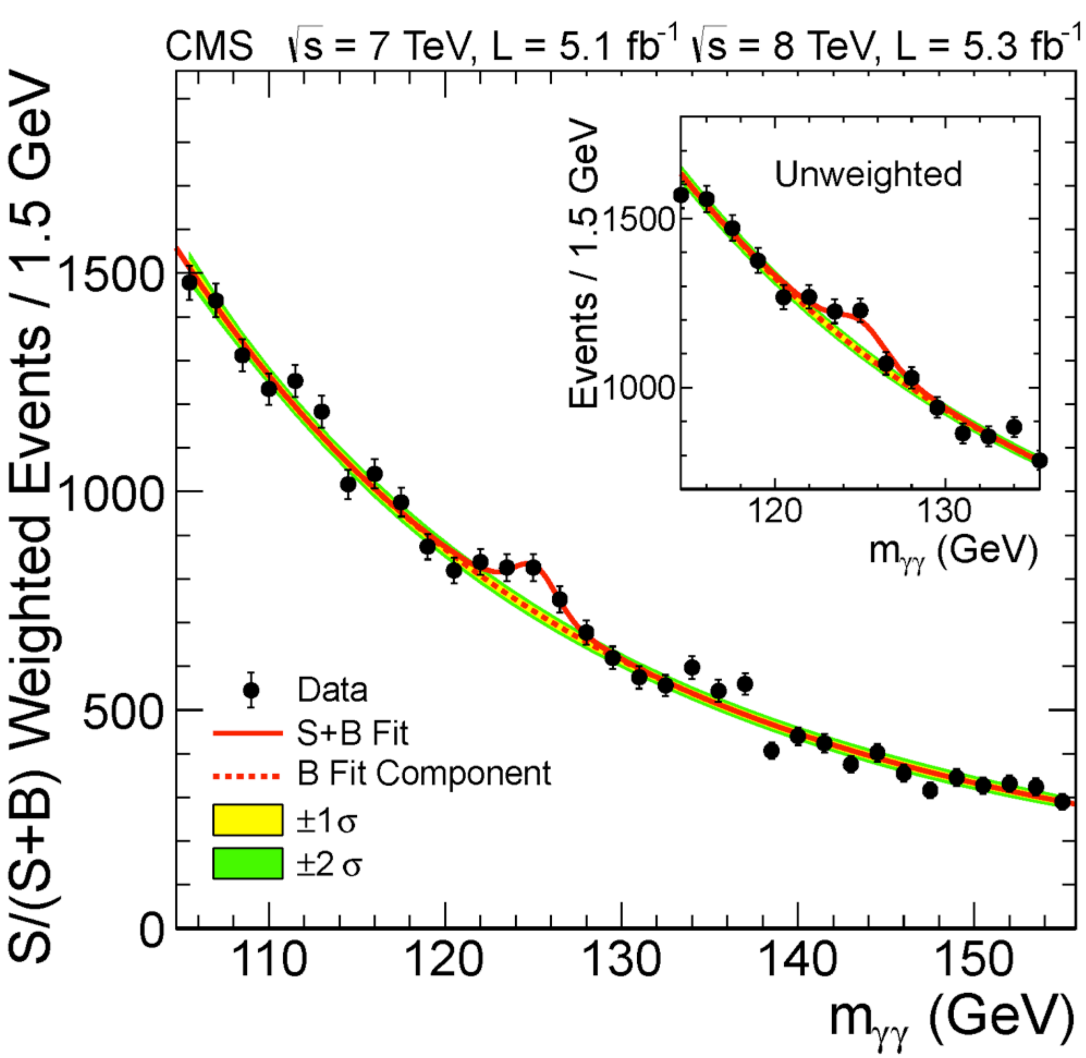
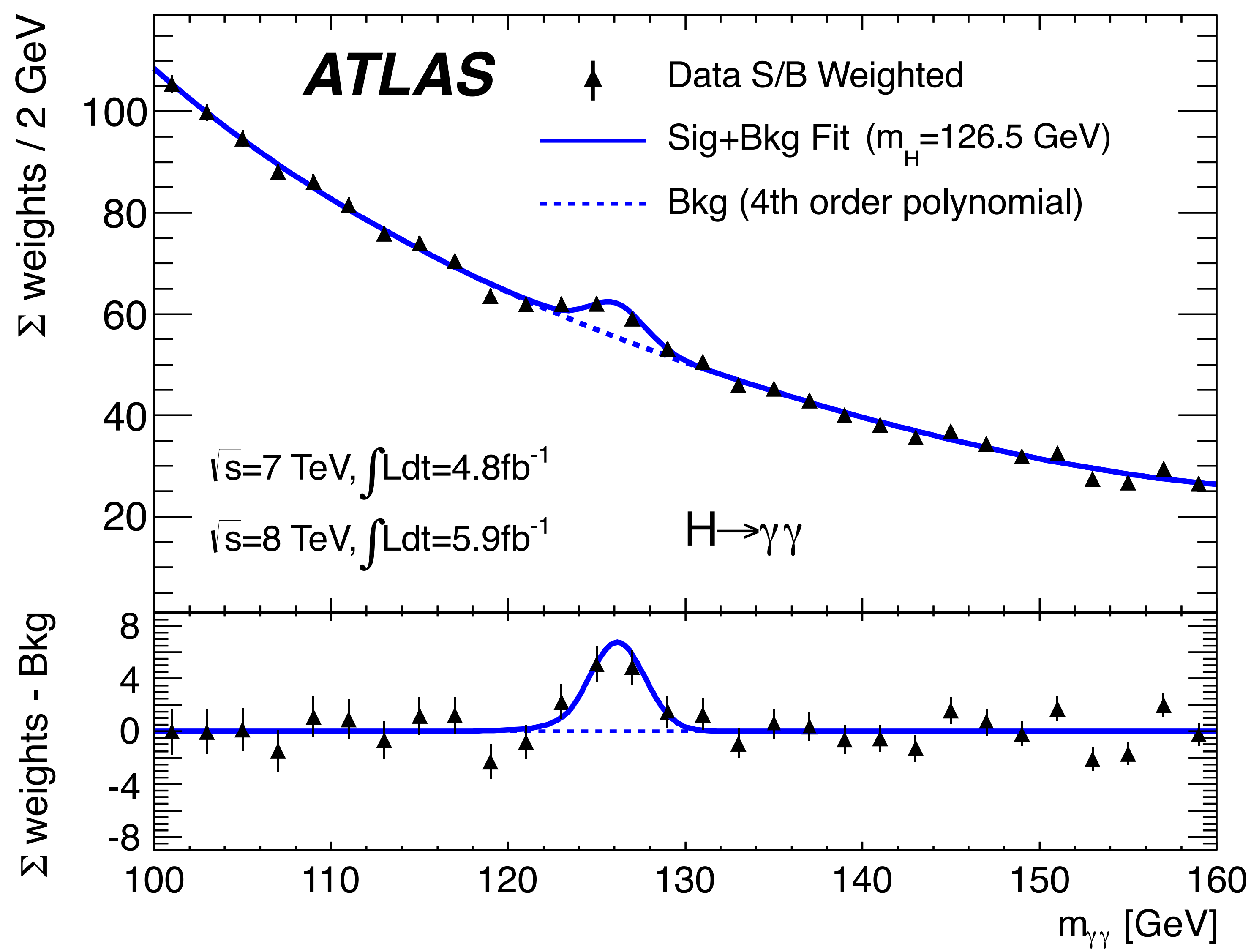
Monte Carlo's: event simulation for the LHC

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3), Belgium

Lecture I

INDEPENDENCE DAY 2012

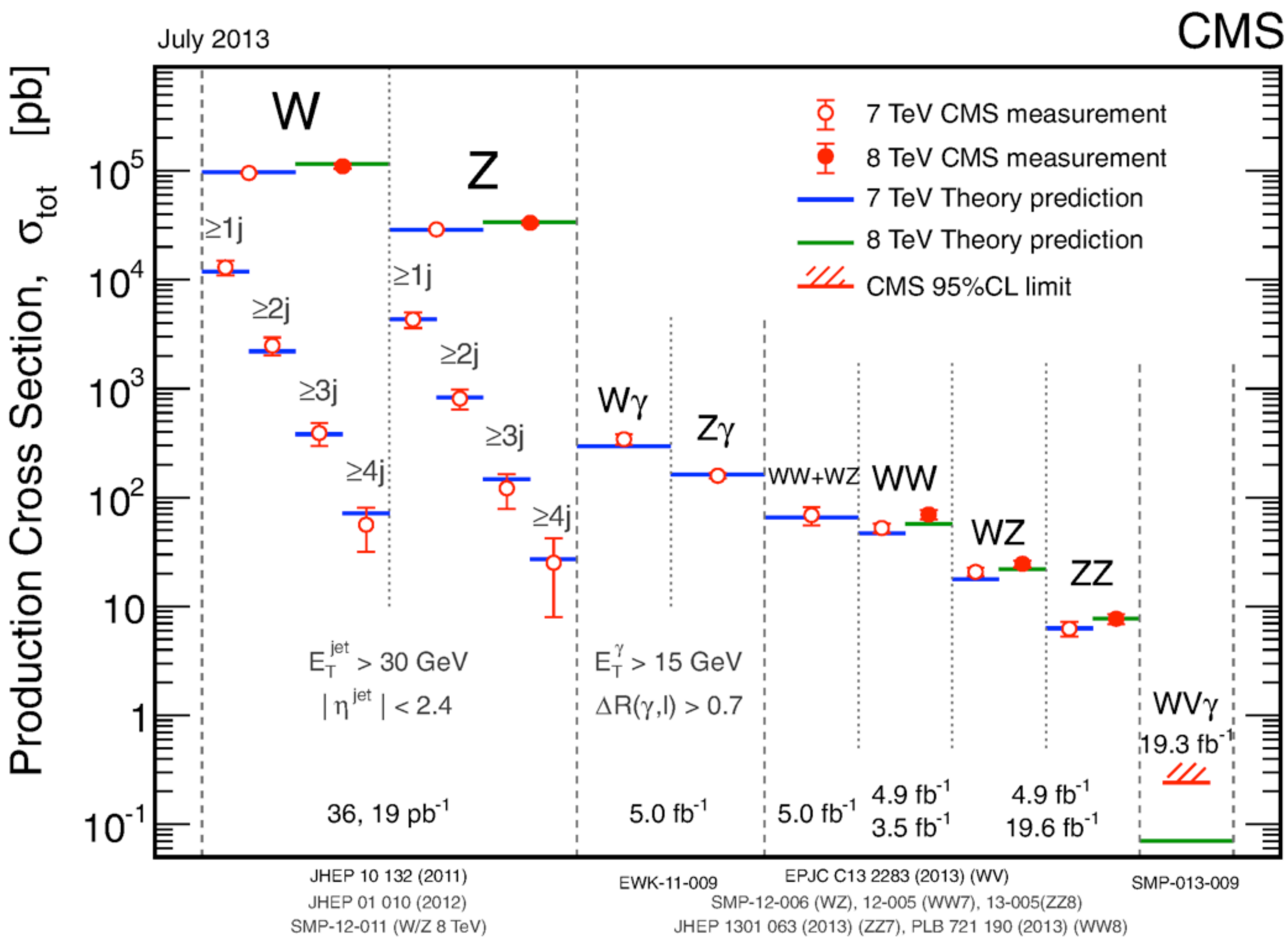




Clear evidence for a new resonance!

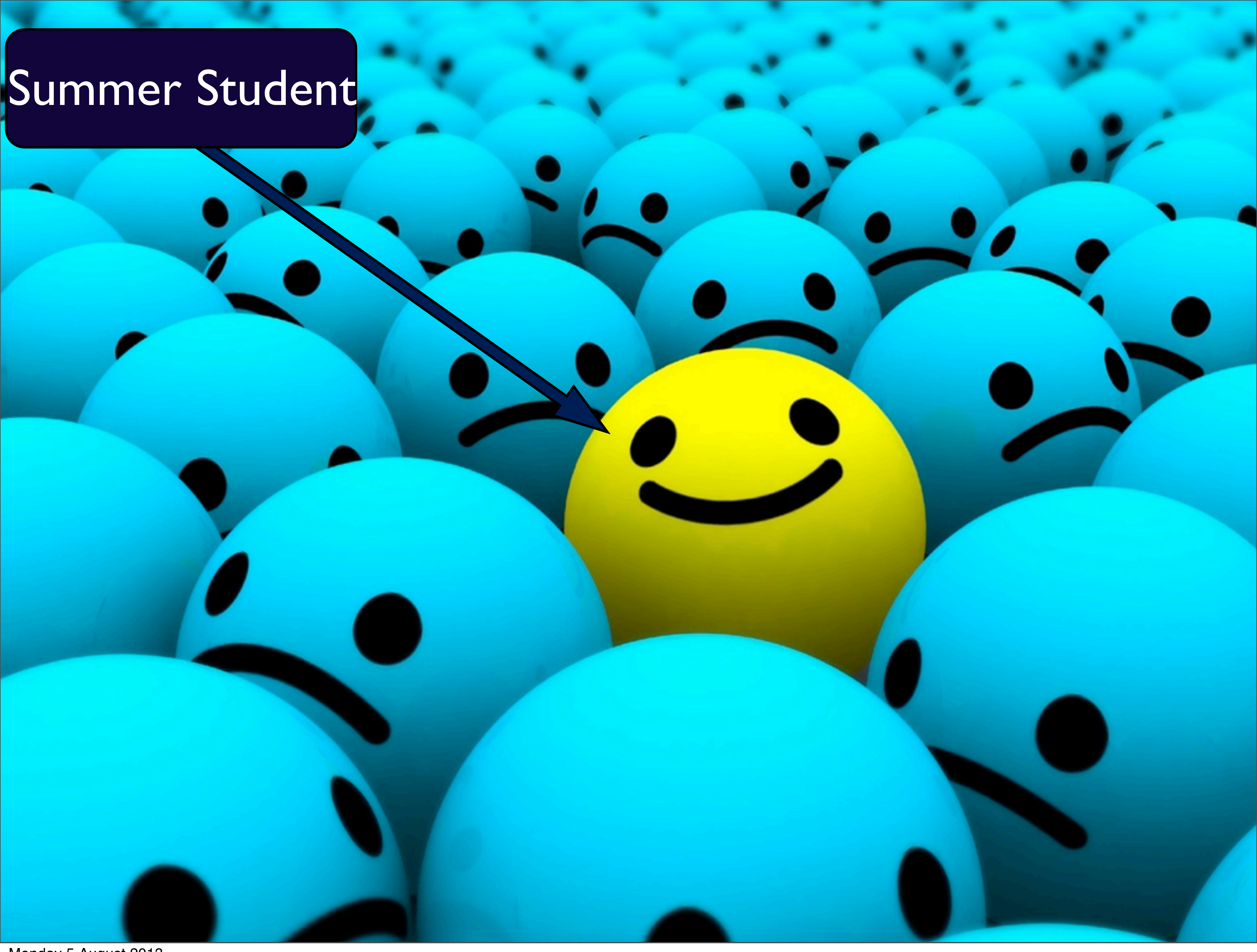
Now reaching >10 σ

Challenges for LHC physicists



Even this plot actually needs theory input (and the total quoted uncertainty in the measurements does have a contribution from theory)!!!

No sign of new physics (so far)!


Summer Student

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  - Accuracy: accurate simulations for both SM and BSM are a must.

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- Confidence on possible excesses, evidences and eventually discoveries builds upon an intense (and often non-linear) process of description/prediction of data via MC's.
- Both **measurements** and **exclusions** rely on accurate predictions.

New generation (LHC) of MC tools

Theory

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
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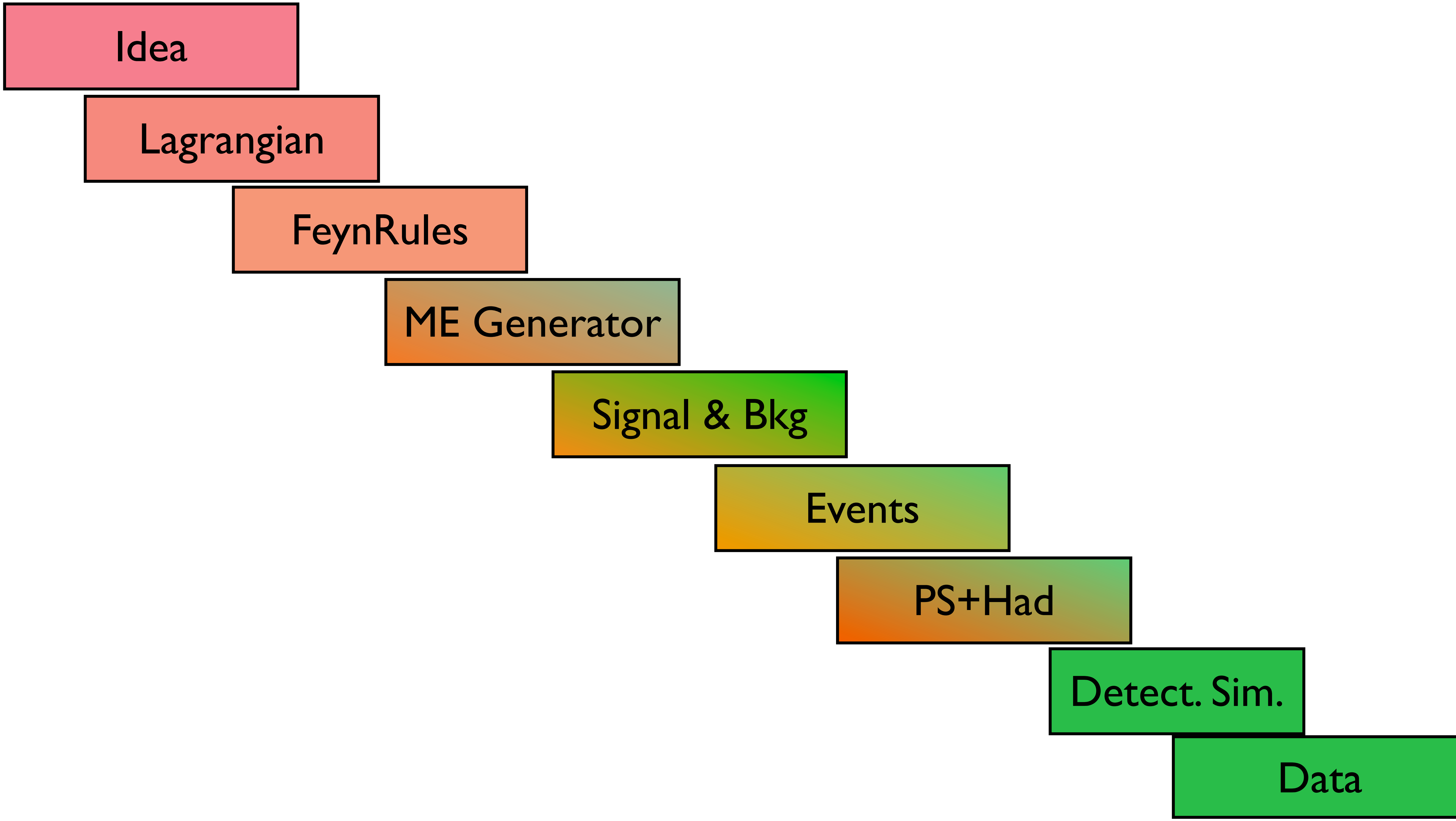
The LHC simulation chain



Aims for these two lectures

- Basics of Monte Carlo techniques.
- Recall the basics of the necessary QCD concepts to understand what is going on in a pp event at the TeV scale.
- Critically revisit the "old" ways of making predictions for hadron colliders: either via fixed-order predictions or parton showers.
- Mention the new ***predictive*** techniques that are available to us.

