Event Generation with MadGraph 5

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with Olivier Mattelaer

Lectures and exercises found at
https://server06.fynu.ucl.ac.be/projects/madgraph/wiki/SchoolKias

Special thanks to Fabio Maltoni from whom I have shamelessly borrowed several of the following slides

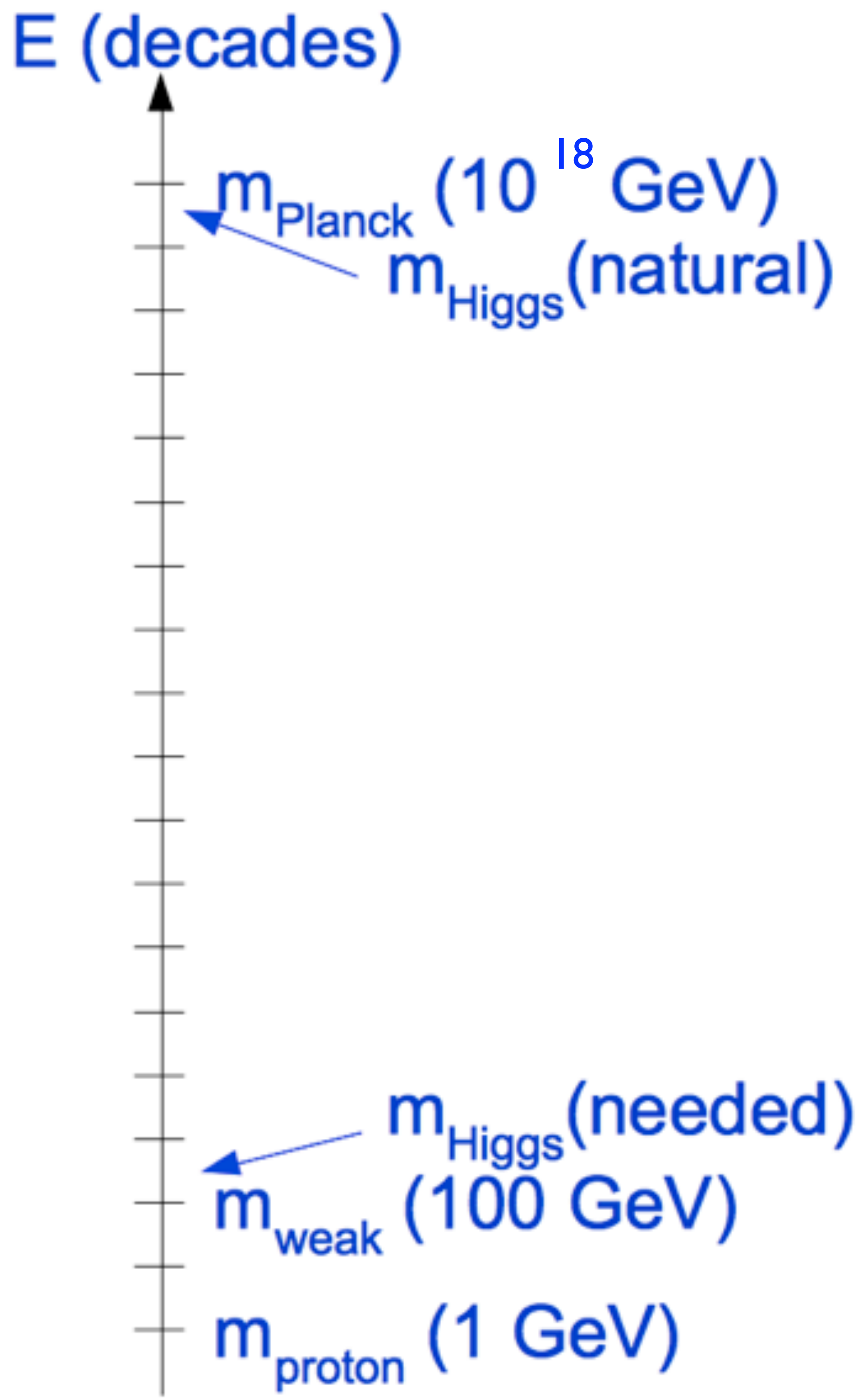
Outline of lectures

- Lecture I:
  - ➡ New Physics at hadron colliders
  - ➡ QCD basics
  - ➡ Monte Carlo integration and generation
- Lecture II:
  - ➡ Complete collider event simulation
  - ➡ Parton showering and jet matching (teaser)
  - ➡ Event simulation in practice using MadGraph
- Lecture III (by Olivier Mattelaer):
  - ➡ What is MadGraph 5?
  - ➡ Implementing new physics models in MadGraph (teaser)

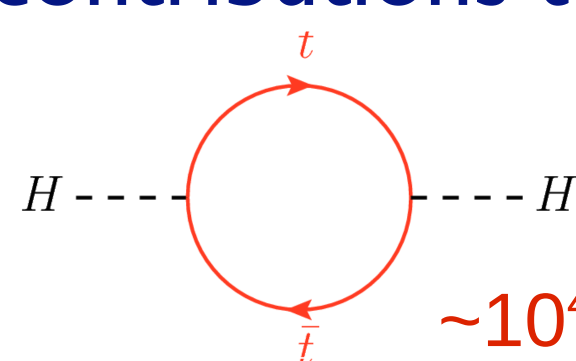
Aims for these lectures

- Get you acquainted with the concepts and techniques used in event generation
- Give you hands-on experience with matrix element generation, event generation and analysis using MadGraph
- Answer as many of your questions as I can (so please ask questions!)

Why the LHC?



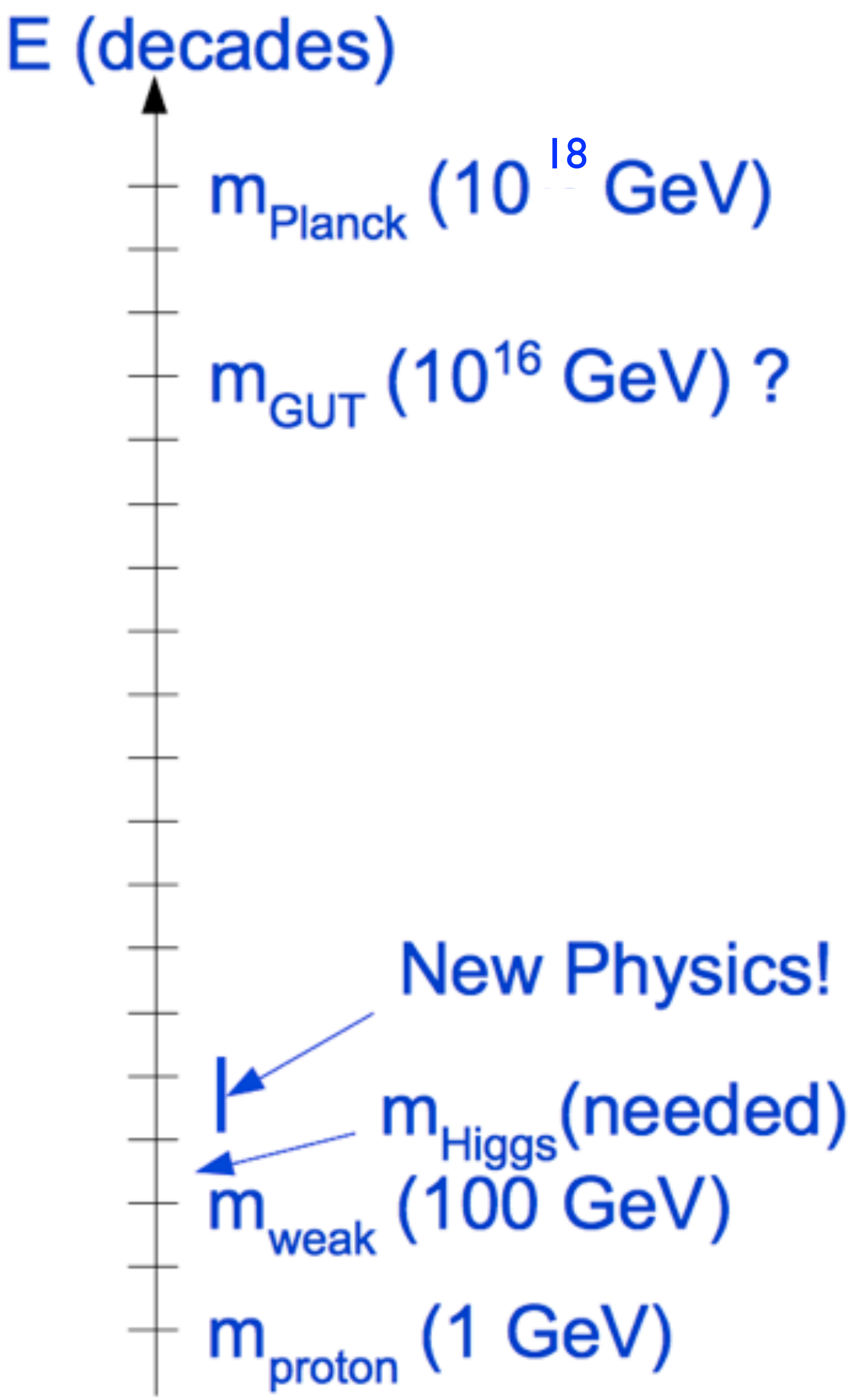
- Higgs boson mass "naturally" at mass of new physics
  (only known "NP scale": Planck scale at ~10^{18} GeV)
- Standard Model only "works" if Higgs mass below ~800 GeV
- New Physics scale communicated through quantum loop contributions to Higgs mass



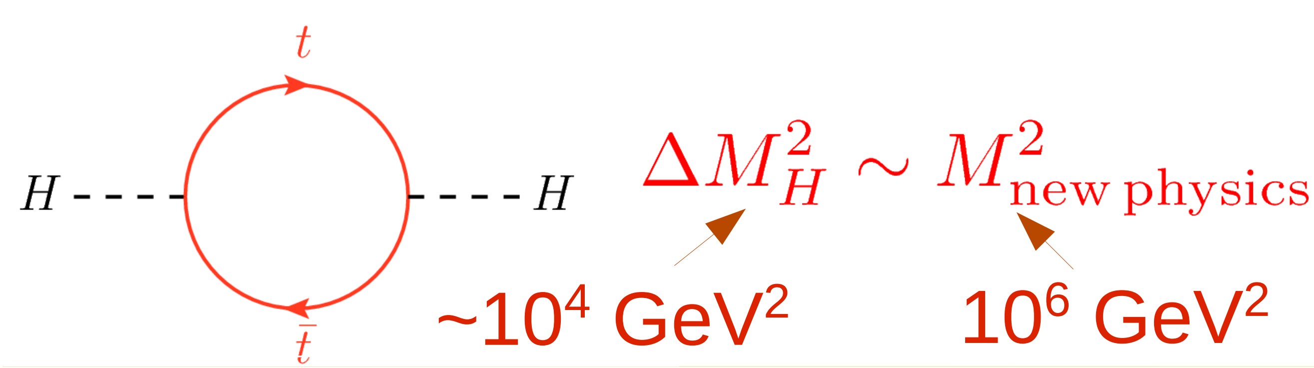
$$\Delta M_H^2 \sim M^2_{\text{new physics}}$$

~10^4 GeV^2 M_{Pl}^2~10^{36} GeV^2

Why the LHC?



- ΔM_H contribution must be canceled by bare mass term. For fine-tuning less than 1%, need new physics which cuts off the quadratic loops at ~1 TeV



Why the LHC?

The Hierarchy problem, together with Dark Matter (and to some extent Grand Unification) have been driving New Physics model building in past 30 years

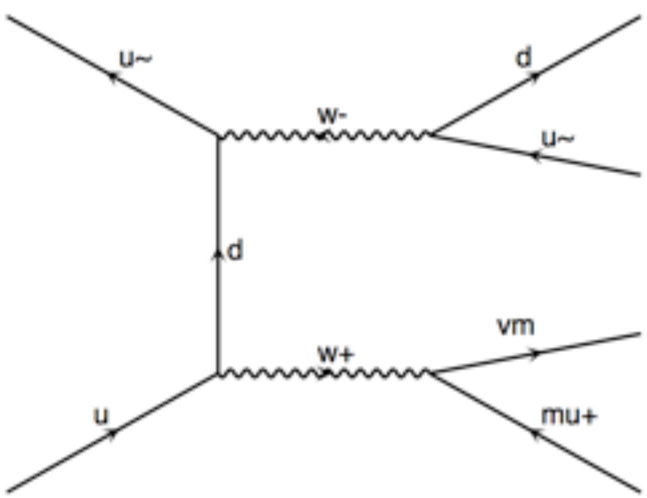
- ➡ Supersymmetry
- ➡ Large Extra Dimensions
- ➡ Randall-Sundrum (warped extra dimensions)
- ➡ Little Higgs theories
- ➡ ... (mostly variants/combinations)

But of course, we might also find something completely unexpected!

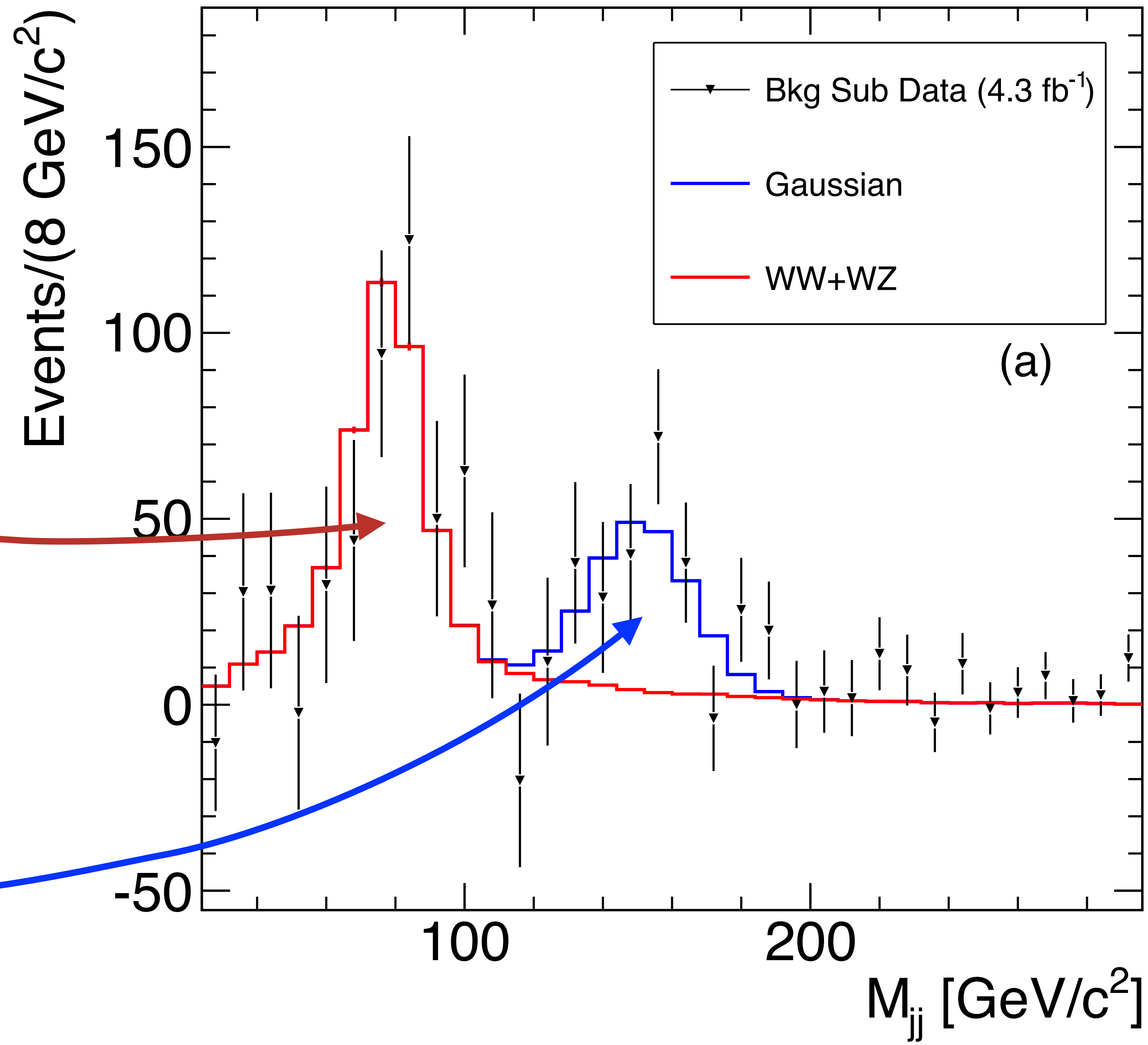
New Physics at hadron colliders

- The LHC has taken over from the Tevatron!
- Significant luminocities
  - ➡ Tevatron collected >10 fb^{-1} in the last 10 years
  - ➡ Fantastic legacy, including several interesting excesses!
  - ➡ LHC already has a spectacular 5 fb^{-1}!
    (perhaps as much as 20 fb^{-1} by end of 2012!)
  - ➡ Allows ever-more stringent tests of the SM!
- How interpret excesses? How determine Standard Model backgrounds?
  - ➡ Monte Carlo simulation!
    (combined with data-driven methods)

Example: CDF excess in W + 2 jets



CDF collaboration, arXiv:1104.0699



WW, WZ

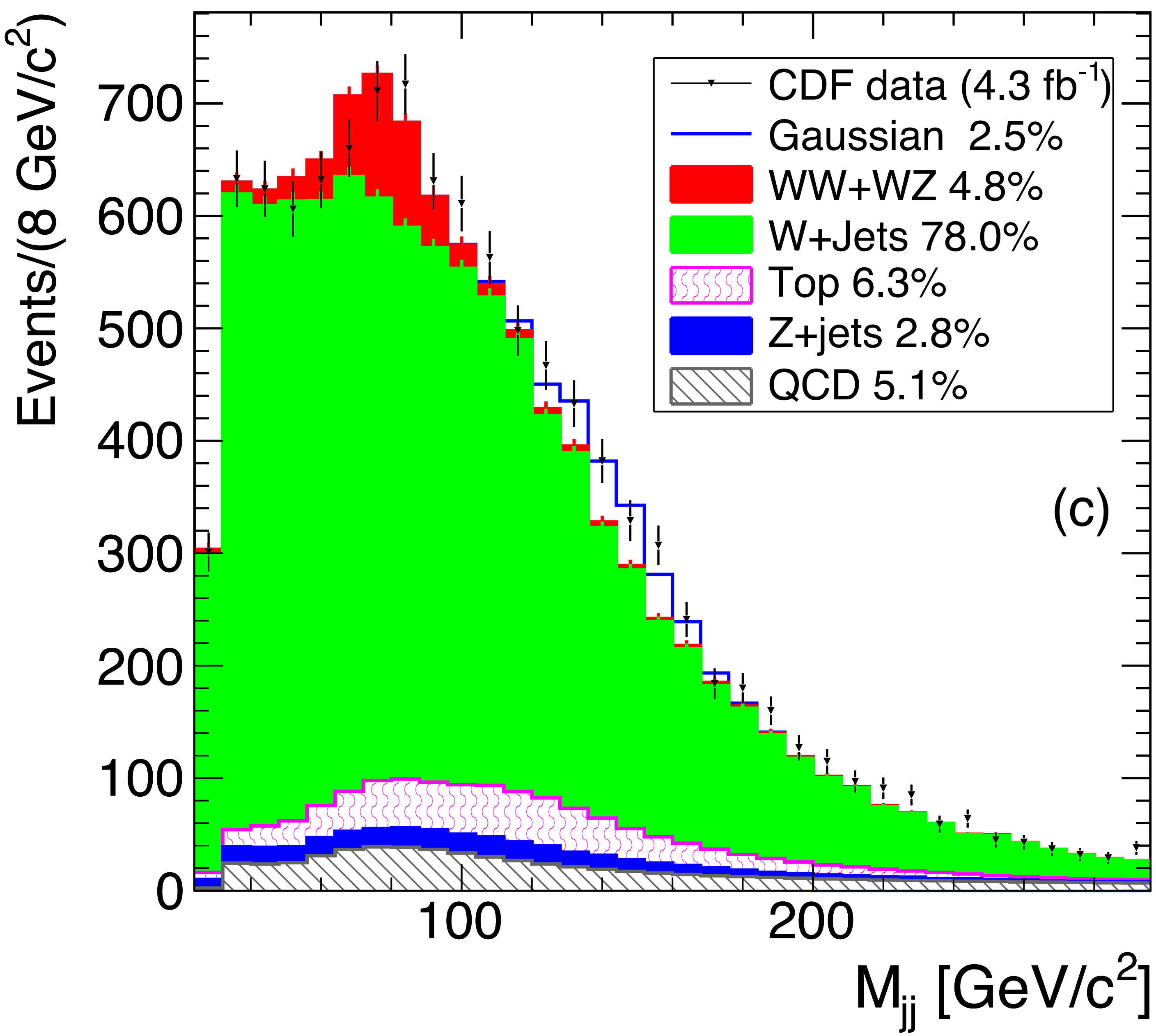
W + Nobody knows what?

Background subtracted data (except WW/WZ)

Example: CDF excess in W + 2 jets

A more complete picture

CDF collaboration, arXiv:1104.0699



Example: CDF excess in W + 2 jets

A more complete picture

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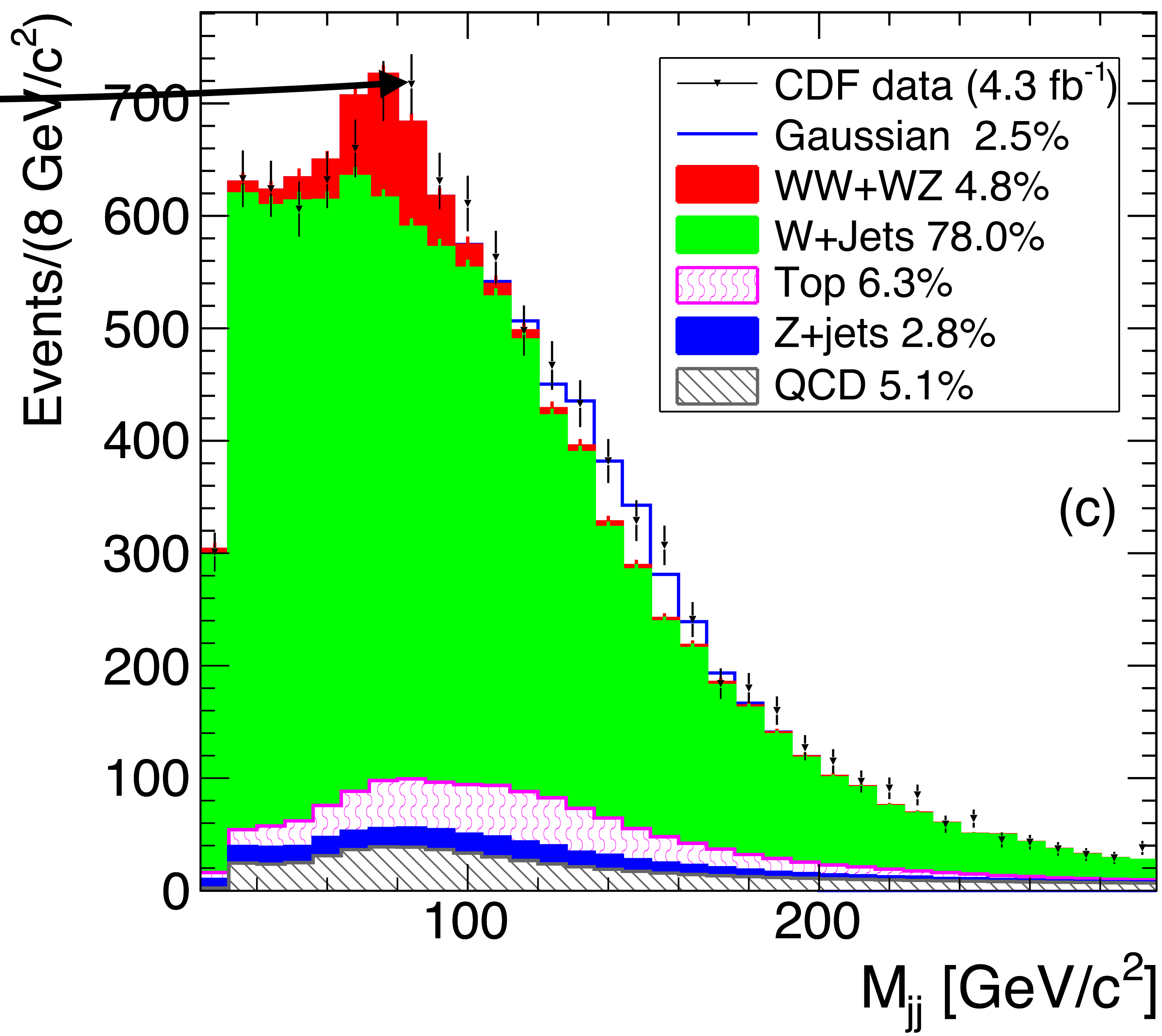
CDF data



Example: CDF excess in W + 2 jets

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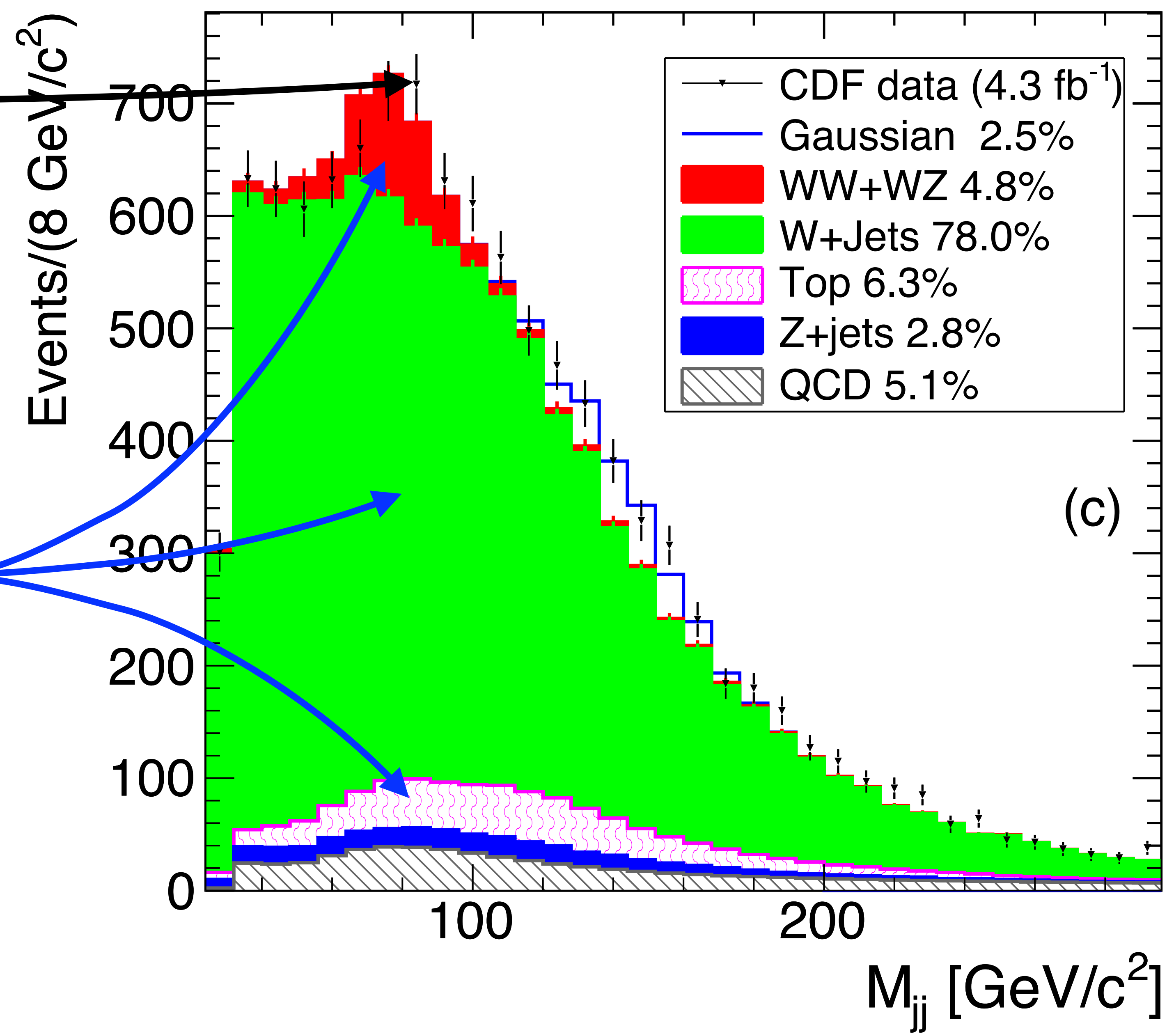
CDF data



Standard Model backgrounds (shape from simulation)

