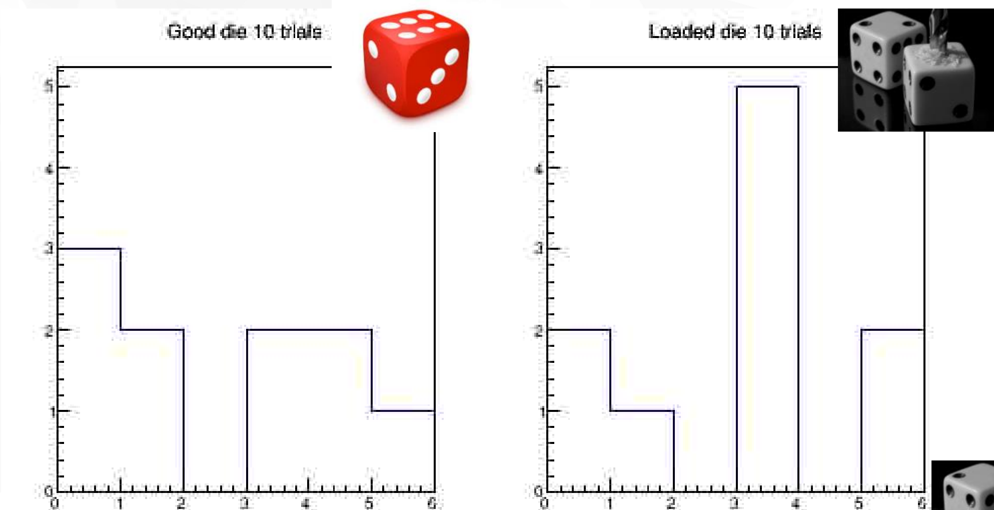
Events with 4 leptons come often from other sources: this is waht we call background!

An example for illustration

Correct dice	Manipulated dice
	
every number has probability 1/6	numbers 1..5 probability <1/6 number 6 probability > 1/6

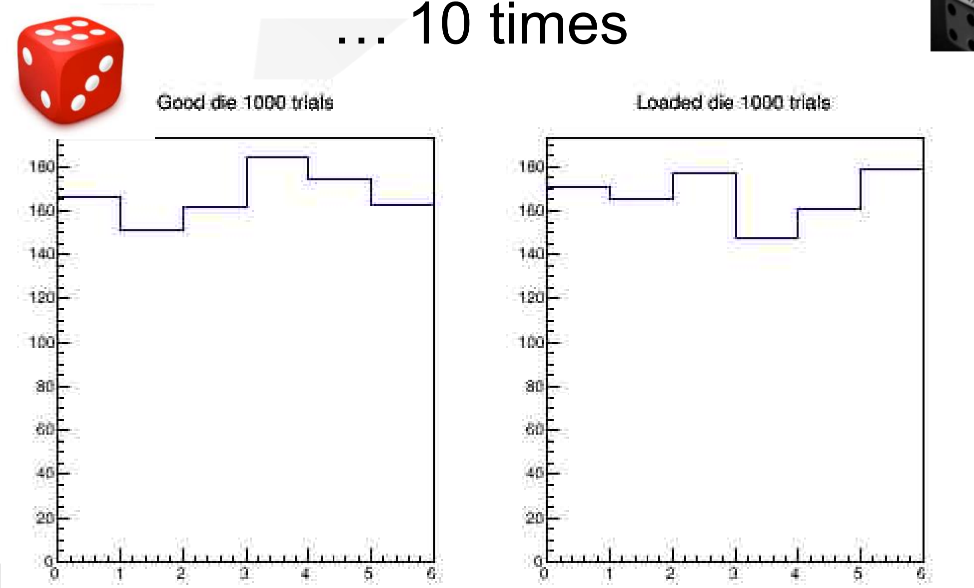
Why we need and have so much data at LHC?