TRY IT OUT YOURSELF

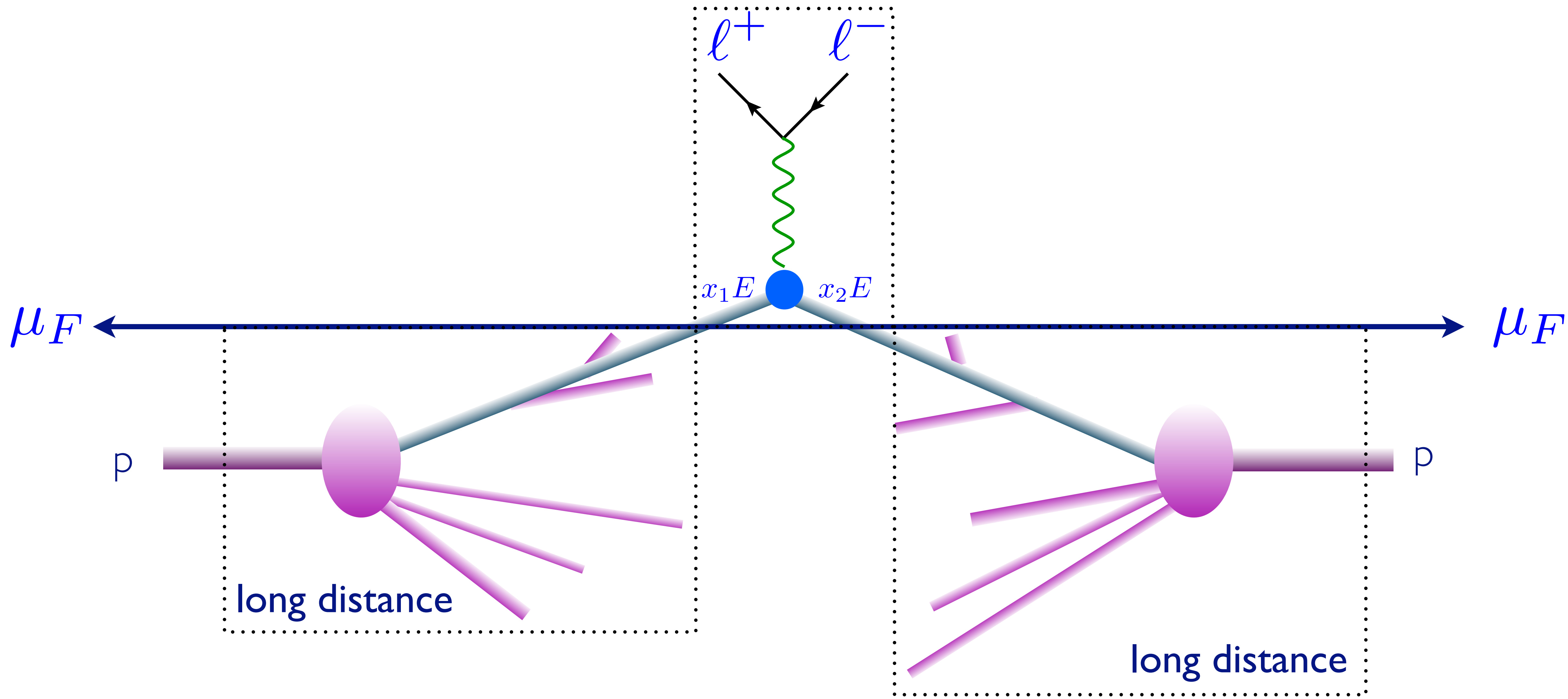
Wiki with exercises on MC integration event generation:

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/MCSummerCERN13

PLAN

- Basics : LO predictions
- Event generation
- Exclusive predictions : Parton Showers
- The simulation frontier

Master formula for the LHC



$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral — Parton density functions — Parton-level cross section

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Phase-space integral — Parton density functions — Parton-level cross section

Two ingredients necessary:

1. Parton distribution functions : non perturbative
(fit from experiments, but evolution from theory)

2. Parton-level cross section: short distance coefficients as an expansion in α_S (from theory)

Perturbative expansion

$\hat{\sigma}_{ab \to X}(\hat{s}, \mu_F, \mu_R)$ Parton-level cross section

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LO predictions | **NLO corrections** | **NNLO corrections** | **NNNLO corrections**

- Including higher corrections improves predictions and reduces theoretical uncertainties

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General and flexible method is needed:
Numerical (Monte Carlo) integration

Phase-space

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$$d\Phi_n = \left[\Pi_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)}\right] (2\pi)^4 \delta^{(4)}(p_0 - \sum_{i=1}^{n} p_i)$$

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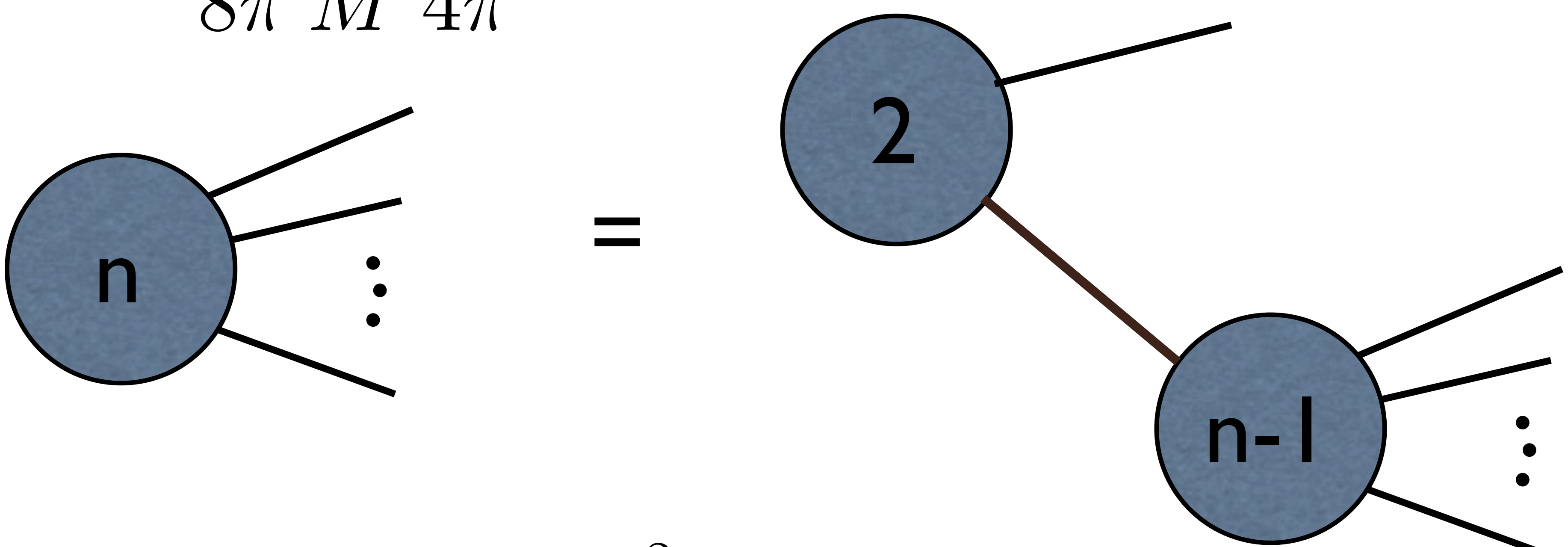

$$d\Phi_n(M) = \frac{1}{2\pi}\int_0^{(M-\mu)^2} d\mu^2 d\Phi_2(M) d\Phi_{n-1}(\mu)$$

Integrals as averages

$$I = \int_{x_1}^{x_2} f(x)dx \quad \Rightarrow \quad I_N = (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x)$$

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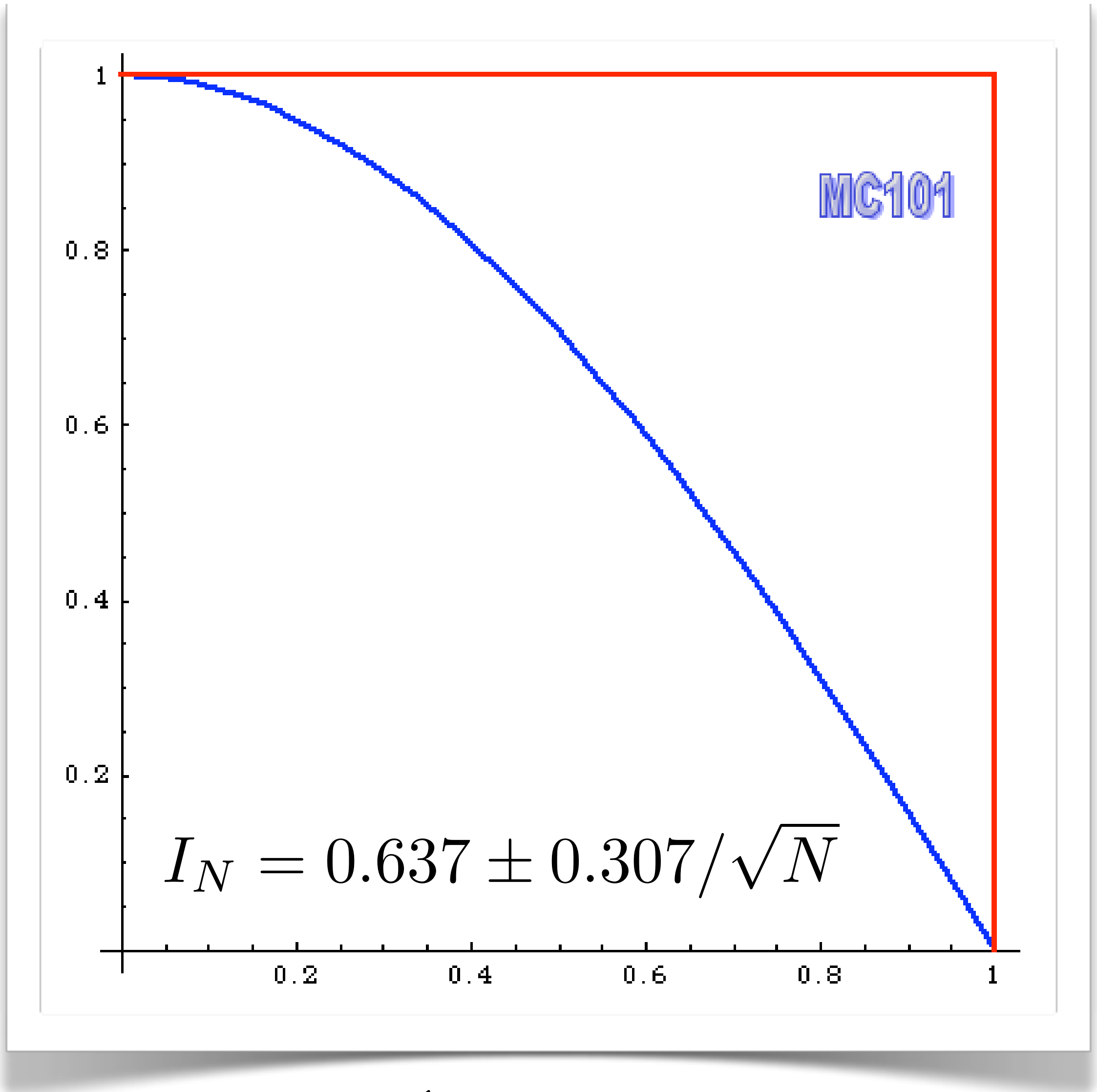
- ☞ Convergence is slow but it can be estimated easily
- ☞ Error does not depend on # of dimensions!
- ☞ Improvement by minimizing V_N
- ☞ Optimal/Ideal case: f(x) = Constant $\Rightarrow$ $V_N = 0$

Importance sampling



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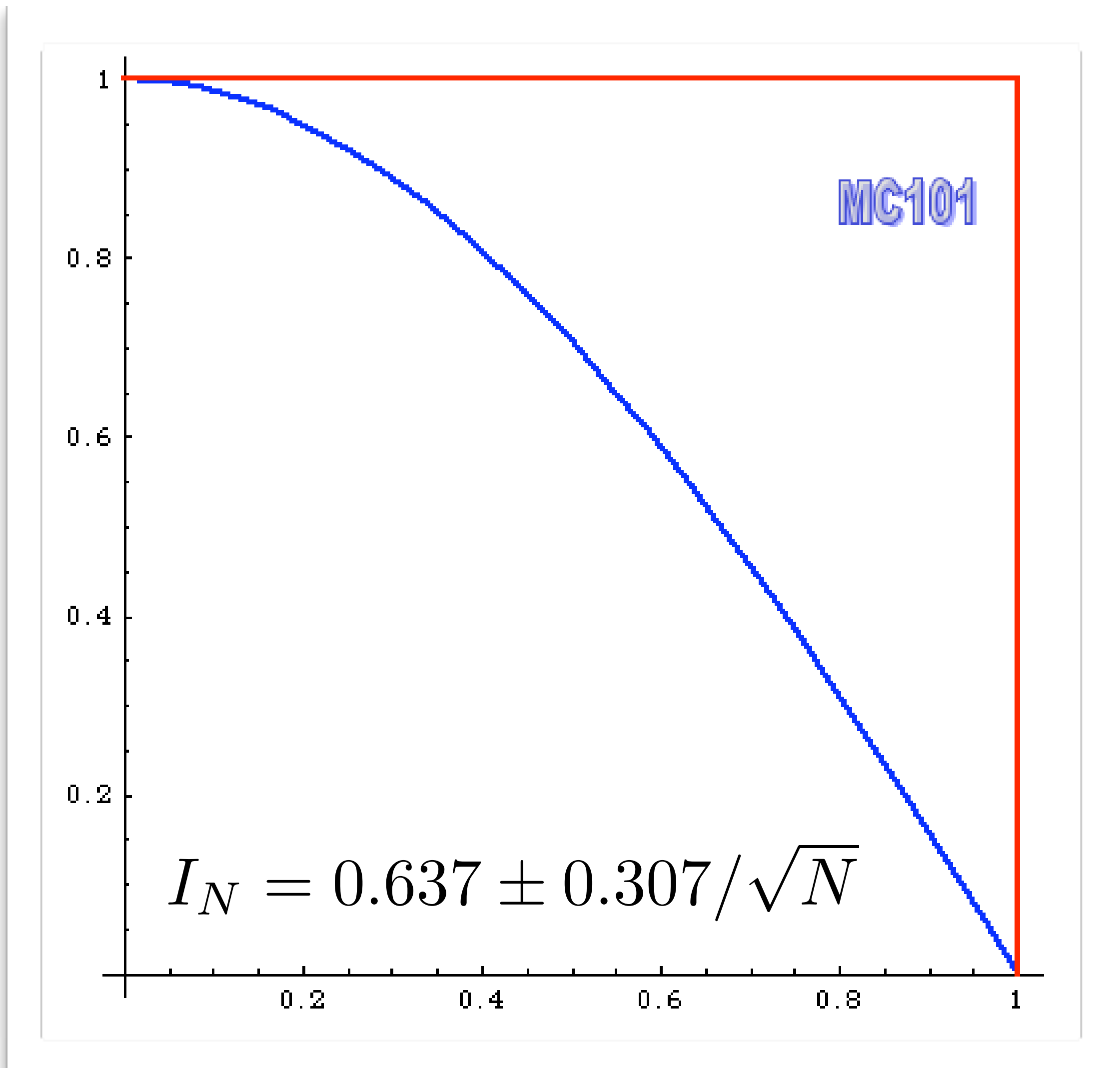

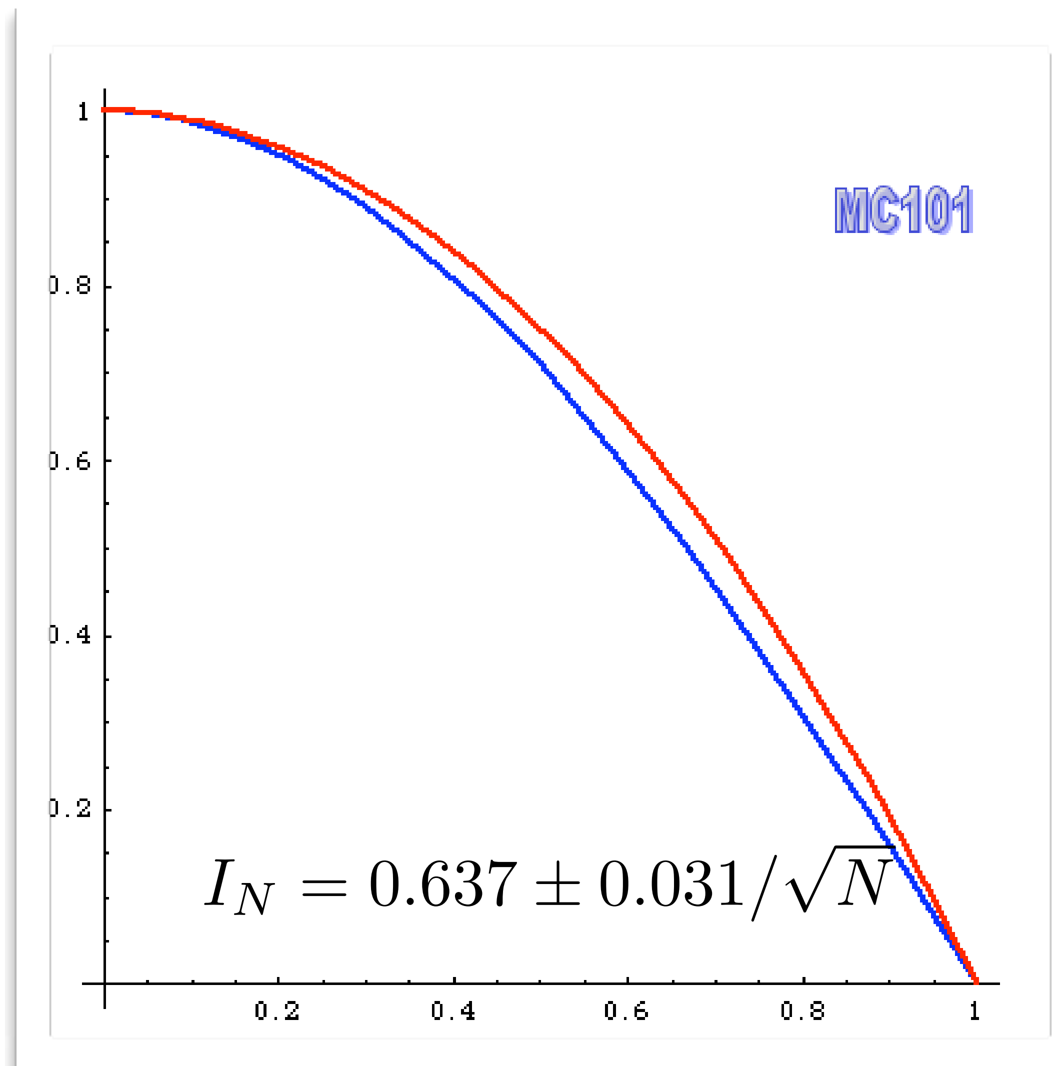

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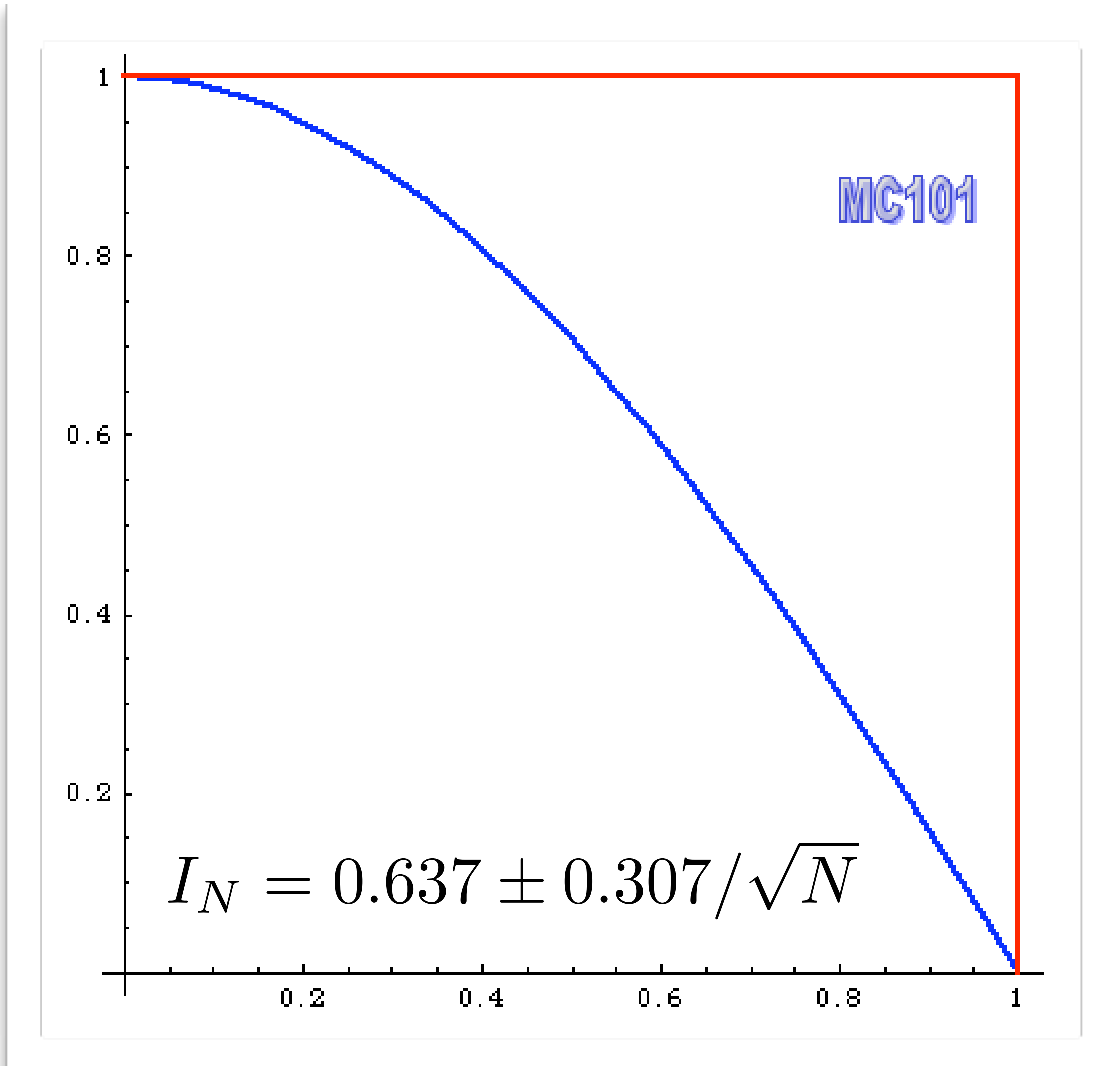