Example: CDF excess in W + 2 jets

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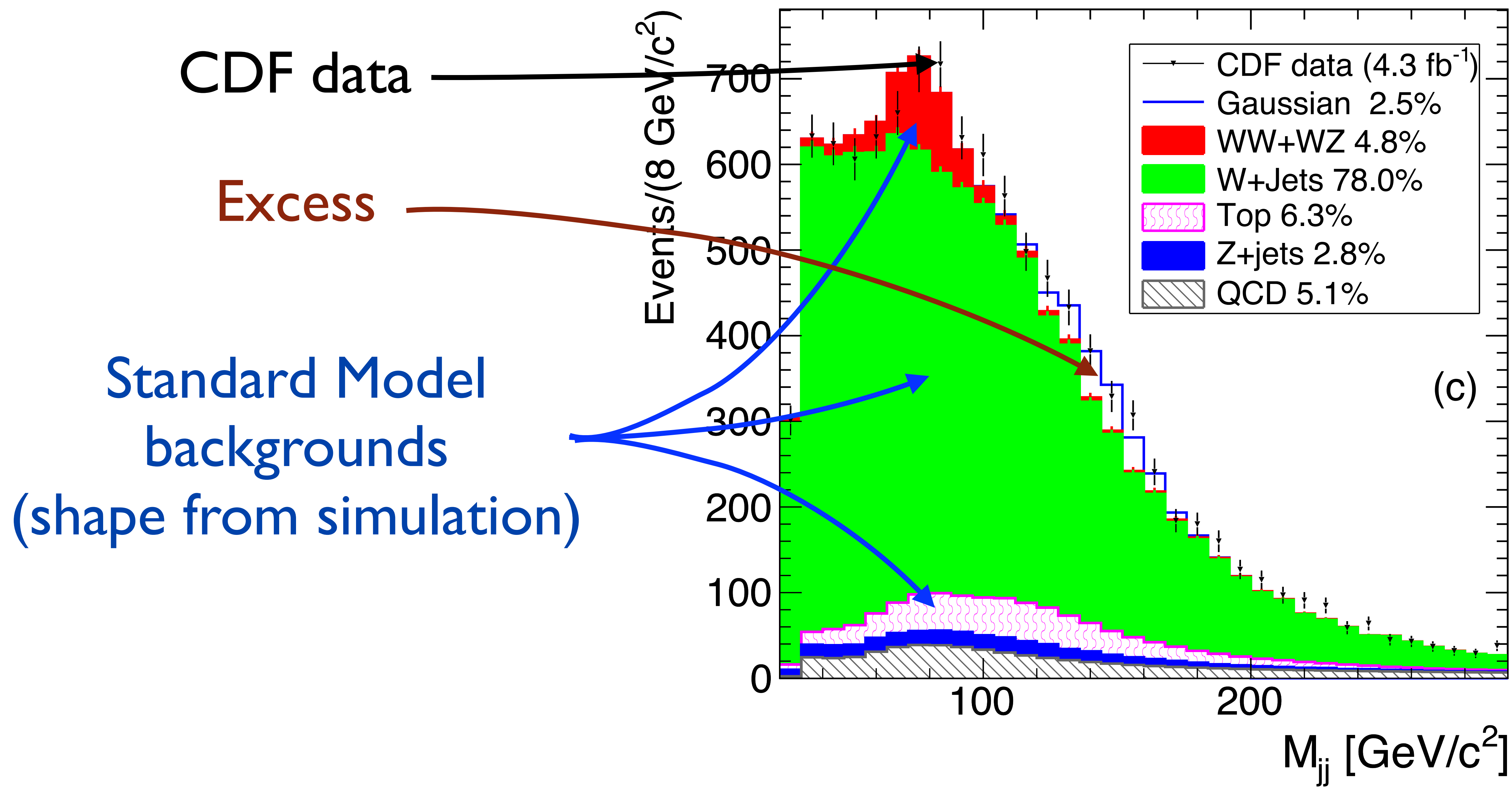

Example: CDF excess in W + 2 jets

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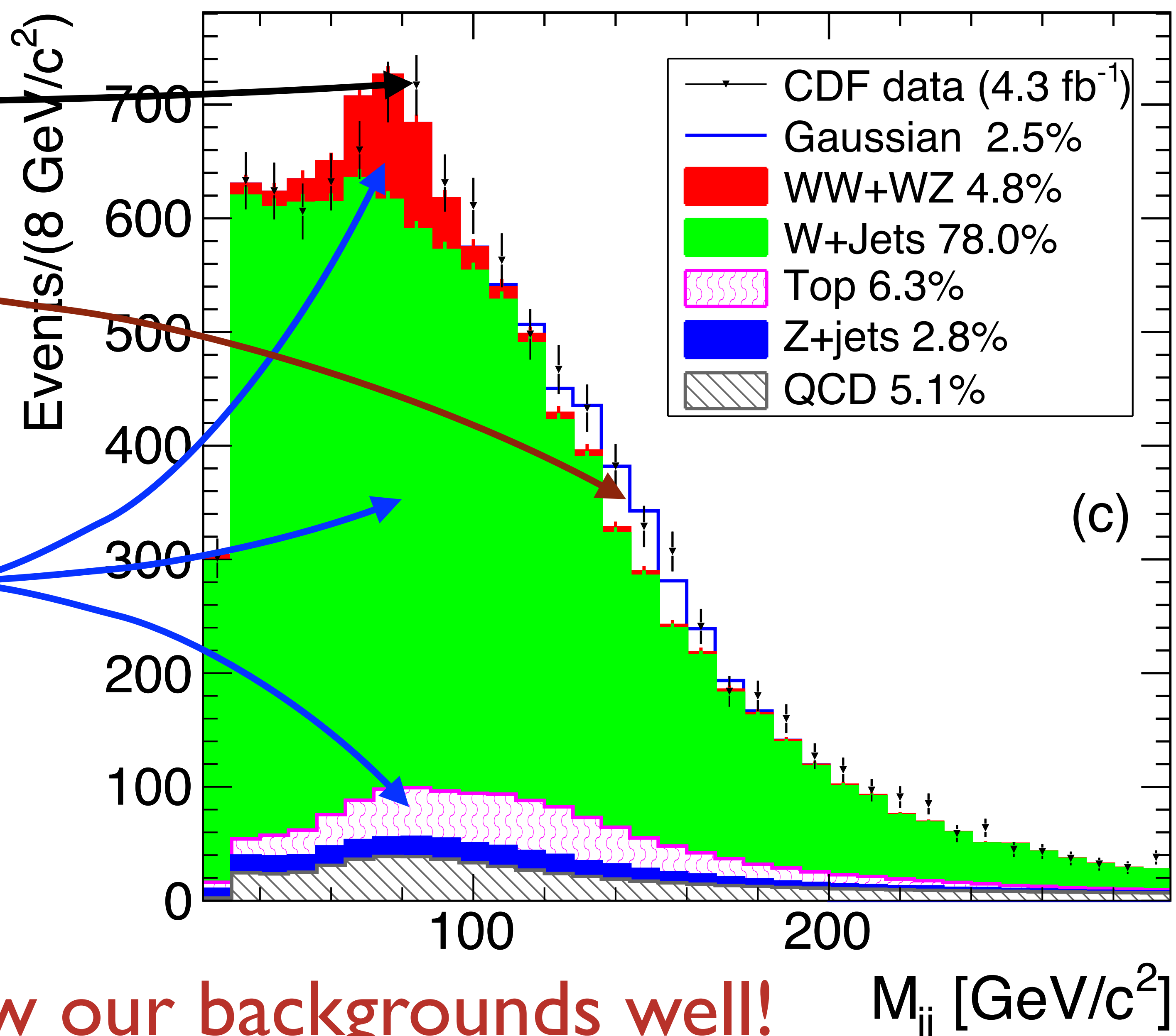
CDF collaboration, arXiv:1104.0699

CDF data

Excess

Standard Model backgrounds (shape from simulation)



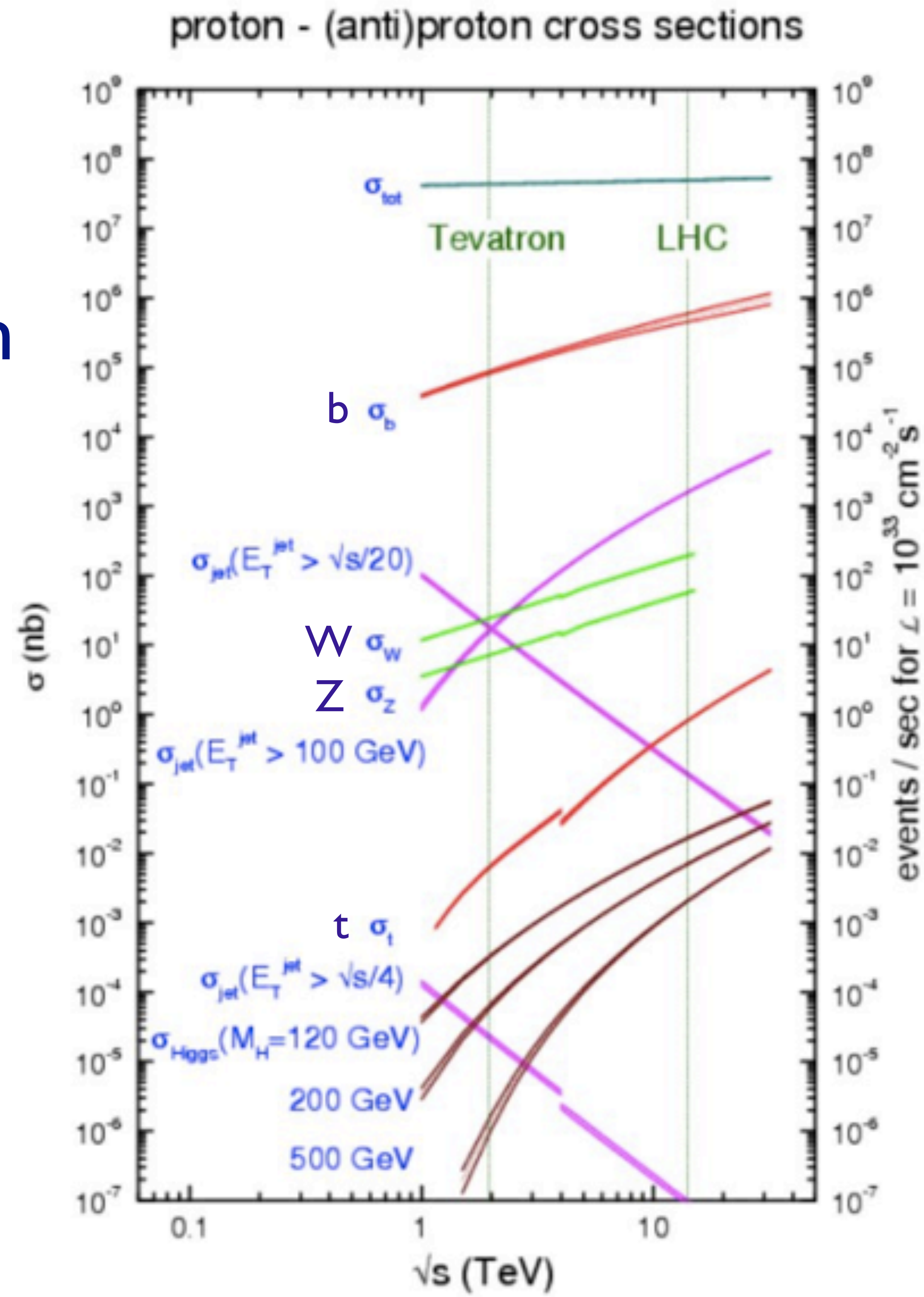
We certainly need to know our backgrounds well!

Processes at Hadron Colliders

First: Understand our processes!

Cross sections at a collider depend on

- Coupling strength
- Coupling to what?
(light quarks, gluons, heavy quarks, EW gauge bosons?)
- Mass
- Single production/pair production



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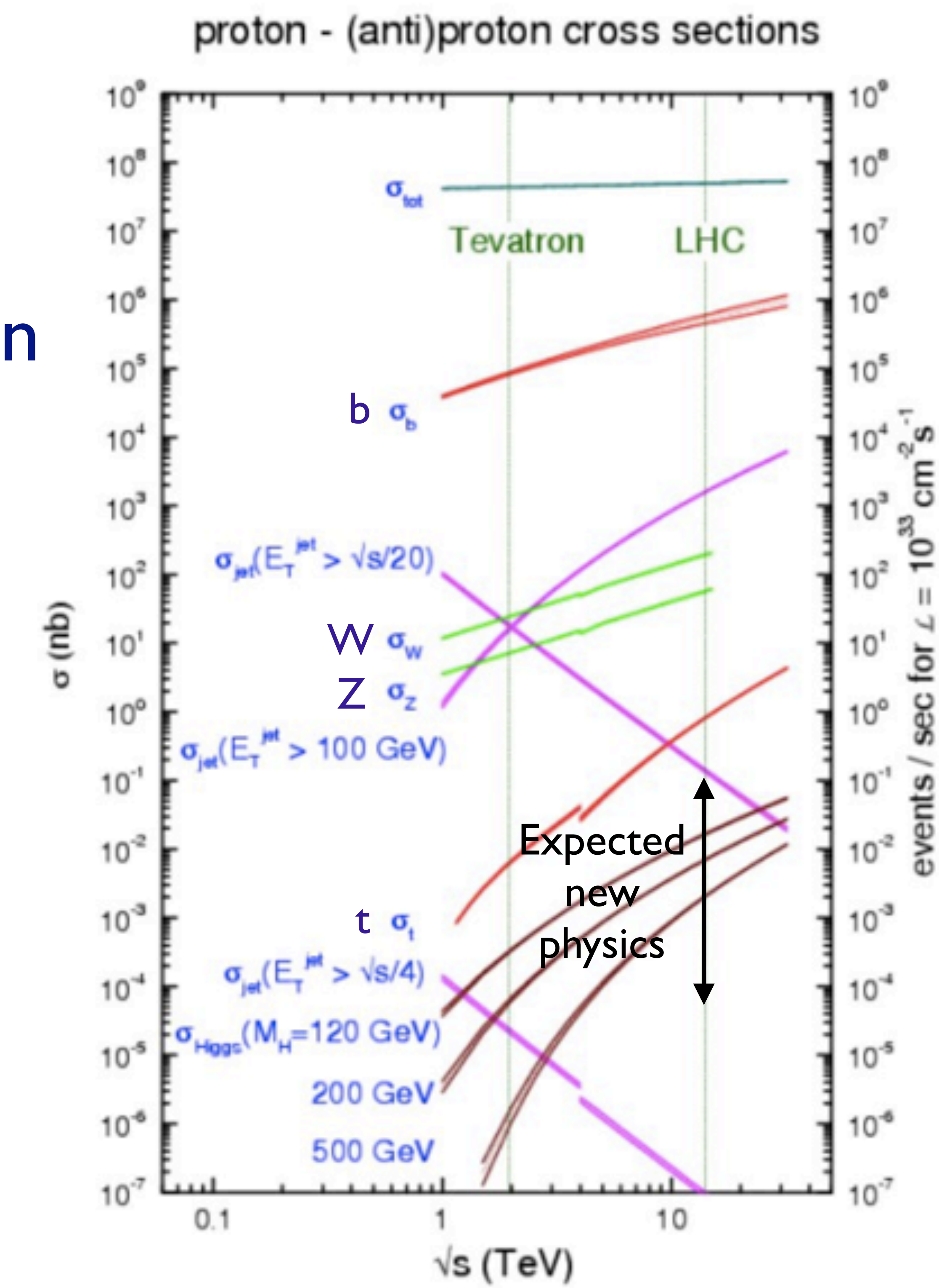

Master formula

Master formula

$$\hat{\sigma}_{ab\to X}(\hat{s},\ldots)$$

Parton level
cross section

- Parton level cross section from matrix element

Master formula

$$\hat{\sigma}_{ab\to X}(\hat{s},\ldots)\,f_a(x_1)f_b(x_2)$$

Parton level cross section

Parton density functions

- Parton level cross section from matrix element
- Parton density (or distribution) functions:
  Process independent, determined by particle type

Master formula

$$\int \hat{\sigma}_{ab\to X}(\hat{s},\ldots)\, f_a(x_1) f_b(x_2)\, dx_1 dx_2 d\Phi_{FS}$$

Parton level cross section | Parton density functions | Phase space integral

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Parton level cross section | Parton density functions | Phase space integral

- Parton level cross section from matrix element
- Parton density (or distribution) functions:
  Process independent, determined by particle type
- $\hat{s} = x_1 x_2 s$ (s = collision energy of the collider)
- Difference between colliders given by parton luminocities

Tevatron vs. the LHC

- Tevatron: 2 TeV proton-antiproton collider
  - ➡ Most important: q-$\bar{q}$ annihilation (85% of t $\bar{t}$)
- LHC: 8-14 TeV proton-proton collider
  - ➡ Most important: g-g annihilation (90% of t $\bar{t}$)

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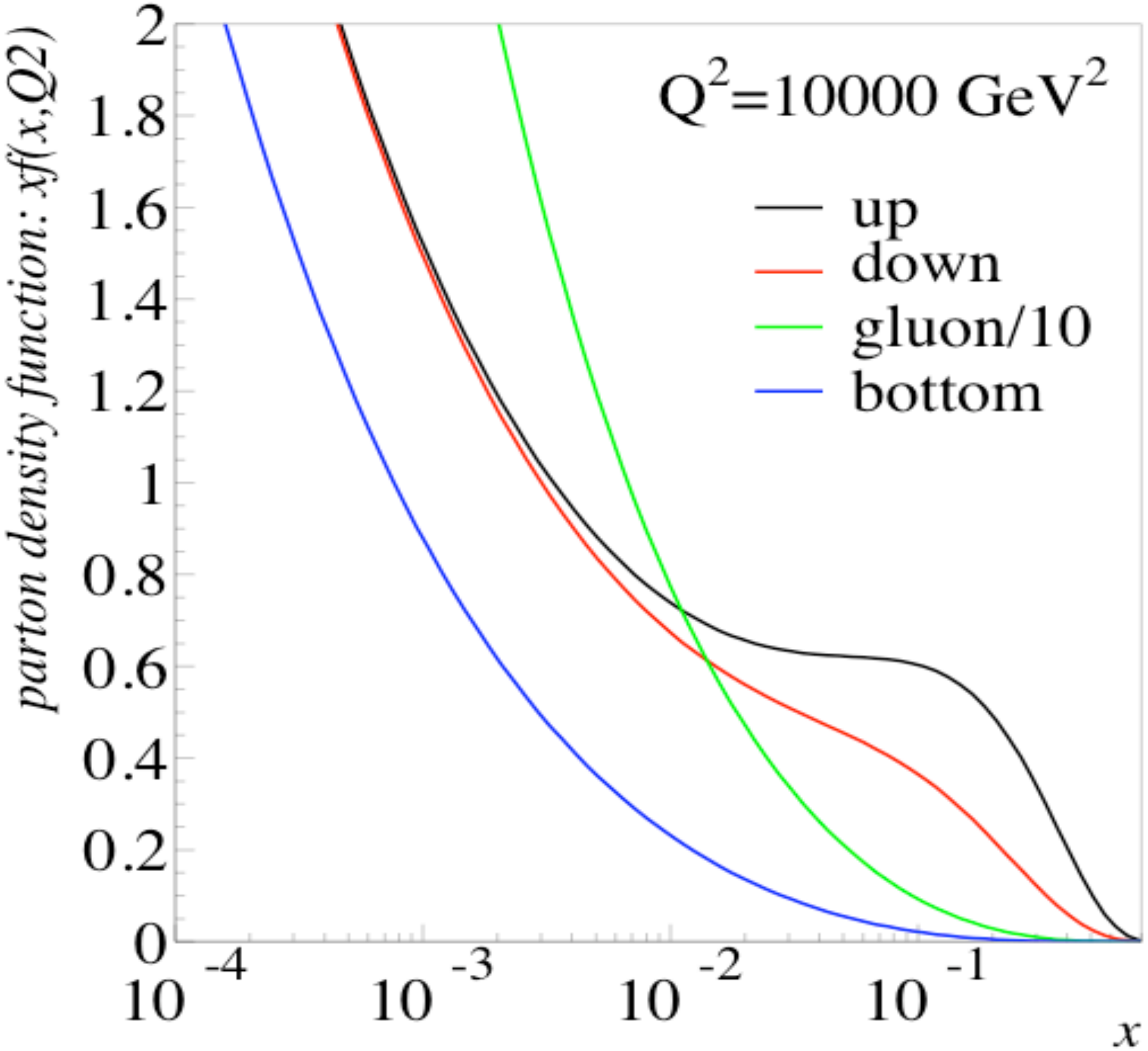
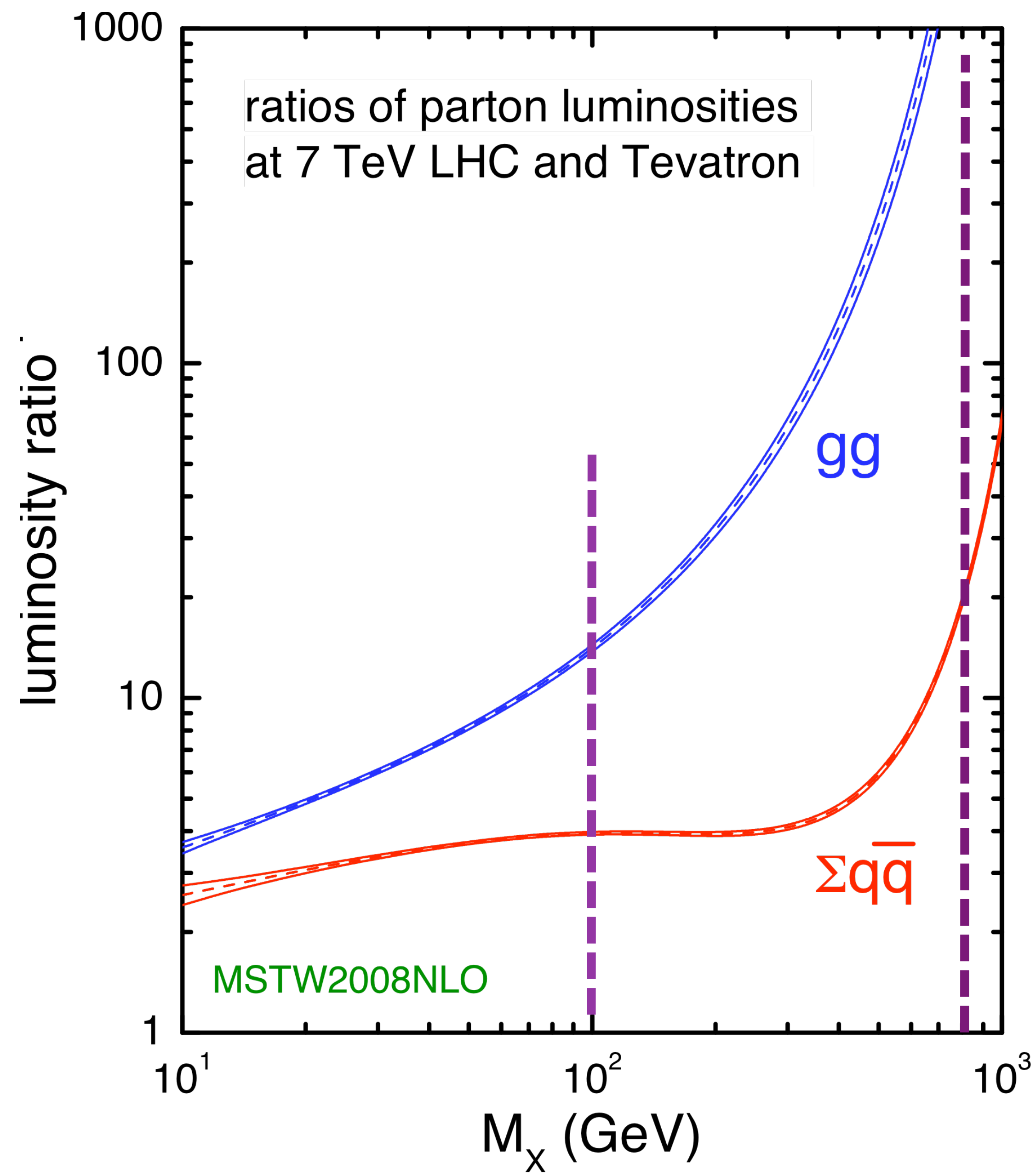
Parton densities