Role the dice and record the number in a bar chart



Just random fluctuations

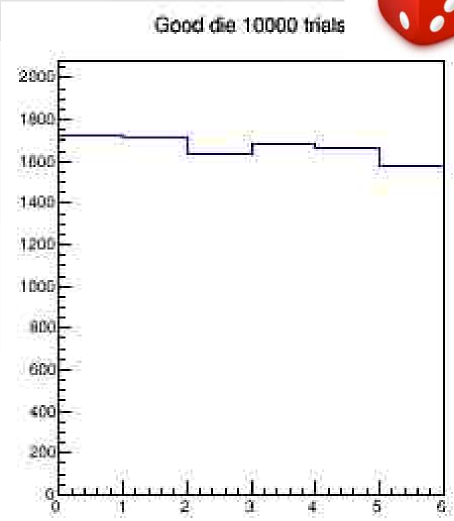
… 10 times

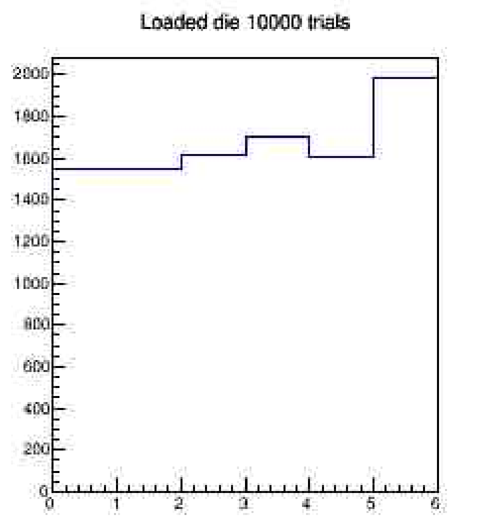


Still nothing can be concluded

… 1000 times

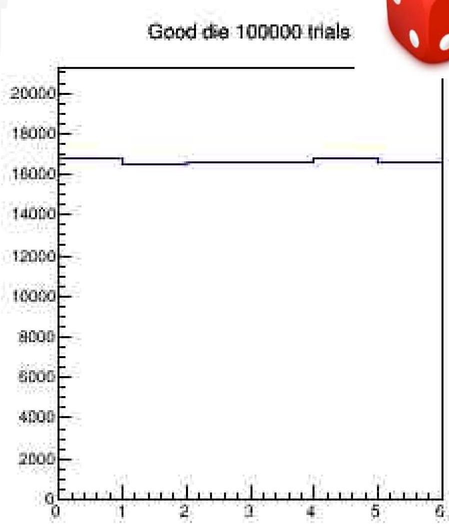
Why we need and have so much data at LHC?