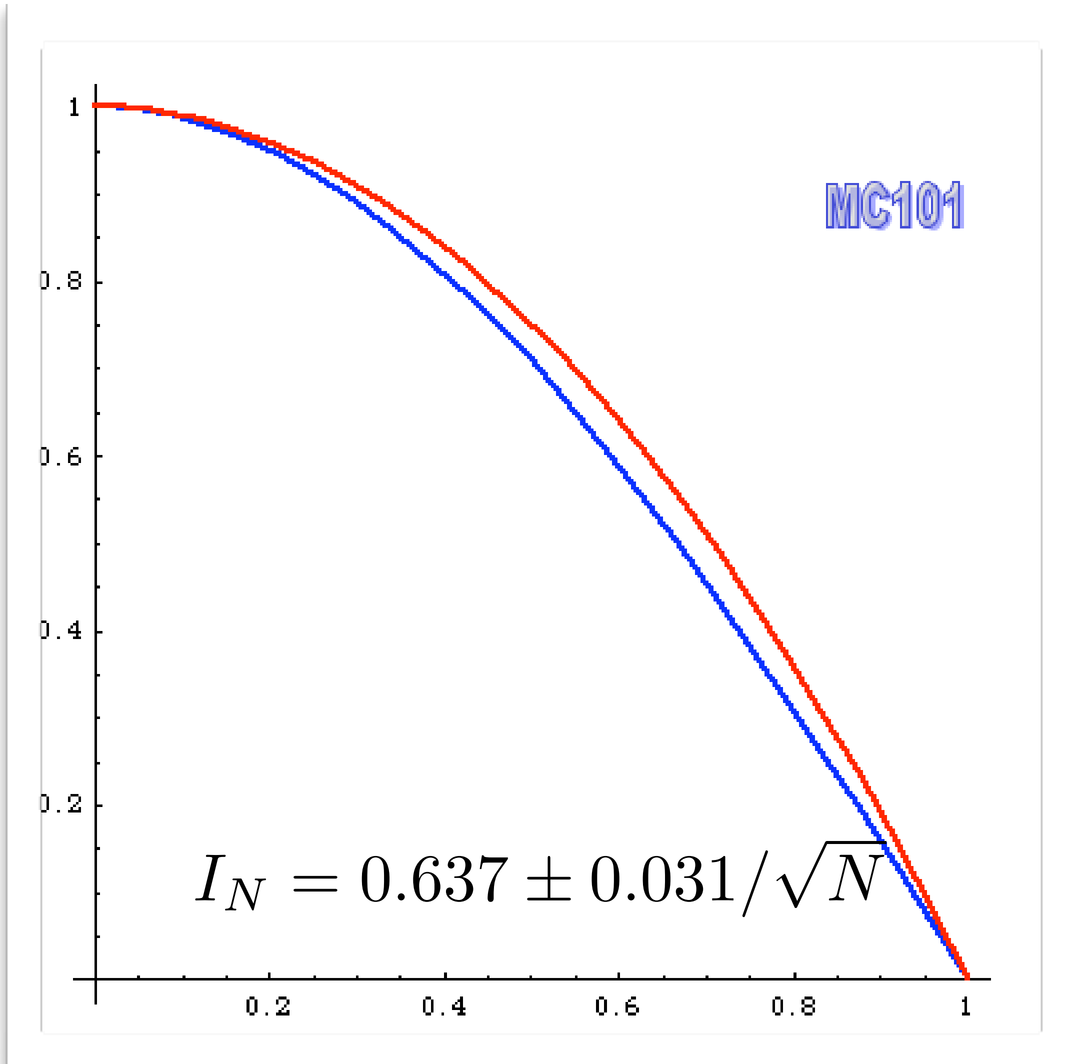

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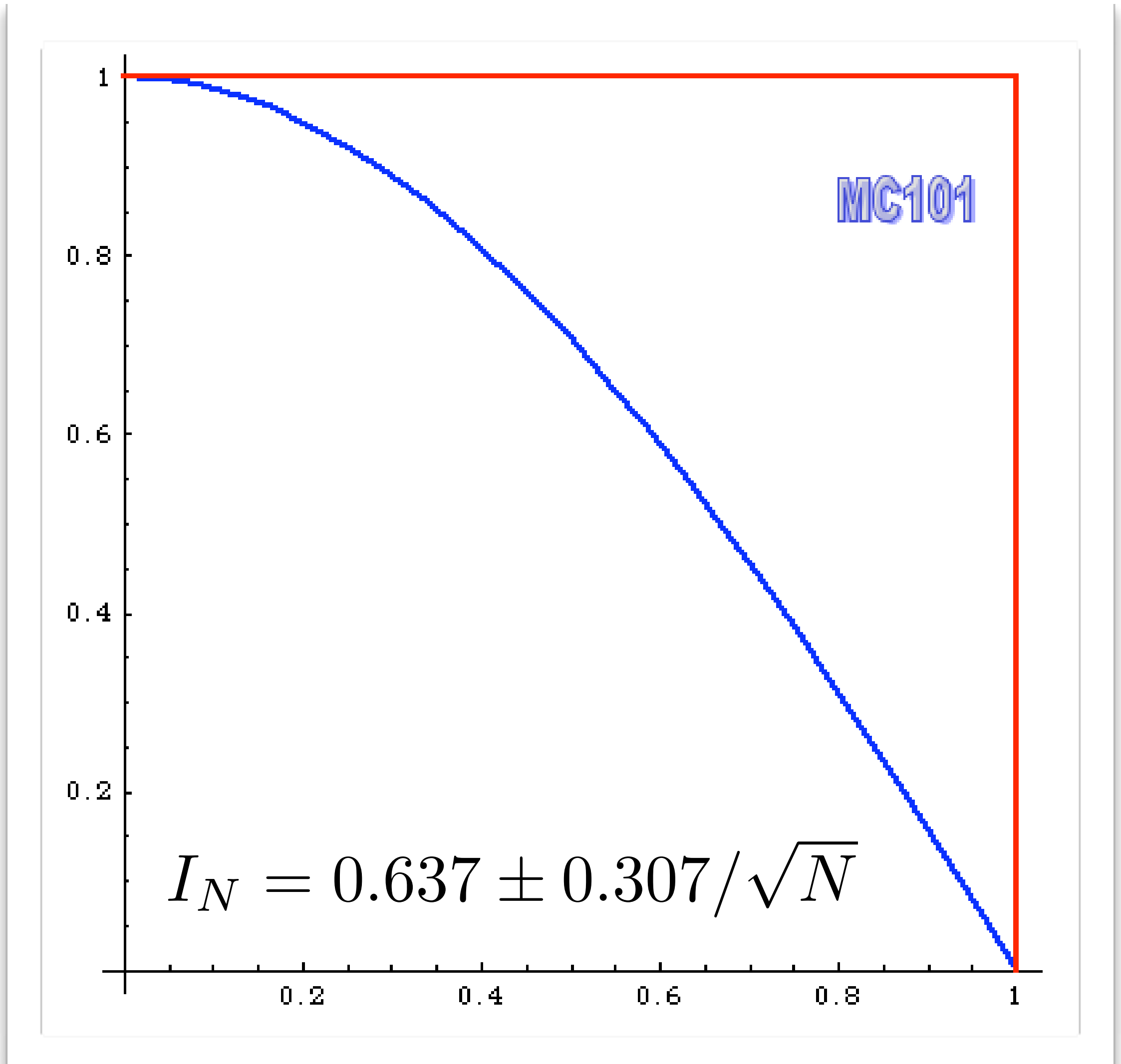

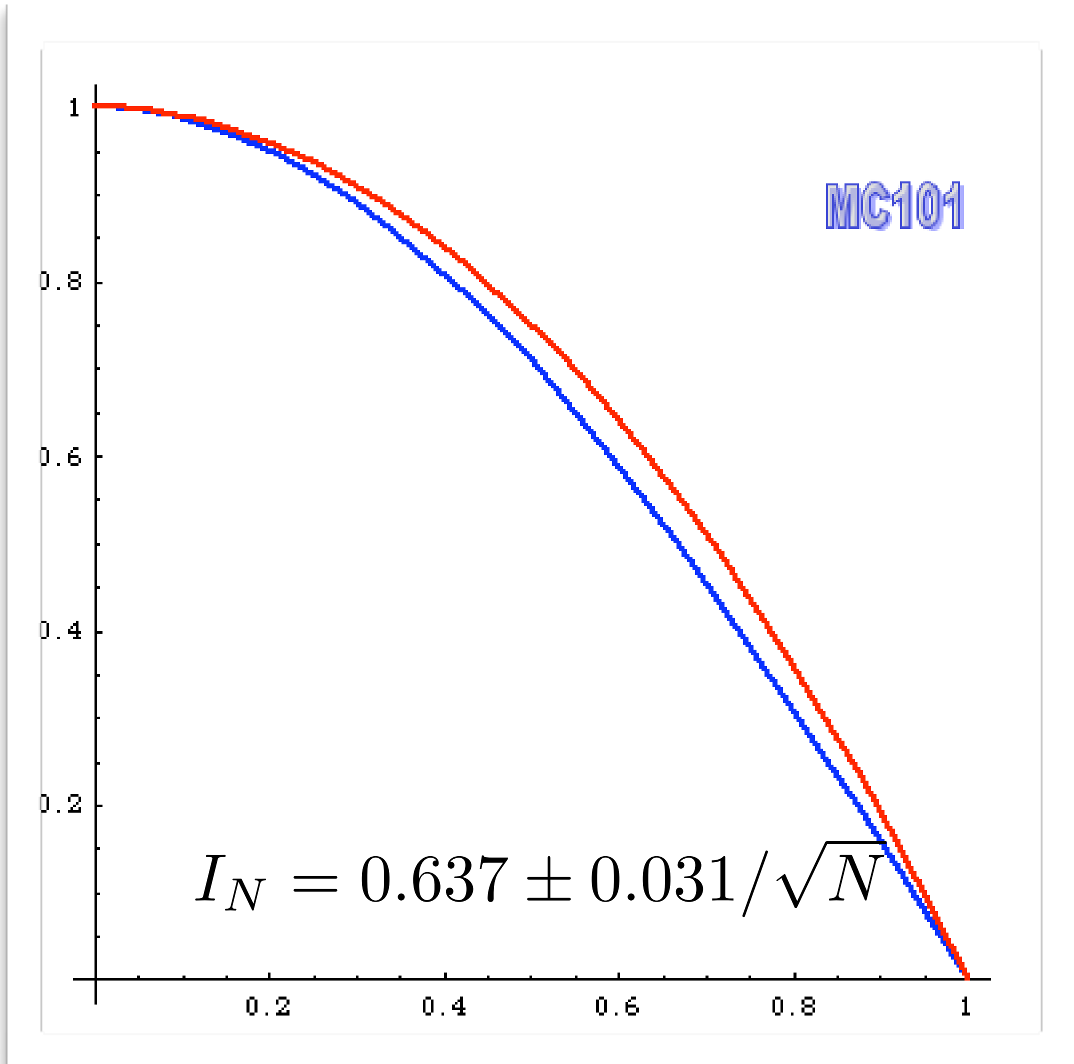

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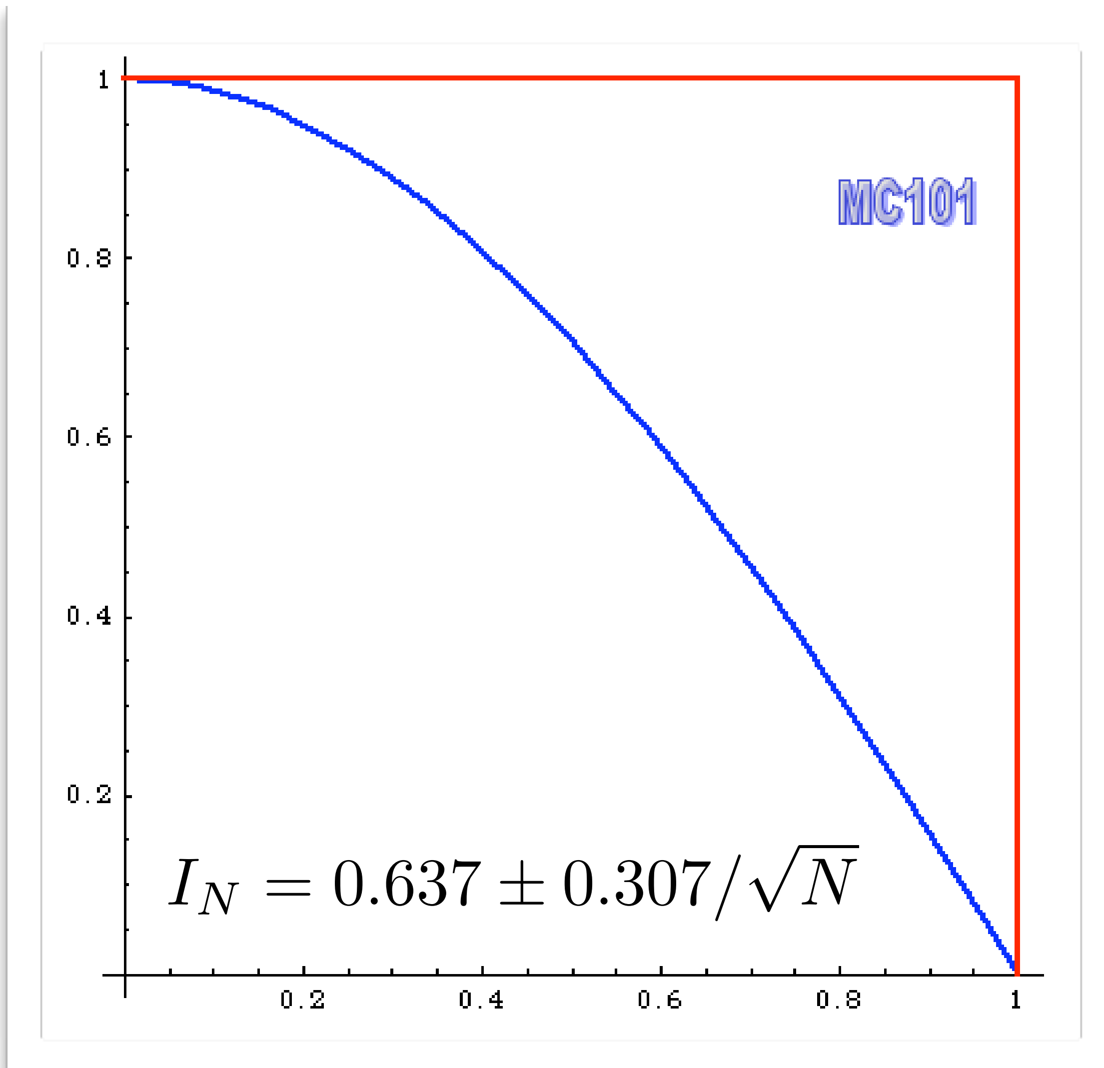

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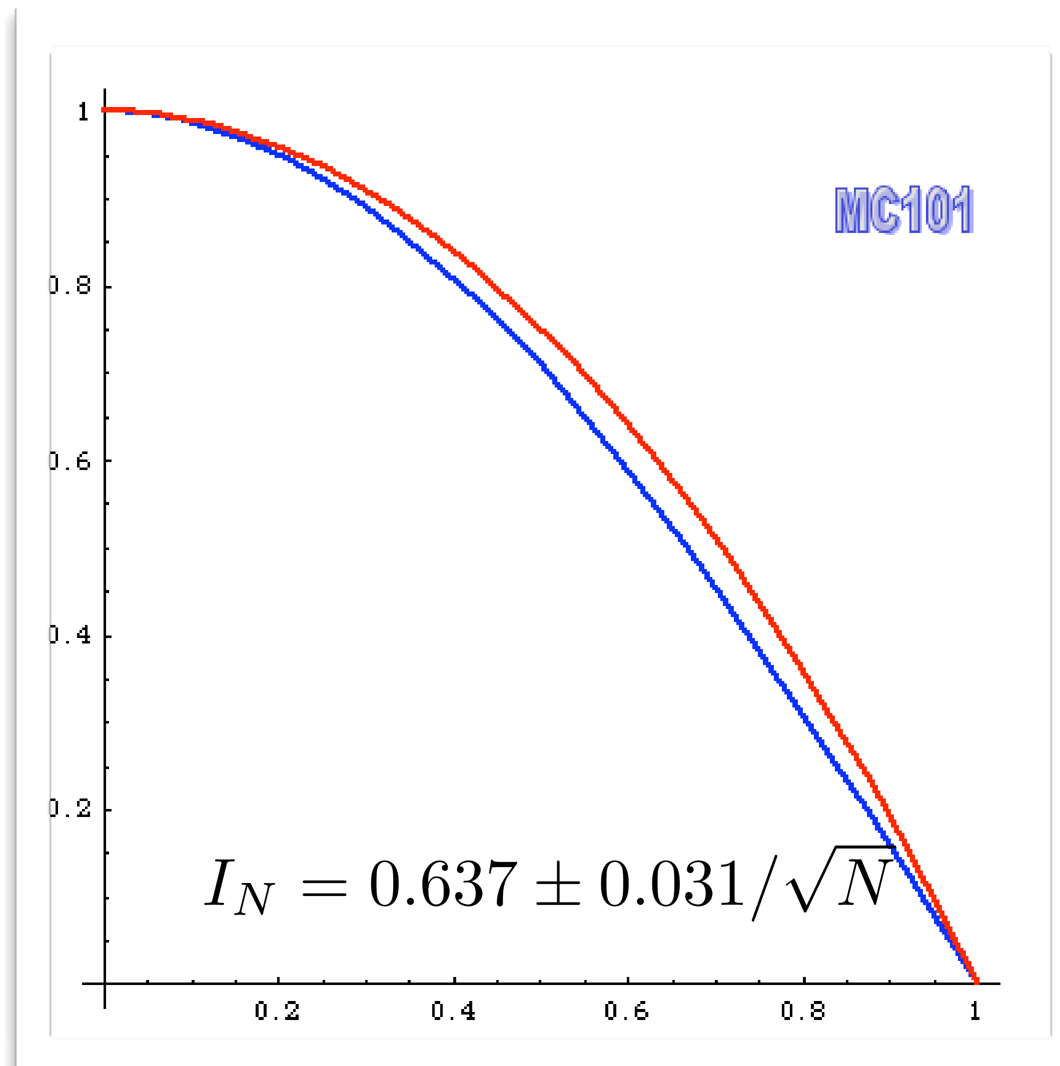

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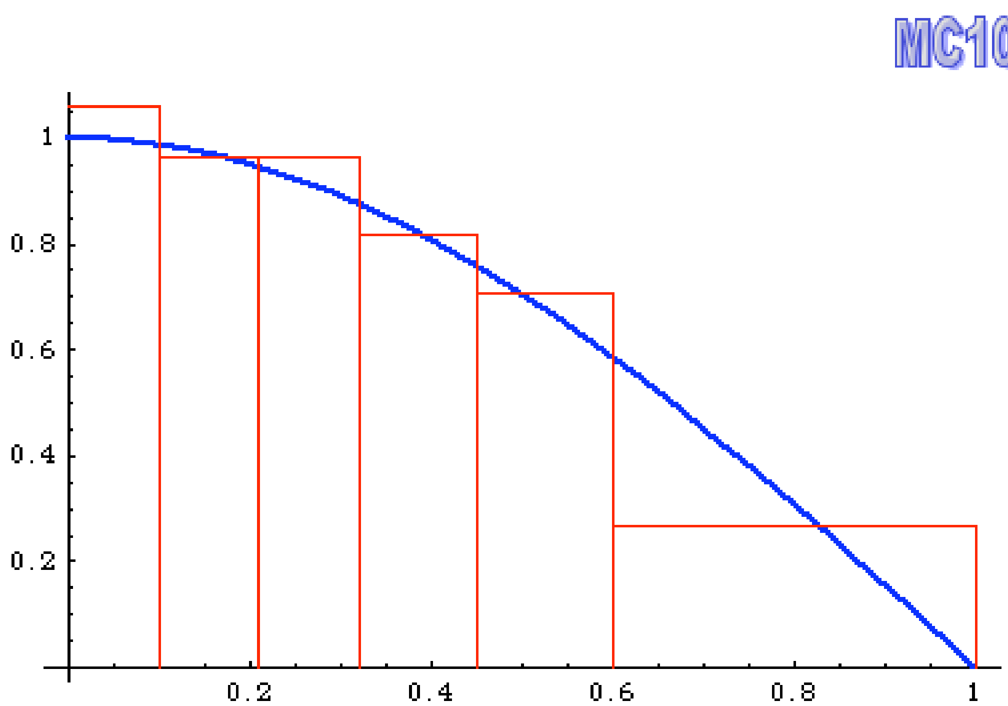