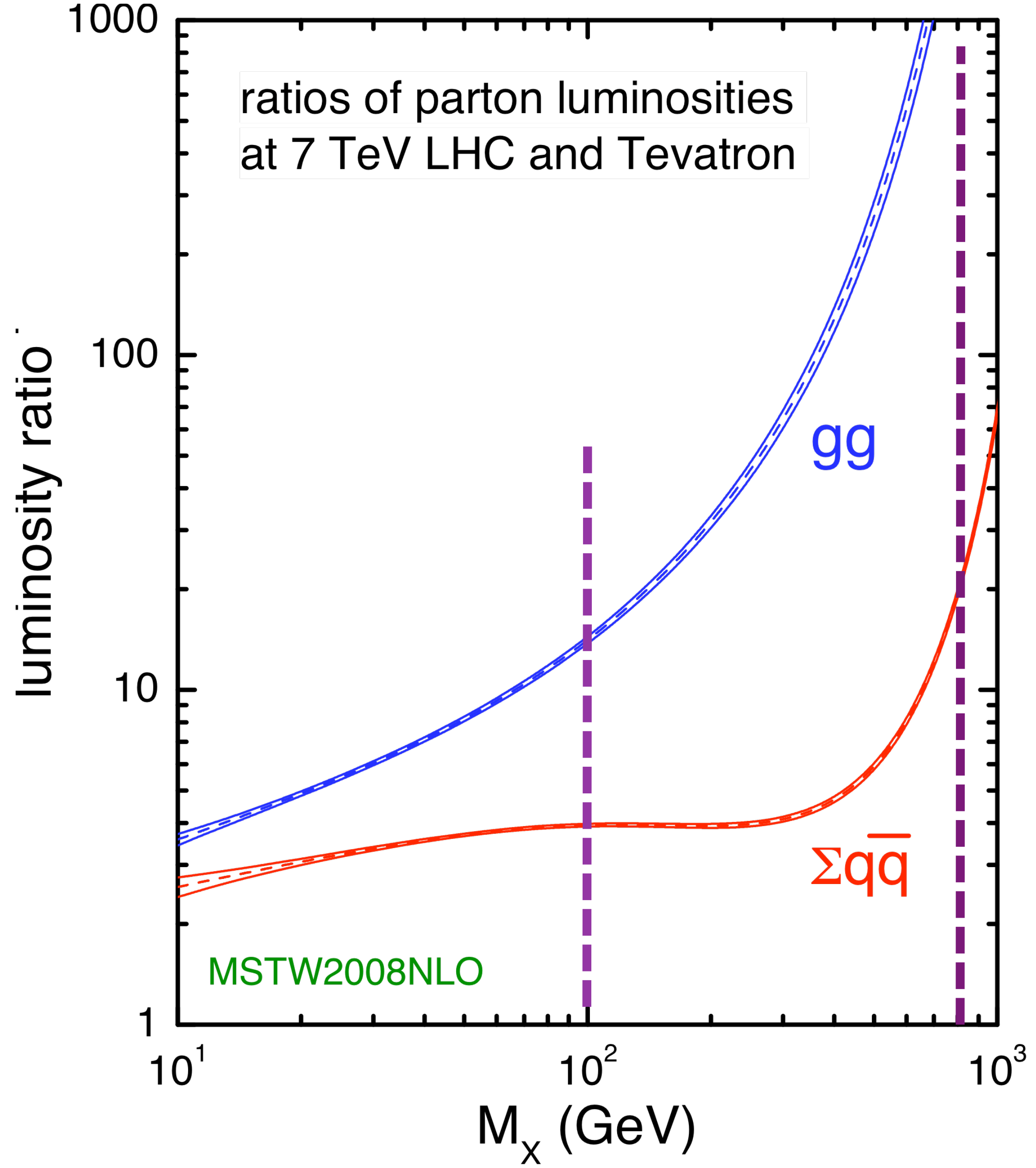


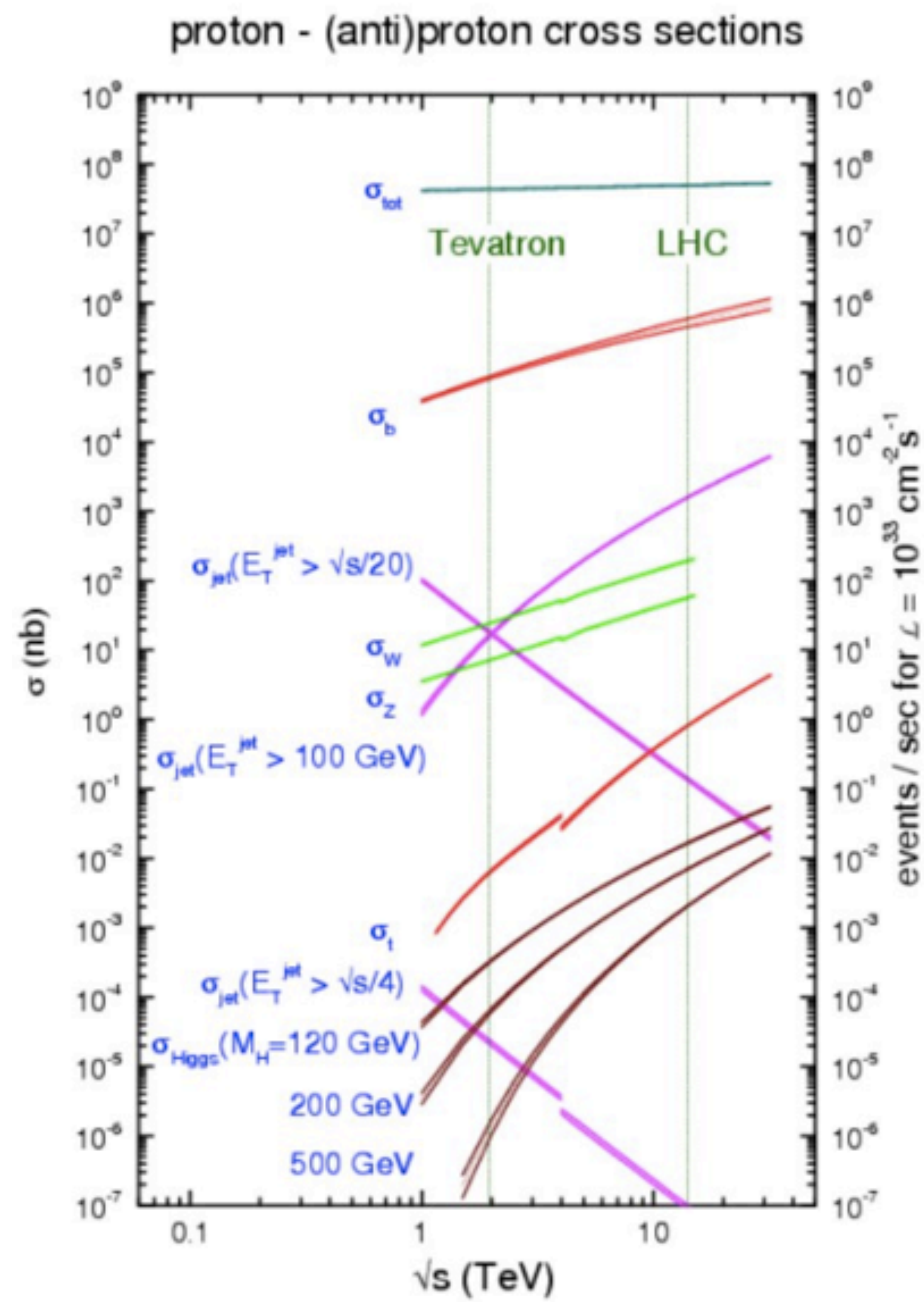


At small x (small $\hat{s}$), gluon domination.
At large x valence quarks

LHC formidable at large mass –
For low mass, Tevatron backgrounds smaller

Back to the processes





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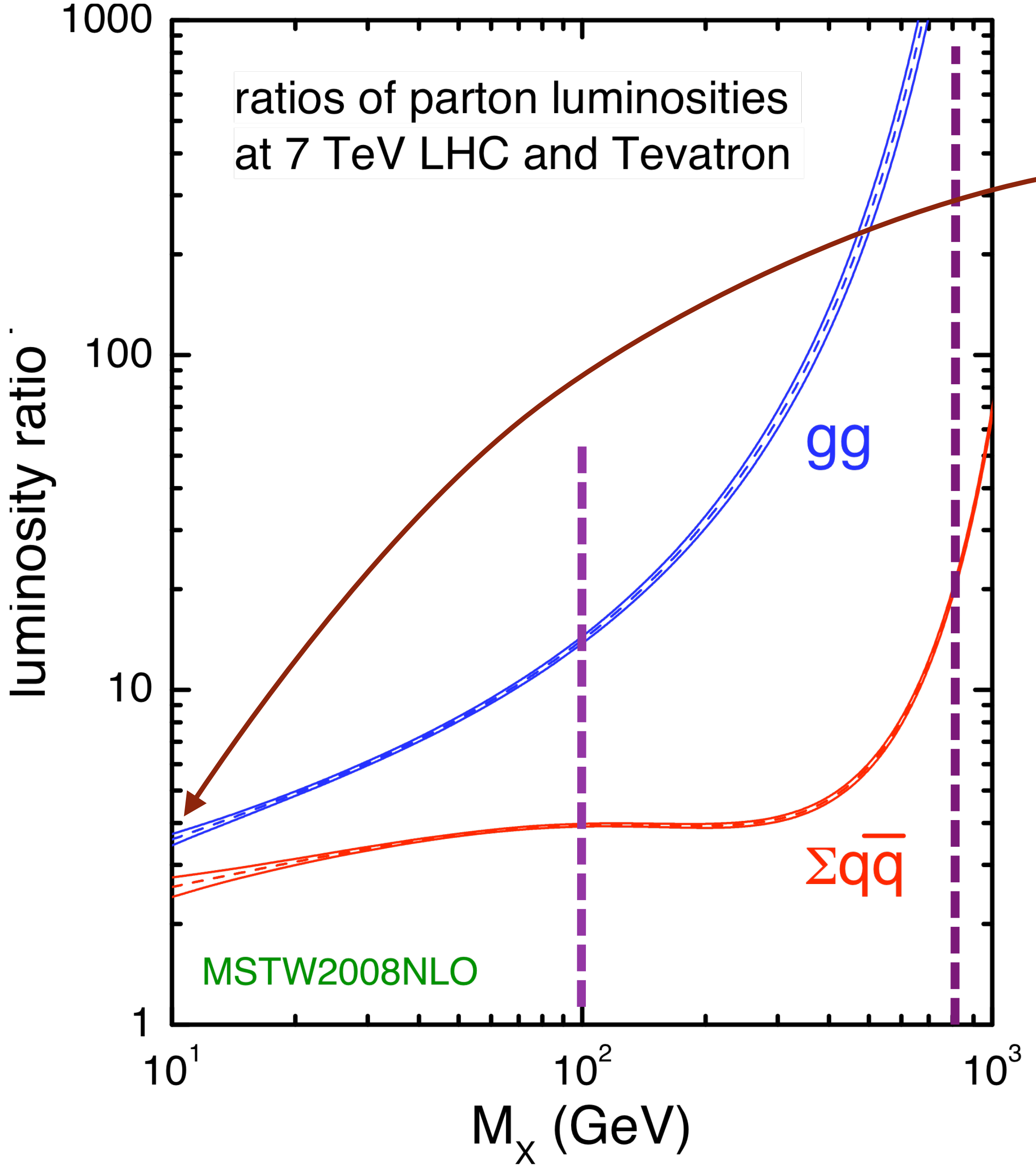

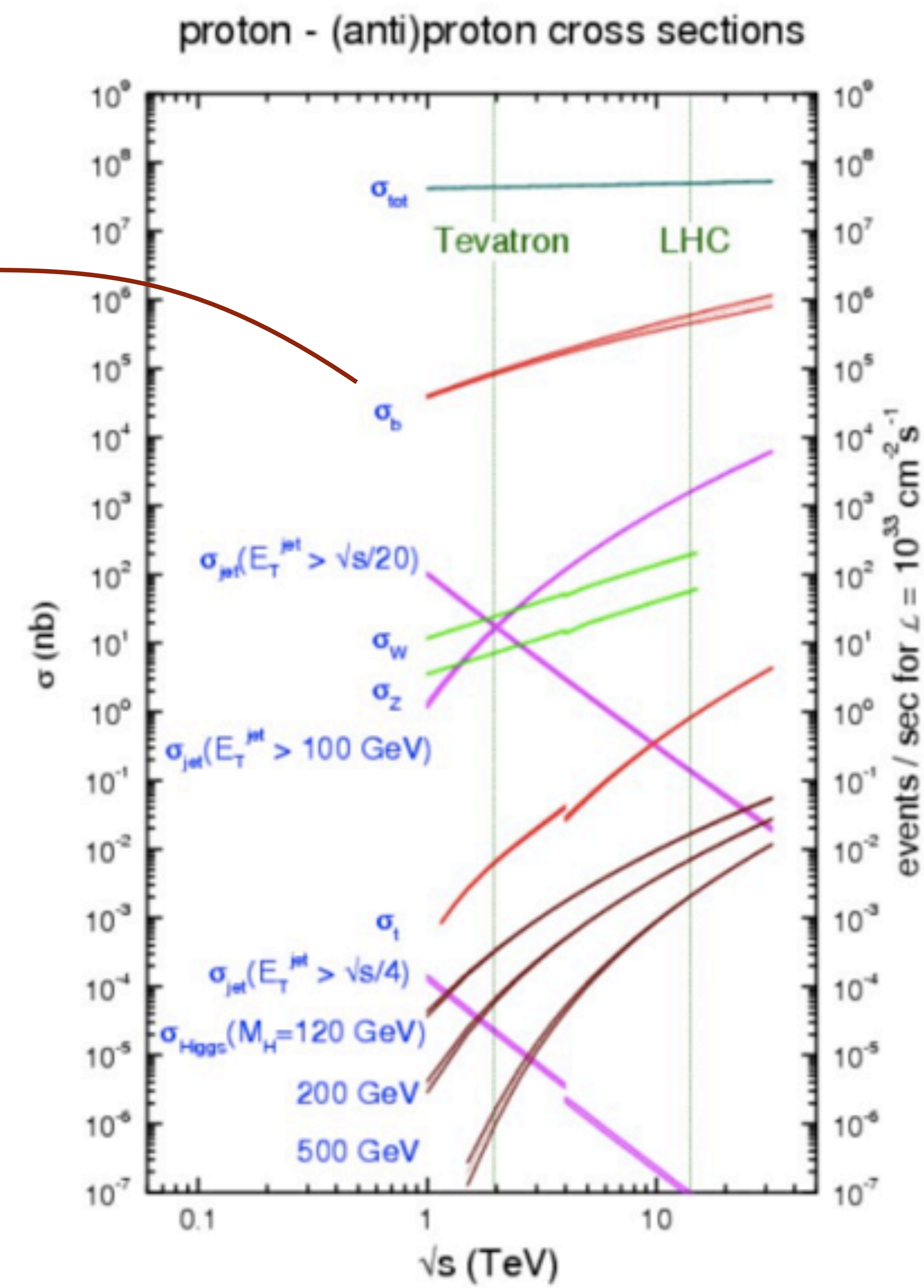

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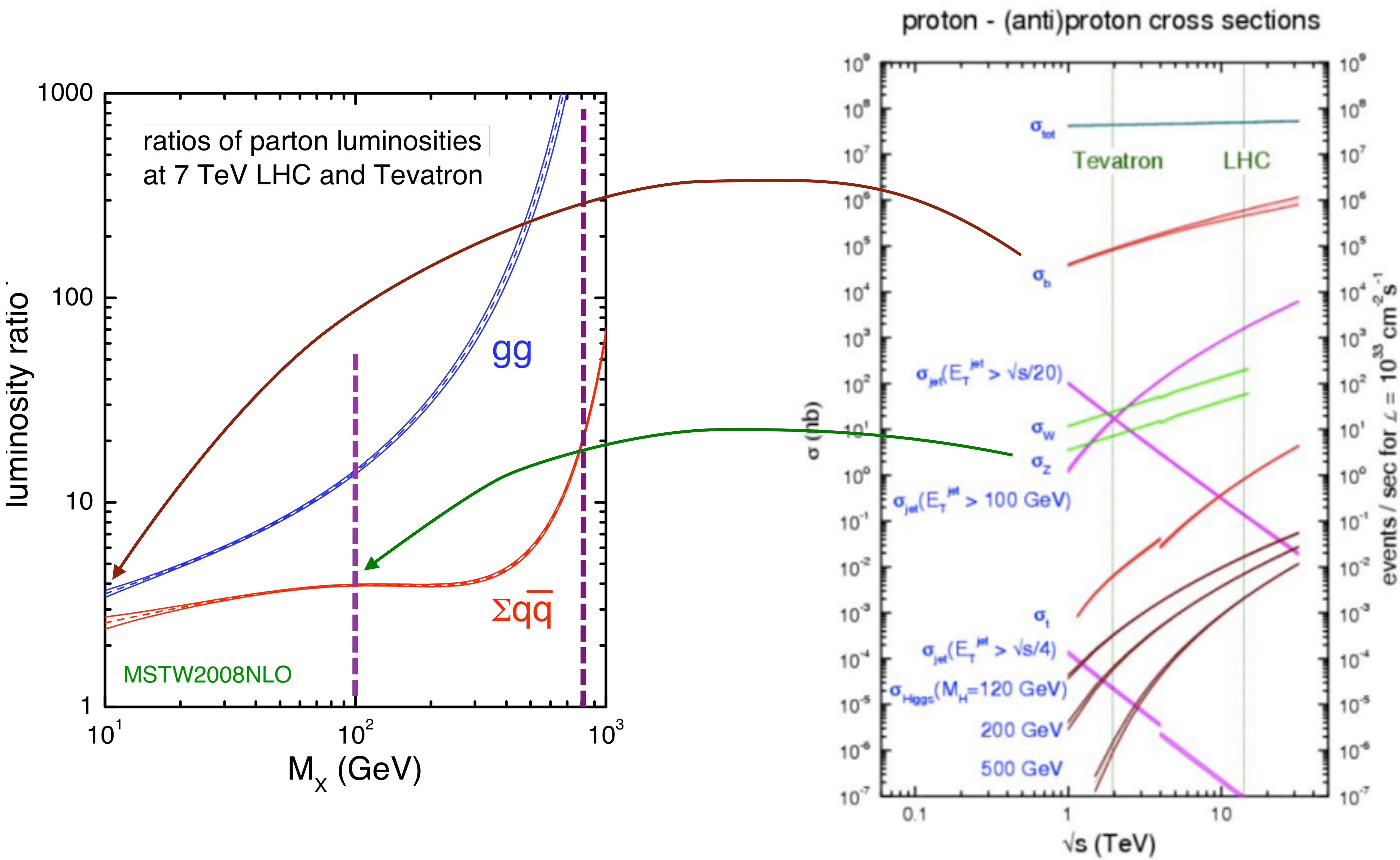

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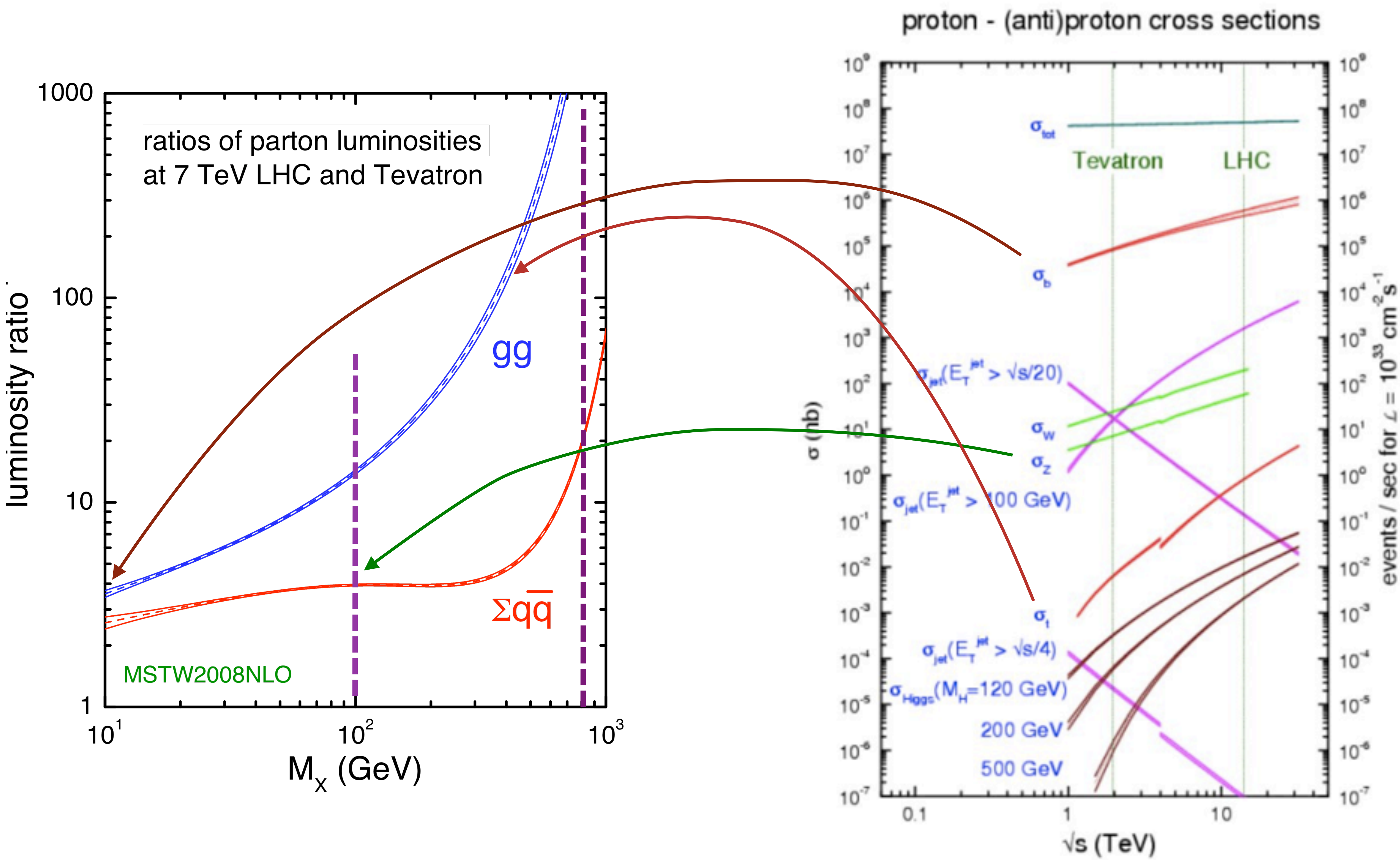
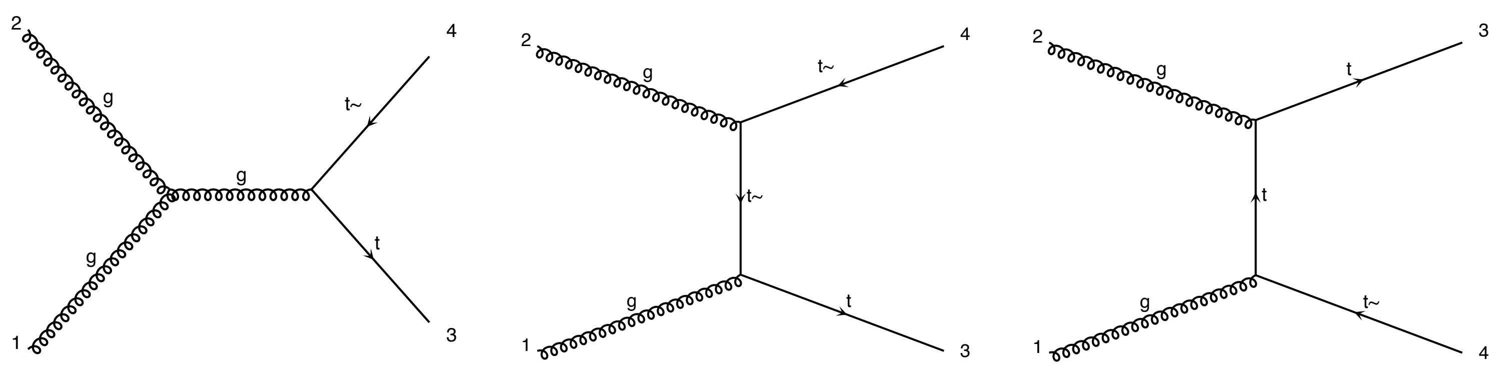


Matrix Element calculation at Hadron Colliders

To calculate a given process (e.g., $p\, p \to t\, \bar{t}$)

1. Determine contributing subprocesses
   $g\, g \to t\, \bar{t},\ q\, \bar{q} \to t\, \bar{t},\ \bar{q}\, q \to t\, \bar{t}$ with $\overset{(-)}{q} = \overset{(-)}{d}, \overset{(-)}{u}, \overset{(-)}{s}, \overset{(-)}{c}, (\overset{(-)}{b})$
2. Determine matrix element for each subprocess



3. Perform phase space integration for each subprocess

$$\sigma = \frac{1}{2s} \int |\mathcal{M}|^2 d\Phi(n)$$

Matrix Element calculation at Hadron Colliders

To calculate a given process (e.g., $p\,p \to t\,\bar{t}$)

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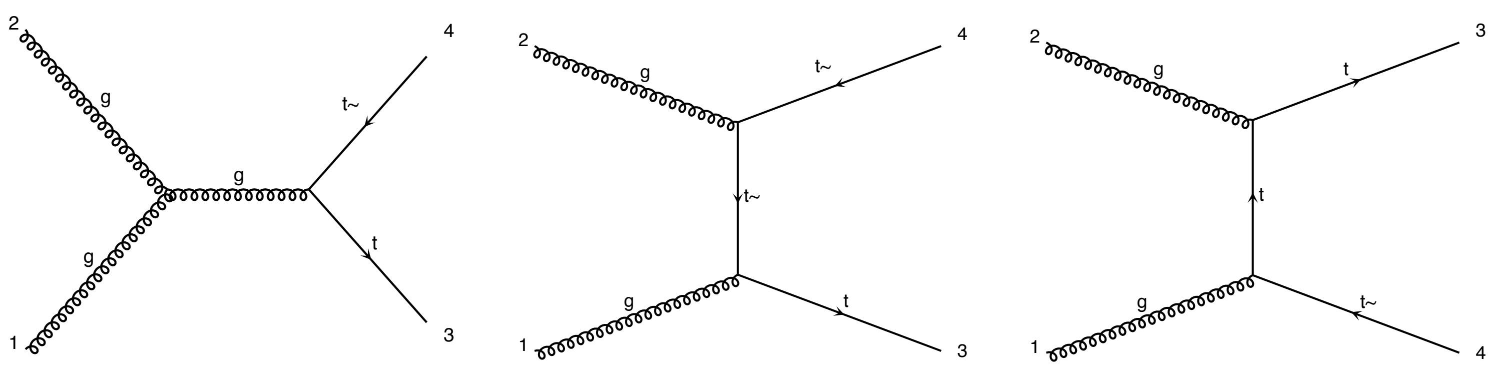
2. Determine matrix element for each subprocess ⇐ Hard



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⇐ Very Hard (in general)

Matrix Element calculation at Hadron Colliders

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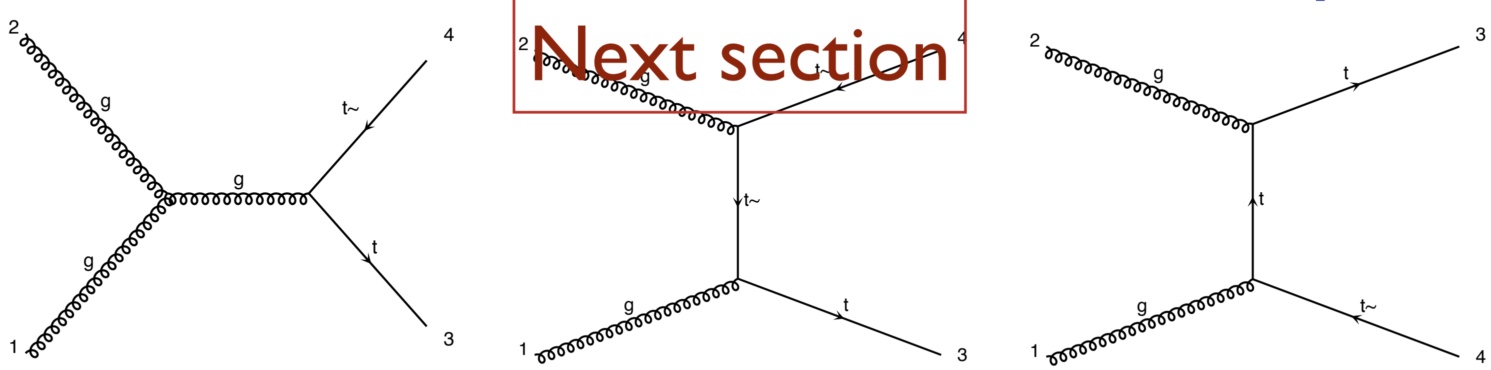
2. Determine matrix element for each subprocess — Hard

Next section



3. Perform phase space integration for each subprocess — Very Hard (in general)

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Matrix Element calculation at Hadron Colliders

To calculate a given process (e.g., $p\,p \to t\,\bar{t}$)

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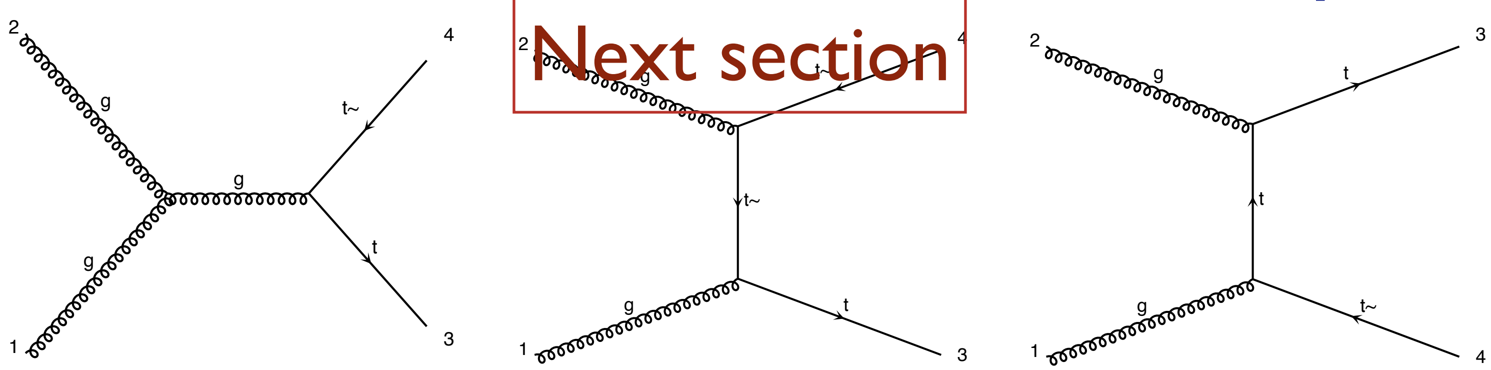
Next section



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The section after ⇐ Very Hard (in general)

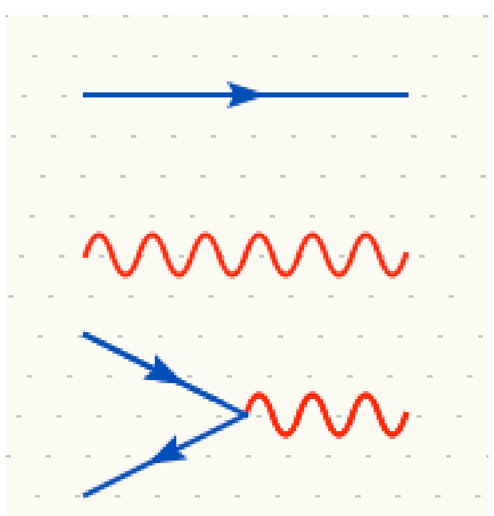
Minimal QCD: Basics

From QED to QCD: abelian vs. non-abelian

The QED Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\not{\partial} - m)\psi - eQ\bar{\psi}\not{A}\psi$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$



$$= \frac{i}{\not{p} - m + i\epsilon} = i\frac{\not{p} + m}{p^2 - m^2 + i\epsilon}$$

$$= -i\frac{g_{\mu\nu}}{p^2 + i\epsilon} \text{ (Feynman gauge)}$$

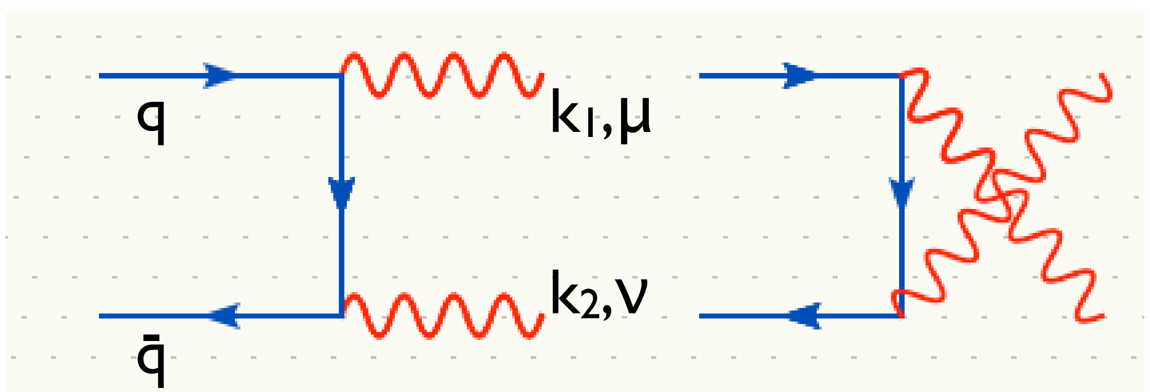
$$= -ie\gamma_\mu Q \quad (Q = -1 \text{ for the electron}, Q = 2/3 \text{ for the u-quark, etc}$$

From QED to QCD: abelian vs. non-abelian

We want to heuristically derive the properties of QCD using gauge invariance.

Let's start with the computation of a simple proces $e^+e^- \to \gamma\gamma$.

There are two diagrams:



$$= D_1 + D_2$$

$$\frac{i}{e^2} M_\gamma \equiv D_1 + D_2 = \bar{v}(\bar{q}) \not{\epsilon}_2 \frac{1}{\not{q} - \not{k}_1} \not{\epsilon}_1 u(q) + \bar{v}(\bar{q}) \not{\epsilon}_1 \frac{1}{\not{q} - \not{k}_2} \not{\epsilon}_2 n(q) \equiv M_{\mu\nu} \epsilon_1^\mu \epsilon_2^\nu$$

From QED to QCD: abelian vs. non-abelian

Gauge invariance demands that:

$$\epsilon_2^\nu \partial^\mu M_{\mu\nu} = \epsilon_1^\mu \partial^\nu M_{\mu\nu} = 0$$

So let us perform the calculation:

$$\begin{aligned} k_1^\mu \epsilon_2^\nu M_{\mu\nu} &= \bar{v}(\bar{q}) \not{\epsilon}_2 \frac{1}{\not{q} - \not{k}_1} (\not{k}_1 - \not{q}) u(q) + \bar{v}(\bar{q}) (\not{k}_1 - \not{\bar{q}}) \frac{1}{\not{k}_1 - \not{\bar{q}}} \not{\epsilon}_2 u(q) \\ &= -\bar{v}(\bar{q}) \not{\epsilon}_2 u(q) + \bar{v}(\bar{q}) \not{\epsilon}_2 u(q) = 0 \end{aligned}$$

Only the sum of the two diagrams is gauge-invariant.