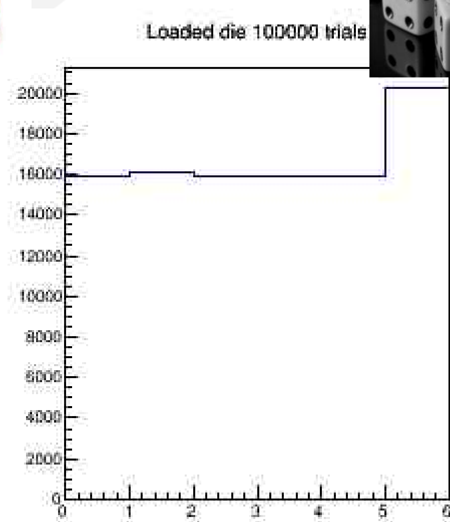




Evidence is rising …

… 10000 times





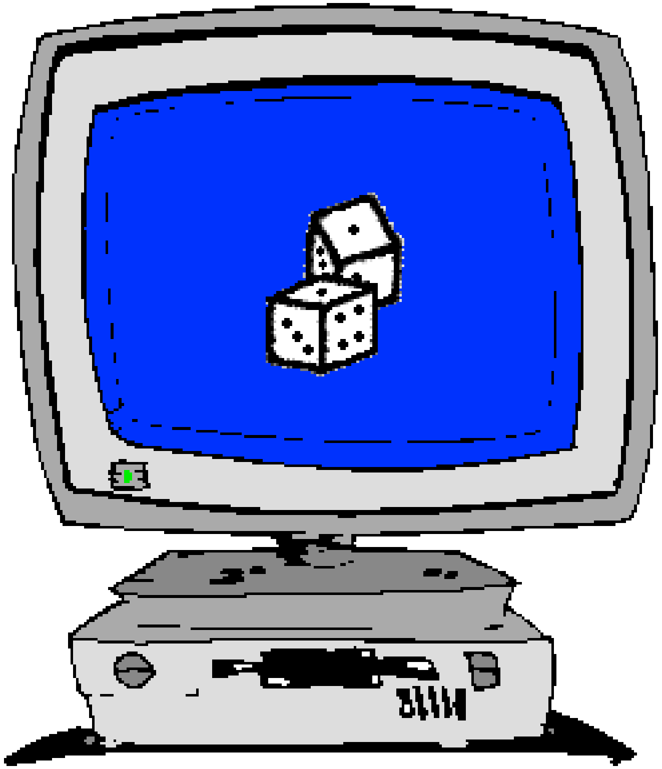
For sure there is something wrong with the dice

The more data you take the smaller your error gets (C.F. Gauss)

… 100000 times

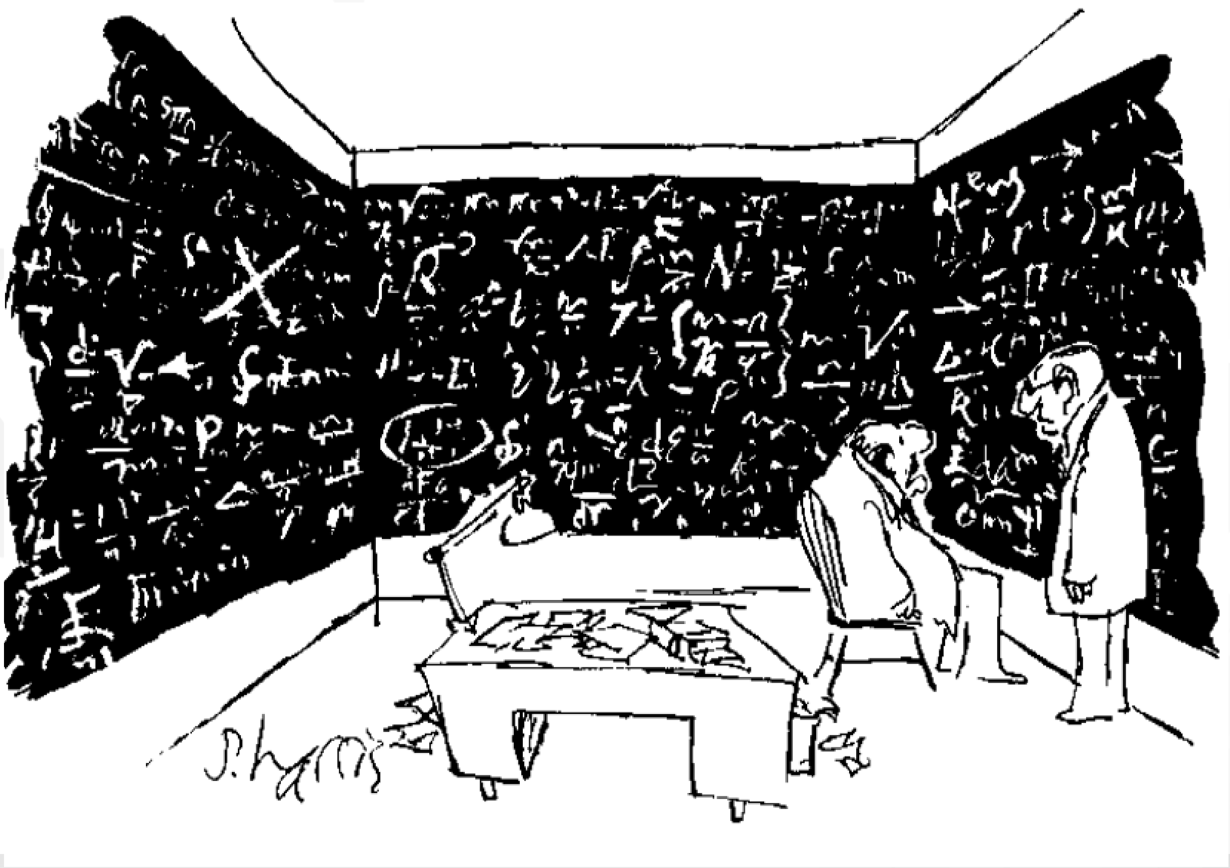
Monte Carlo Method

- A numerical simulation method which uses sequences of random numbers to solve complex problems



Why Monte Carlo?