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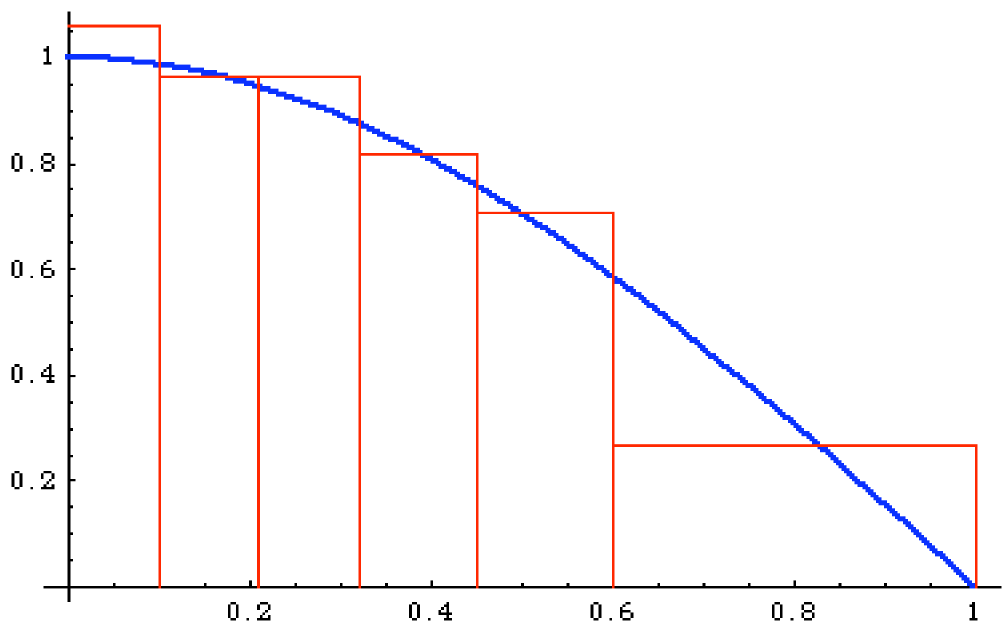
MC101



more bins where f(x) is large

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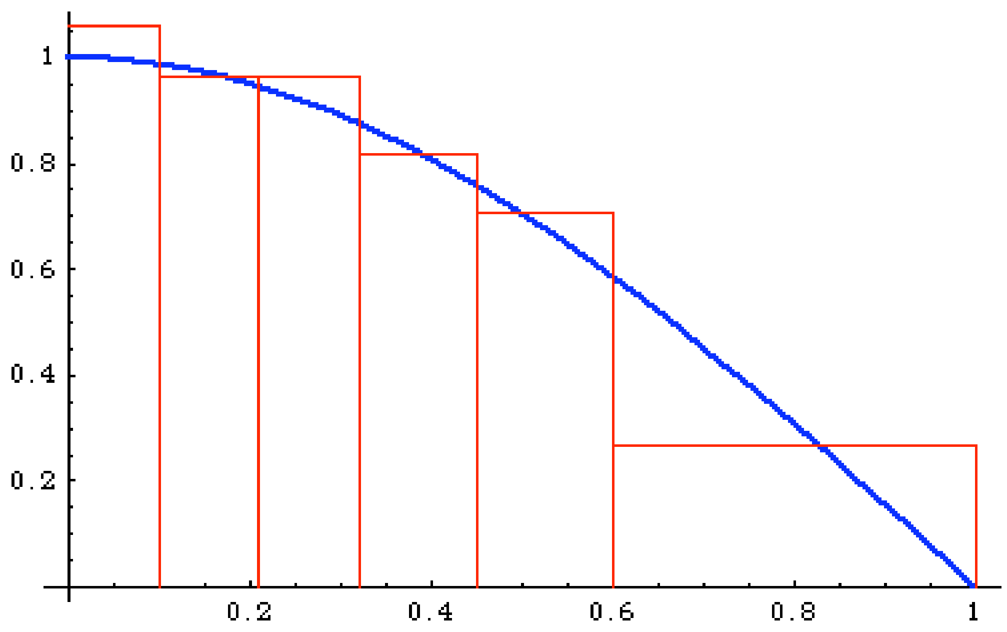

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$$p(x) = \frac{1}{N_b \Delta x_i}, \quad x_i - \Delta x_i < x < x_i$$

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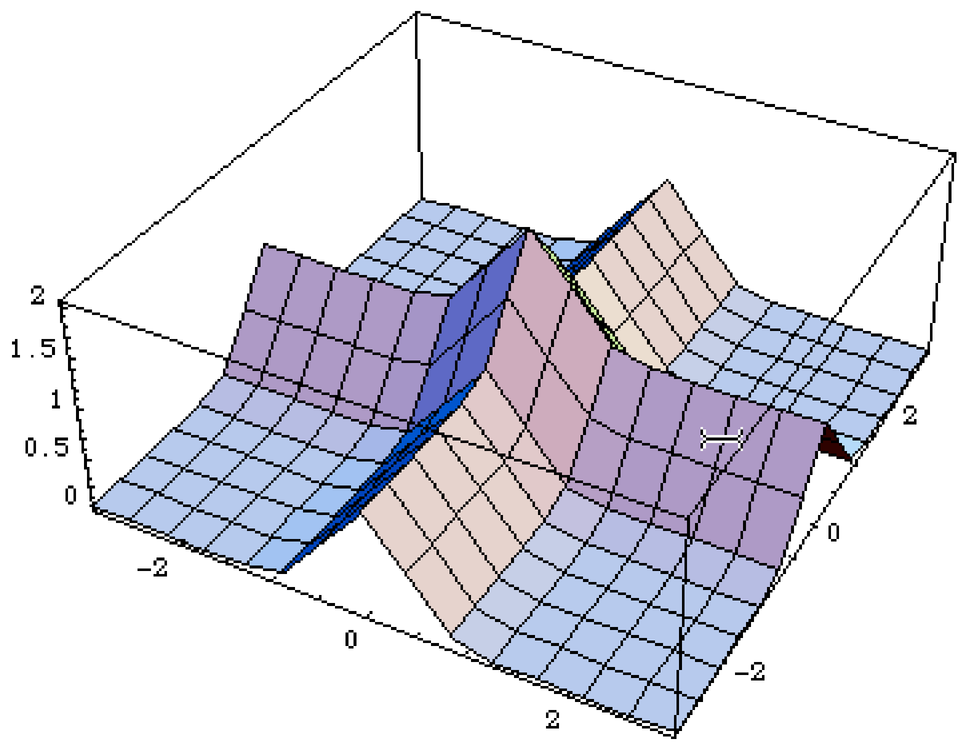

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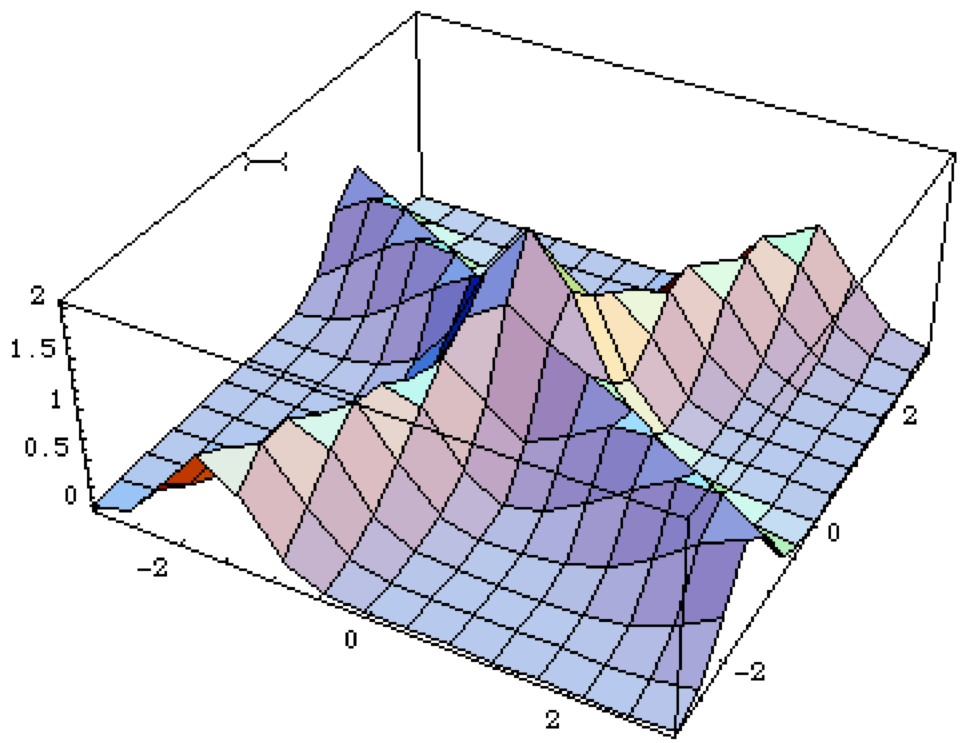

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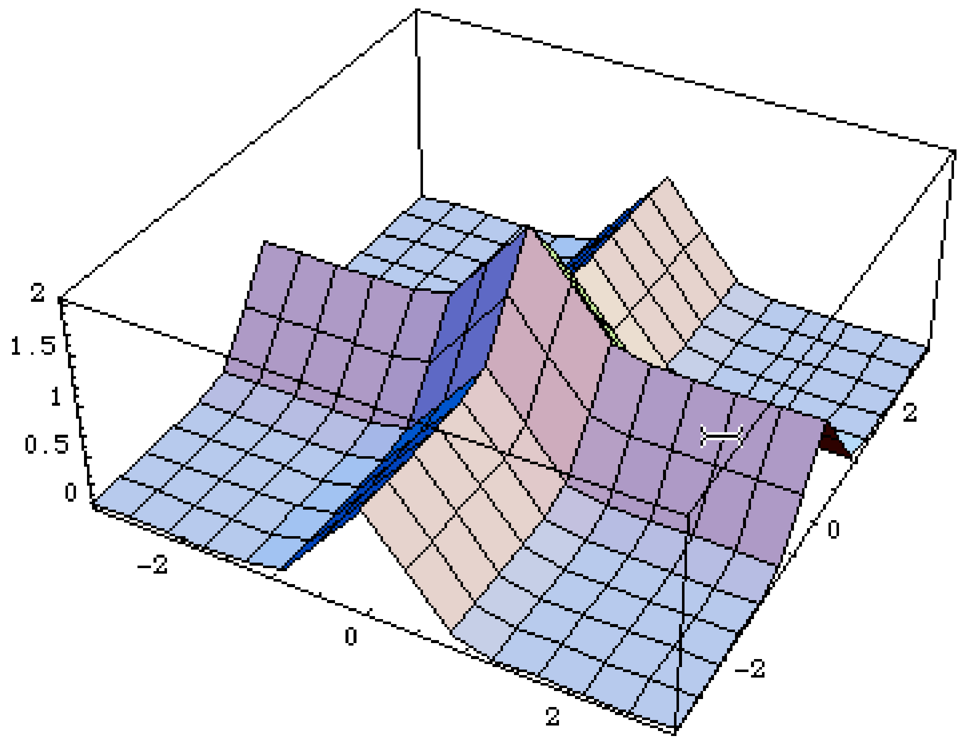
Importance Sampling

can be generalized to n dimensions:

$$p(\vec{x}) = p(x) \bullet p(y) \bullet p(z) \ldots$$

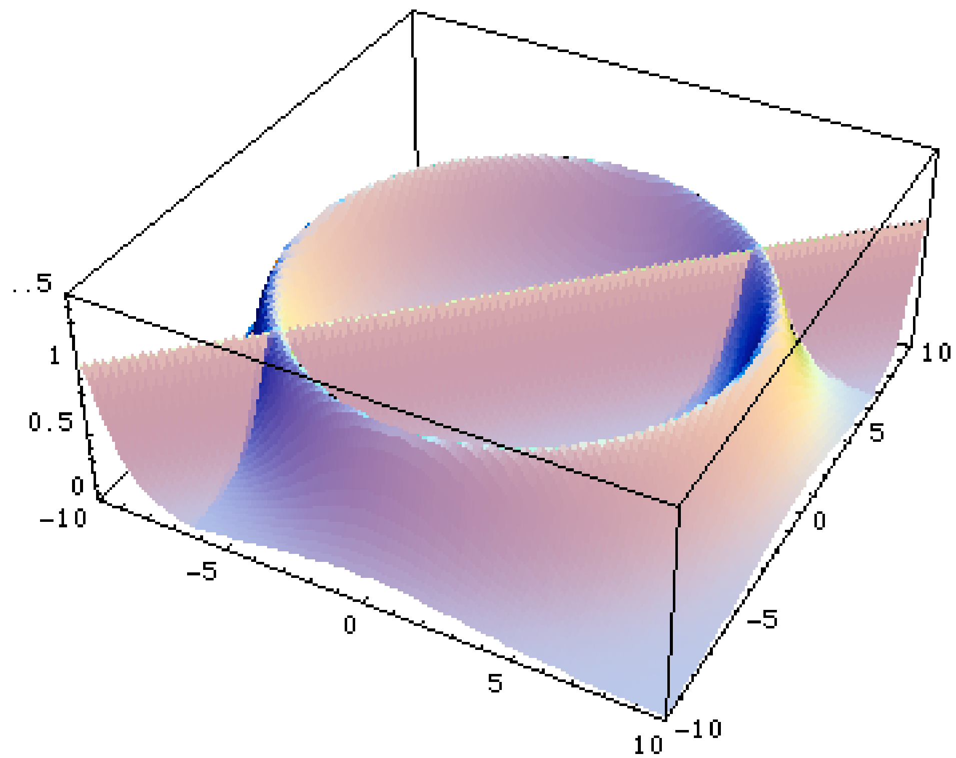
but the peaks of $f(\vec{x})$ need to be "aligned" to the axis!



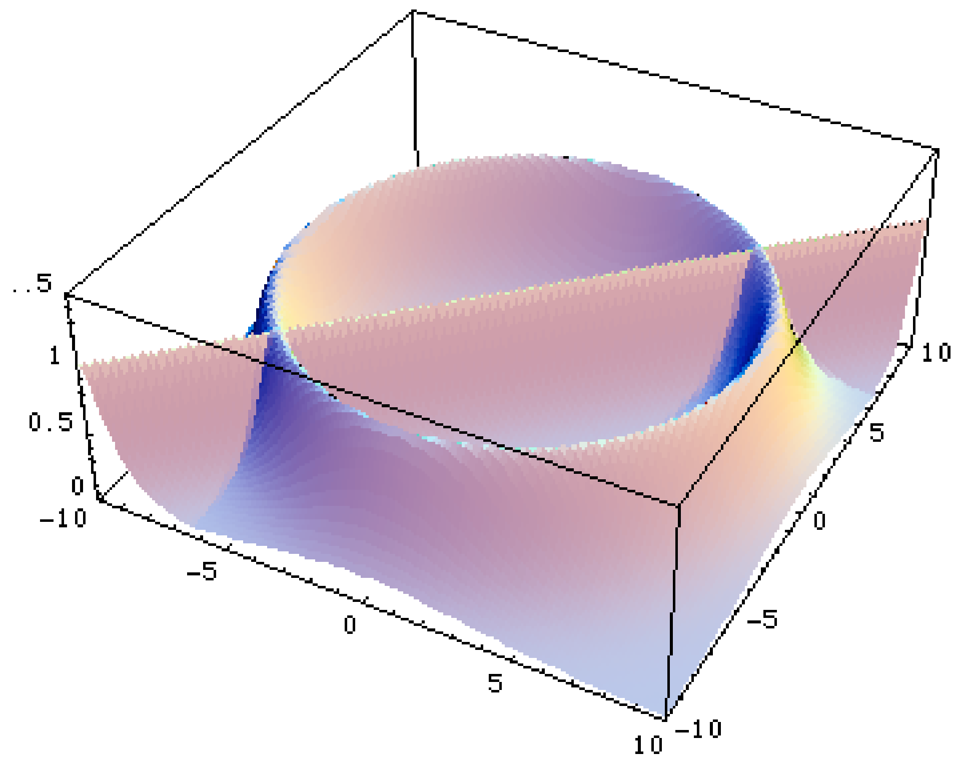
but it is sufficient to make a change of variables!

Multi-channel

Multi-channel

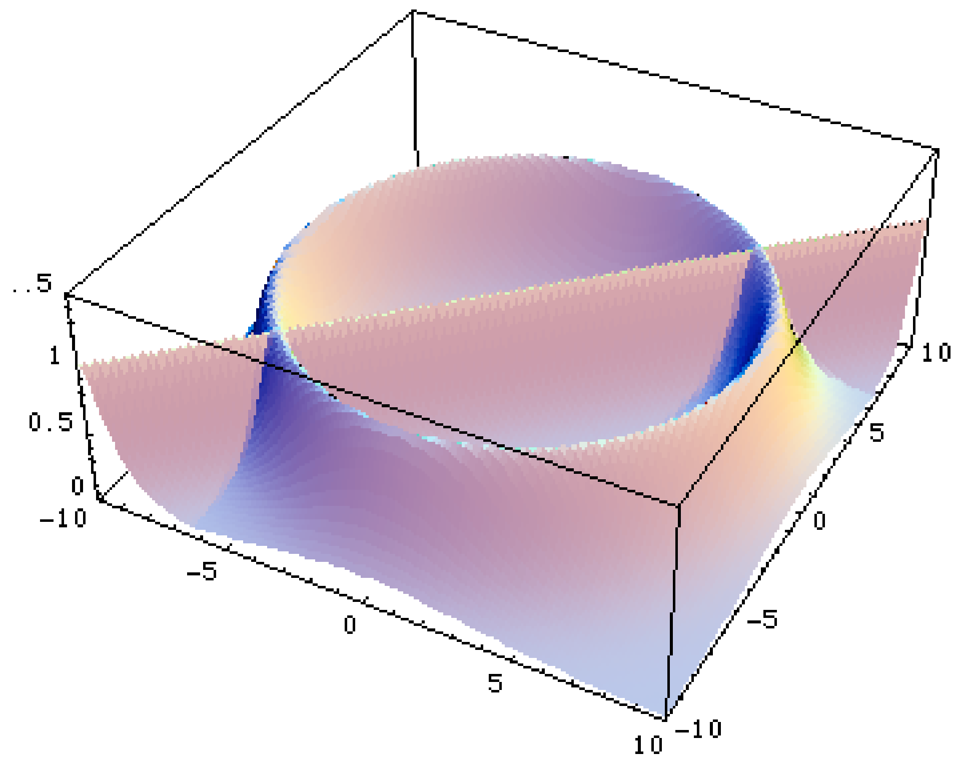


Multi-channel



In this case there is no unique tranformation: Vegas is bound to fail!

Multi-channel



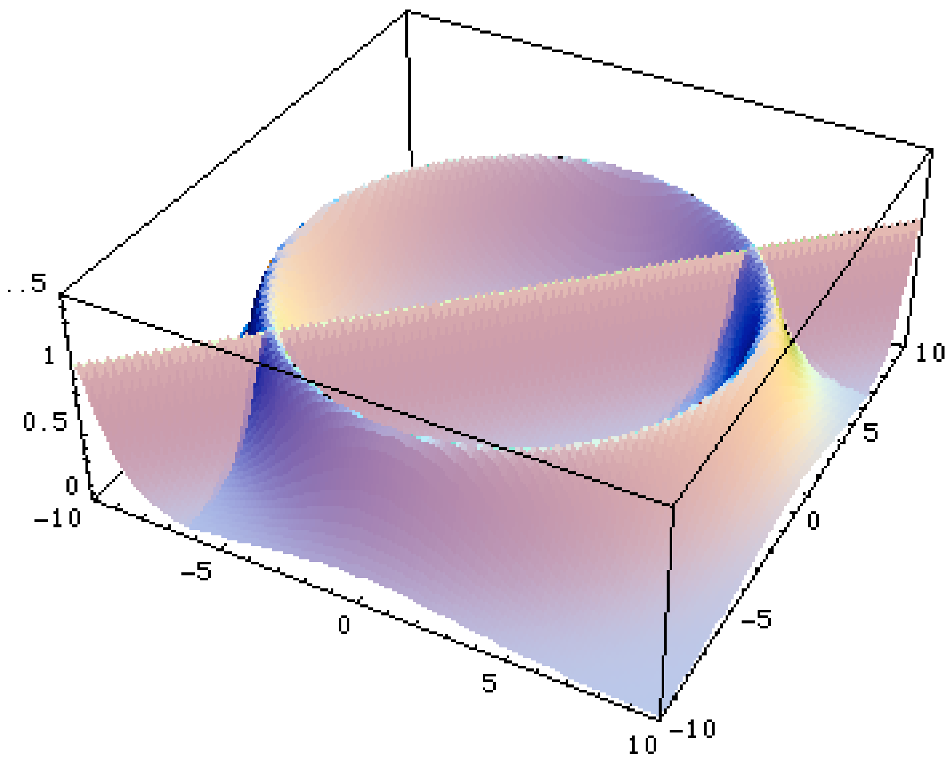
In this case there is no unique tranformation: Vegas is bound to fail!

Solution: use different transformations= channels

$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x) \qquad \text{with} \qquad \sum_{i=1}^{n} \alpha_i = 1$$

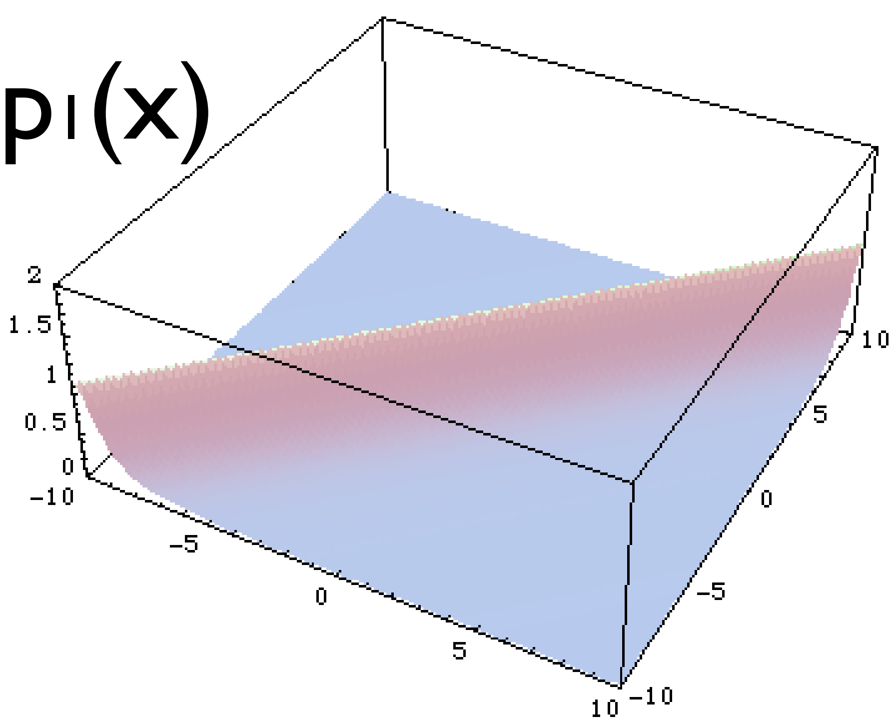
with each $p_i(x)$ taking care of one "peak" at the time

Multi-channel

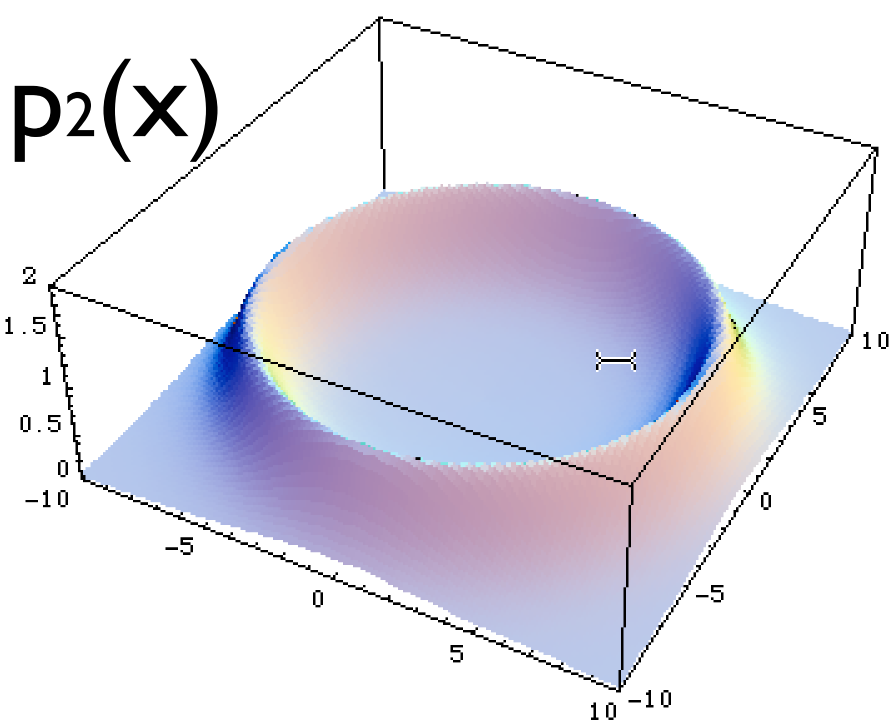


In this case there is no unique tranformation: Vegas is bound to fail!