From QED to QCD: abelian vs. non-abelian

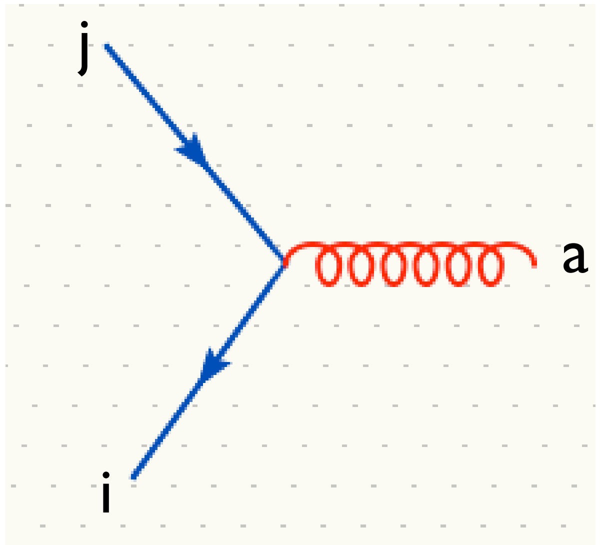
Let's now generalize what we have done for the non-abelian SU(3) of color, with

$$[t^a, t^b] = i f^{abc} t^c$$

In this case we take the (anti-)quarks
to be in the (anti-)fundamental representation of SU(3), 3 and 3^*.
The current is in a $3 \otimes 3^* = 1 \oplus 8$.

We identify the gluon with the octet and generalize the QED vertex to :

$$-i g_s t^a_{ij} \gamma^\mu$$



From QED to QCD: abelian vs. non-abelian

So now let's calculate $q\bar{q} \to gg$ and we obtain

$$\frac{i}{g_s^2} M_g \equiv (t^b t^a)_{ij} D_1 + (t^a t^b)_{ij} D_2$$

$$M_g = (t^a t^b)_{ij} M_\gamma - g^2 f^{abc} t^c_{ij} D_1$$

To satisfy gauge invariance we still need:

$$k_1^\mu {\epsilon_2}^\nu M_g^{\mu,\nu} = k_2^\nu \epsilon_1^\mu M_g^{\mu,\nu} = 0.$$

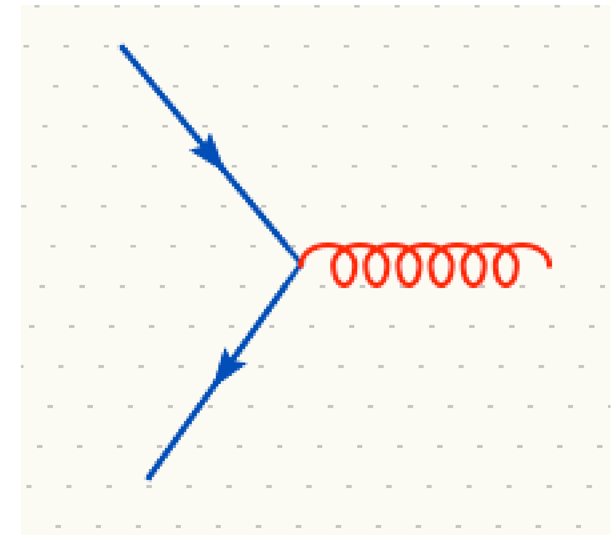
But in this case one piece is left out

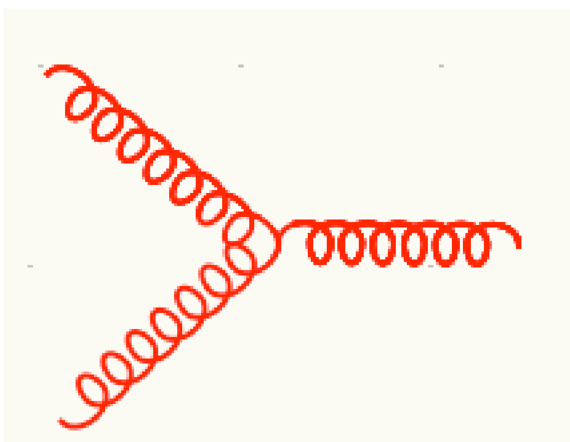
$$k_{1\mu} M_g^\mu = -g_s^2 f^{abc} t^c_{ij} \bar{v}_i(\bar{q}) \not{\epsilon}_2 u_i(q)$$

$$k_{1\mu} M_g^\mu = i(-g_s f^{abc} \epsilon_2^\mu)(-i g_s t^c_{ij} \bar{v}_i(\bar{q}) \gamma_\mu u_i(q))$$

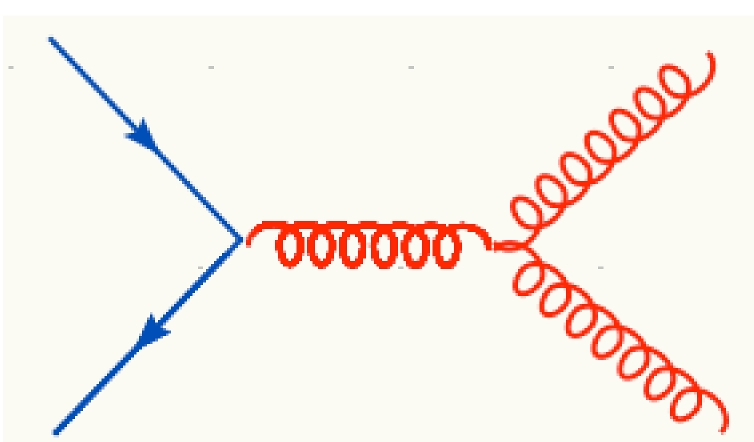
From QED to QCD: abelian vs. non-abelian

We can interpret this as the normal vertex times a new 3 gluon vertex:





$$-g_s f^{abc} V_{\mu_1 \mu_2 \mu_3}(p_1, p_2, p_3)$$



$$-ig_s^2 D_3 = \left(-ig_s t^a_{ij} \bar{v}_i(\bar{q}) \gamma^\mu u_j(q)\right) \times \left(\frac{-i}{p^2}\right) \times$$

$$\left(-g f^{abc} V_{\mu\nu\rho}(-p, k_1, k_2) \epsilon_1^\nu(k_1) \epsilon_2^\rho(k_2)\right)$$

From QED to QCD: abelian vs. non-abelian

Can we guess the Lorentz part for this new interaction? If we assume

1. Lorentz invariance : only structure of the type $g_{\mu\nu}$ p_ρ are allowed
2. Fully anti-symmetry : only structure of the type remain $g_{\mu 1 \mu 2}(k_1)_{\mu 3}$ are allowed...
3. Dimensional analysis : only one power of the momentum.

Then we get a unique form of the vertex:

$$V_{\mu_1\mu_2\mu_3}(p_1,p_2,p_3) = V_0\left[(p_1-p_2)_{\mu_3}g_{\mu_1\mu_2} + (p_2-p_3)_{\mu_1}g_{\mu_2\mu_3} + (p_3-p_1)_{\mu_2}g_{\mu_3\mu_1}\right]$$

With this expression we obtain the contribution to the gauge variation:

$$k_1 \cdot D_3 = g^2 f^{abc} t^c V_0 \left[\bar{v}(\bar{q}) \not{\epsilon}_2 u(q) - \frac{k_2 \cdot \epsilon_2}{2k_1 \cdot k_2} \bar{v}(\bar{q}) \not{k}_1 u(q)\right]$$

The first term cancels the gauge variation of D_1+ D_2 if V_0=1, the second term is zero IFF the other gluon is physical ($k_2 \cdot \epsilon_2 = 0$).

The QCD Lagrangian

This means that the gluon is itself charged under QCD!

For full gauge invariance, also a 4-gluon vertex is necessary.

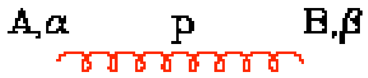
$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \sum_f \bar{\psi}_i^{(f)}(i\partial\!\!\!/ - m_f)\psi_i^{(f)} - \bar{\psi}_i^{(f)}(g_s t^a_{ij} A\!\!\!/_a)\psi_j^{(f)}$$

Gauge Fields and their interact.

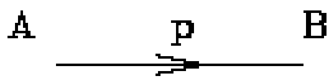
Matter

Interaction

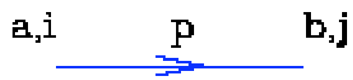
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$



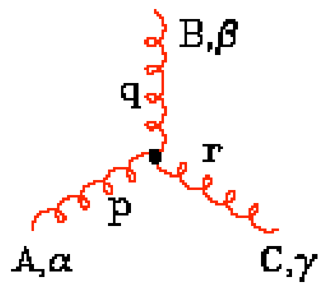
$$\delta^{AB}\left[-g^{\alpha\beta}+(1-\lambda)\frac{p^\alpha p^\beta}{p^2+i\epsilon}\right]\frac{i}{p^2+i\epsilon}$$



$$\delta^{AB}\frac{i}{(p^2+i\epsilon)}$$

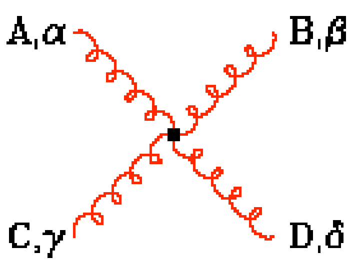


$$\delta^{ab}\frac{i}{(\not p-m+i\epsilon)_{ji}}$$

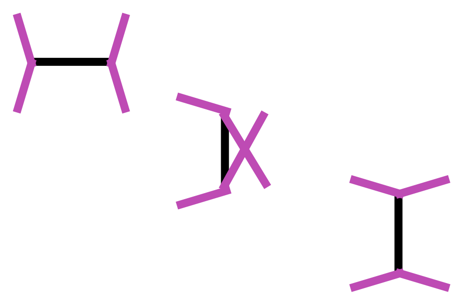


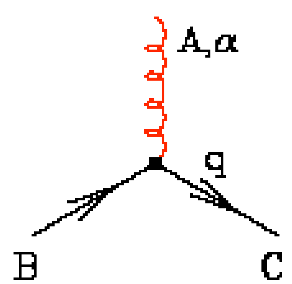
$$-g\ f^{ABC}[(p-q)^\gamma g^{\alpha\beta}+(q-r)^\alpha g^{\beta\gamma}+(r-p)^\beta g^{\gamma\alpha}]$$

(all momenta incoming)

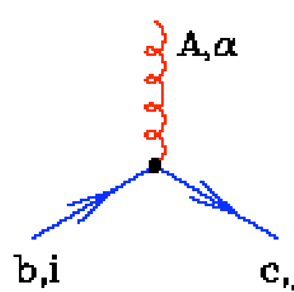


$$-ig^2\ f^{XAC}f^{XBD}\ [g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$
$$-ig^2\ f^{XAD}f^{XBC}\ [g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\gamma}g^{\beta\delta}]$$
$$-ig^2\ f^{XAB}f^{XCD}\ [g^{\alpha\gamma}g^{\beta\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$





$$g\ f^{ABC}q^\alpha$$



$$-ig\ (t^A)_{cb}\ (\gamma^\alpha)_{ji}$$

Monte Carlo Integration and Generation

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Calculations of cross section or decay widths involve integrations over high-dimension phase space of very peaked functions:

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General and flexible method is needed

Integrals as averages

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

$$V = (x_2 - x_1)\int_{x_1}^{x_2} [f(x)]^2 dx - I^2 \quad \Rightarrow \quad V_N = (x_2 - x_1)^2\frac{1}{N}\sum_{i=1}^{N}[f(x)]^2 - I_N^2$$

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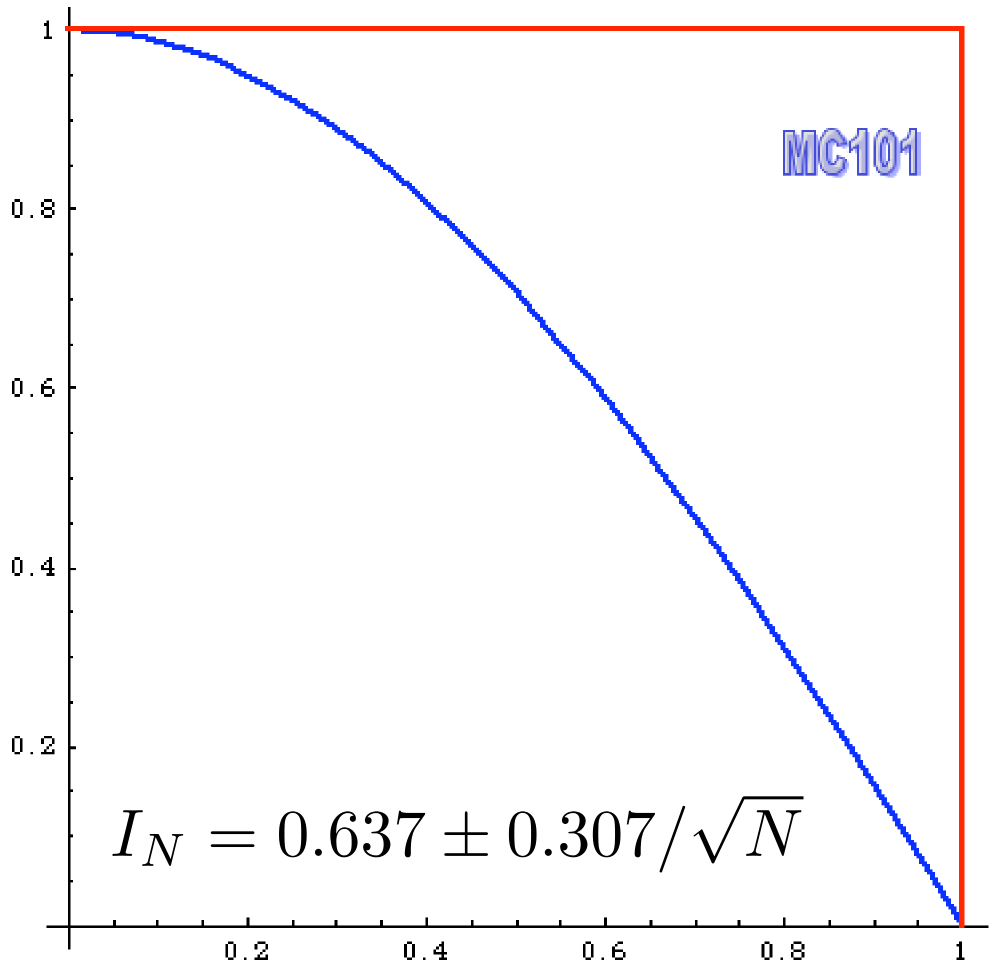
- ☞ Convergence is slow but it can be easily estimated
- ☞ Error does not depend on # of dimensions!
- ☞ Improvement by minimizing V_N.
- ☞ Optimal/Ideal case: f(x)=C $\Rightarrow V_N=0$

Importance Sampling



$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$

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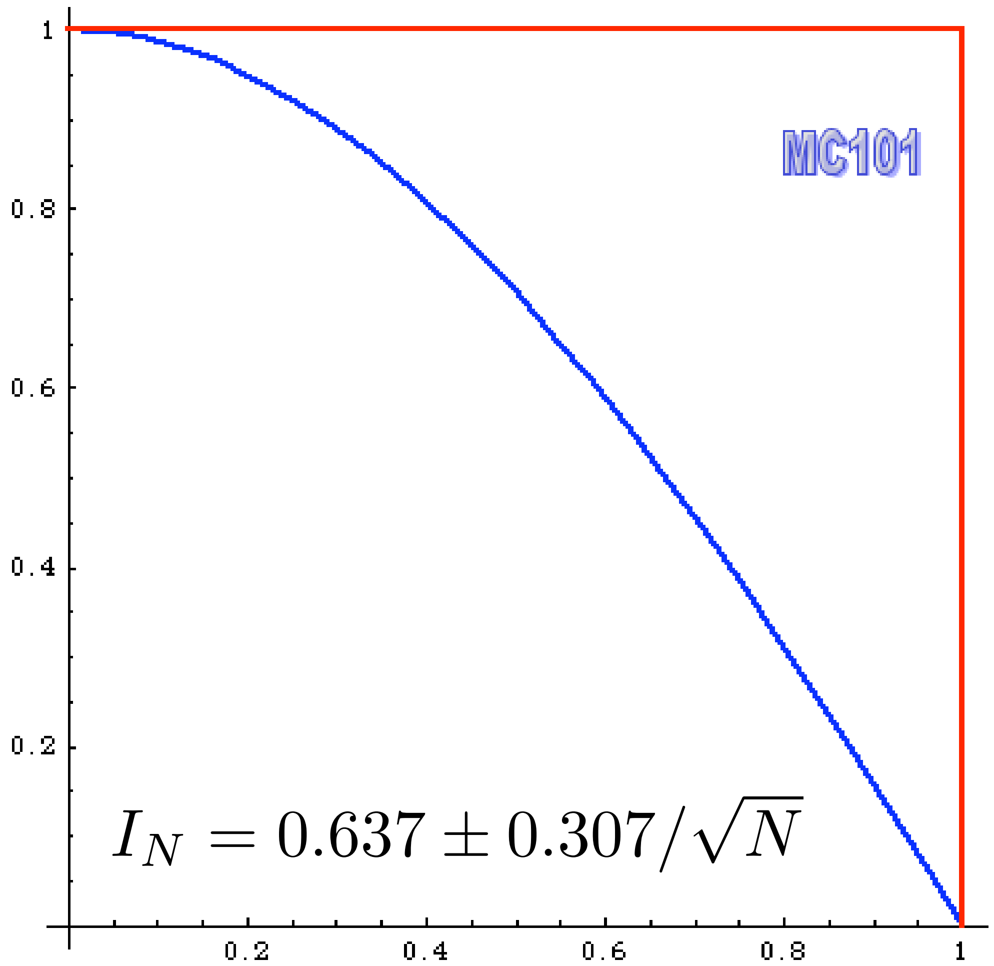

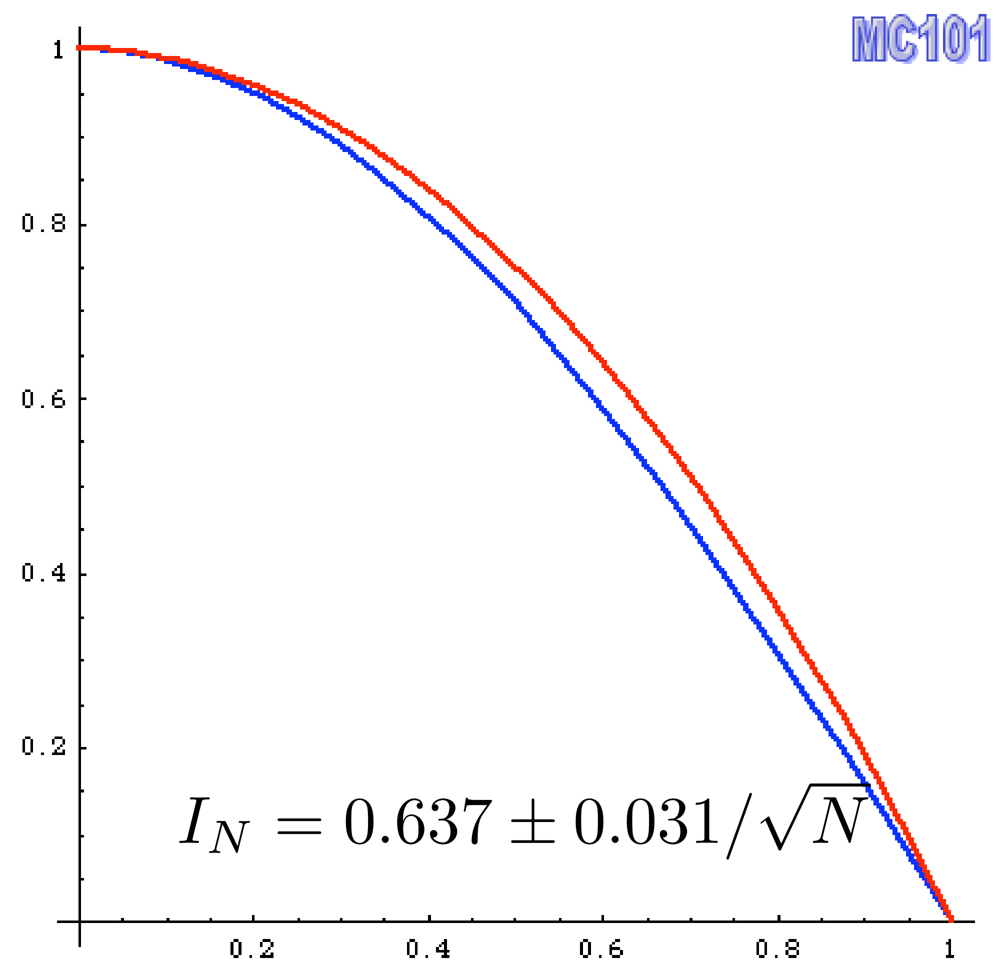

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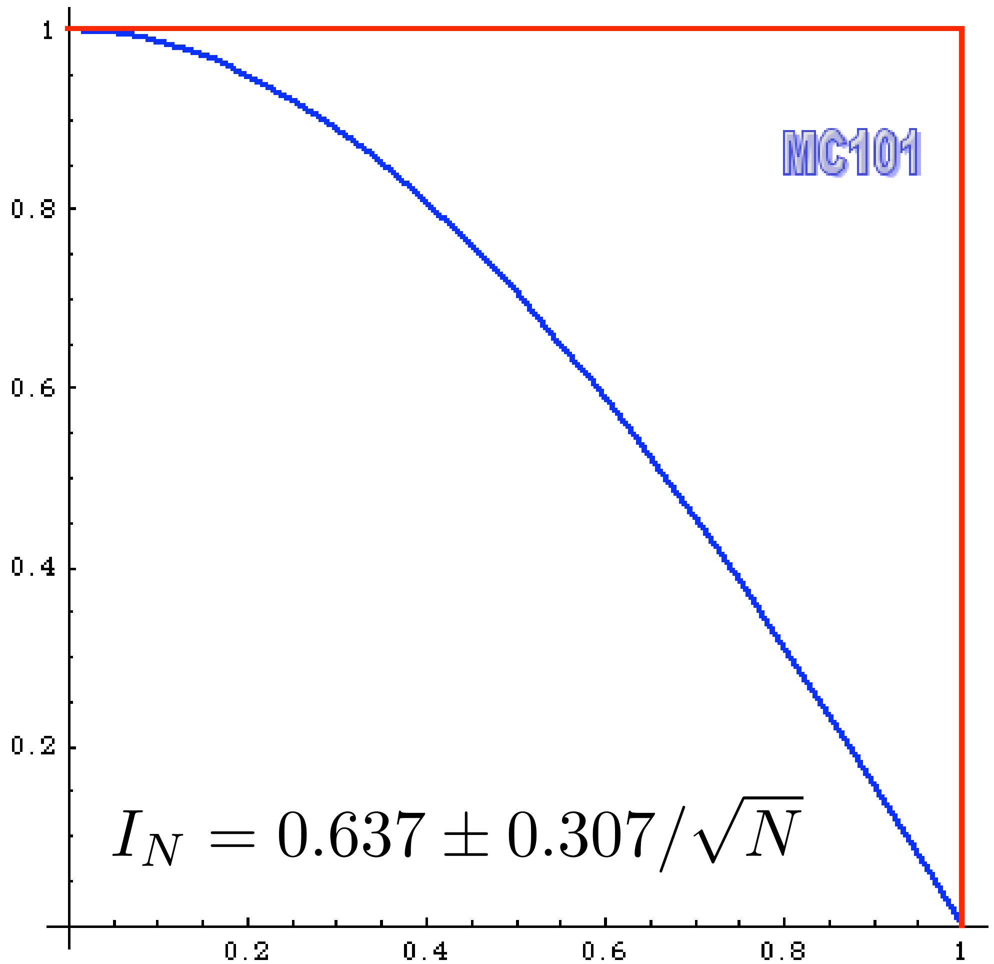

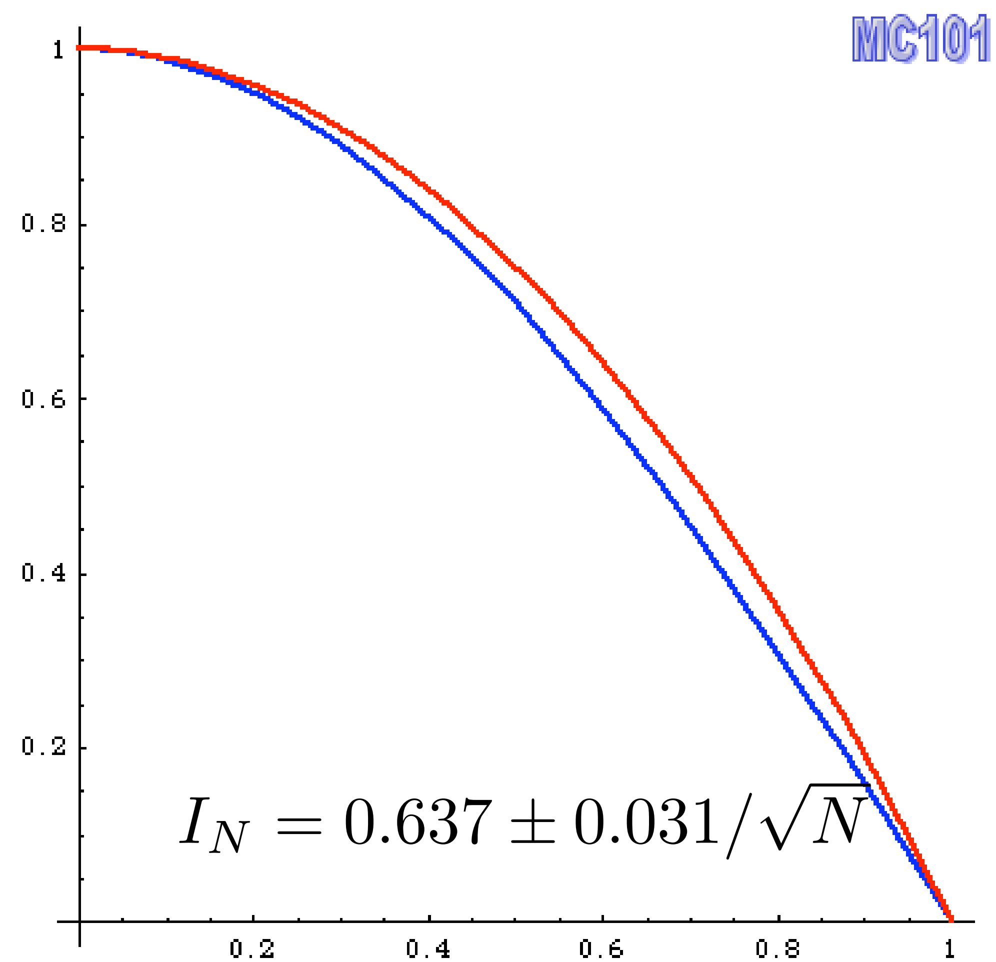

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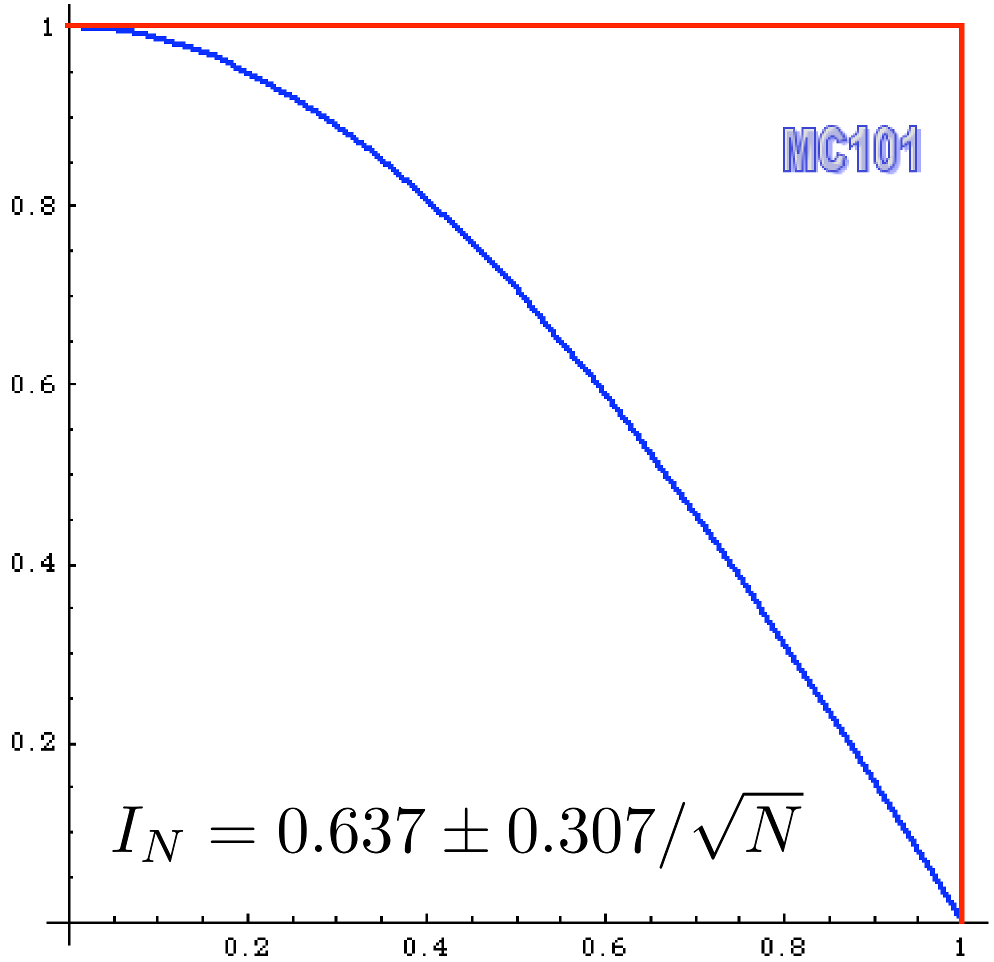