- Other numerical methods typically need a mathematical description of the system
- More and more difficult to solve as complexity increases



Monte Carlo in High Energy Physics

- In HEP (in particular in hadron collider physics)
- MC are very useful:
  - To generate simulated collision events:
    - Quantum Field Theory obey probability laws
    - Proton PDF's have to be taken into account
    - Final state kinematical distributions with many alternatives (correlation of observables might be a problem...)
    - Complex soft and non-perturbative QCD
    - (parton shower and hadronization)
  - To simulate the response of the detector:
    - Particle interaction with matter can be complicated
    - Huge number of different detector components

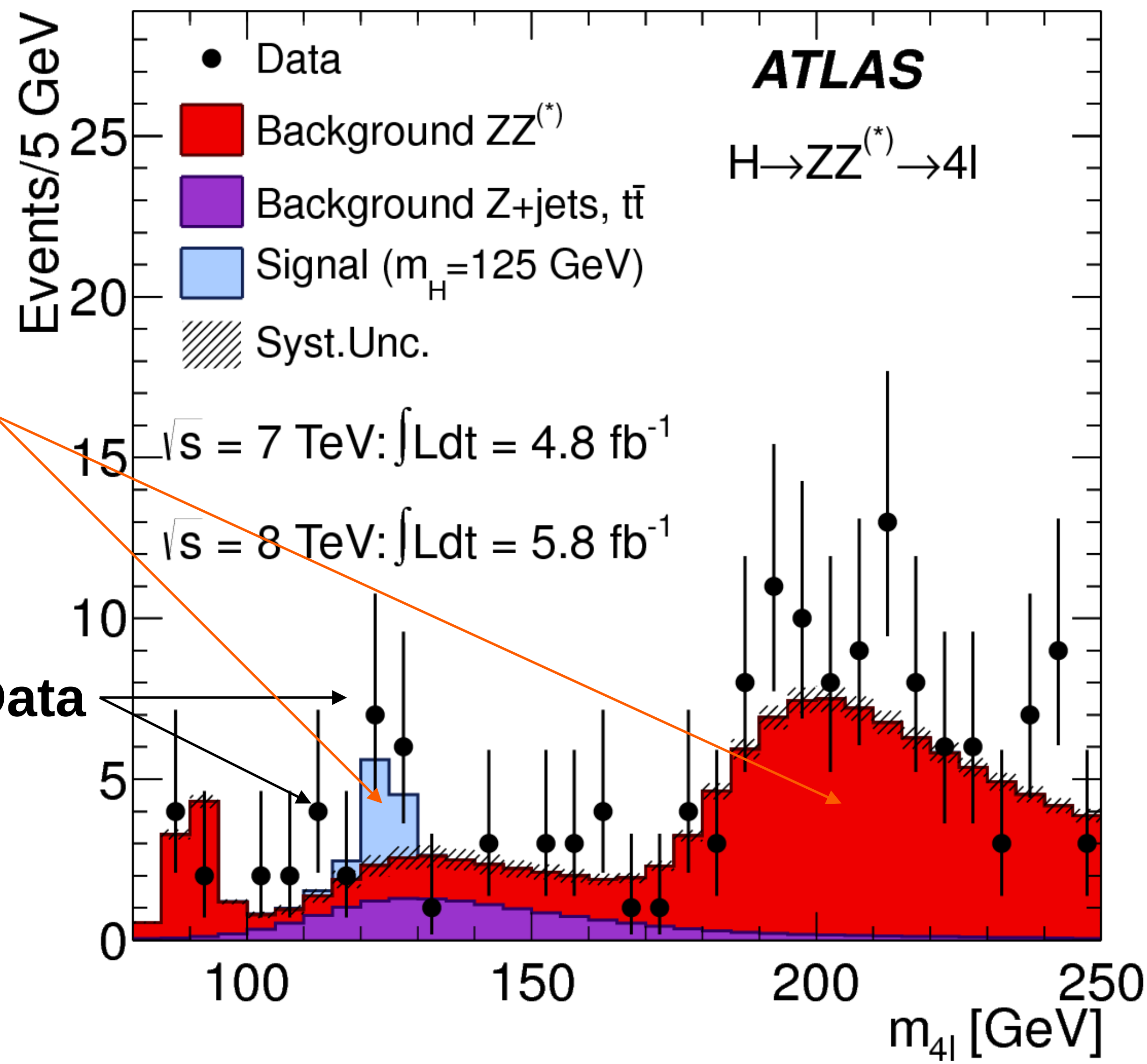
What to do with Monte Carlo events?