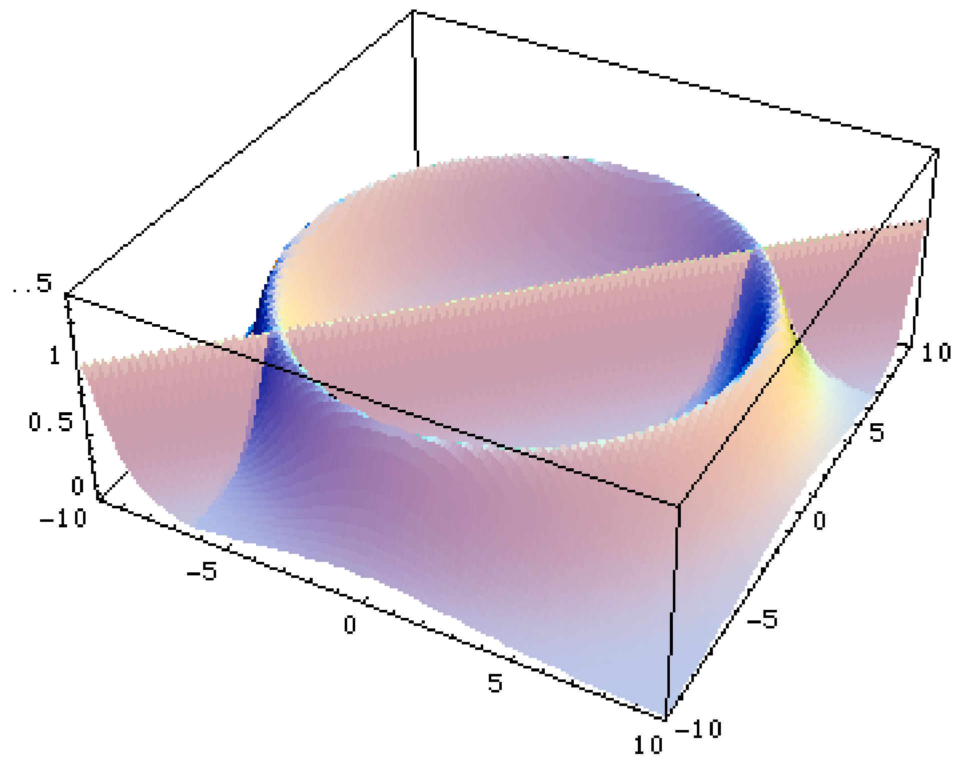
$p_1(x)$



$p_2(x)$



Multi-channel



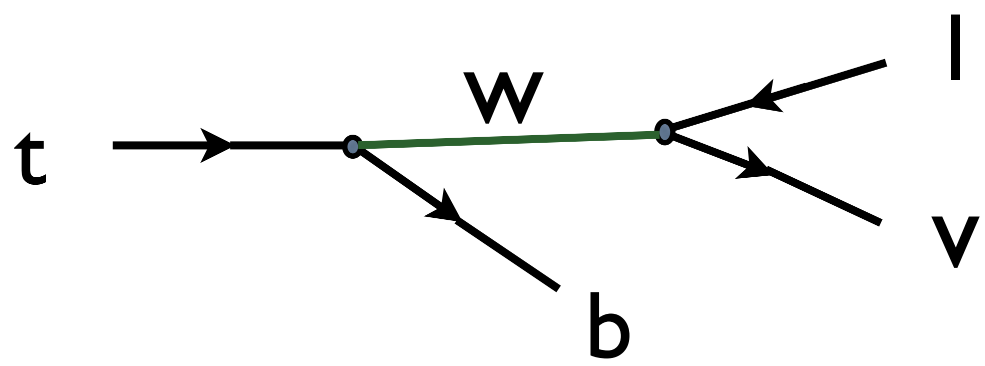
In this case there is no unique tranformation: Vegas is bound to fail!

But if you know where the peaks are (=in which variables) we can use different transformations= channels:

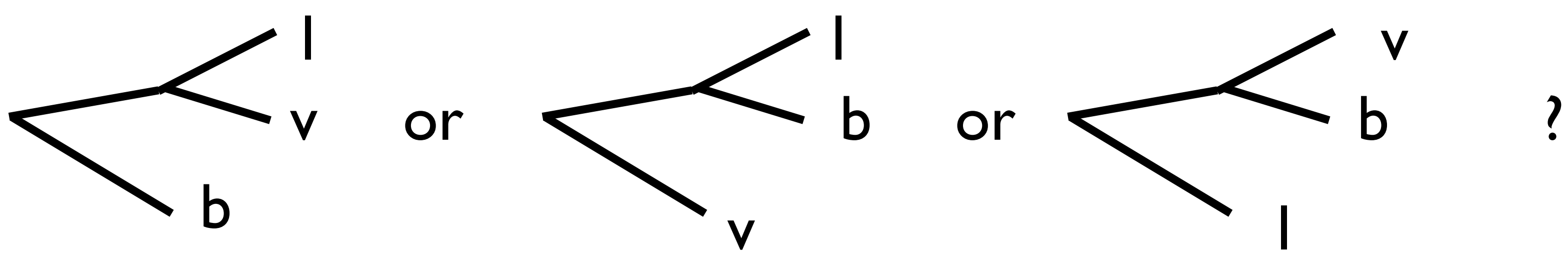
$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x) \qquad \text{with} \qquad \sum_{i=1}^{n} \alpha_i = 1$$

$$I = \int f(x)dx = \sum_{i=1}^{n} \alpha_i \int \frac{f(x)}{p(x)} p_i(x)dx$$

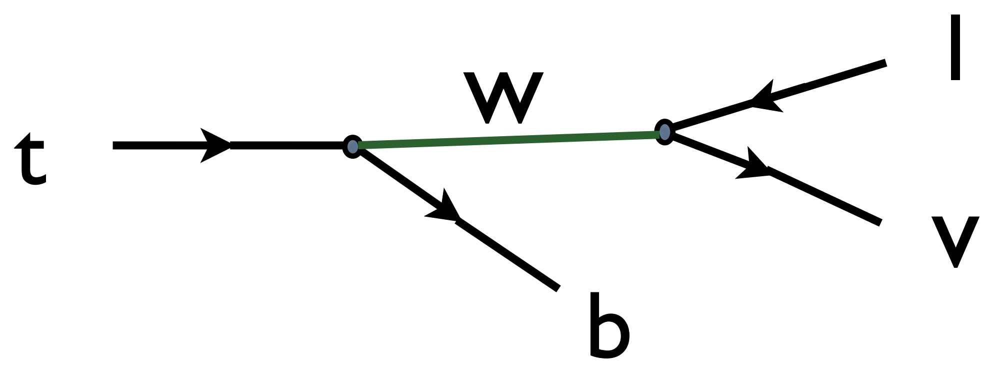
Exercise: Top decay

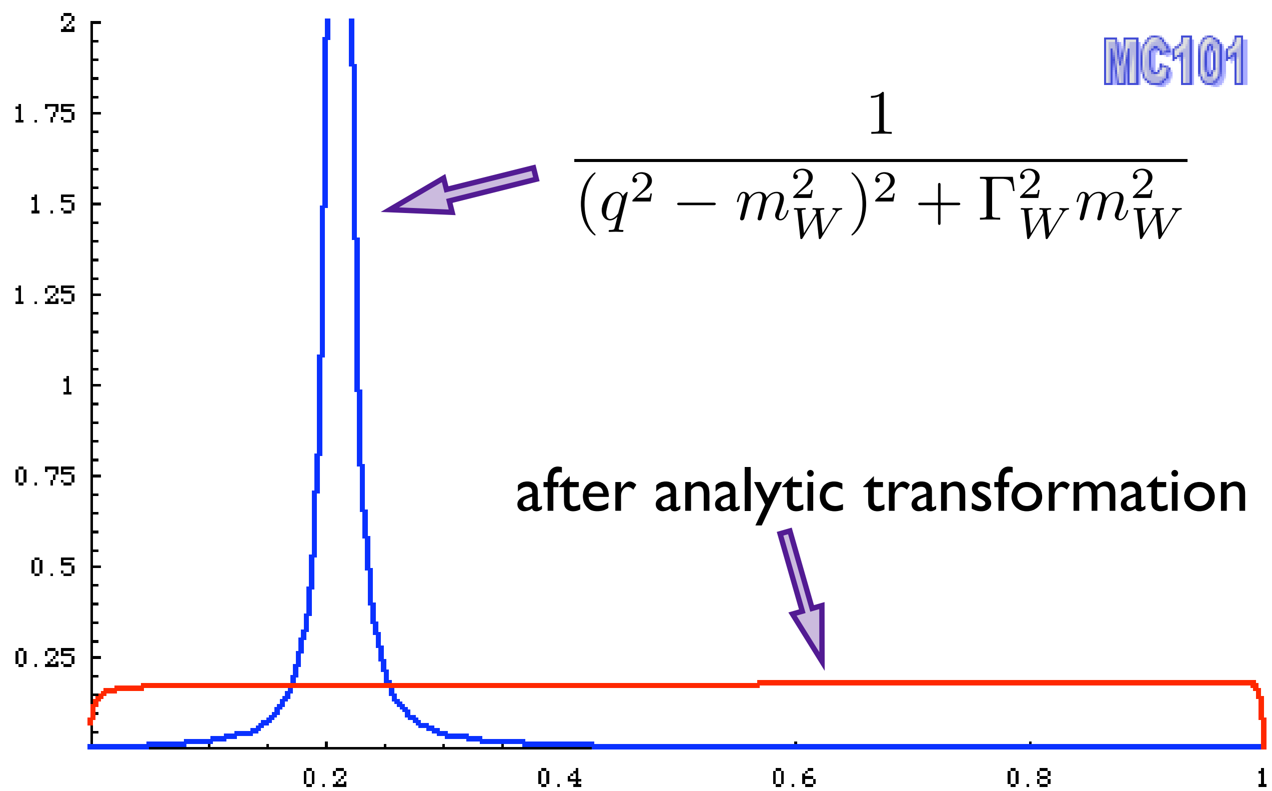


- Easy but non-trivial
- Breit-Wigner peak $\dfrac{1}{(q^2 - m_W^2)^2 + \Gamma_W^2 m_W^2}$ to be "flattened":
- Choose the right "channel" for the phase space:



Exercise: Top decay

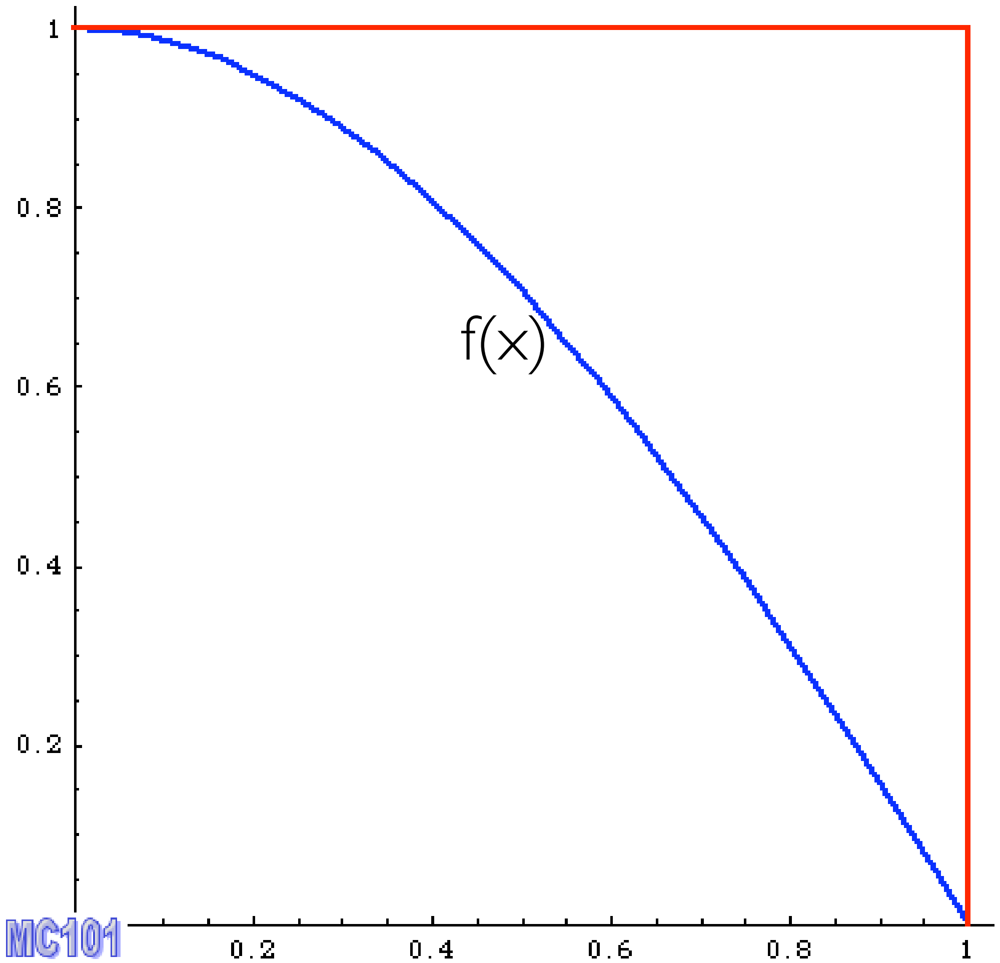




Event generation

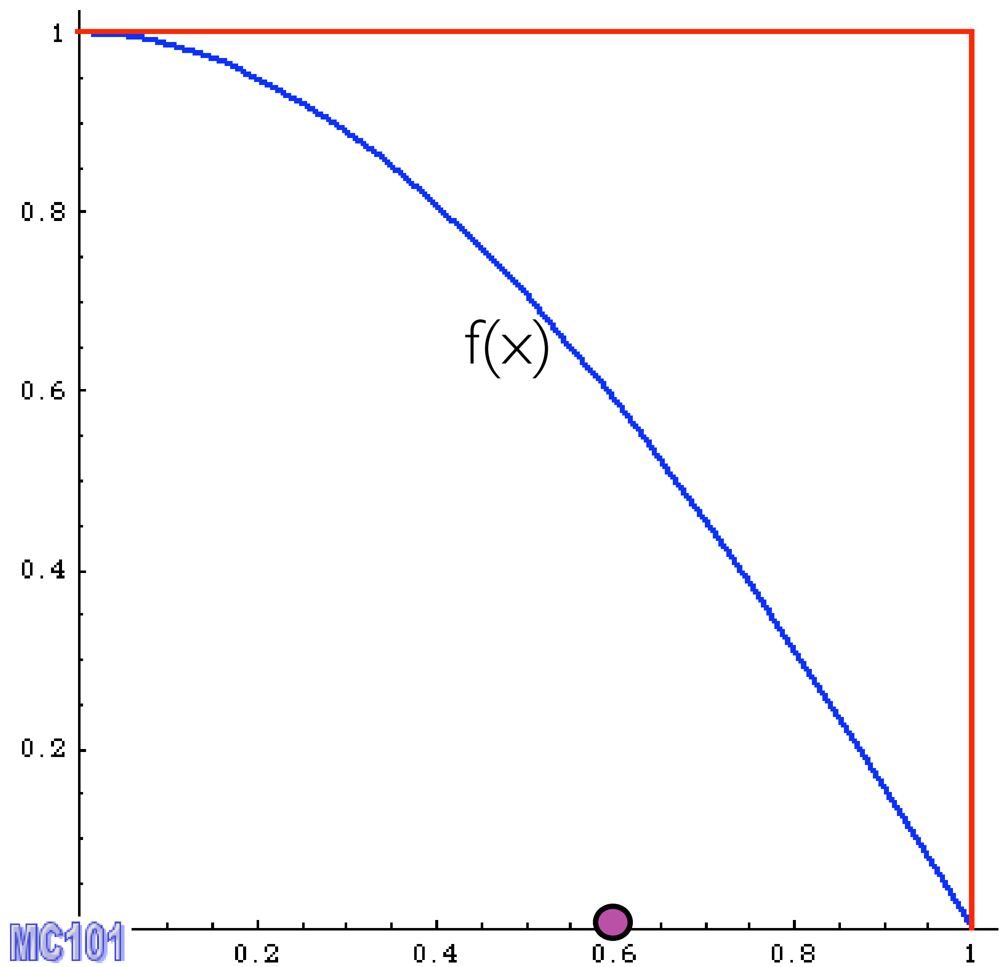
- Every phase-space point computed in this way, can be seen as an event (=collision) in a detector
- However, they still carry the "weight" of the matrix elements:
  - events with large weights where the cross section is large
  - events with small weights where the cross section is small
- In nature, the events don't carry a weight:
  - more events where the cross section is large
  - less events where the cross section is small
- How to go from weighted events to unweighted events?