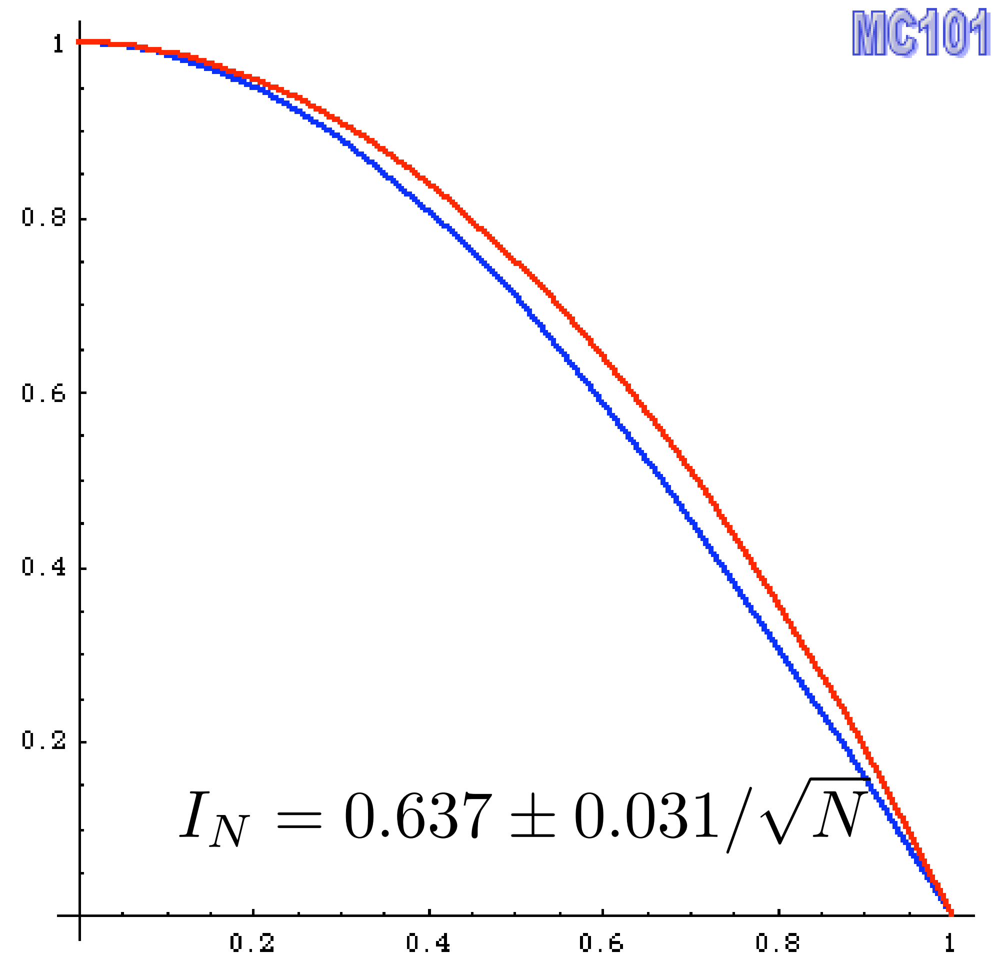

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Monday, October 24, 2011

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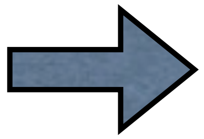
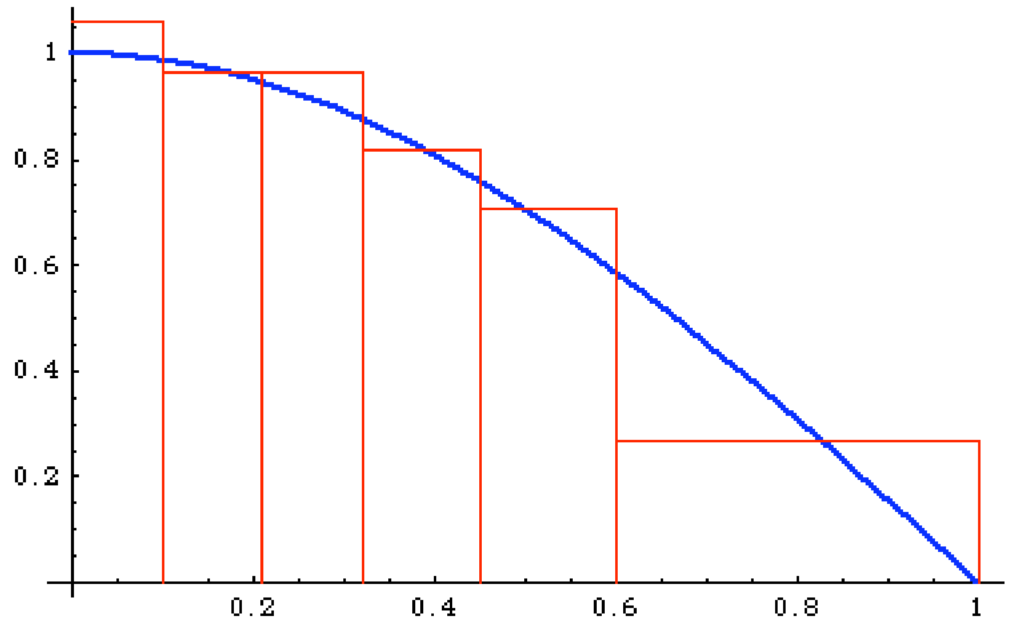
Alternative: learn during the run and build a step-function approximation p(x) of f(x)  VEGAS

MC101



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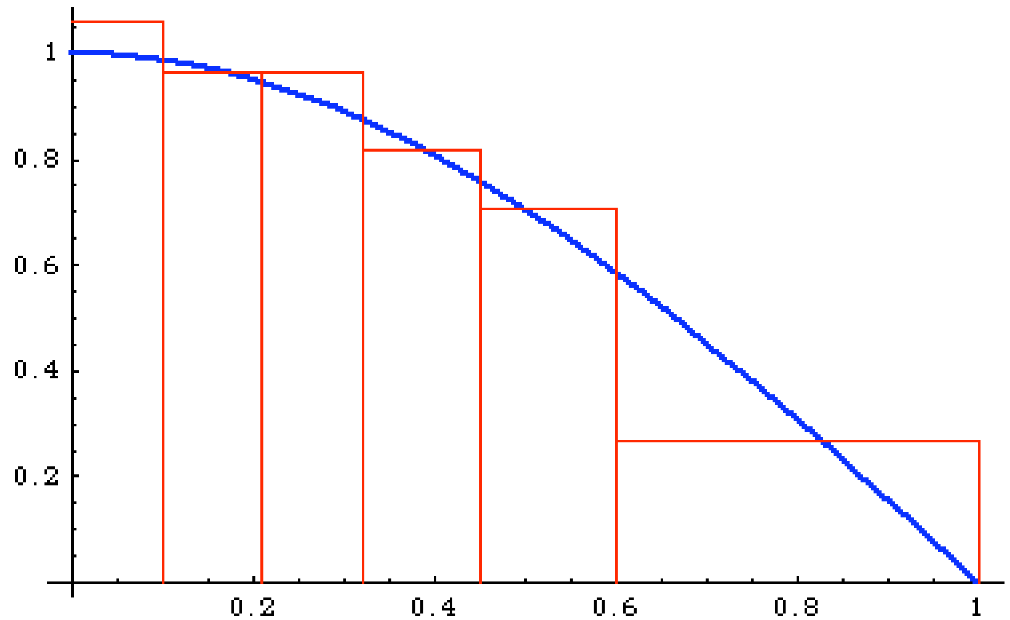

many bins where f(x) is large

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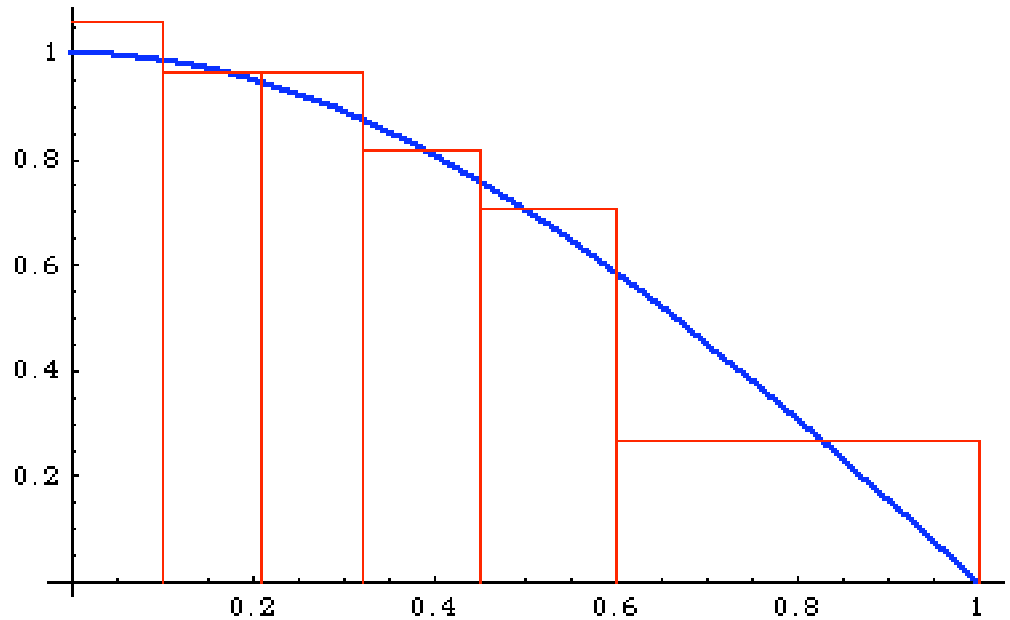

many bins where f(x) is large

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

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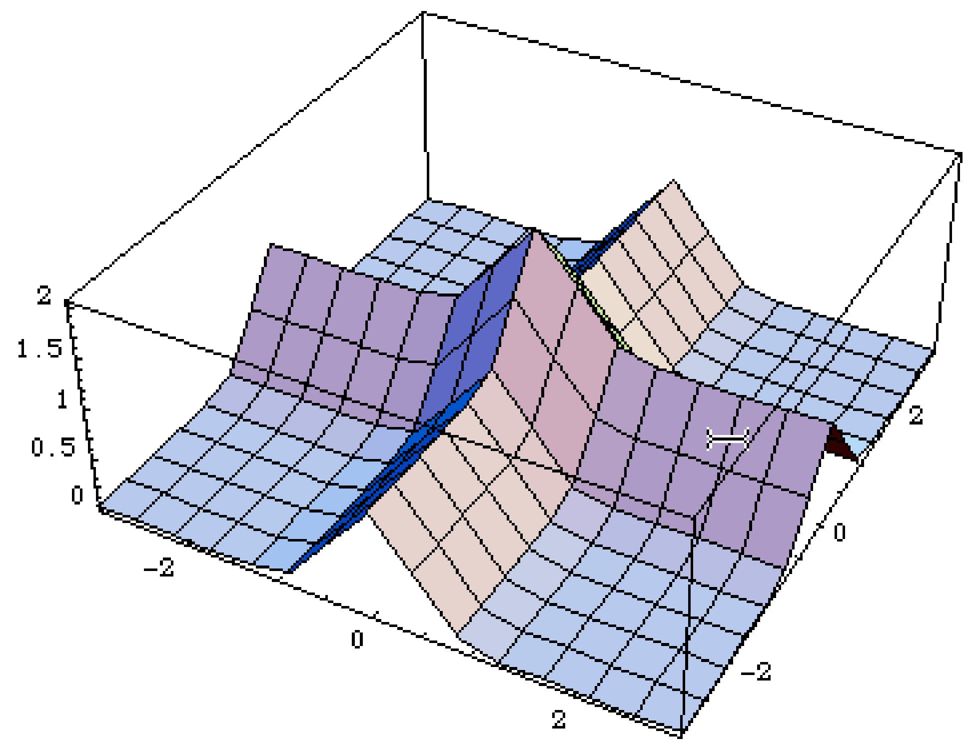

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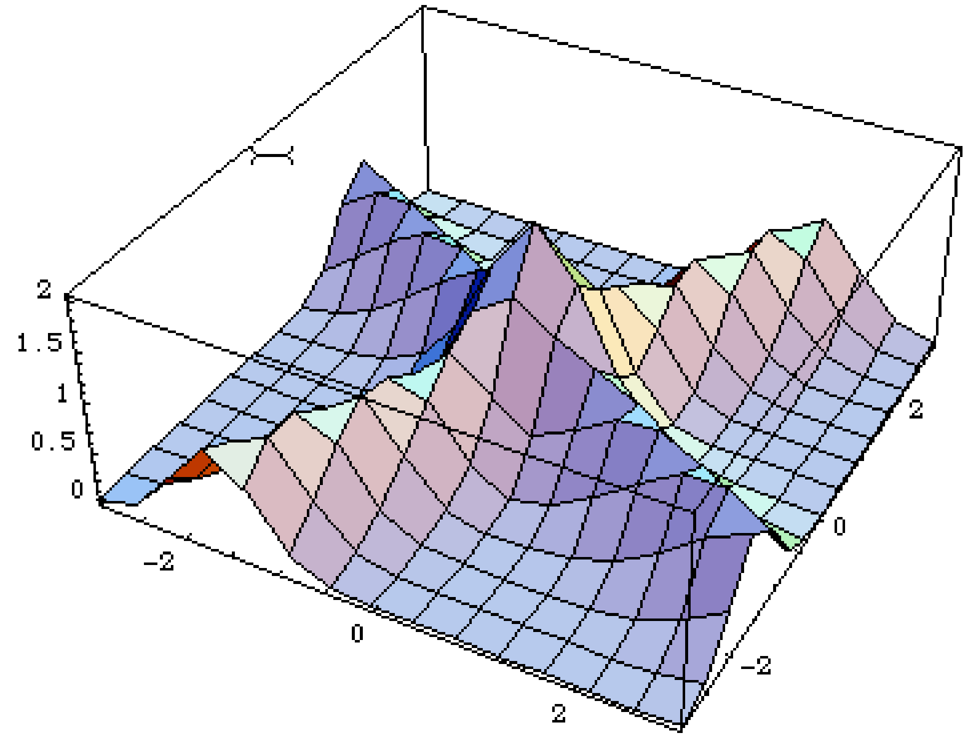

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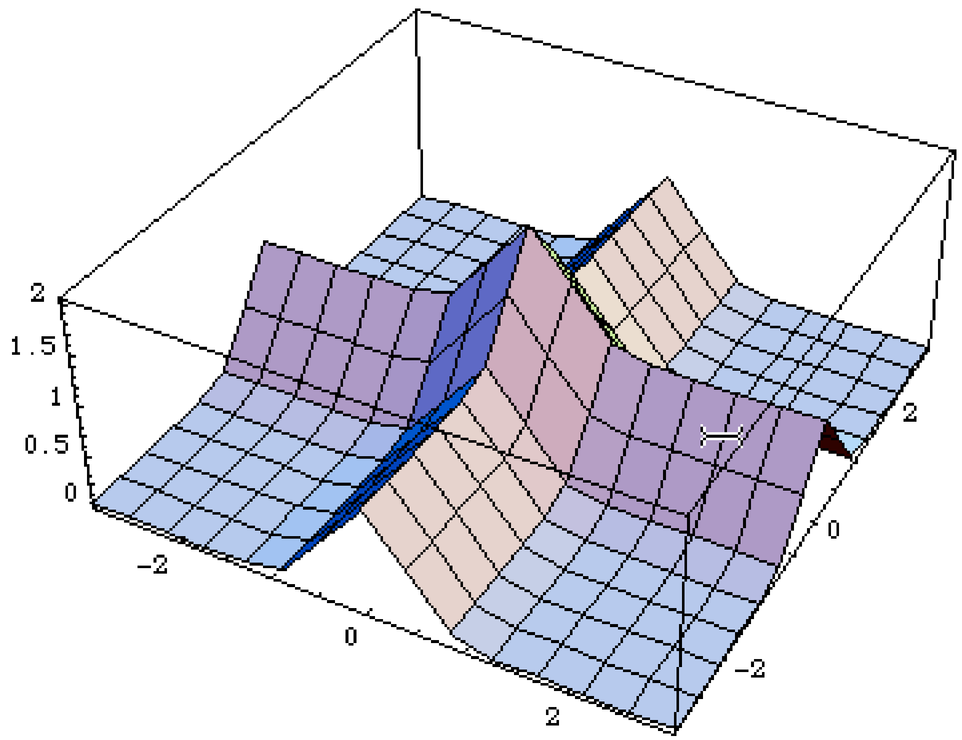
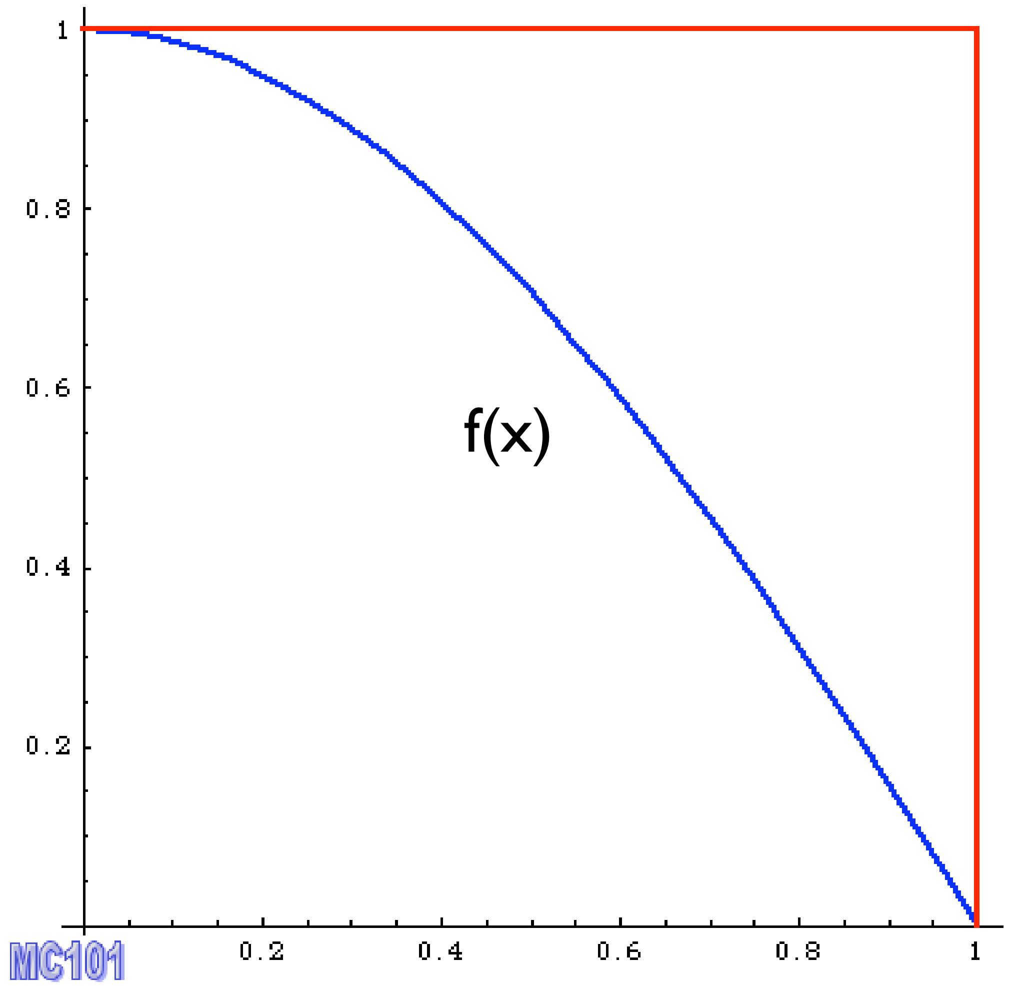


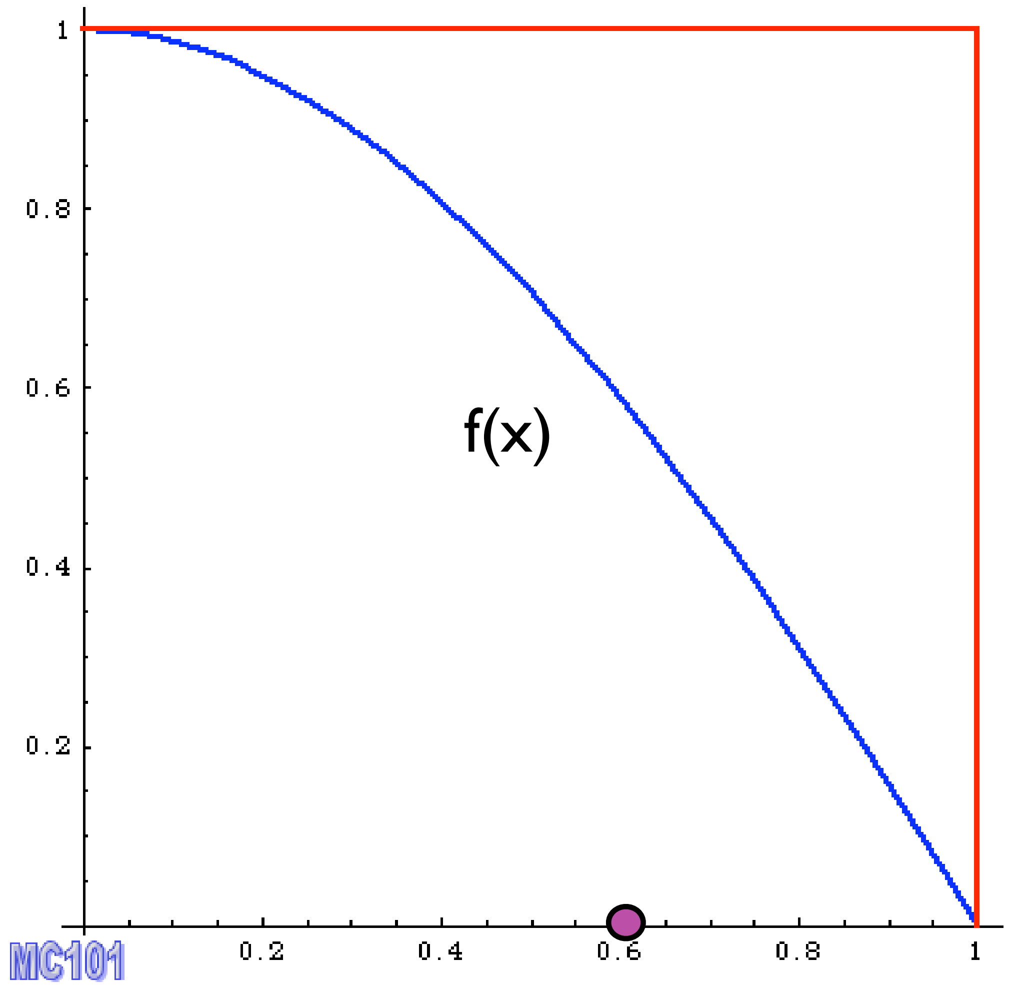
but it is sufficient to make a change of variables!

Event generation



Alternative way

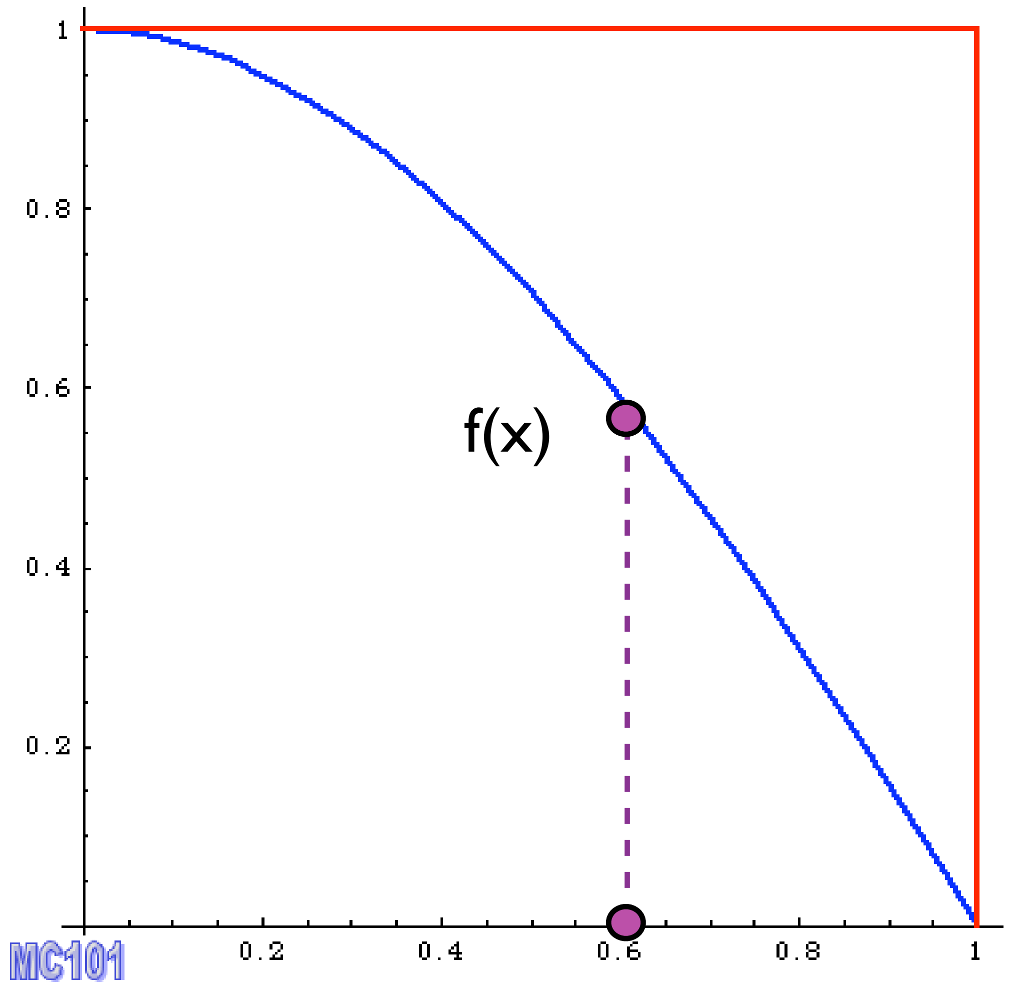
Event generation



Alternative way

1. pick x

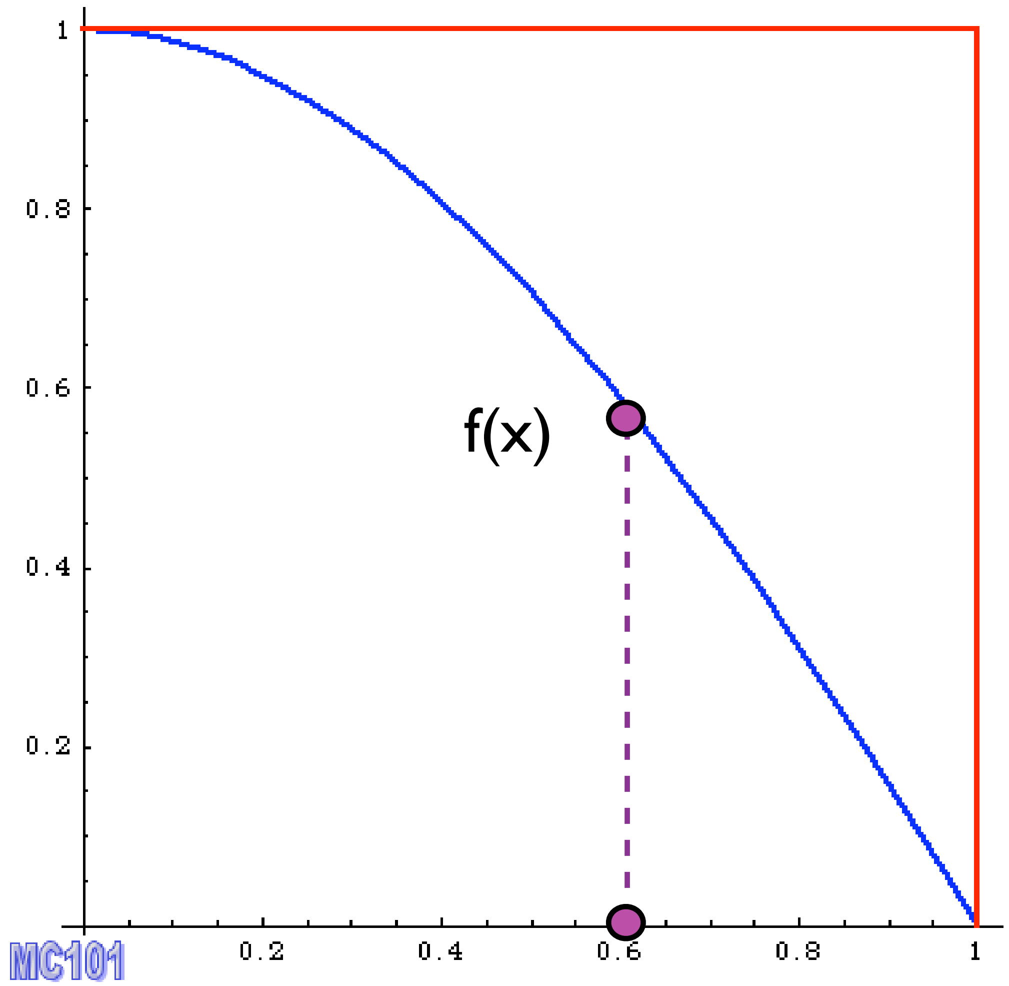
Event generation



Alternative way

1. pick x
2. calculate f(x)