- To test performances:
  - Perform feasibility studies before looking at Data
  - Predict the performances of the detector
  -
- To compare with real collision Data to
- extract physics results:
  - Background modeling
  - Signal selection efficiency (acceptance) determination

Example: Higgs discovery at ATLAS

Monte Carlo Simulation

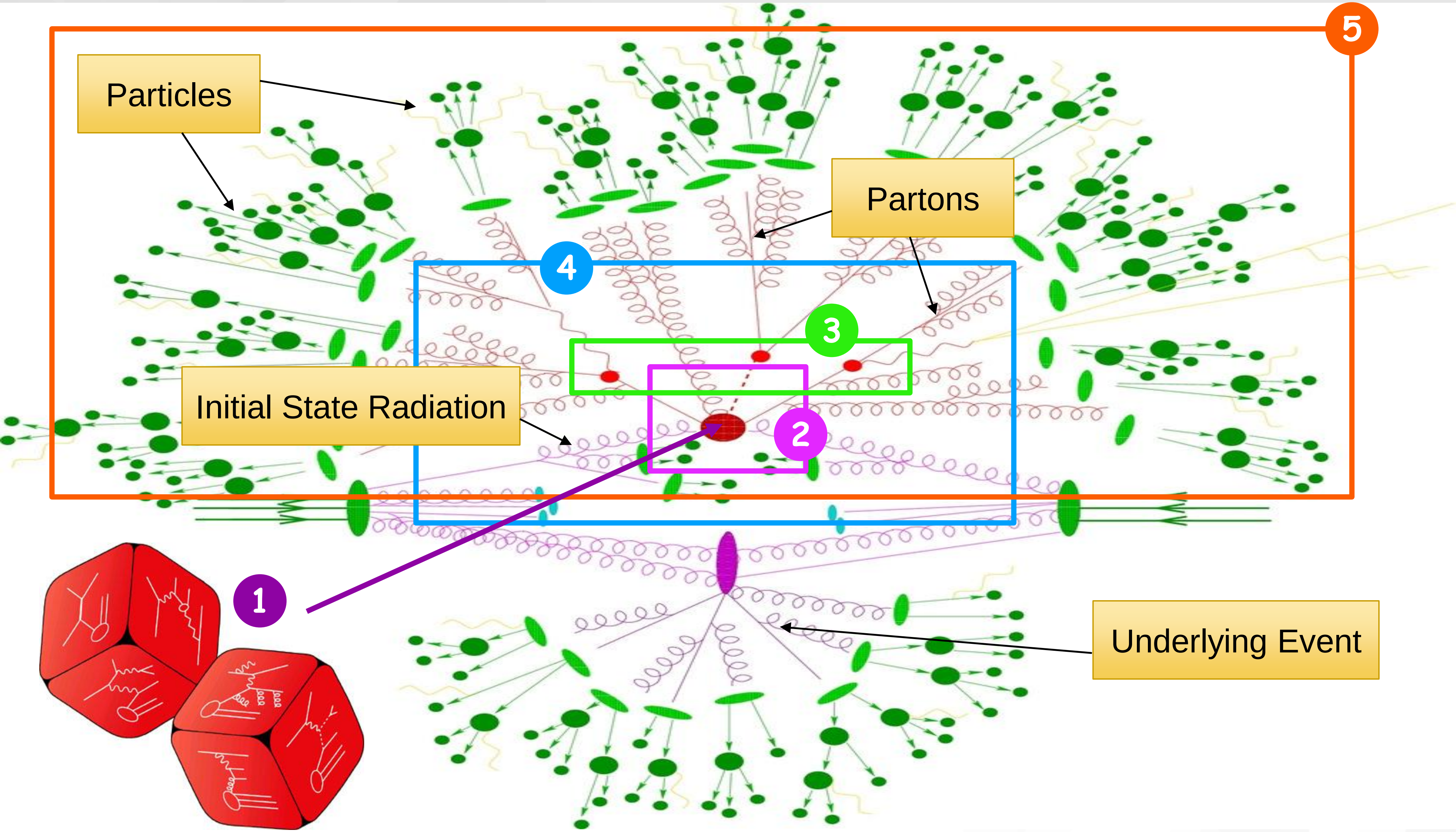
Real Data



Collision Event Simulation

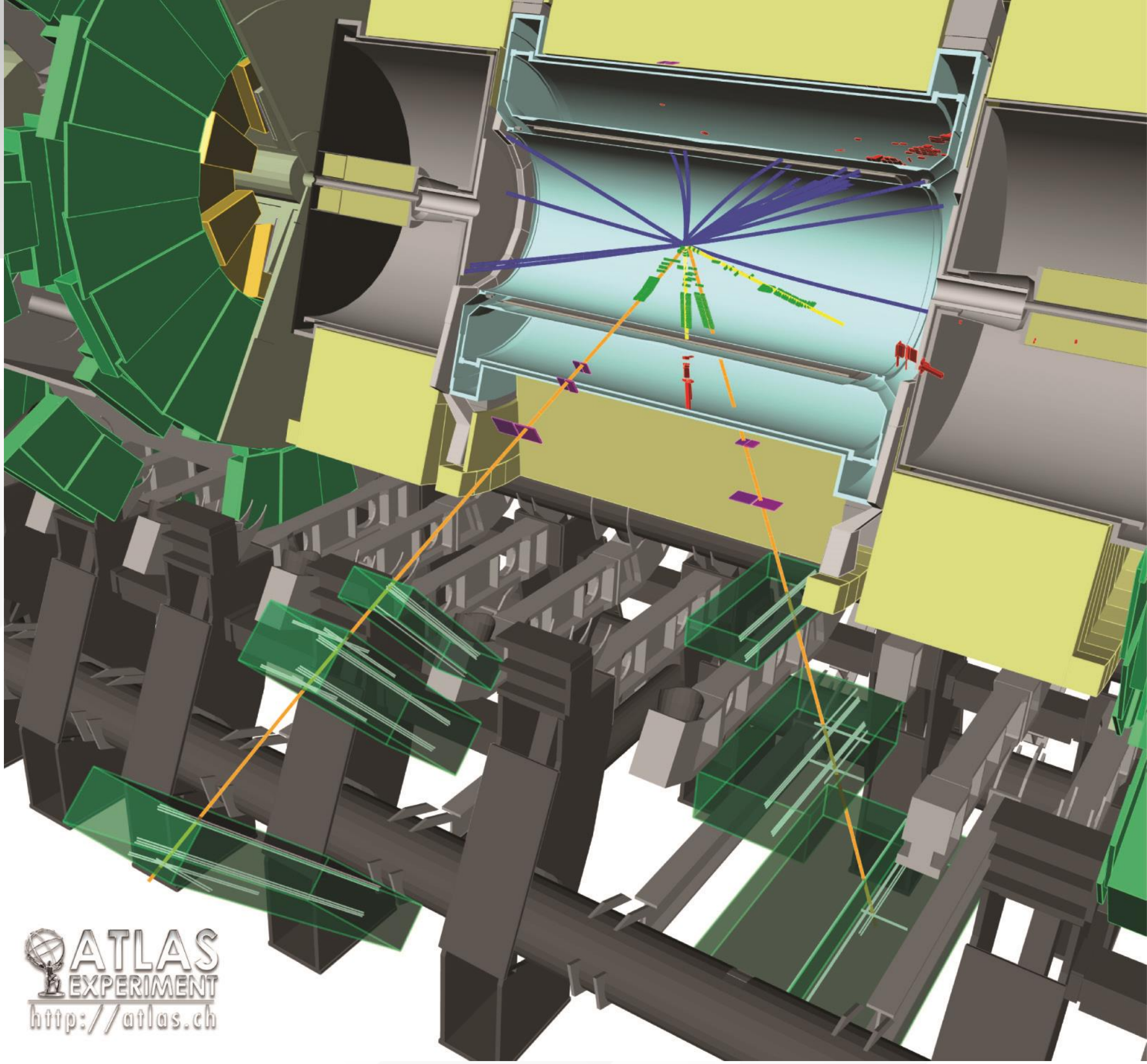
- Different steps are required:
- Start by determining the hard process:
  - 1) Choice of the interesting process to generate (start from a generic pp collision would be inefficient...)
  - 2) Randomly generate kinematics of initial and final states (using PDF's for initial state)
- Evolve the final state:
  - 3) Decays of heavy particles according to BR's
  - 4) Parton shower evolution
  - 5) Hadronization of partons to form particles