Event generation



Alternative way

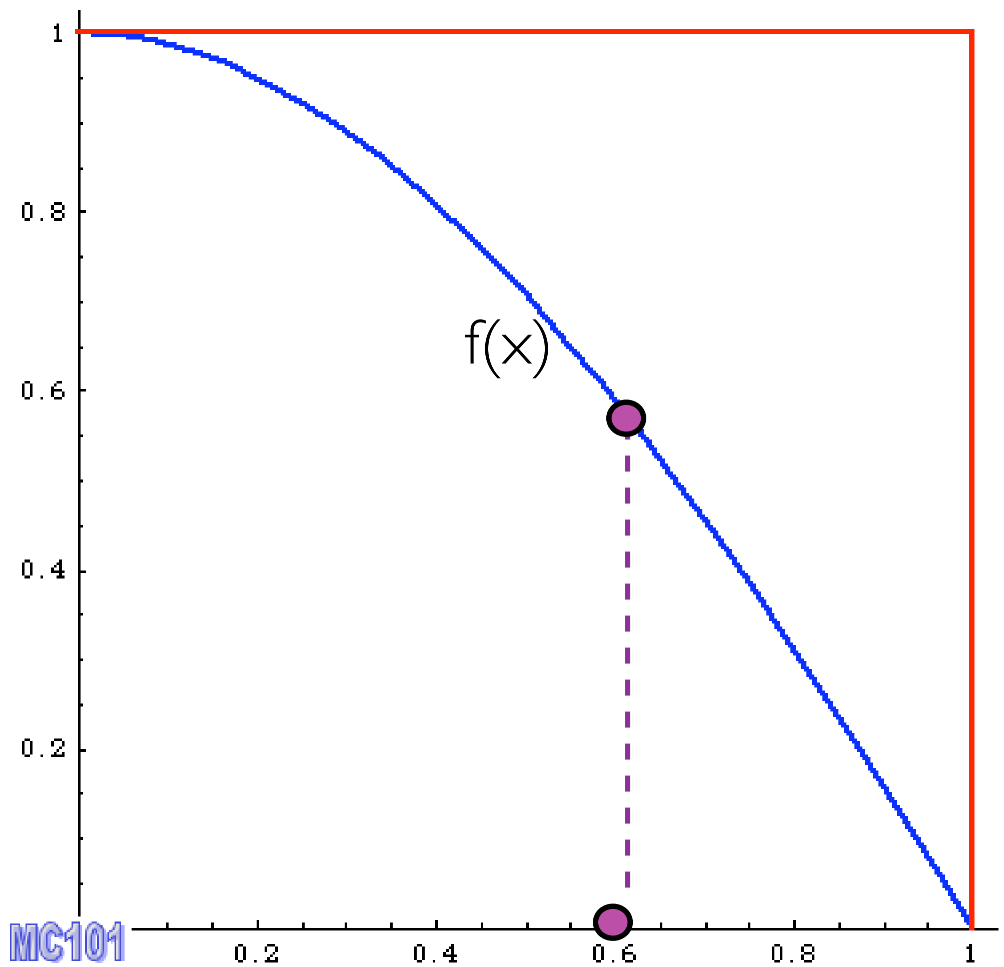
Event generation



Alternative way

1. (randomly) pick x

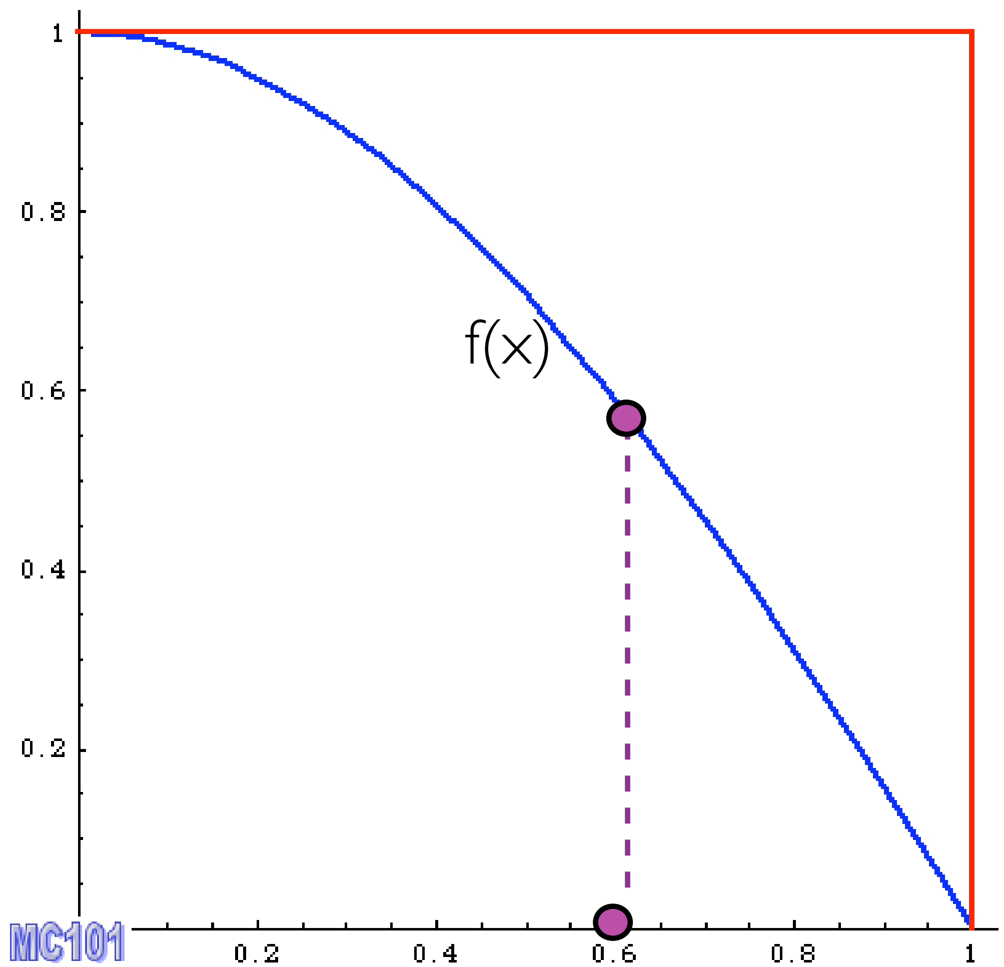
Event generation



Alternative way

1. (randomly) pick x
2. calculate f(x)

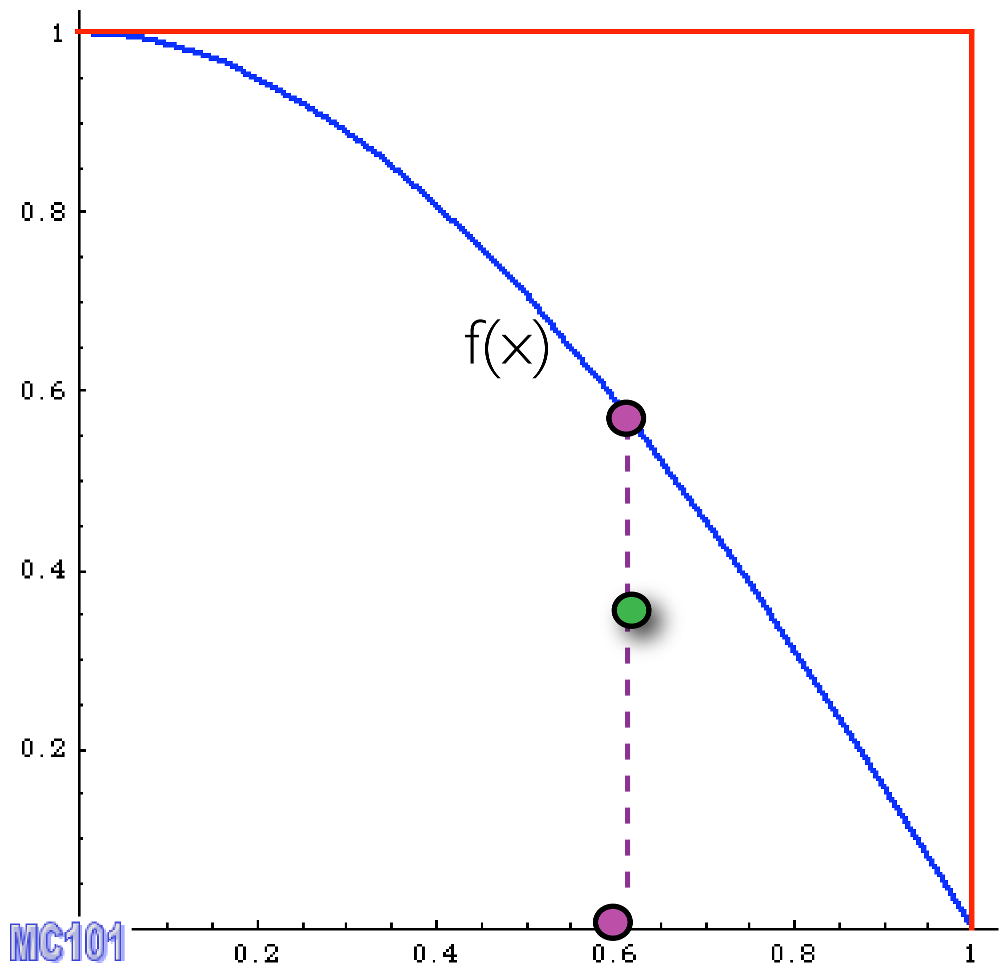
Event generation



Alternative way

1. (randomly) pick x
2. calculate f(x)
3. (randomly) pick 0<y<fmax

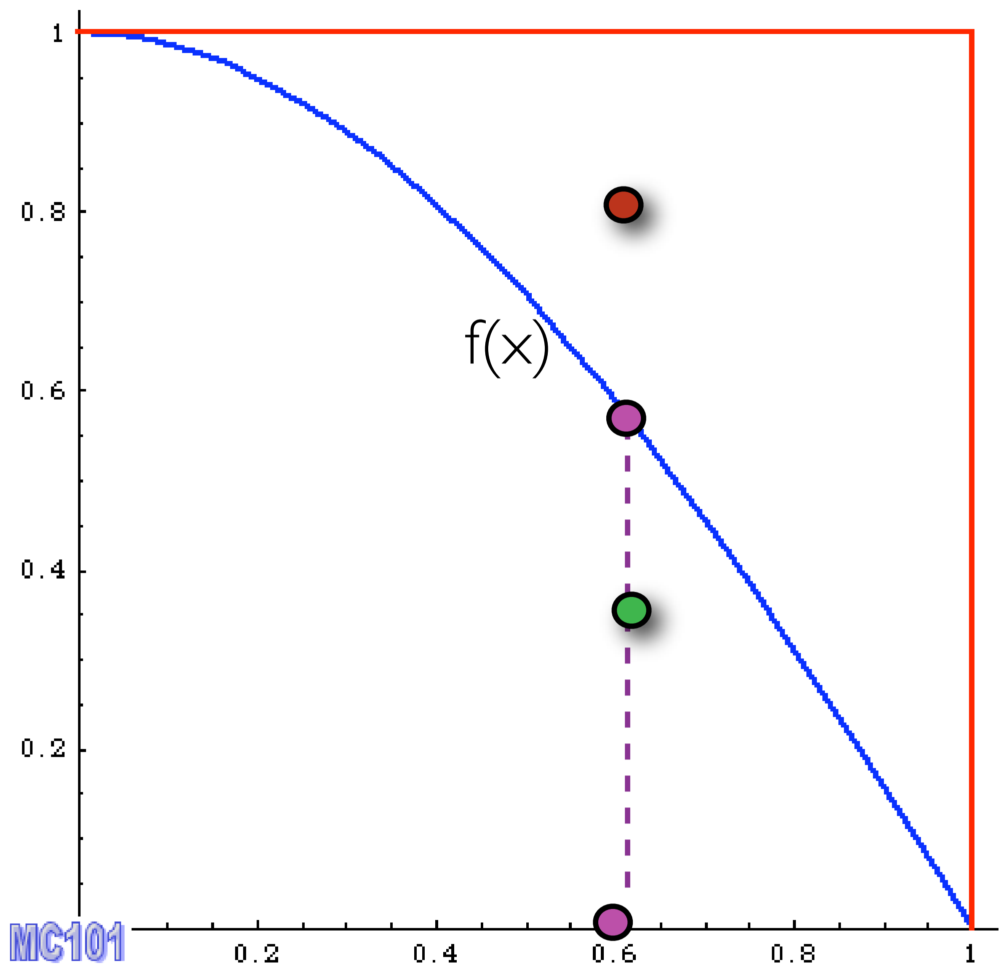
Event generation



Alternative way

1. (randomly) pick x
2. calculate f(x)
3. (randomly) pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

Event generation

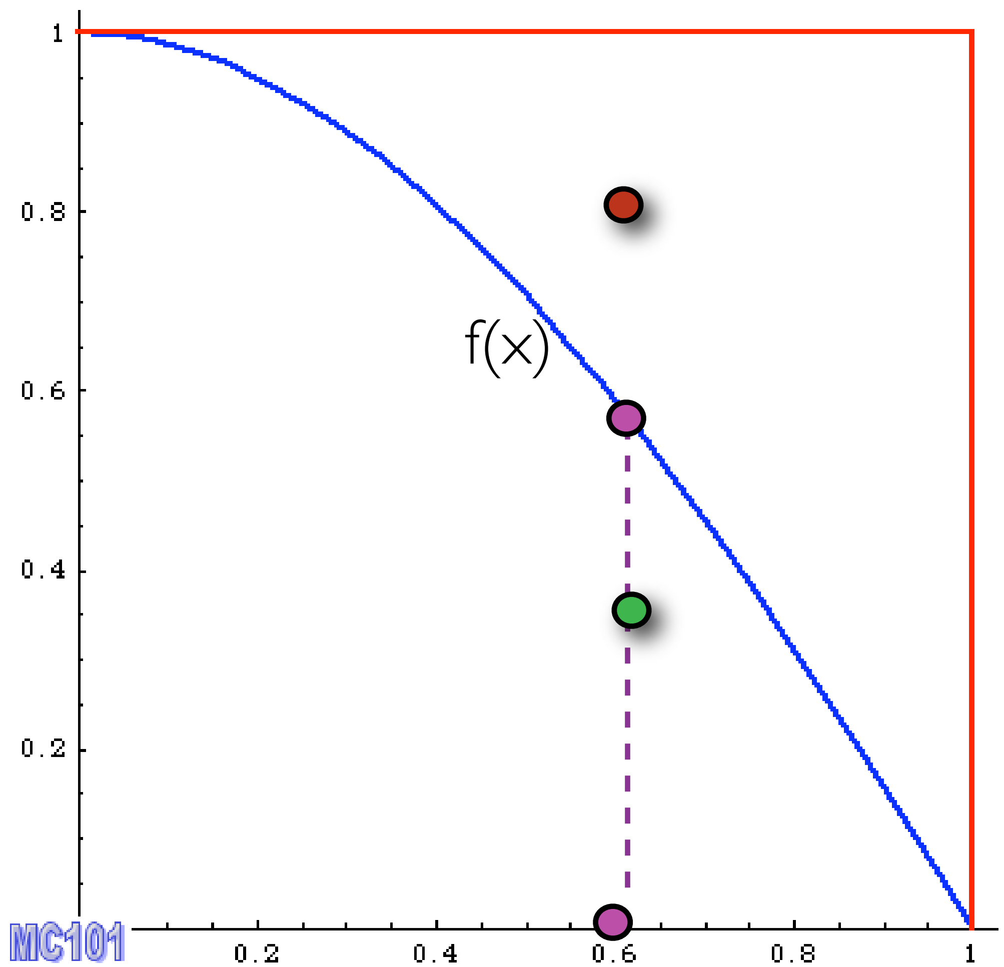


Alternative way

1. (randomly) pick x
2. calculate f(x)
3. (randomly) pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

   else reject it.

Event generation



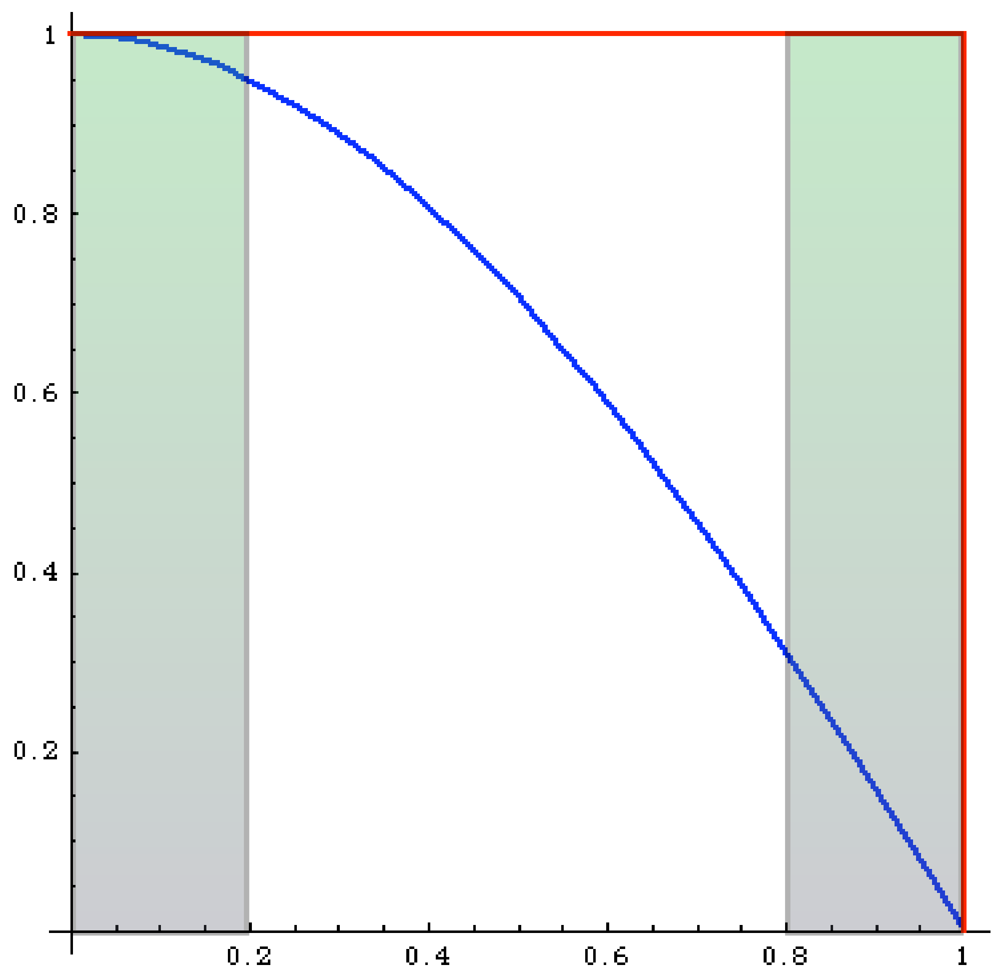
Alternative way

1. (randomly) pick x
2. calculate f(x)
3. (randomly) pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

   else reject it.

$$\text{Integral} = \frac{\text{accepted}}{\text{total tries}} = \text{efficiency}$$

Event generation



What's the difference?

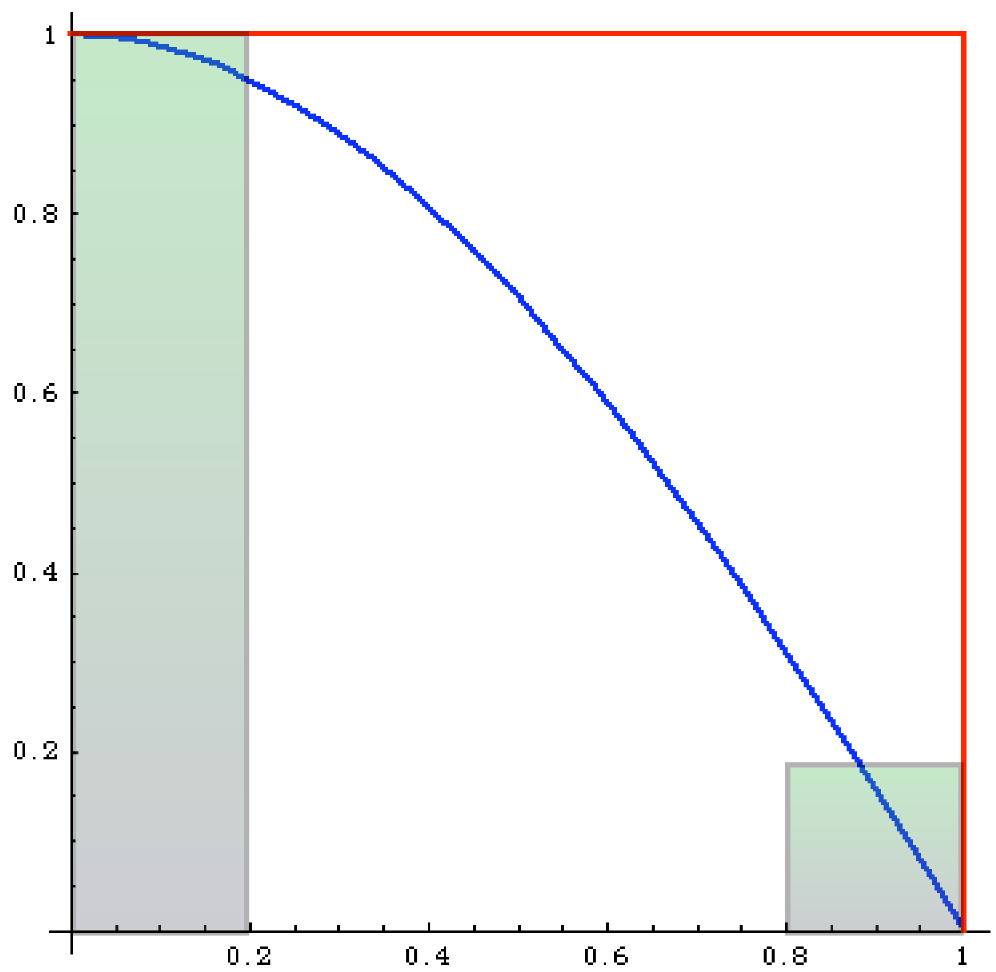
before:

Same # of events in areas of phase space with very different probabilities:

Events must have different weights:

$$w_i = p(x_i)$$

Event generation



What's the difference?

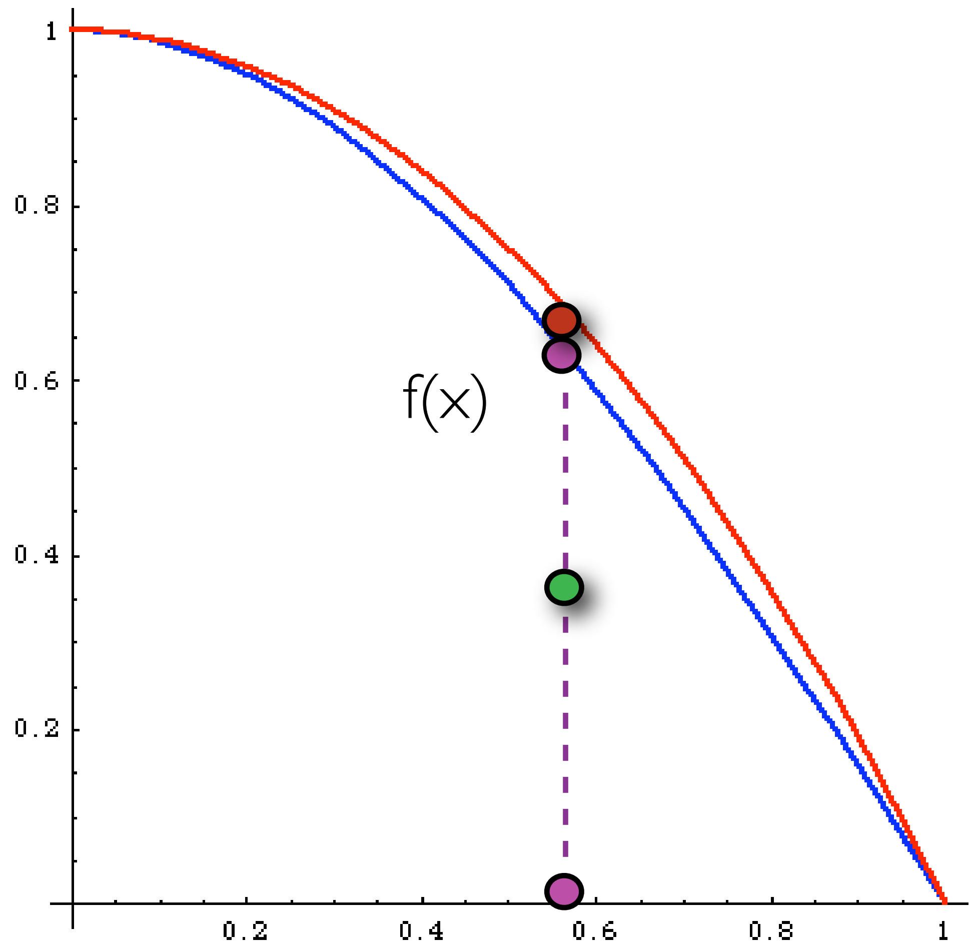
after:

events is proportional to the probability of areas of phase space:

Events have all the same weight ("unweighted")

Events distributed as in Nature

Event Generation



Improved

1. pick x distributed as p(x)
2. calculate f(x) and p(x)
3. pick 0<y<1
4. Compare:
   if f(x)>y p(x) accept event,

else reject it.

much better efficiency!!!