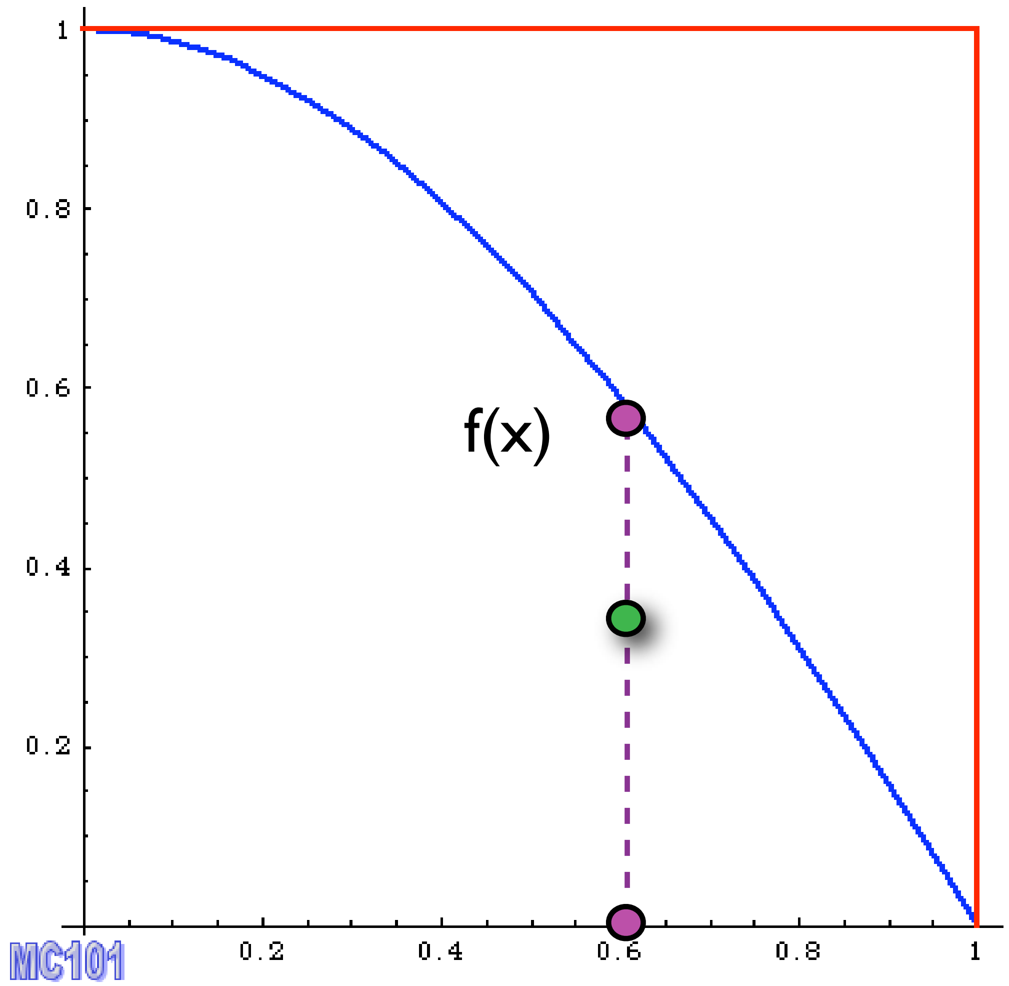
Event generation



Alternative way

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

Event generation



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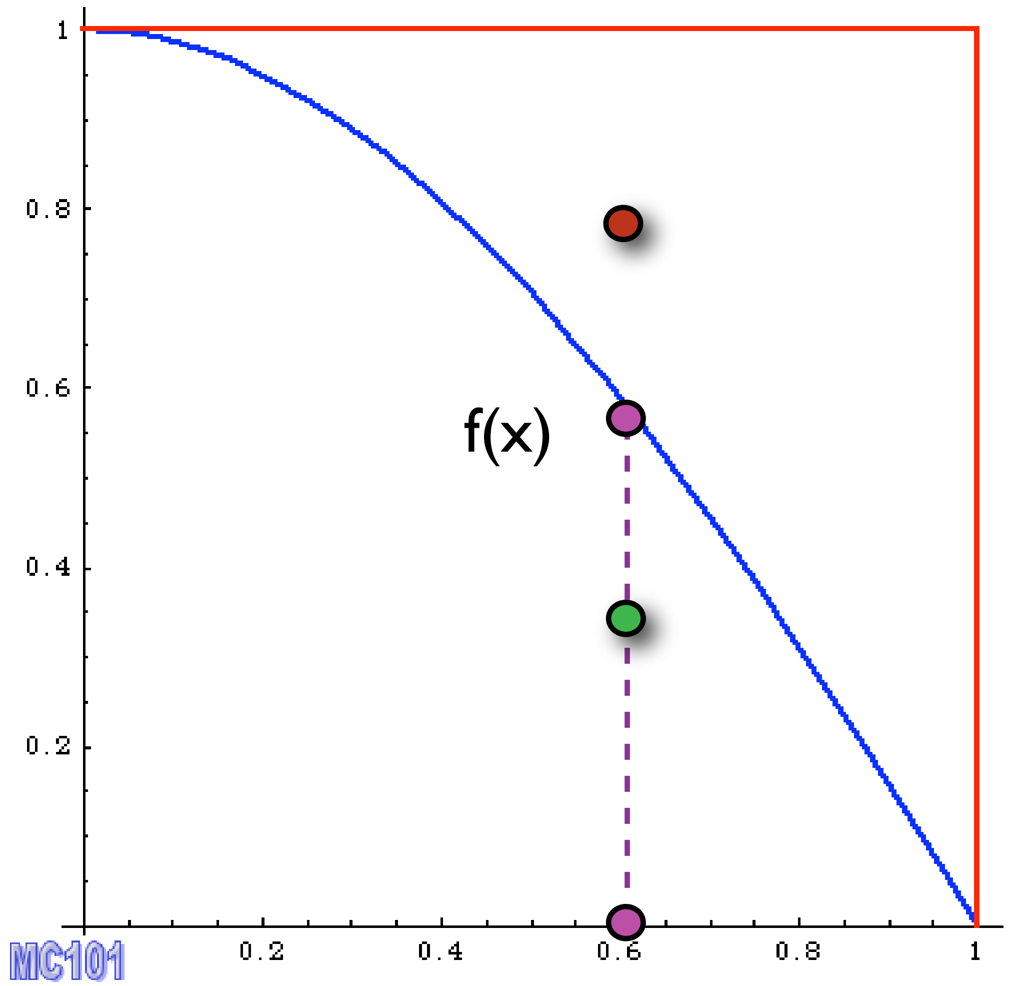
Event generation



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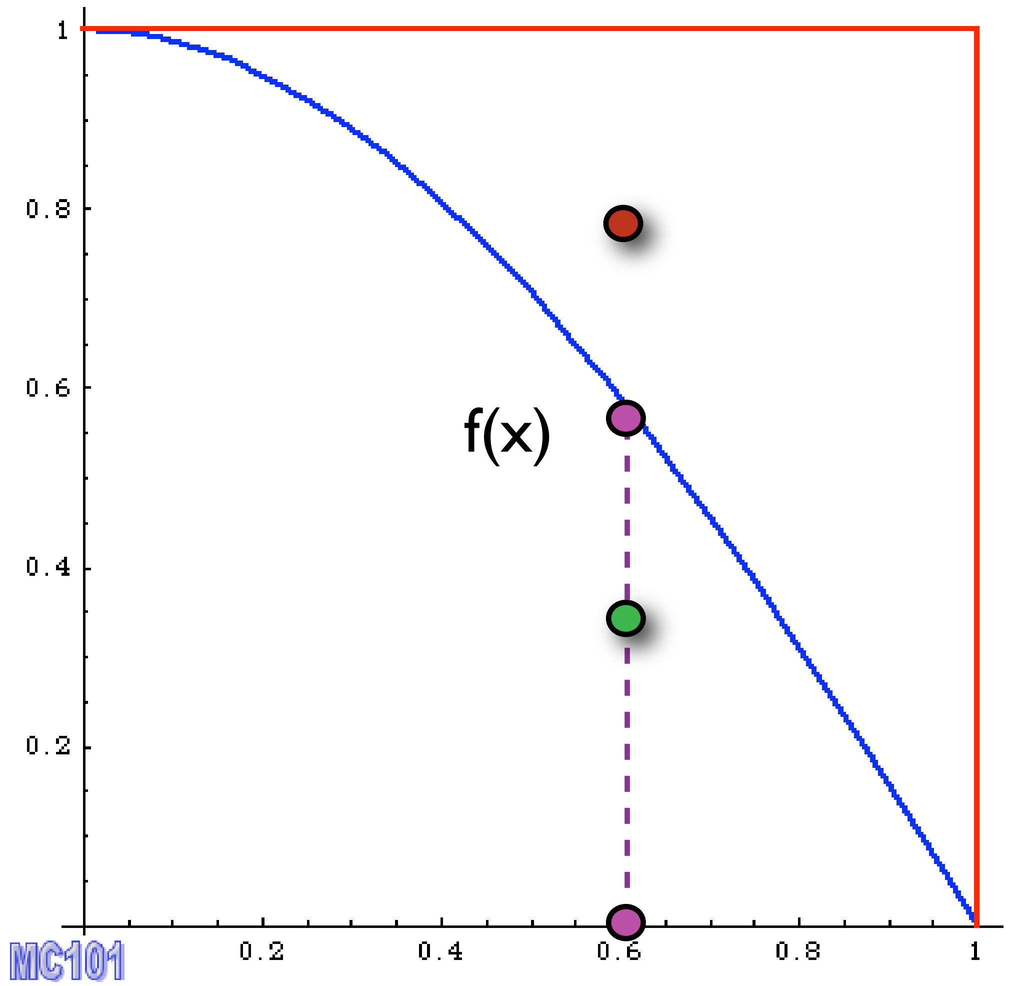

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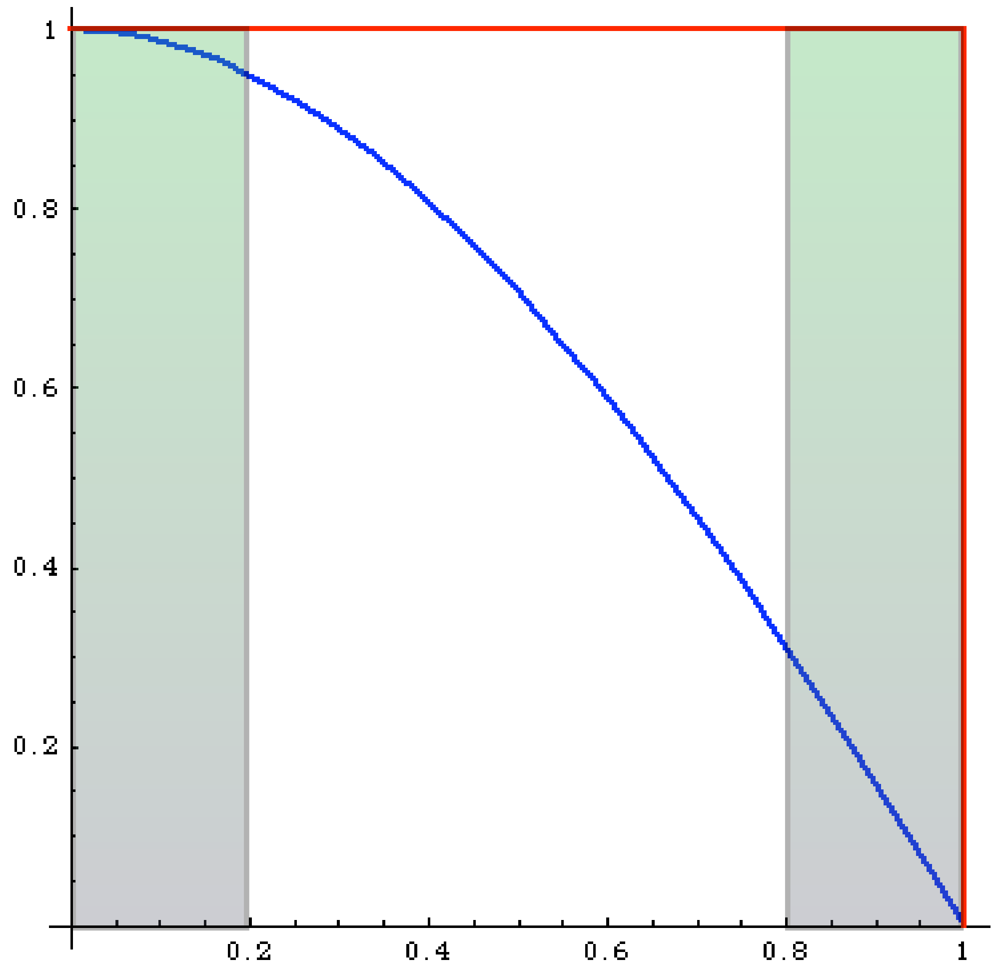
3. pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

   else reject it.

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

Event generation

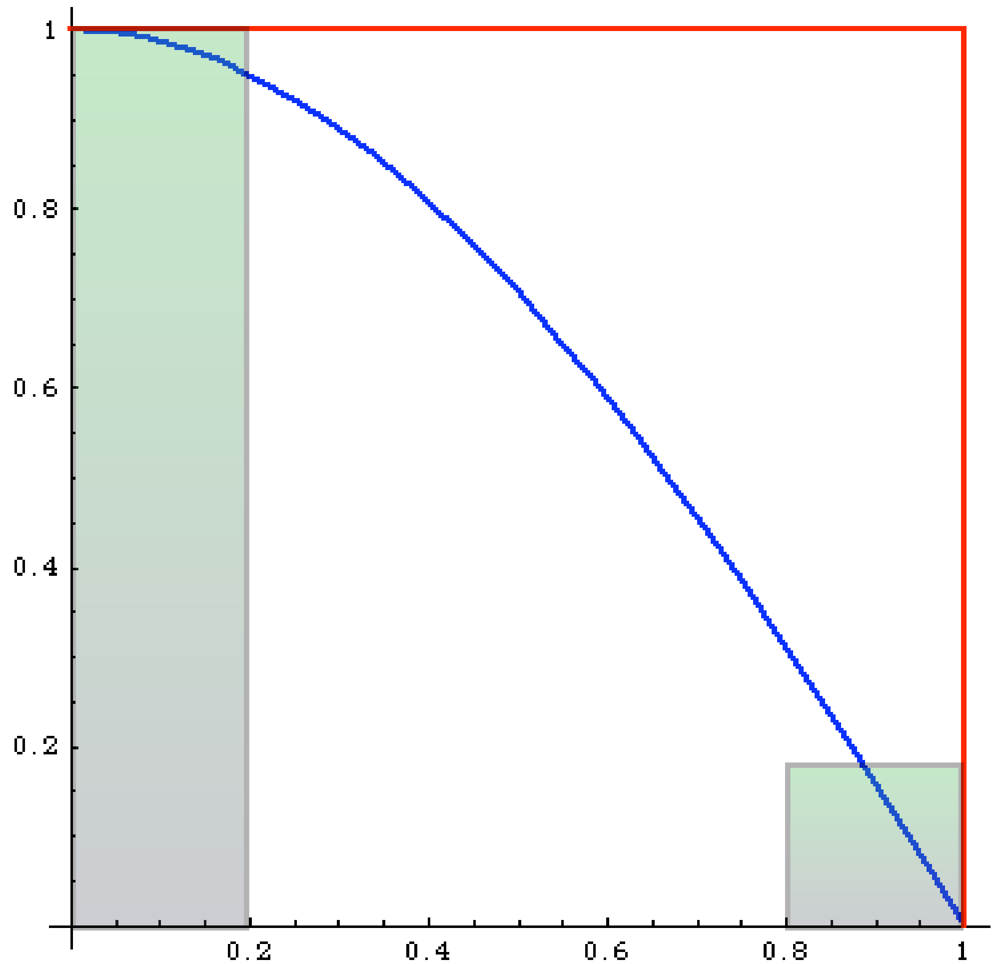


What's the difference?

Before:

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

Event generation



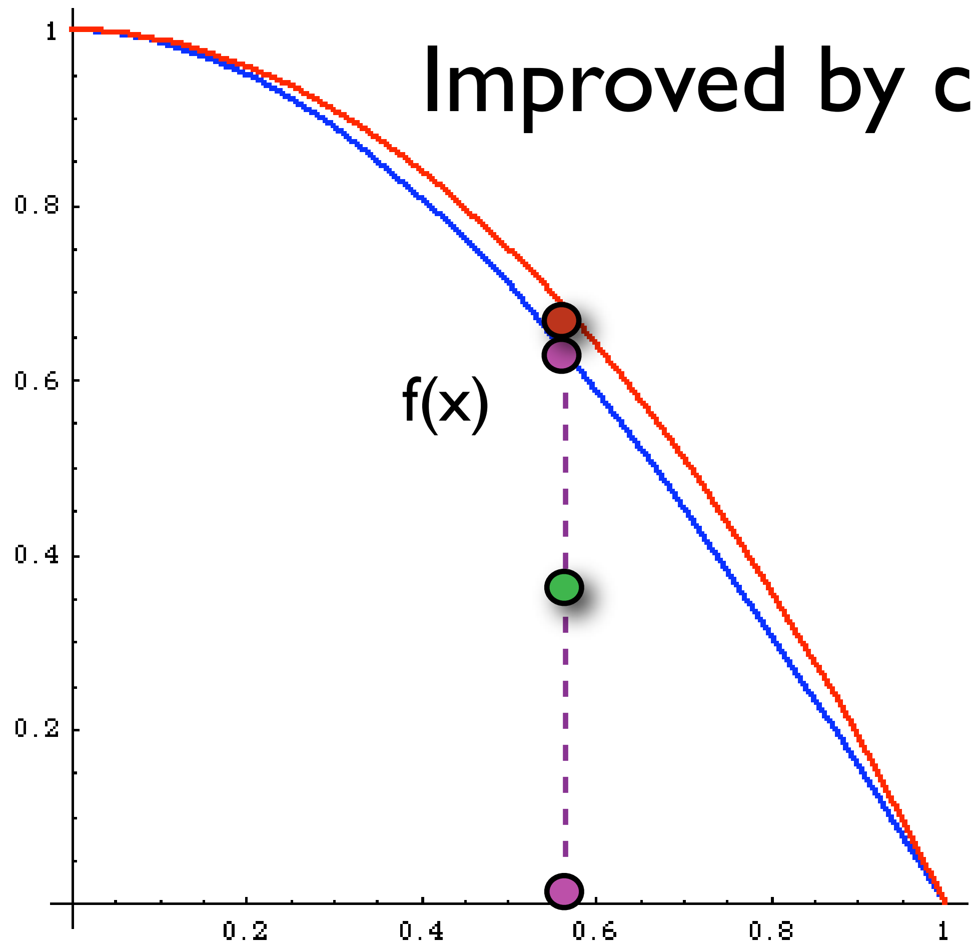
What's the difference?

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 by combining with importance sampling:

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.

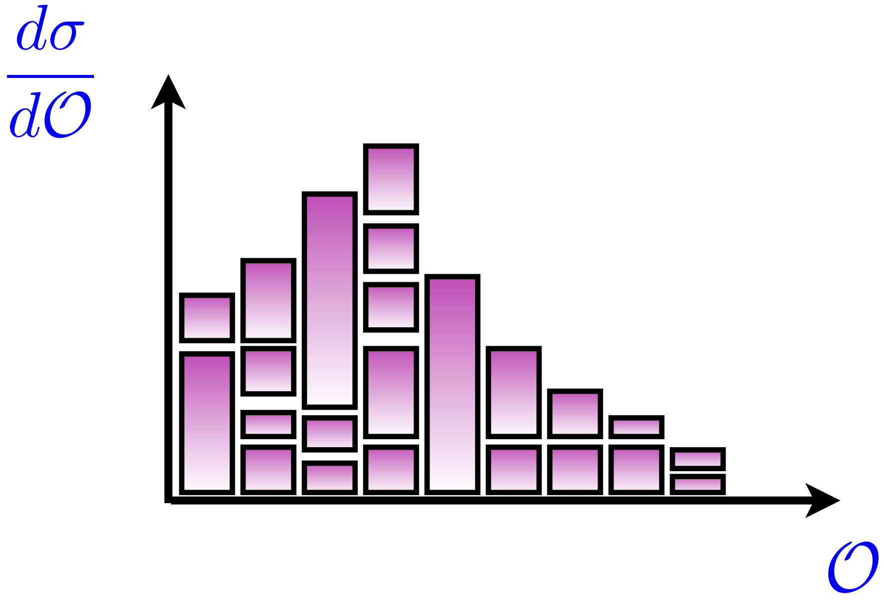
much better efficiency!!!

Event generation

MC integrator

Event generation

MC integrator



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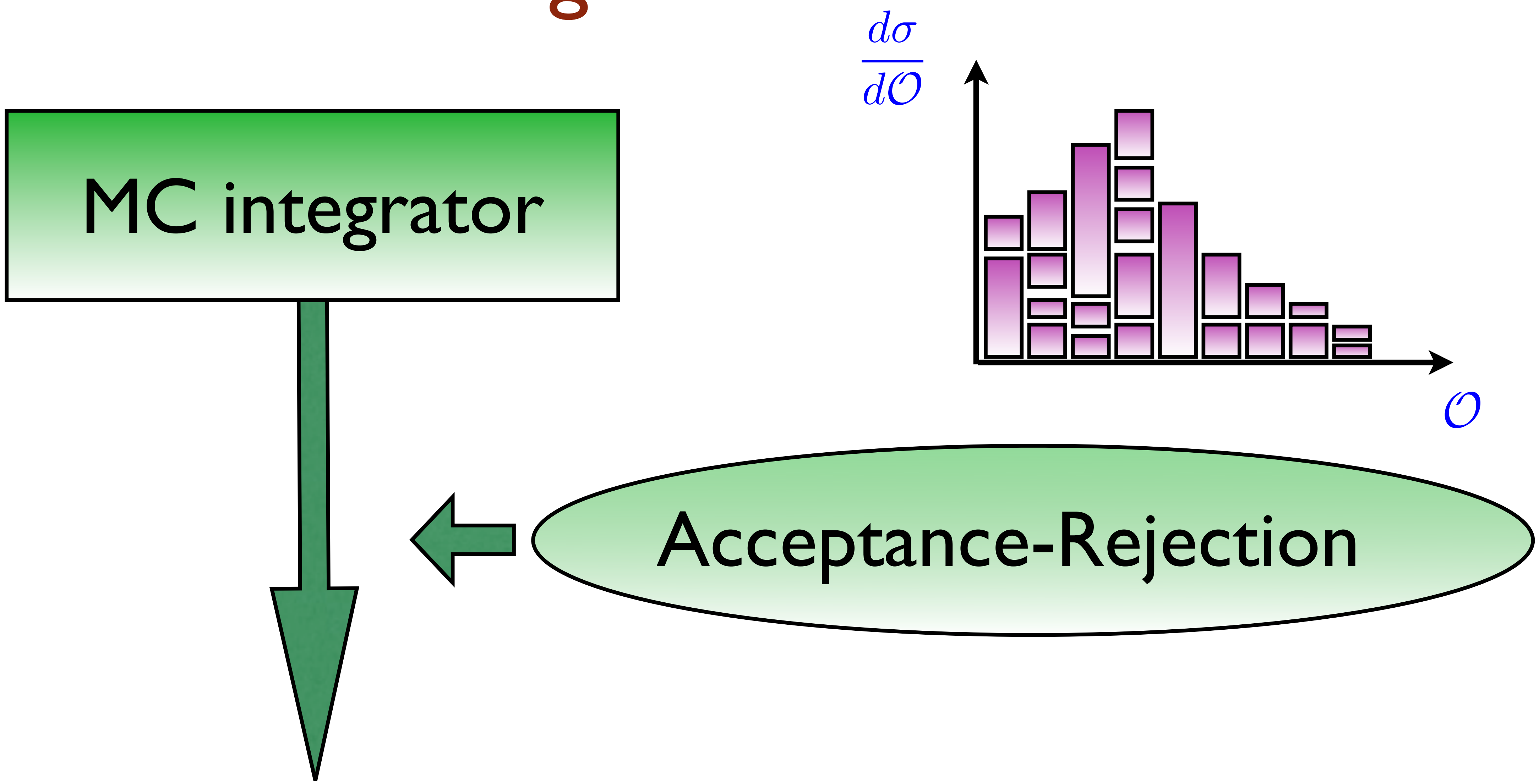

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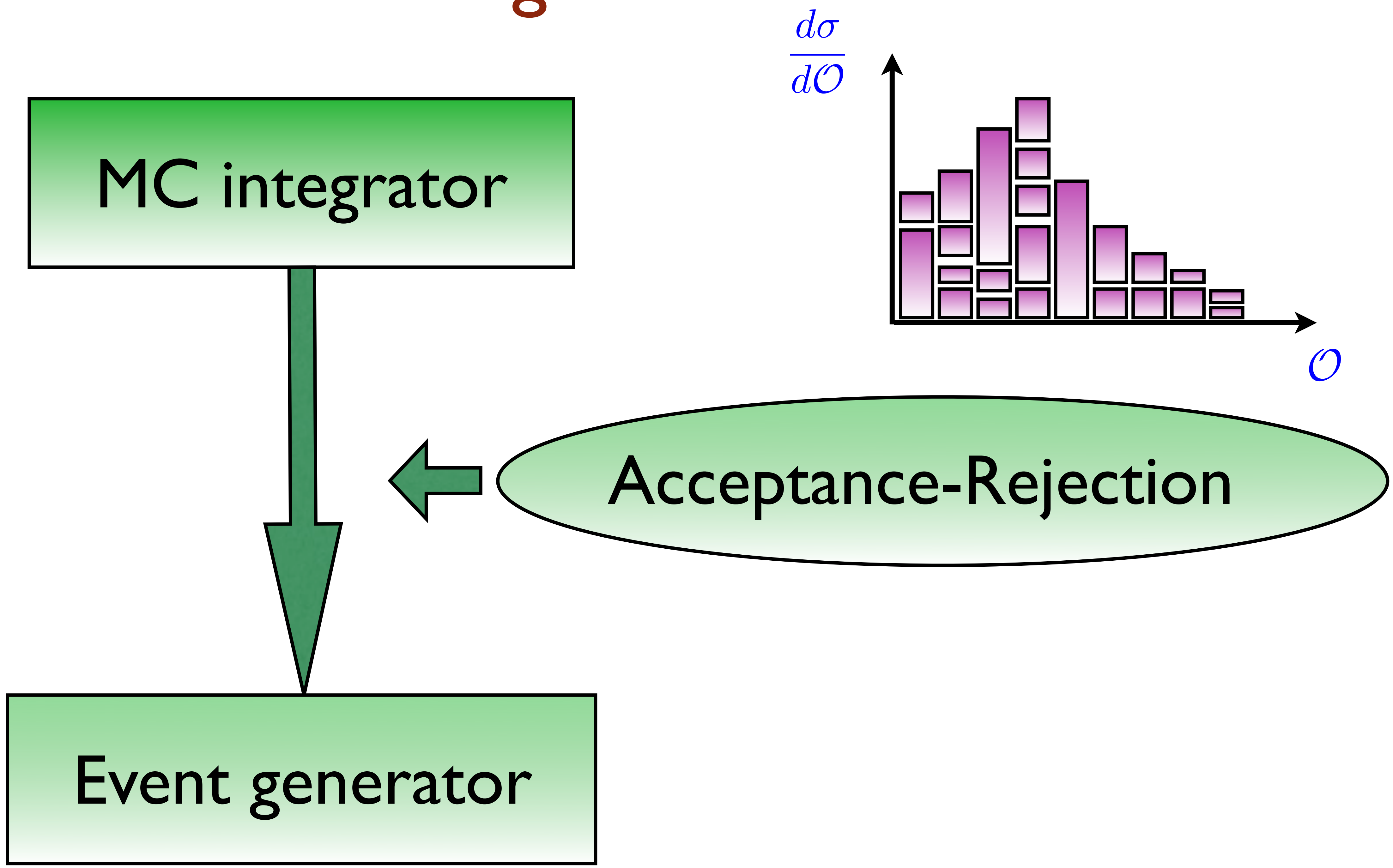