In pictures



5
Particles
Partons
4
3
2
Initial State Radiation
1
Underlying Event

Detector Simulation



- Each particle after
- step 5) is considered
- Their path trough the
- full detector is followed
- Simulating the particle-
- matter interaction at
- all the different active
- and passive layers
- Simulating the generated signal: hits in pixel detector, calorimeter energy deposit, etc...
- In the end one has a set of events in the same format as the real collision Data events

Practical example: estimating the value of π using the Monte Carlo method

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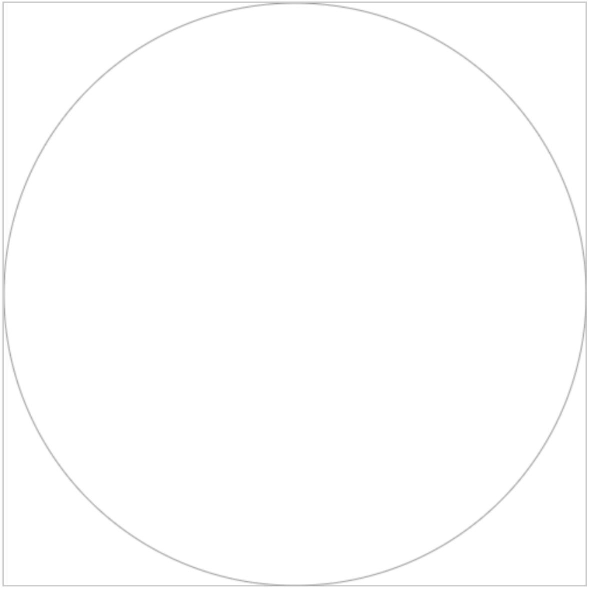
- A: Generate a large number of random points and see how many fall in the circle enclosed by the unit square.

Practical example: estimating the value of π using the Monte Carlo method

- A: Generate a large number of random points and see how many fall in the circle enclosed by the unit square

- Build a circle of radius 0.5, enclosed by a 1 × 1 square. The area of the circle is: $\pi R^2 = \pi/4$