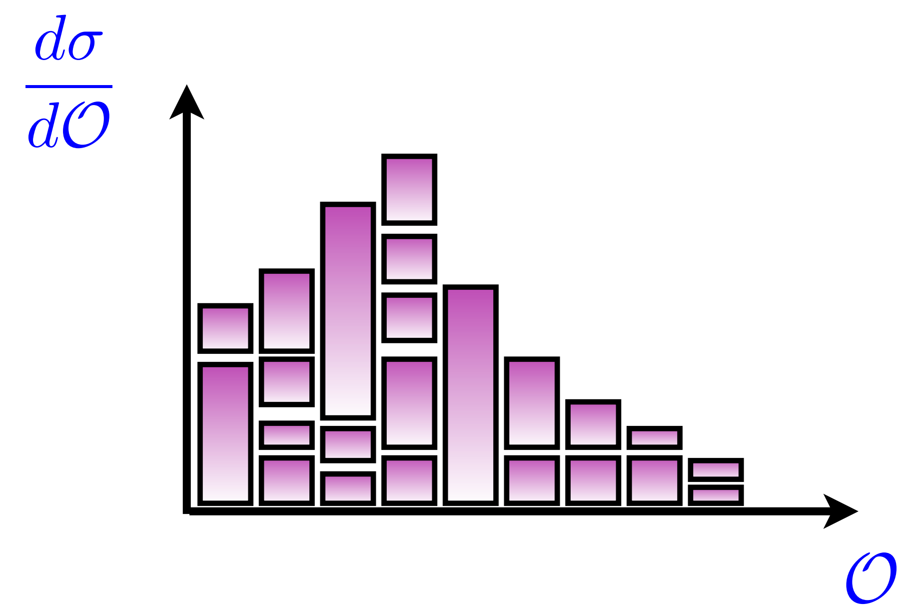
Event generation

Event generation

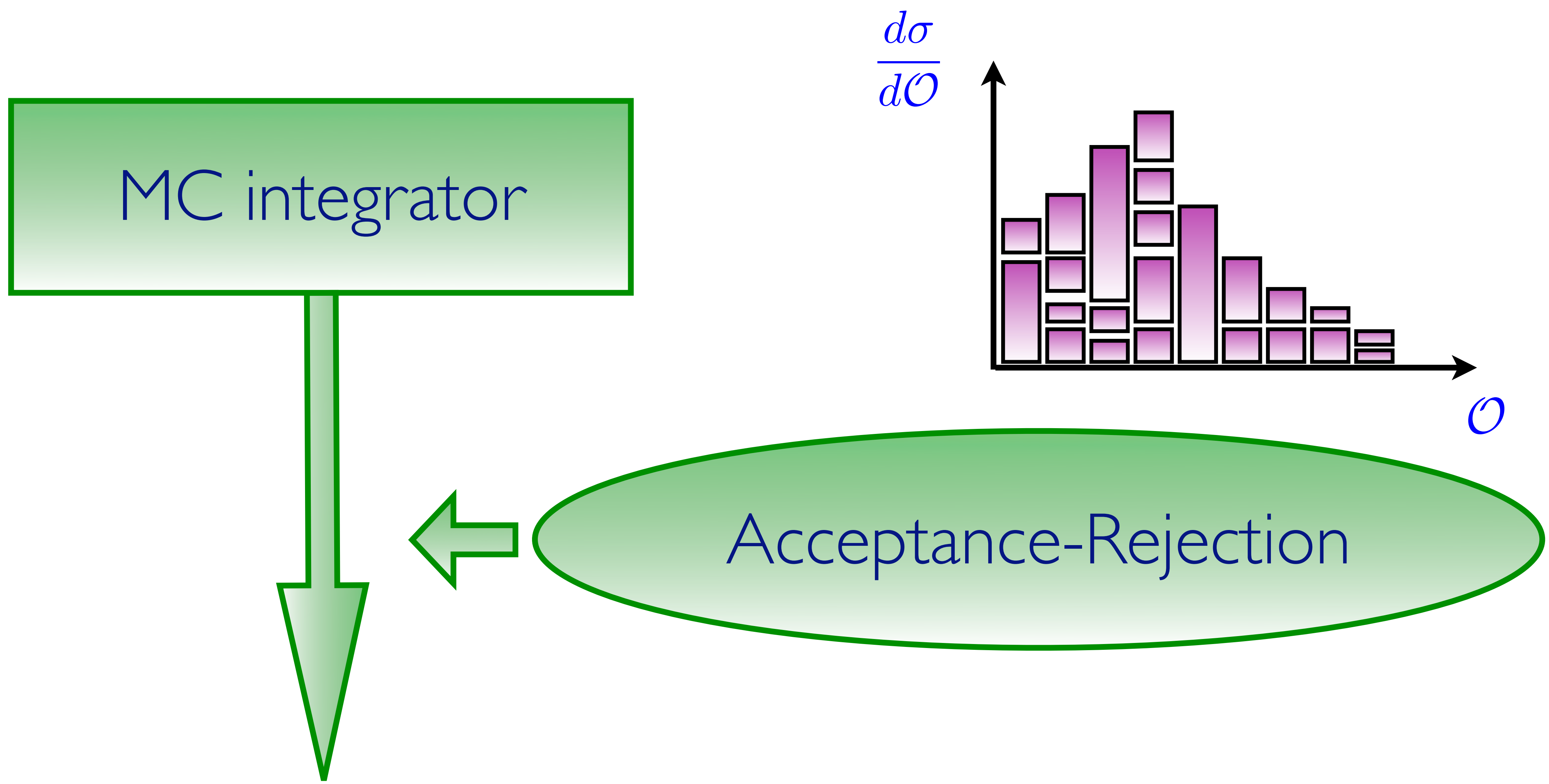
MC integrator

Event generation

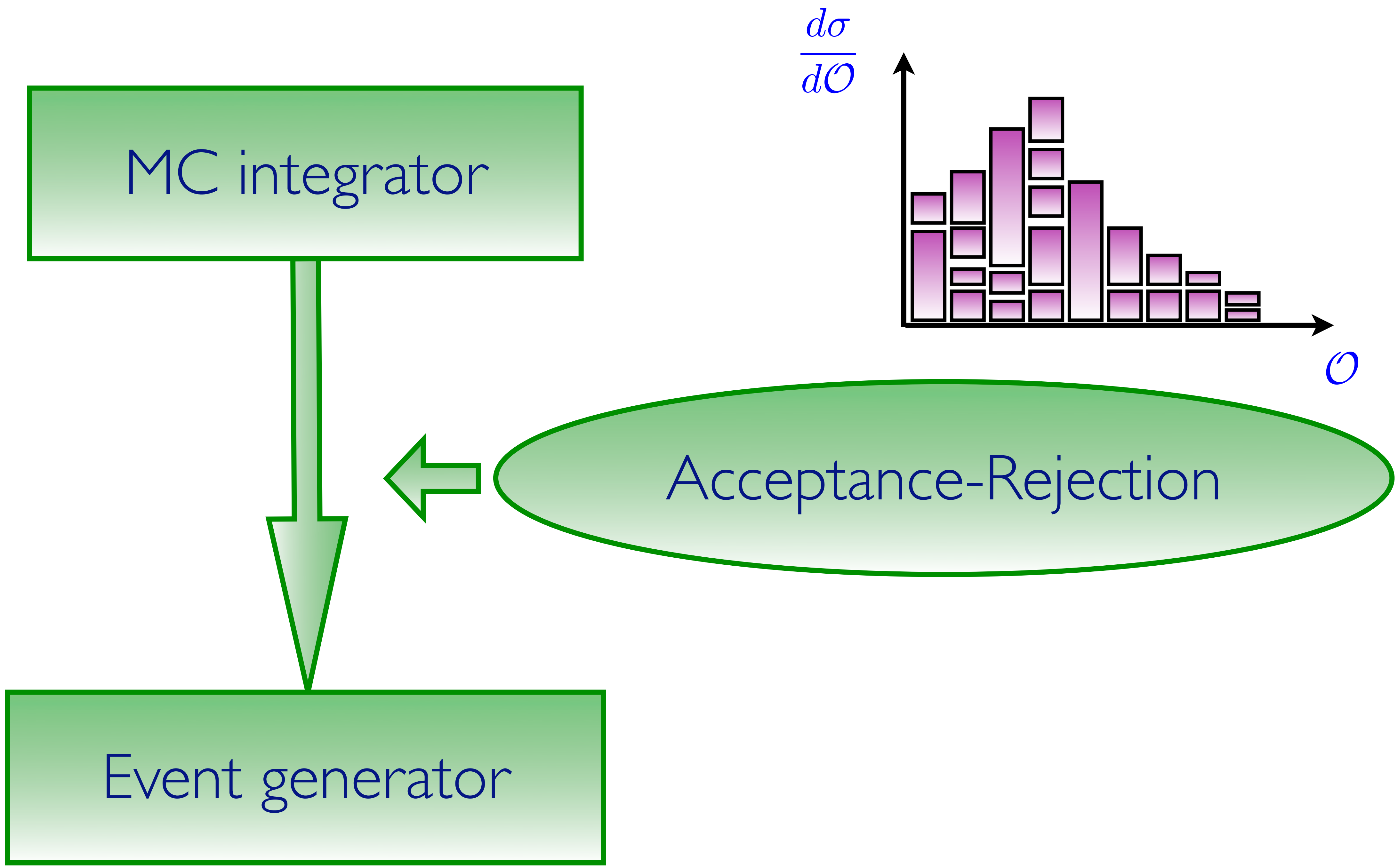
MC integrator



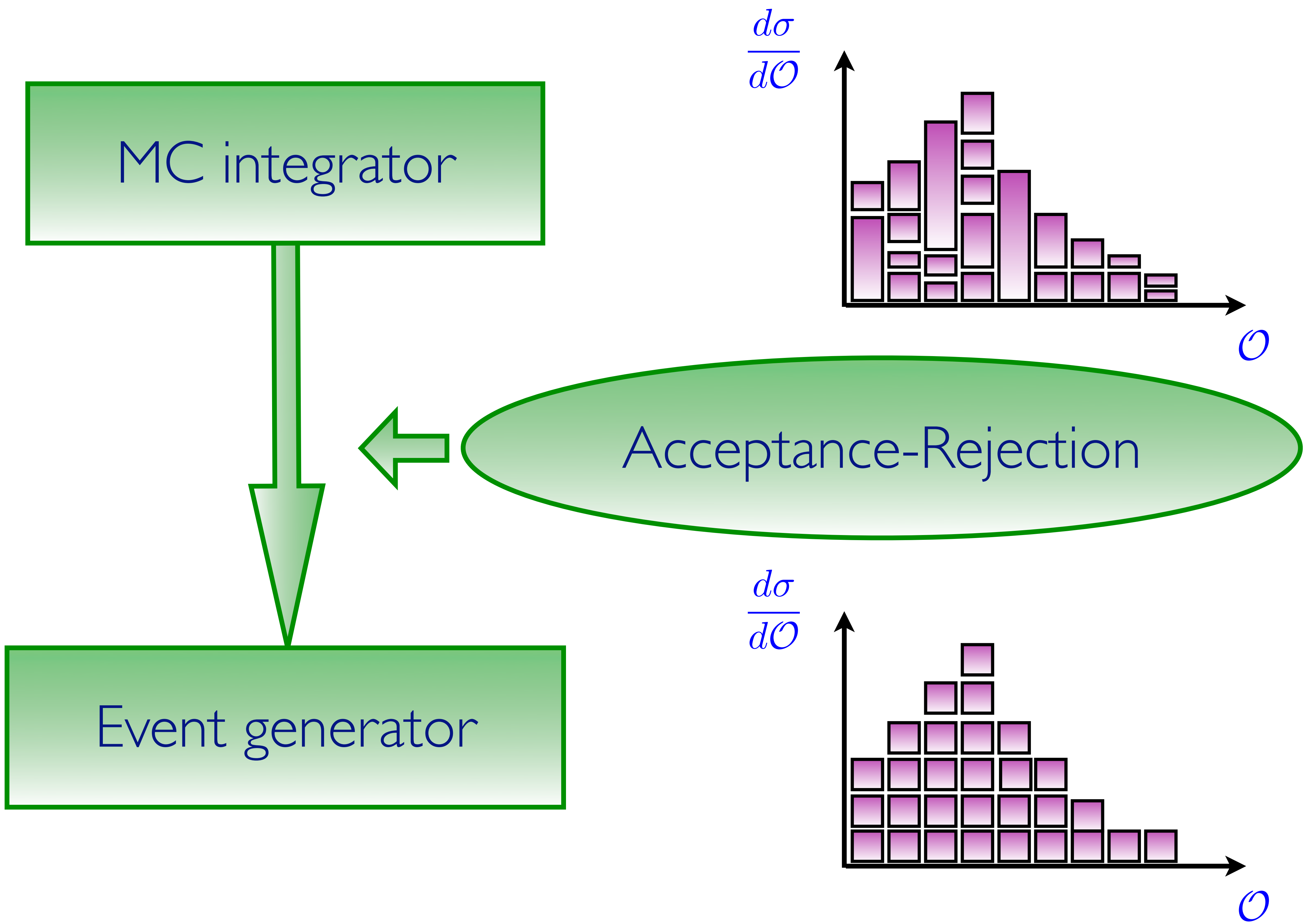
Event generation



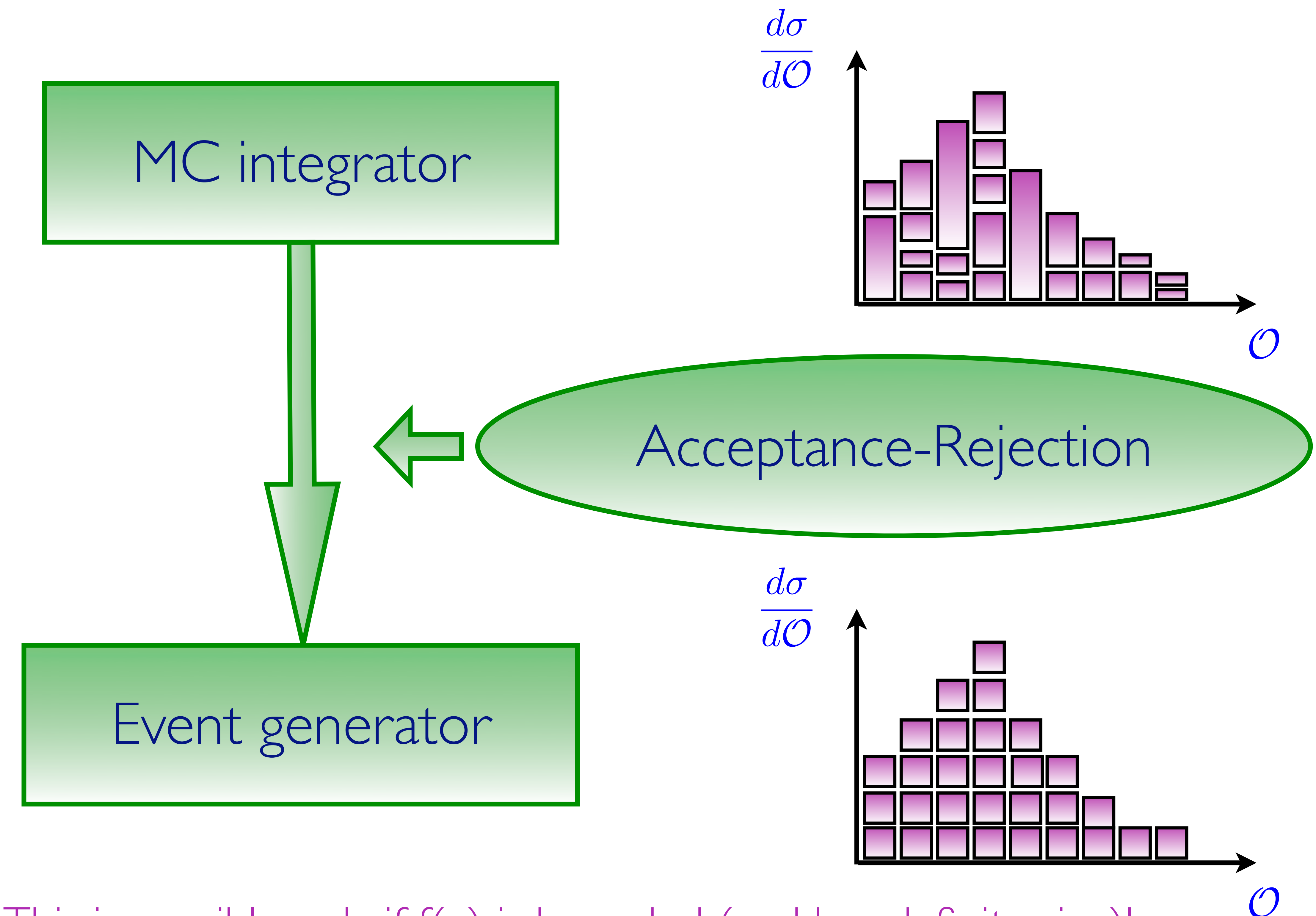
Event generation



Event generation



Event generation



☞ This is possible only if f(x) is bounded (and has definite sign)!

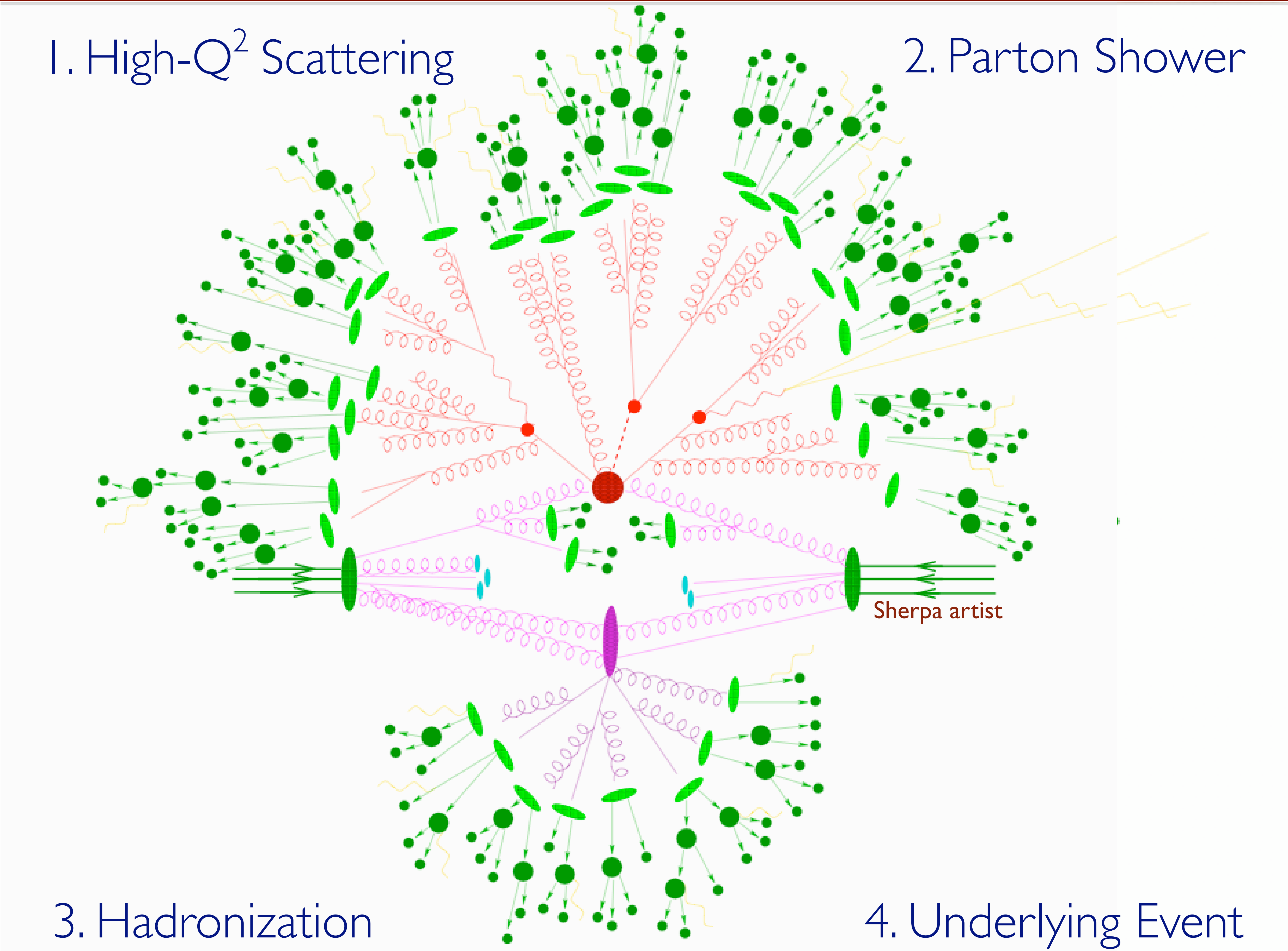
MC Event generator: definition

At the most basic level a Monte Carlo event generator is a program which produces particle physics events with the same probability as they occur in nature (virtual collider).