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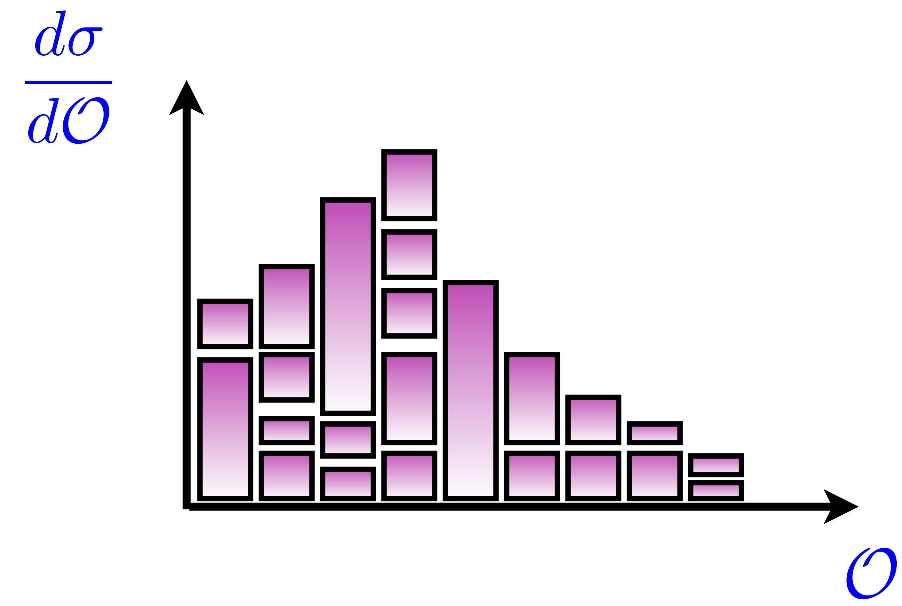
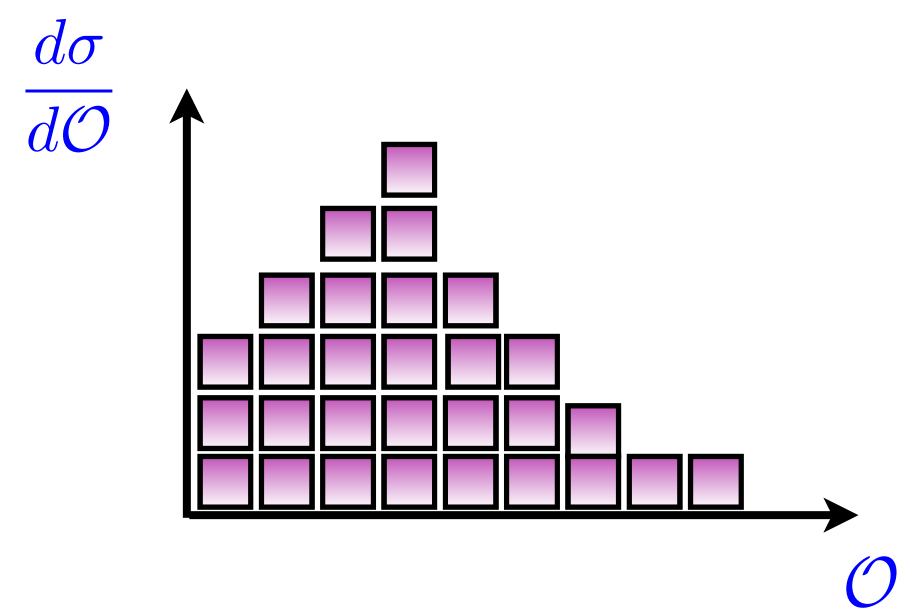


MC integrator

↓

Acceptance-Rejection

Event generator



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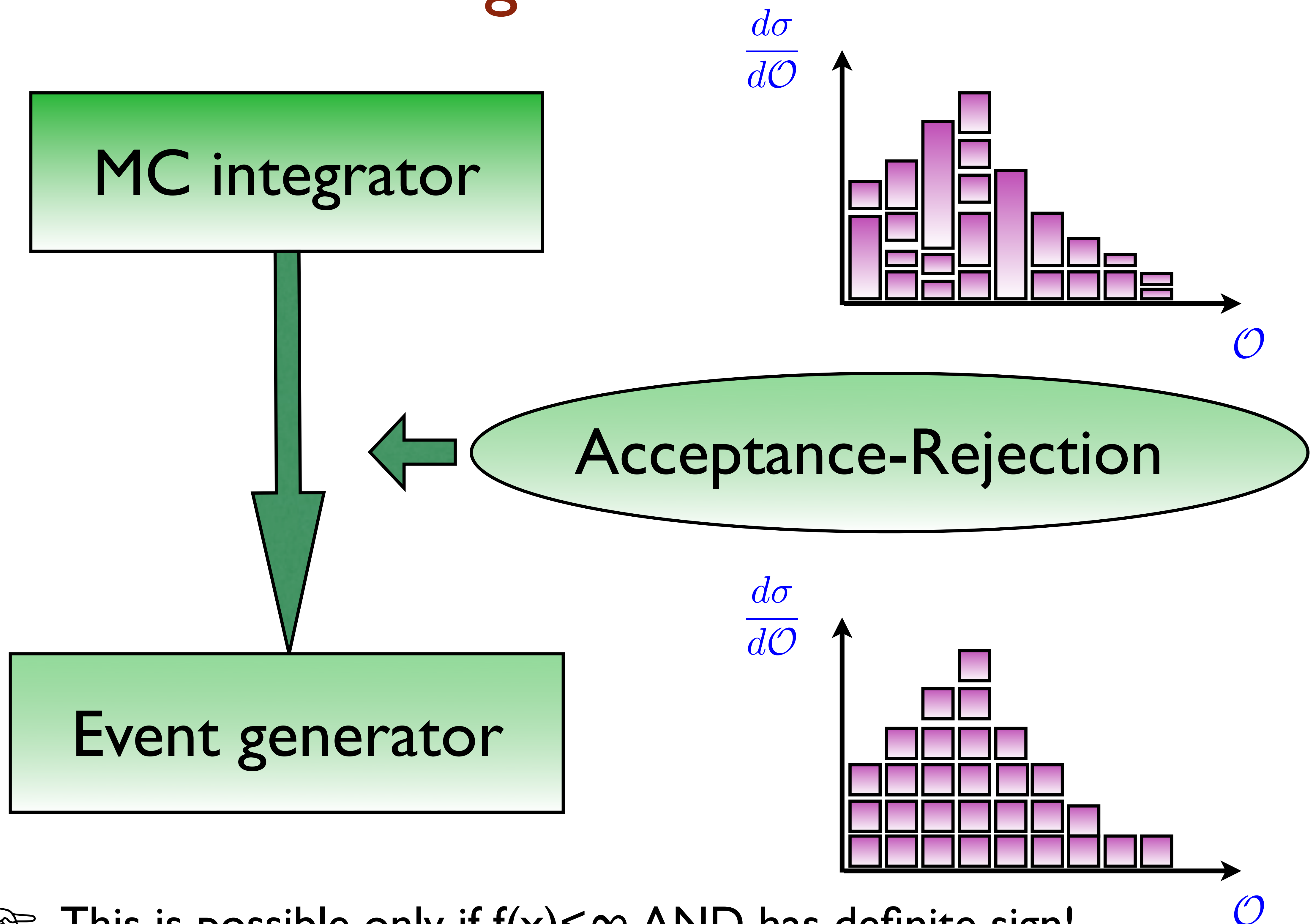


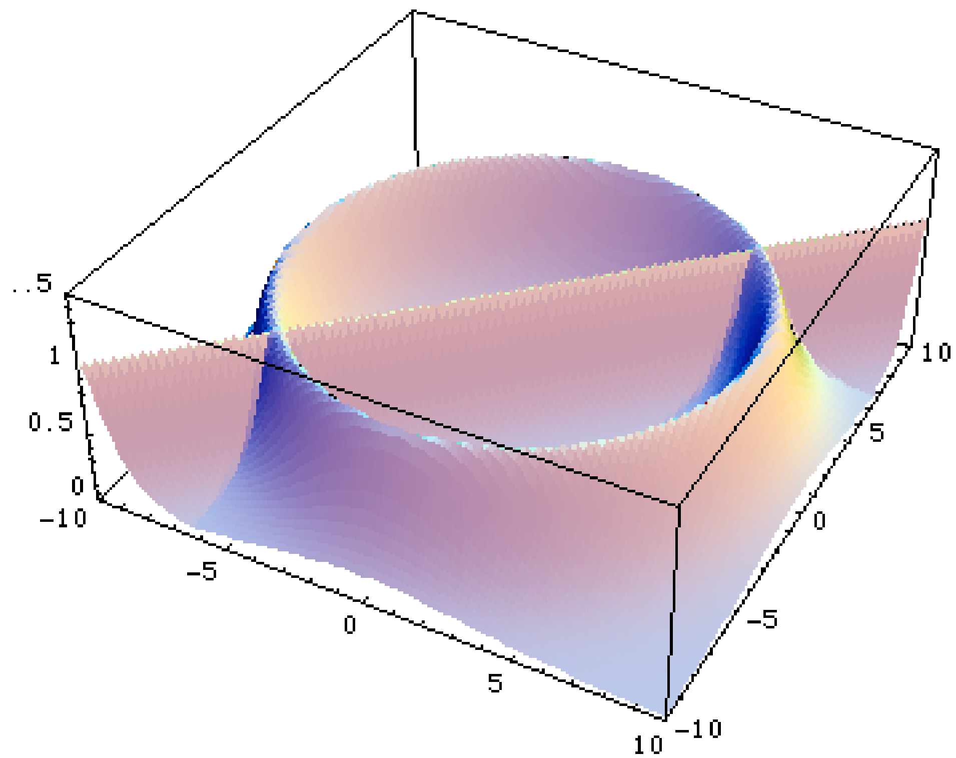
☞ This is possible only if f(x)<∞ AND has definite sign!

Monte Carlo Event Generator: Definiton

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).

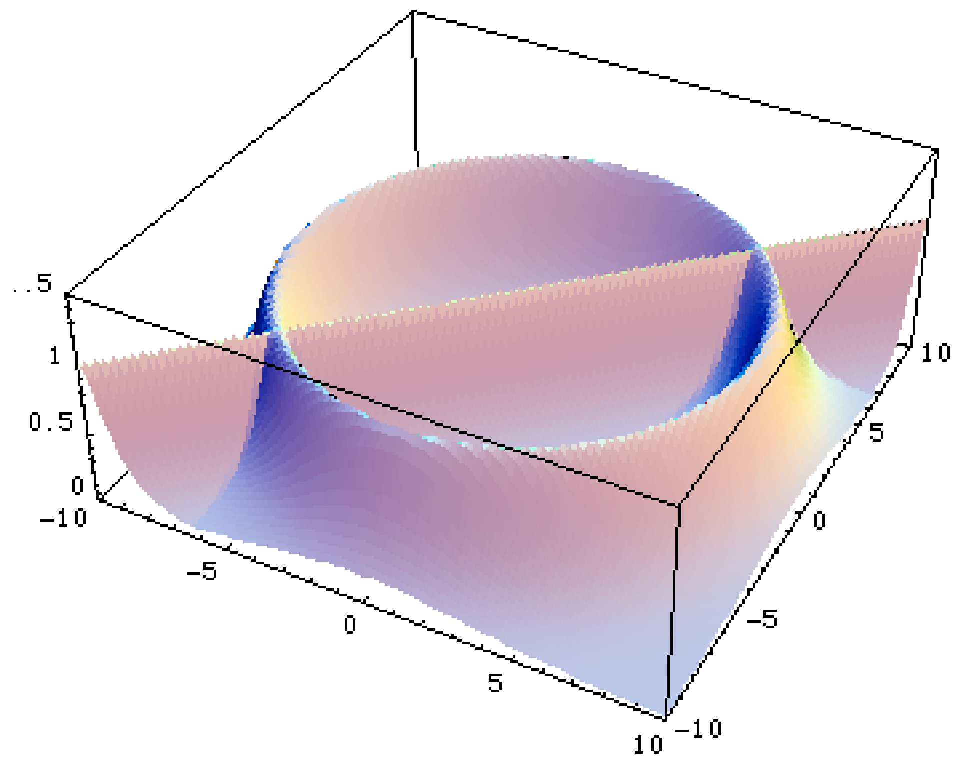
In practice it performs a large number of (sometimes very difficult) integrals and then unweight to give the four momenta of the particles that interact with the detector (simulation).

Multi-channel



What do we do if there is no transformation that aligns all integrand peaks to the chosen axes? Vegas is bound to fail!

Multi-channel



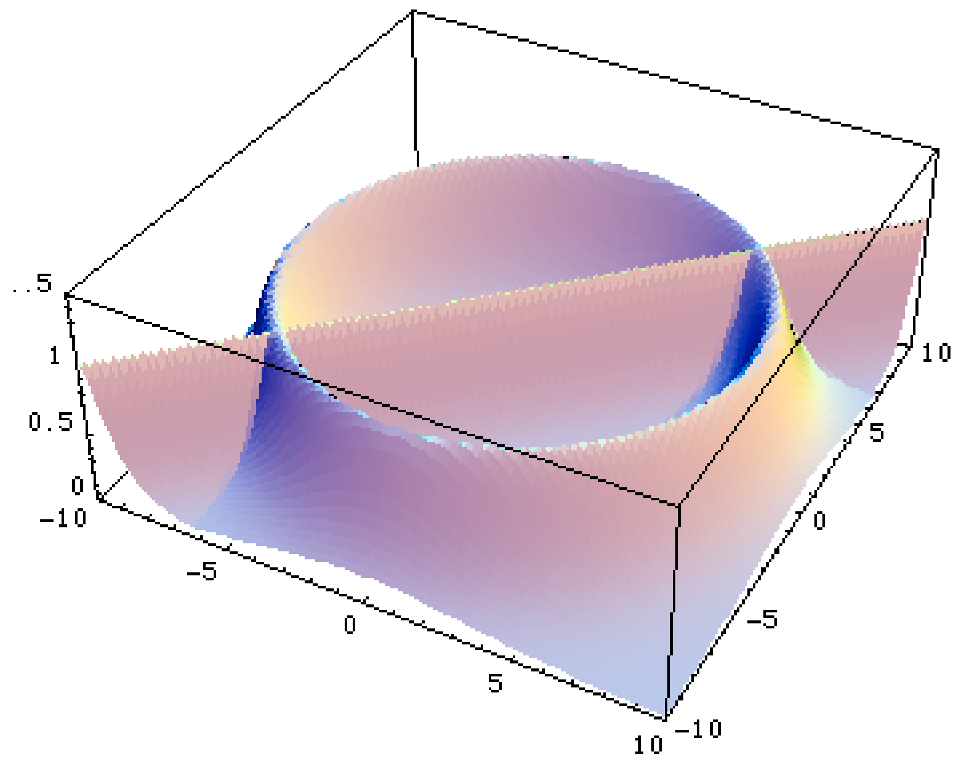
What do we do if there is no transformation that aligns all integrand peaks to the chosen axes? Vegas is bound to fail!

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



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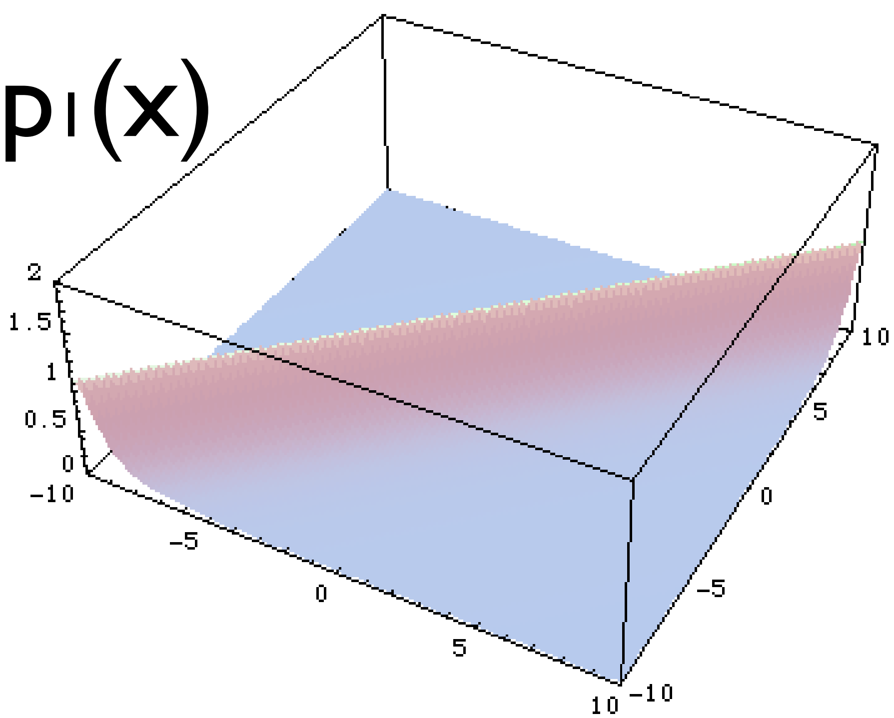
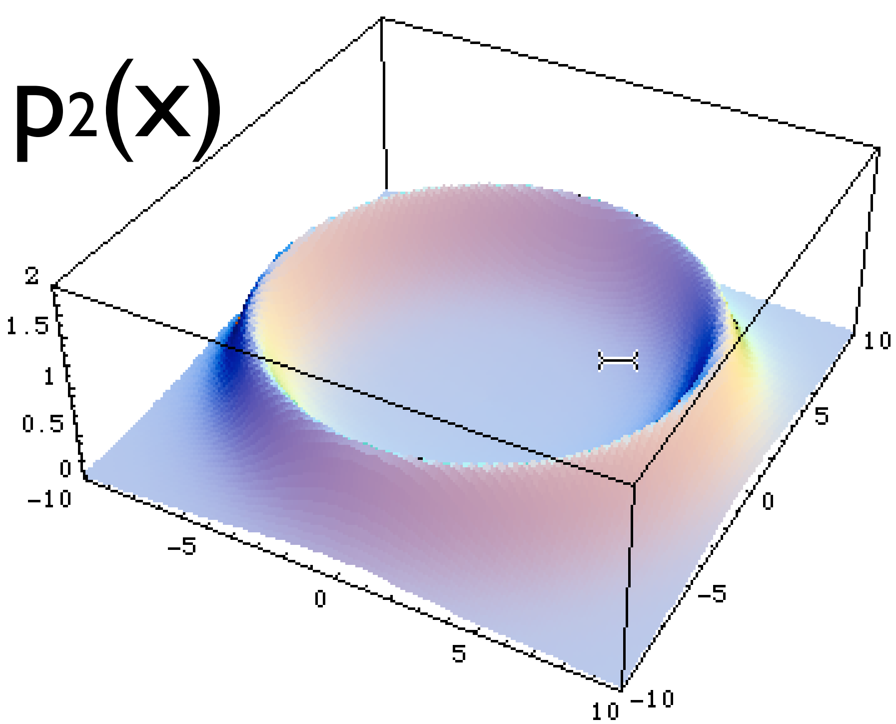
$p_1(x)$



$p_2(x)$



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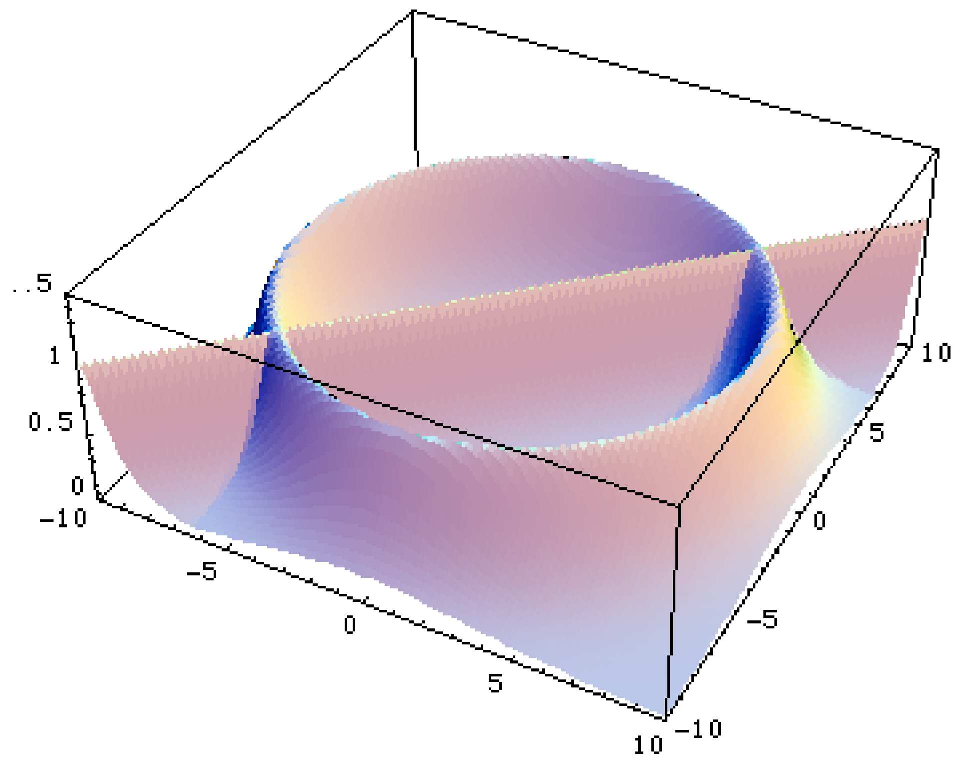

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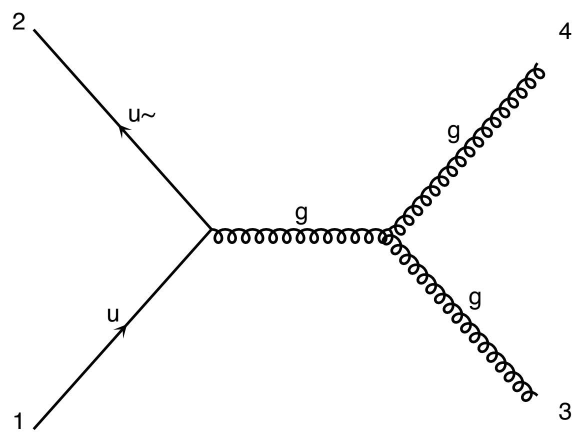
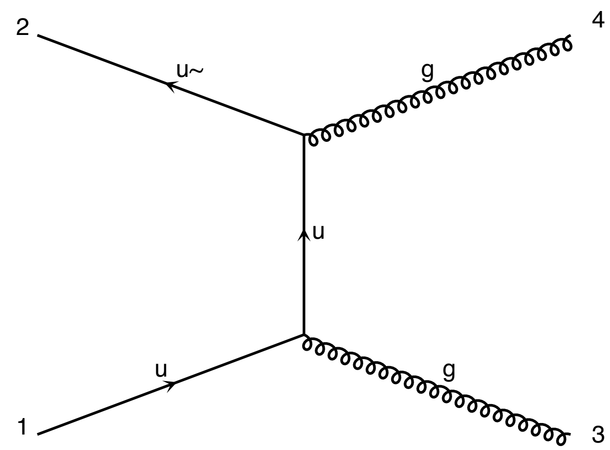
$$I = \int f(x)dx = \sum_{i=1}^{n} \alpha_i \int \frac{f(x)}{p(x)} p_i(x) dx$$

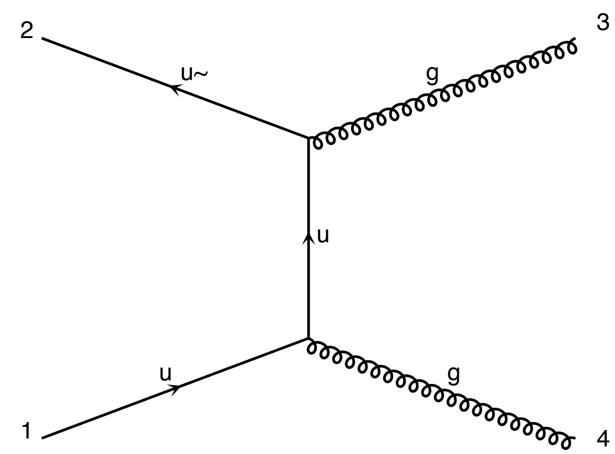
Multi-channel

- Advantages
  - The integral does not depend on the α_i but the variance does and can be minimized by a careful choice
- Drawbacks
  - Need to calculate all g_i values for each point
  - Each phase space channel must be invertible
  - N coupled equations for α_i so it might only work for small number of channels

Example: QCD 2 → 2 production







$$\propto \frac{1}{\hat{s}} = \frac{1}{(p_1 + p_2)^2} \qquad \propto \frac{1}{\hat{t}} = \frac{1}{(p_1 - p_3)^2} \qquad \propto \frac{1}{\hat{u}} = \frac{1}{(p_1 - p_4)^2}$$

Three very different pole structures contributing to the same matrix element.

Multi-channel based on single diagrams

Consider the integration of an amplitude |M|^2 at treel level which many contributing diagrams. If there were a basis of functions,

$$f = \sum_{i=1}^{n} f_i \quad \text{with} \quad f_i \geq 0\,, \quad \forall\ i\,,$$

such that:

1. we know how to integrate each one of them,
2. they describe all possible peaks,

then the problem would be solved:

$$I = \int d\vec{\Phi} f(\vec{\Phi}) = \sum_{i=1}^{n} \int d\vec{\Phi}\, g_i(\vec{\Phi})\, \frac{f_i(\vec{\Phi})}{g_i(\vec{\Phi})} = \sum_{i=1}^{n} I_i\,,$$

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2. they describe all possible peaks,

then the problem would be solved:

$$I = \int d\vec{\Phi} f(\vec{\Phi}) = \sum_{i=1}^{n} \int d\vec{\Phi}\, g_i(\vec{\Phi})\, \frac{f_i(\vec{\Phi})}{g_i(\vec{\Phi})} = \sum_{i=1}^{n} I_i\,,$$

Does such a basis exist?

Multi-channel based on single diagrams*

YES! $$f_i = \frac{|A_i|^2}{\sum_i |A_i|^2}|A_{\rm tot}|^2$$

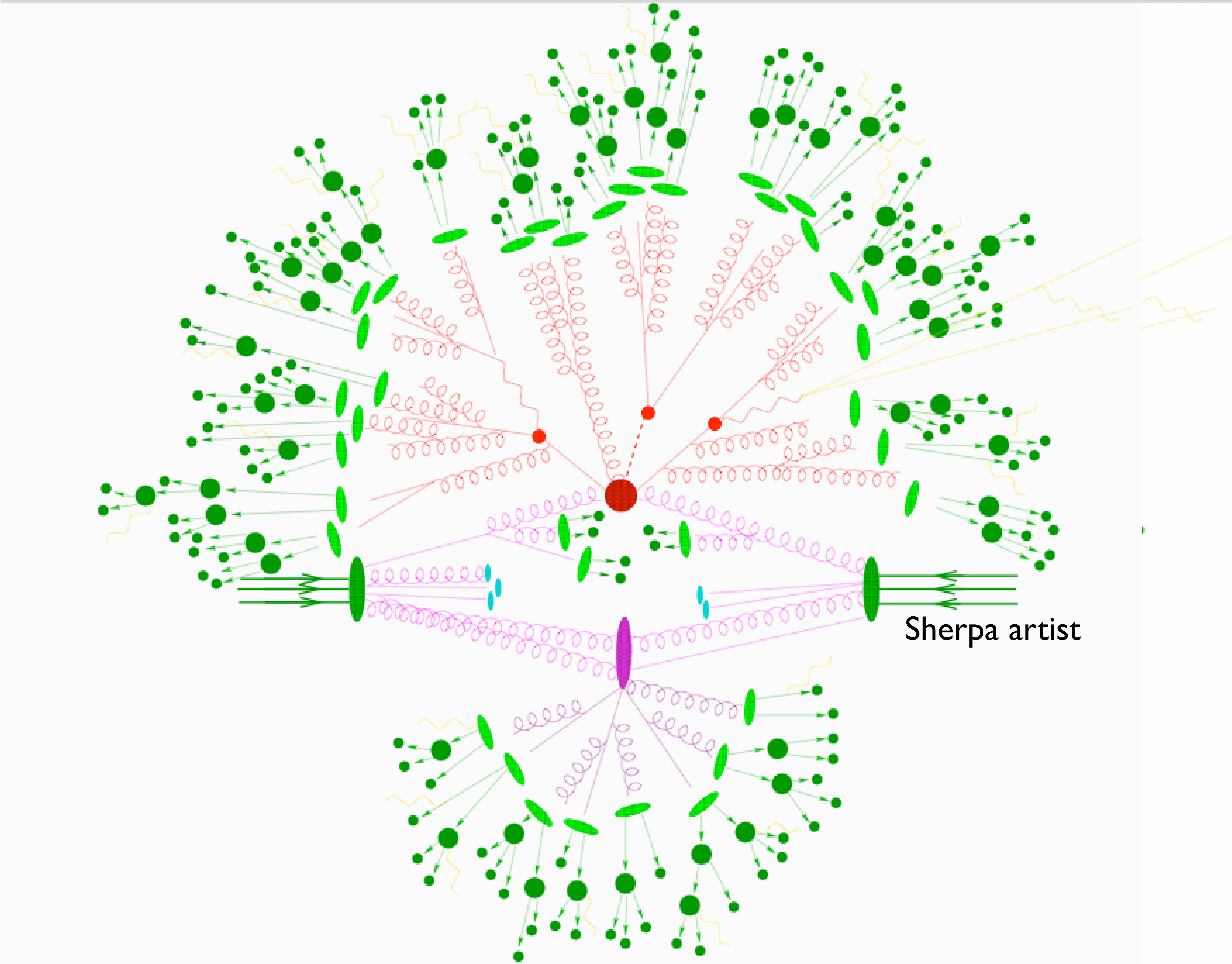
Multi-channel based on single diagrams*

YES! $$f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\text{tot}}|^2$$

- Key Idea
  - Any single diagram is "easy" to integrate (pole structures known based on propagators)
  - Divide integration into pieces, based on diagrams
- Get N independent integrals
  - Errors add in quadrature so no extra cost
  - No need to calculate "weight" function from other channels.
  - Can optimize # of points for each one independently
  - Parallel in nature
- What about interference?
  - Never creates "new" peaks, so we're OK!