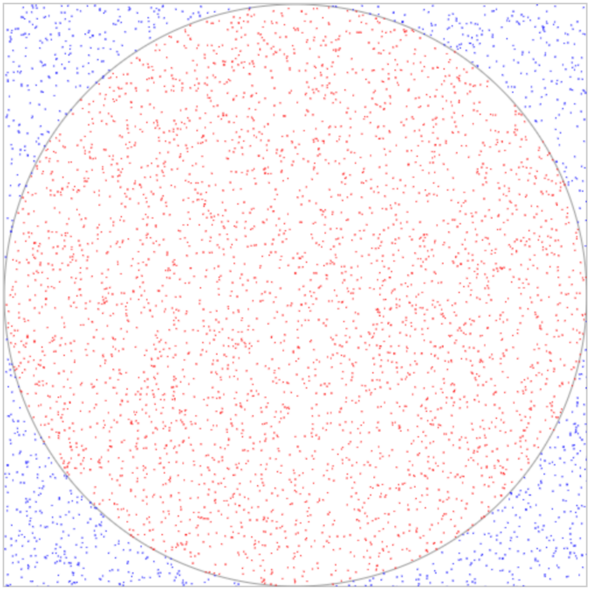


- The area of the square is 1.

- If we divide the area of the circle, by the area of the square we get: $\pi/4$

Practical example: estimating the value of π using the Monte Carlo method

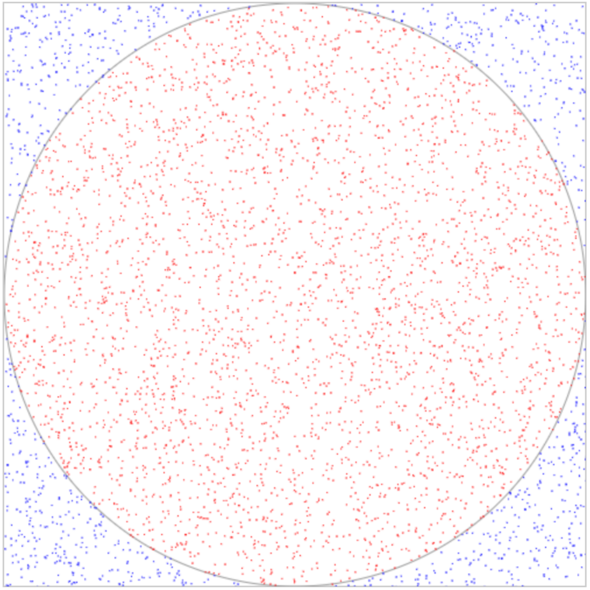
- Generate a large number of uniformly distributed random points and plot them on the graph. These points can be in any position within the square i.e. between (0,0) and (1,1).
- If they fall within the circle, they are coloured red, otherwise they are coloured blue.



Practical example: estimating the value of π using the Monte Carlo method

- We keep track of the total number of points, and the number of points that are inside the circle.
- If we divide the number of points within the circle, Ninner, by the total number of points, Ntotal, we should get a value that is an approximation of the ratio of the areas we calculated above, π/4

$$\pi \approx 4\frac{N_{inner}}{N_{total}}$$



- With a small number of points, the estimation is not very accurate, but with thousands of points, we get closer to the actual value

Softwares used for Monte Carlo Simulation

- Steps 1) and 2) - “Matrix Element” or “Event” generation:
  - LO (2→2):
    - Pythia (http://home.thep.lu.se/~torbjorn/Pythia.html)
    - Herwig (http://www.hep.phy.cam.ac.uk/theory/webber/Herwig/)
  - LO + additional parton (2→n):
    - Alpgen (http://mlm.home.cern.ch/mlm/alpgen/)
    - Sherpa (http://www.sherpa-mc.de/)
    - Madgraph (http://madgraph.hep.uiuc.edu/)
  - NLO:
    - MC @NLO (http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/)
    - Powheg (http://powhegbox.mib.infn.it/)

Softwares used for Monte Carlo Simulation

- Steps 3), 4) and 5) – Parton Shower and Hadronization:
  - Pythia, Herwig, Sherpa
- Detector Simulation:
  - Full simulation:
    - Geant4
  - Fast simulation:
    - PGS (http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-olympics.htm)
    - Delphes (https://cp3.irmp.ucl.ac.be/projects/delphes)

- Lots of progress in the last years on these topics: ask us later if you are interested!

QUESTIONS