In practice it performs (a possibly large) number of (sometimes very difficult) integrals and then unweights to give the four momenta of the particles that interact with the detector (simulation).

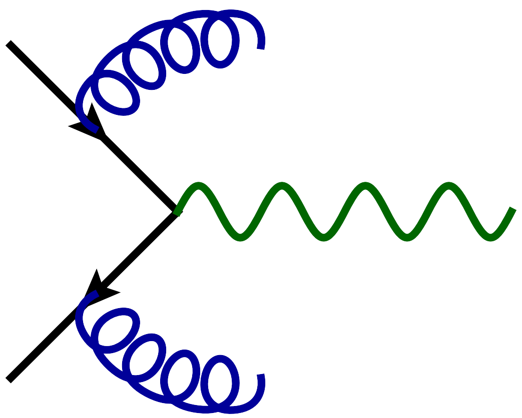
Note that, at least among theorists, the definition of a "Monte Carlo program" also includes codes which don't provide a fully exclusive information on the final state but only cross sections or distributions at the parton level, even when no unweighting can be performed (typically at NLO).

I will refer to these kind of codes as "MC integrators".

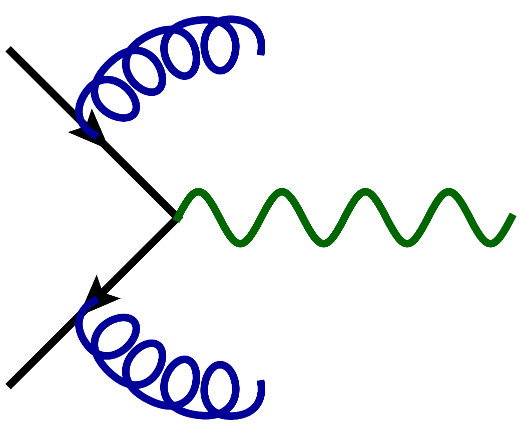

1. High-Q^2 Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event
Sherpa artist

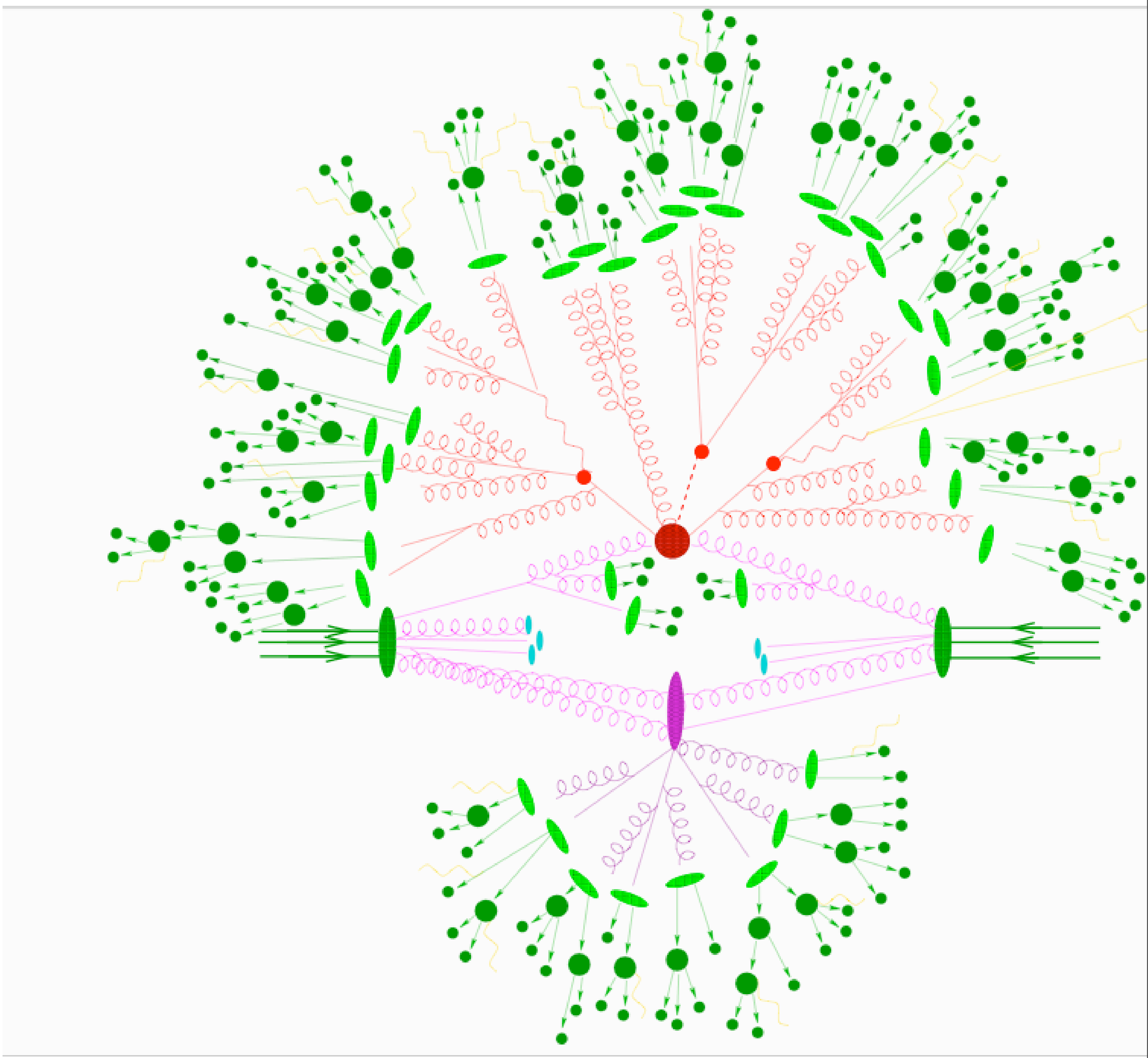
Limits of fixed-order predictions

Limits of fixed-order predictions

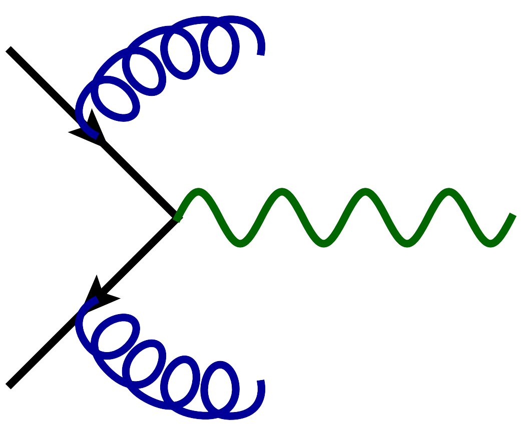


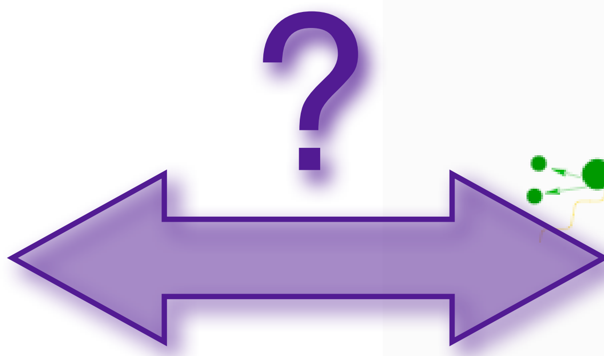
Limits of fixed-order predictions

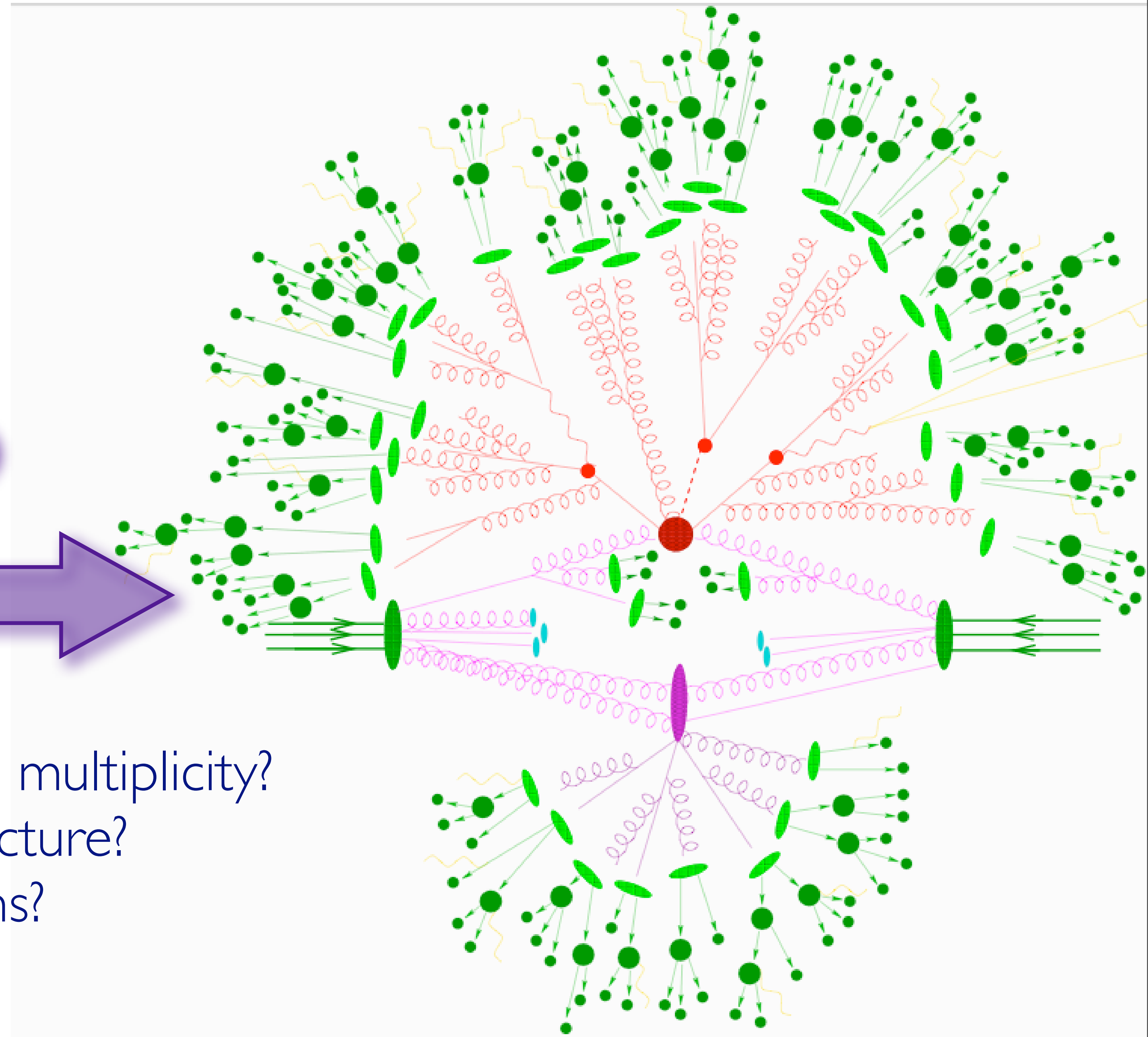




Limits of fixed-order predictions

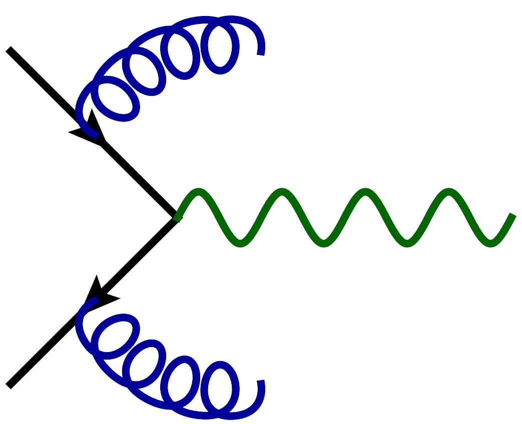


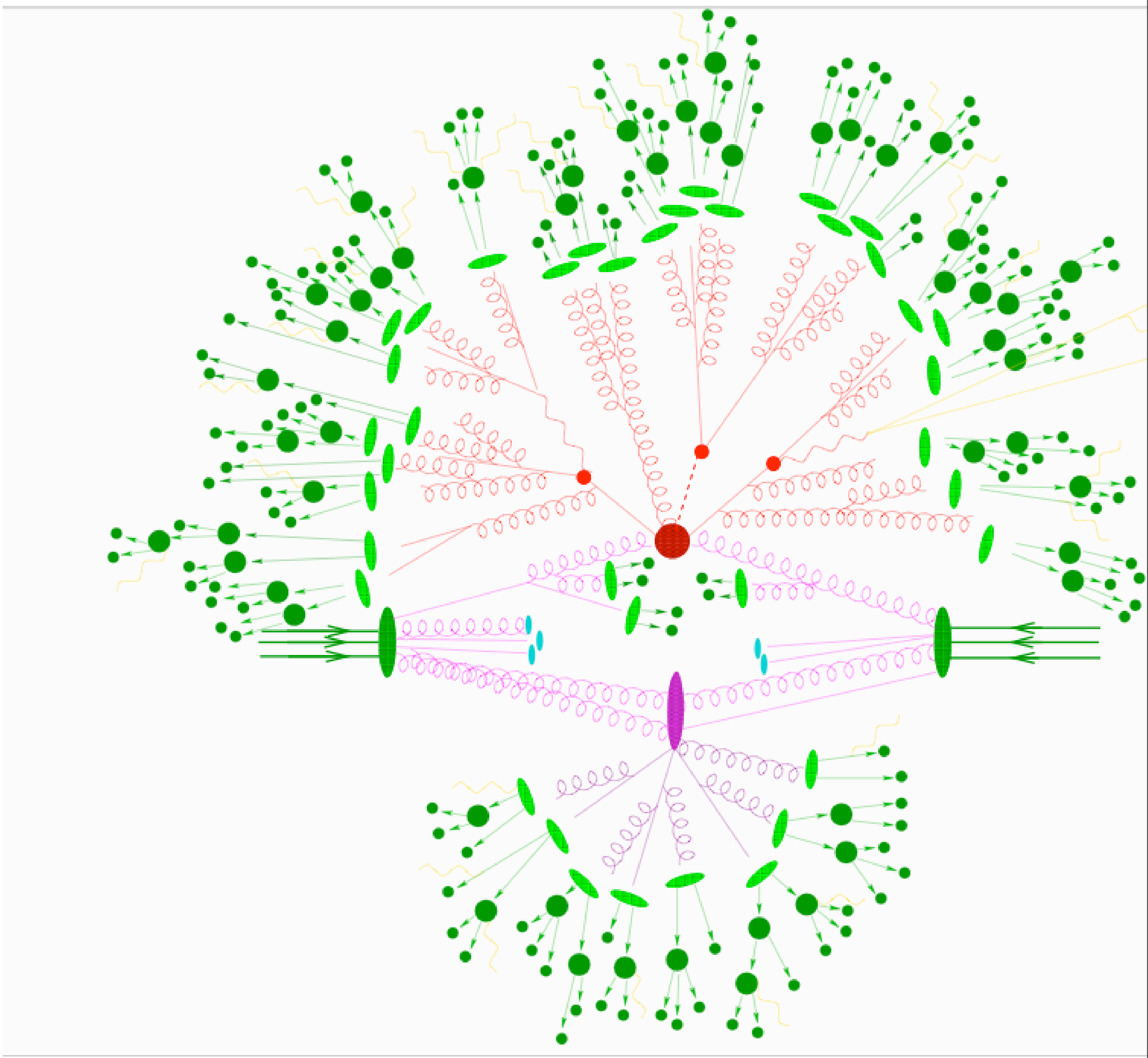




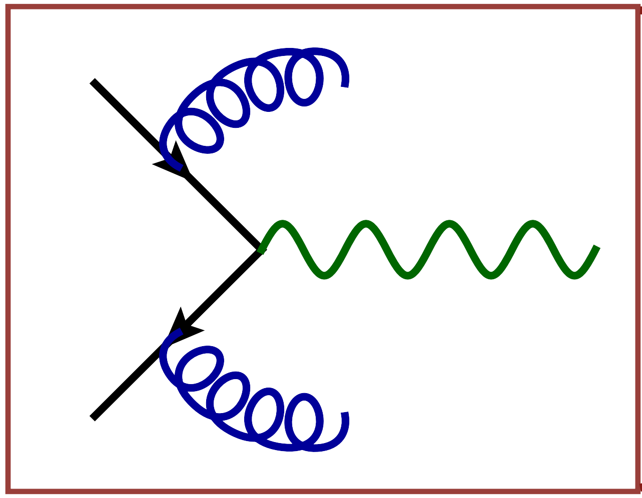
- Particle multiplicity?
- Jet structure?
- Hadrons?

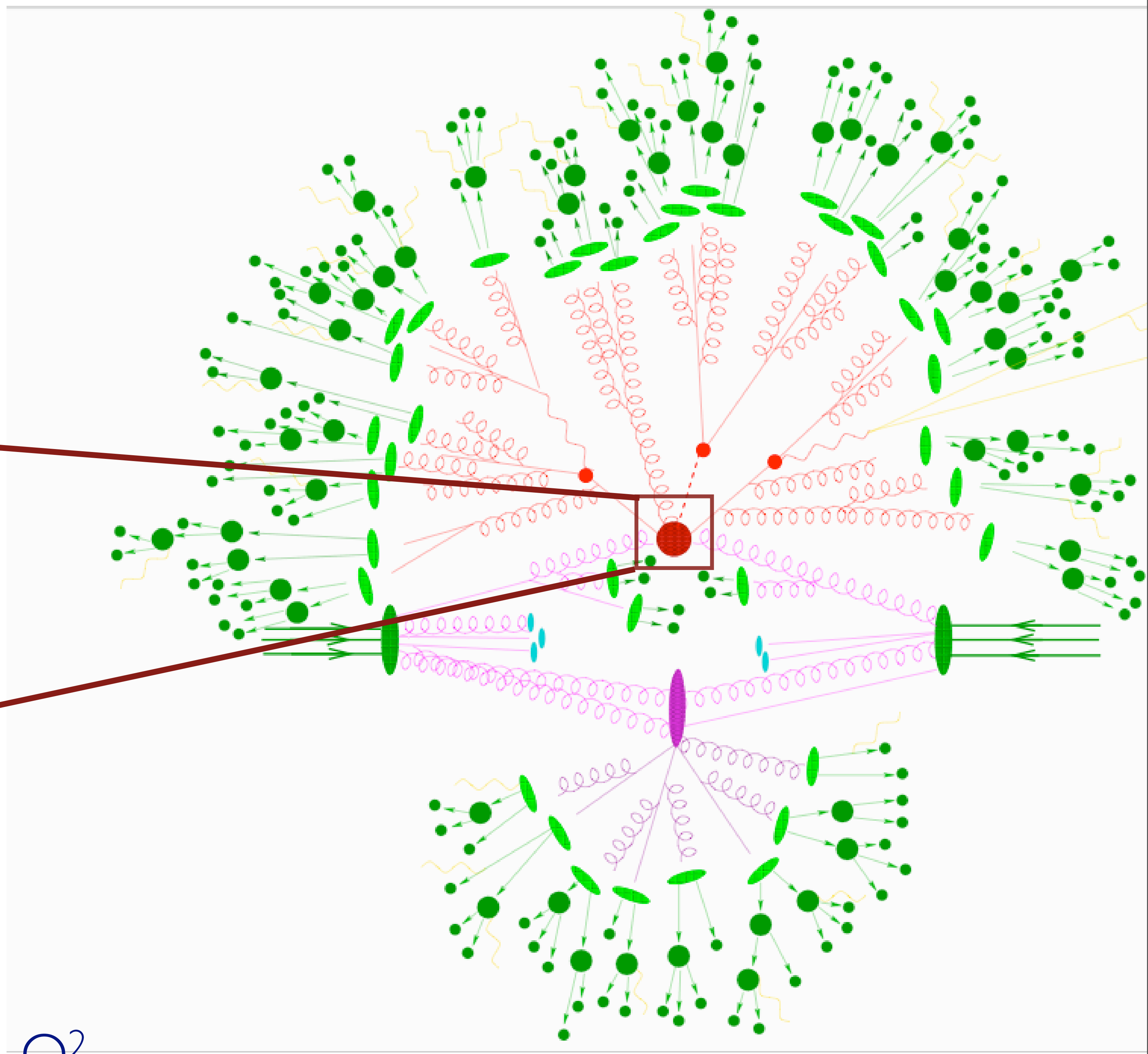
Limits of fixed-order predictions





Limits of fixed-order predictions





High Q^2

Summary

- Having accurate and flexible simulations tools available for the LHC is a necessity (even more now!!)
- At LO event generation is technically challenging, yet conceptually straightforward.

Credits

To organize this presentation I have benefited from lectures (and actual slides), talks and discussions with many people.
In particular:

- Mike Seymour (MC basics)
- Claude Duhr (FeynRules)
- Johan Alwall (ME+PS merging)
- Rikkert Frederix, Paolo Torrielli (NLO+PS)
- Stefano Frixione, Michelangelo Mangano, Paolo Nason (for QCD, PS, LO, NLO, and more...)
- ....

Whom I all warmly thank!!