*Method used in MadGraph

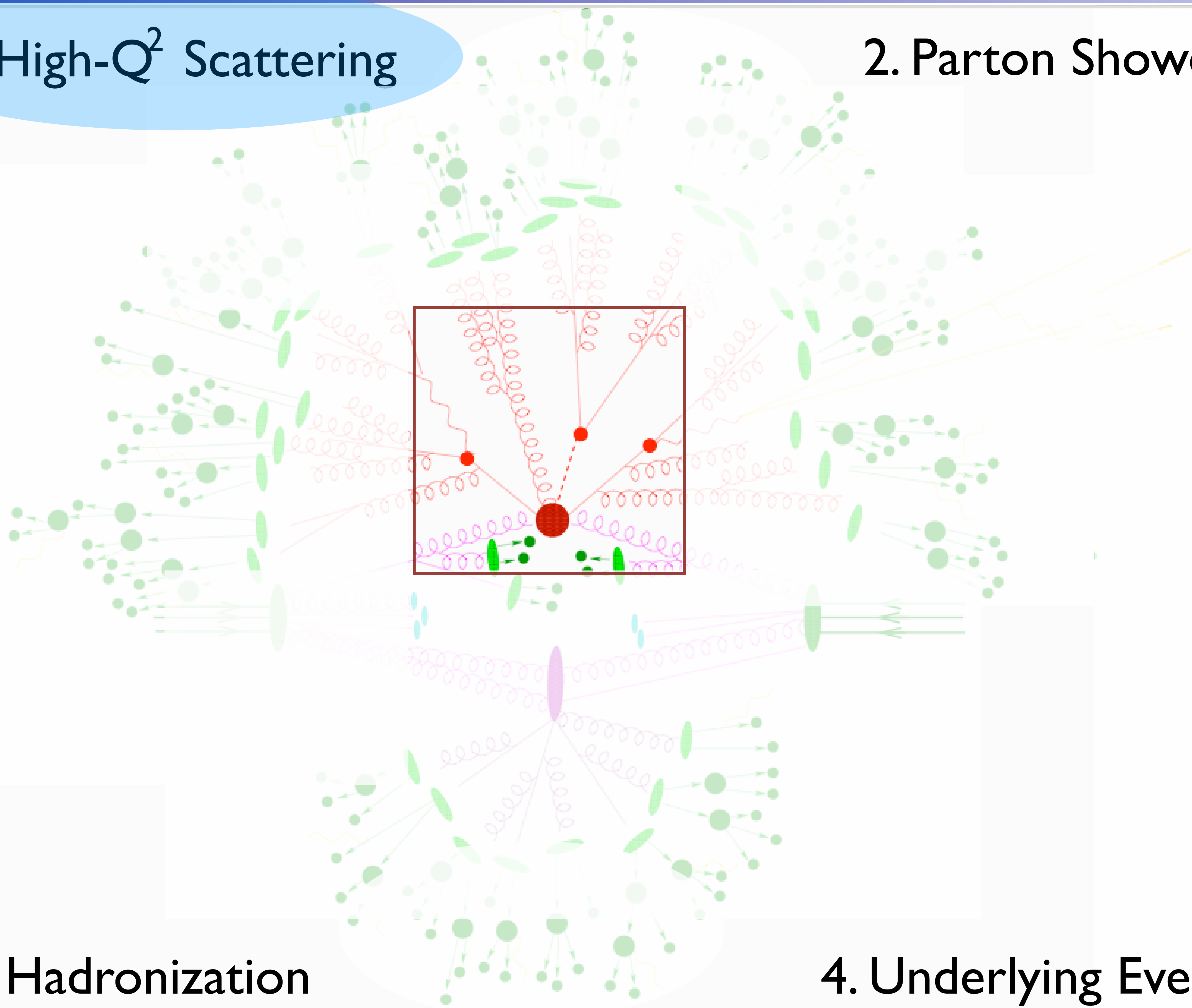
Complete simulation of collider events



Sherpa artist

1. High-Q^2 Scattering

2. Parton Shower



3. Hadronization

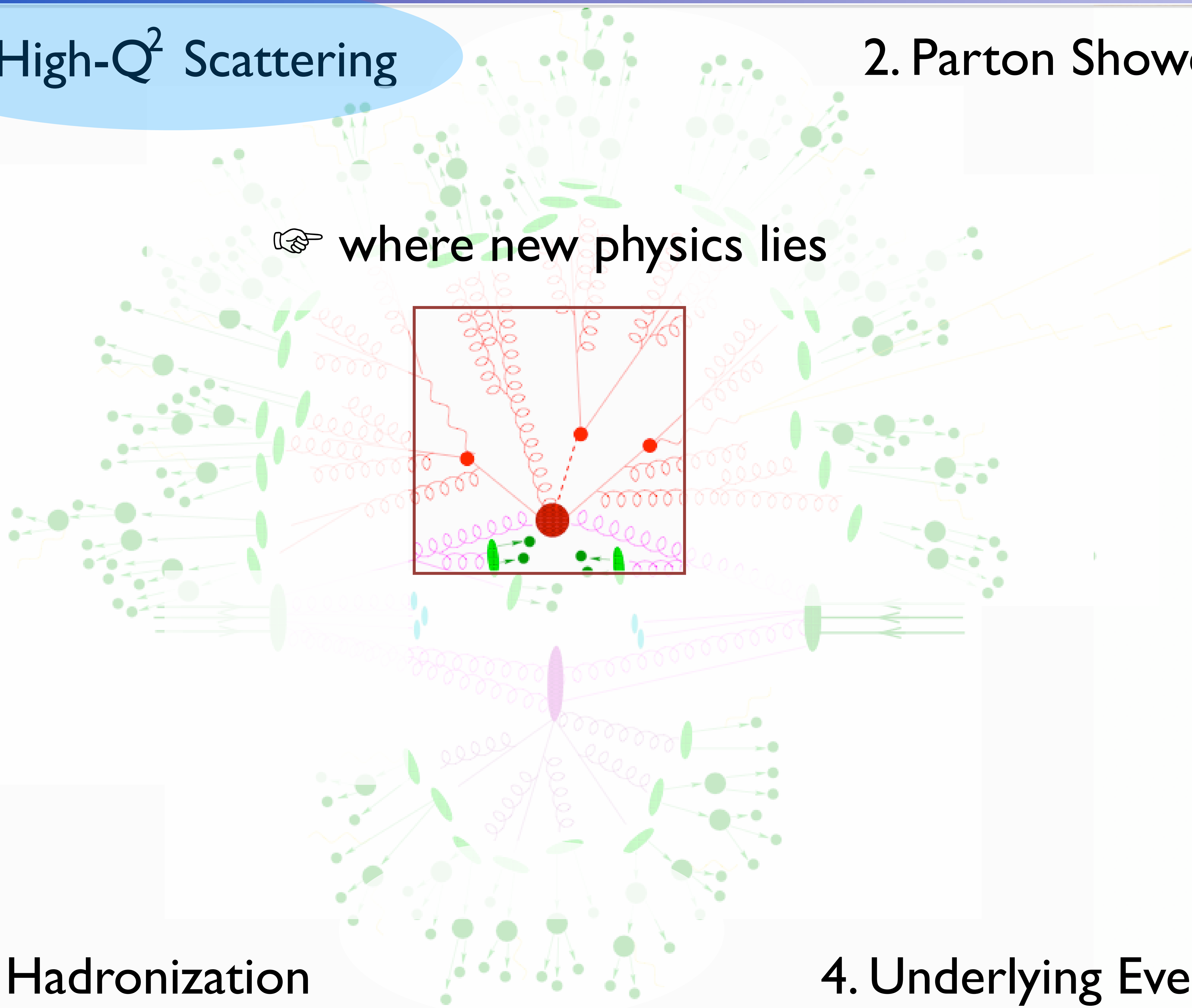
4. Underlying Event

Fermilab

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



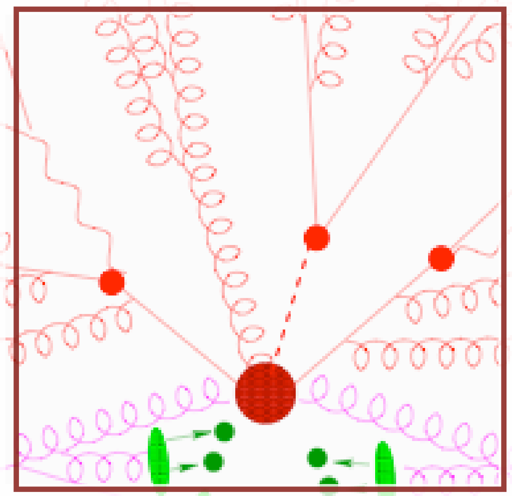
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

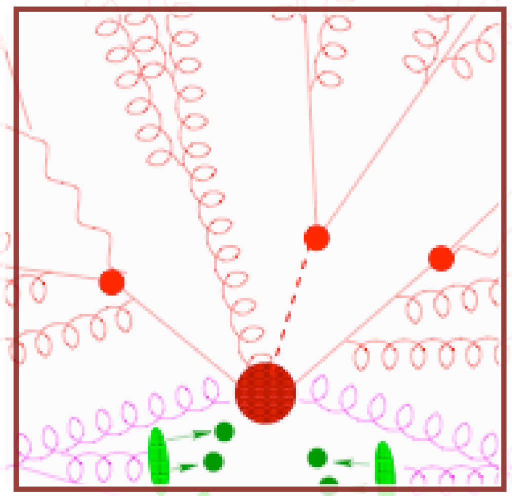
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

☞ first principles description

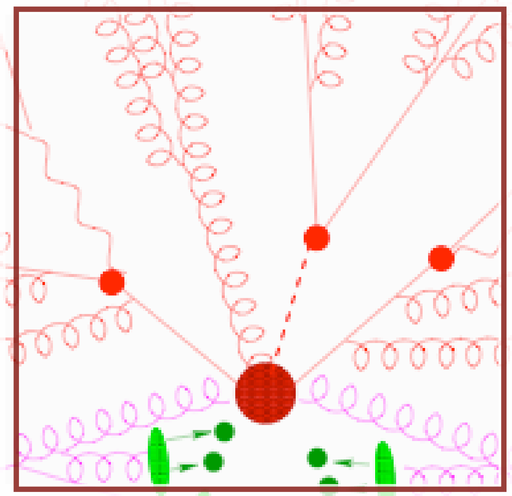
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

☞ first principles description

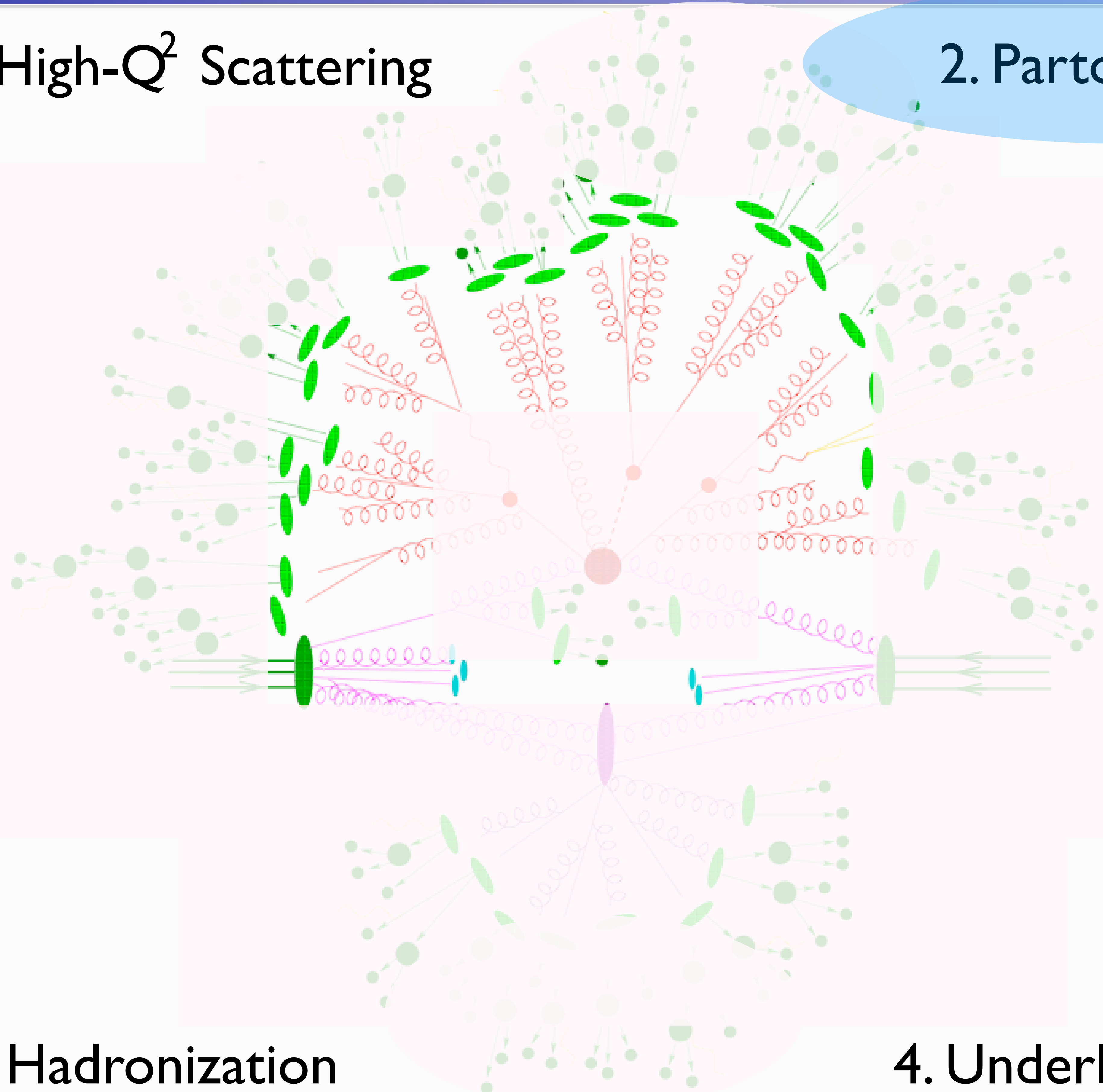
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

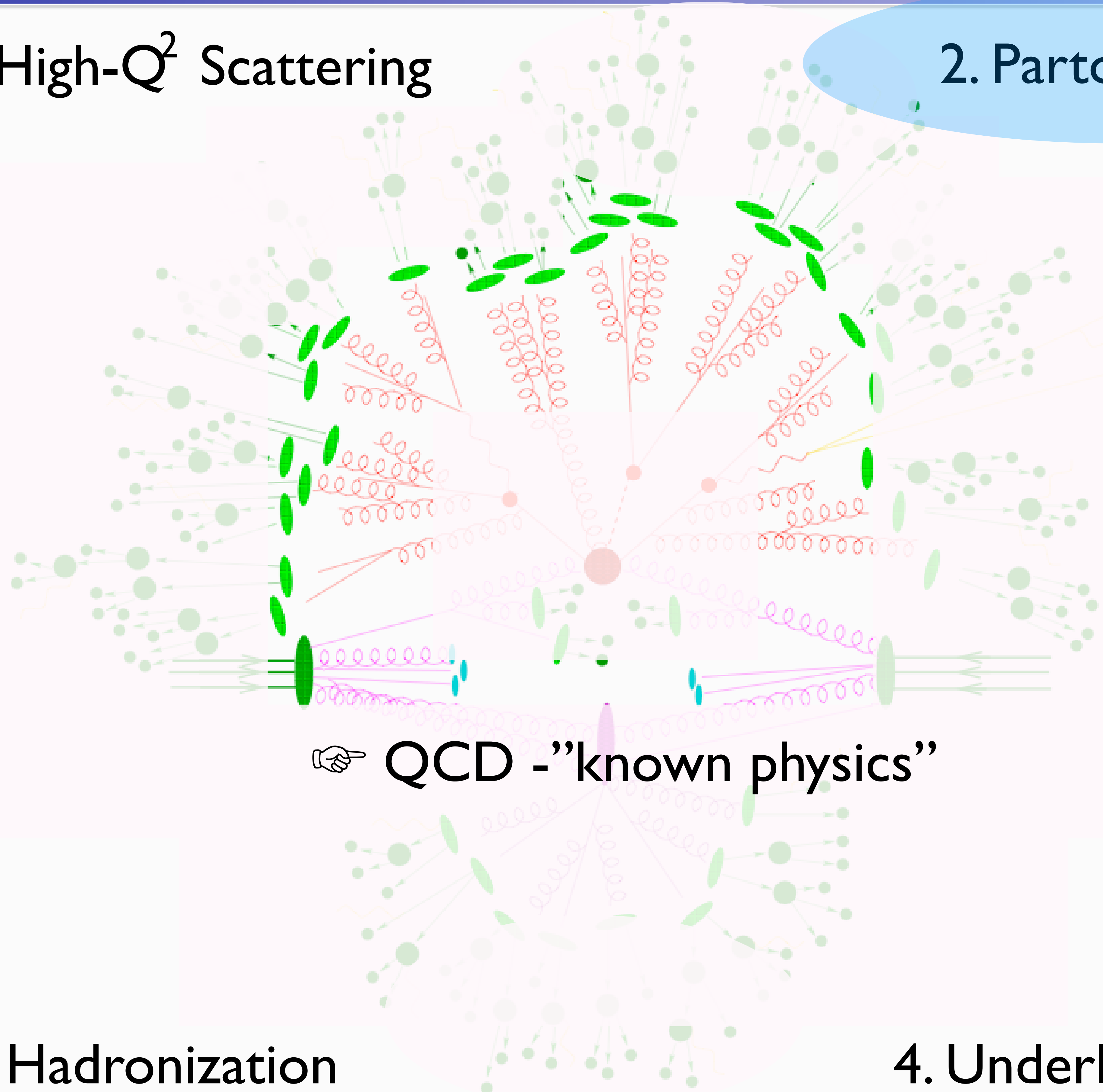


3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



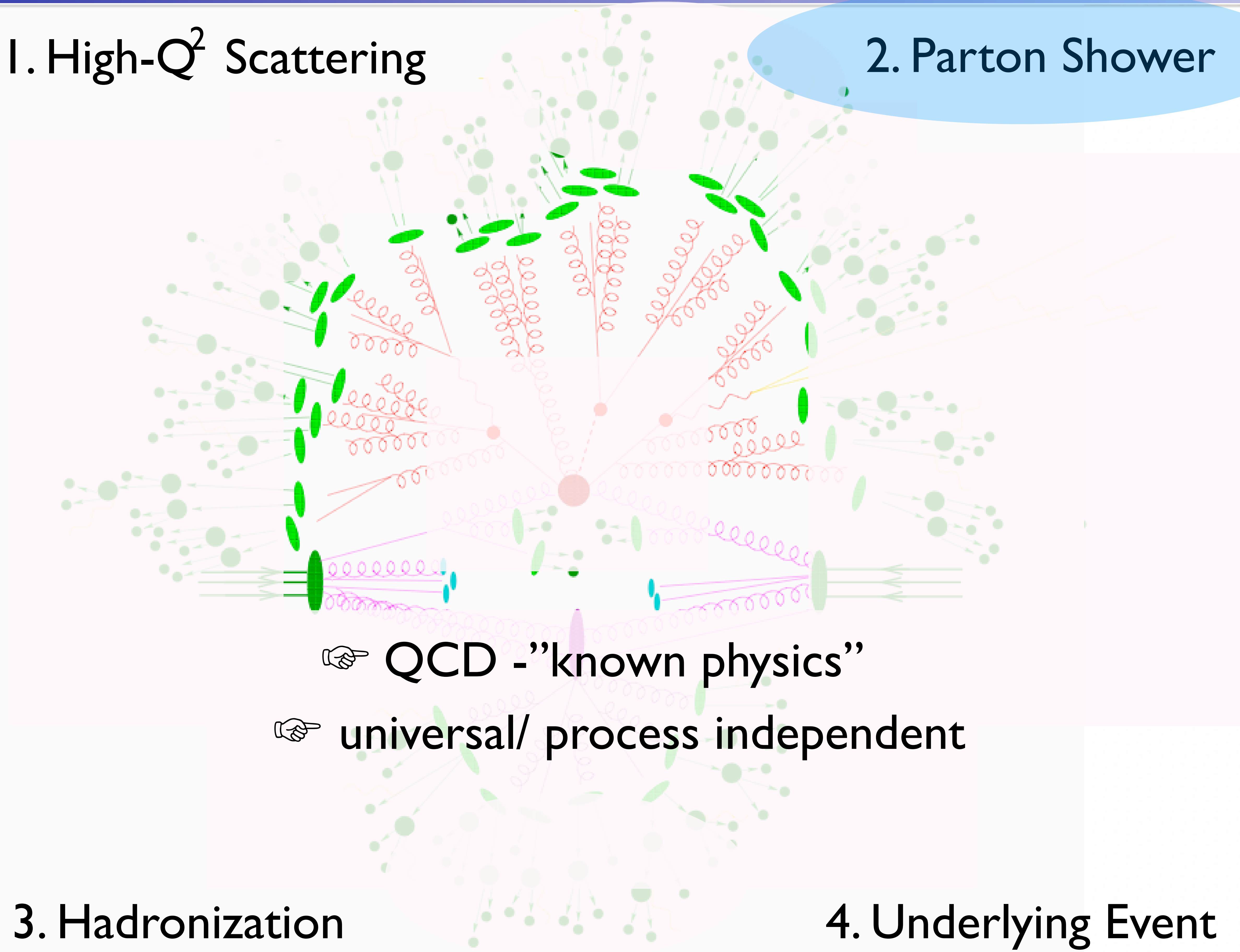
☞ QCD -"known physics"

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ QCD -"known physics"

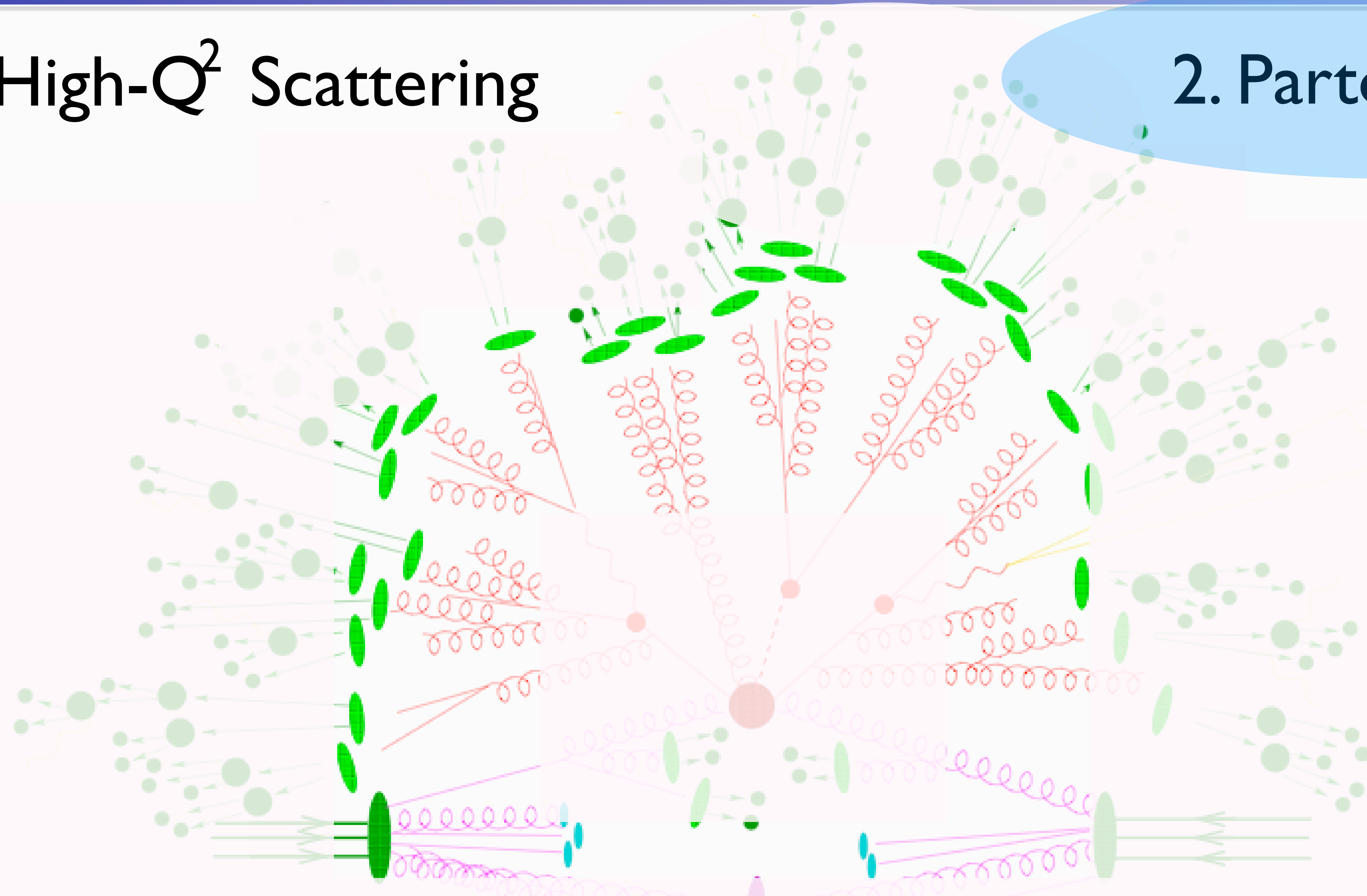
☞ universal/ process independent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



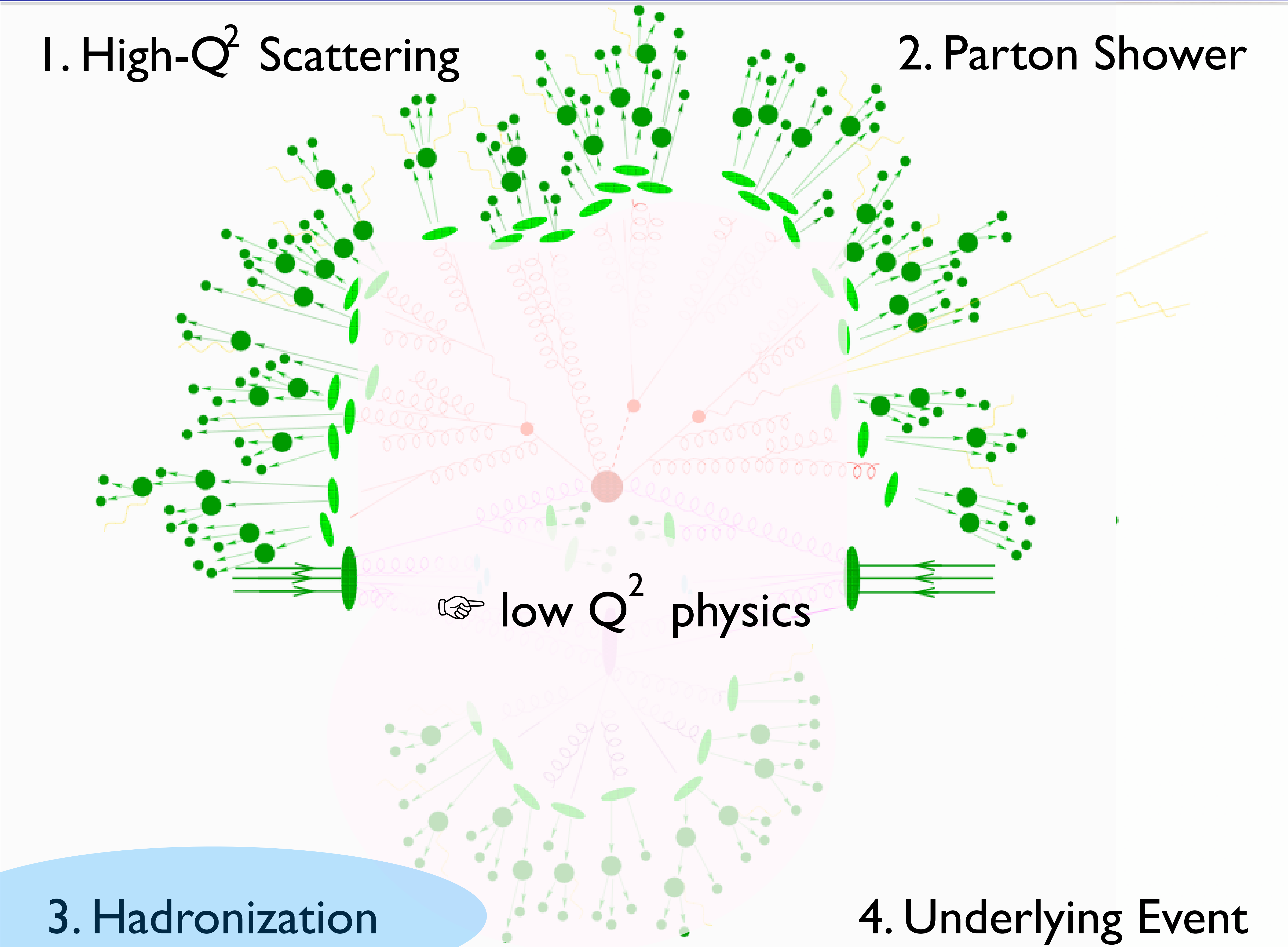
☞ QCD -"known physics"

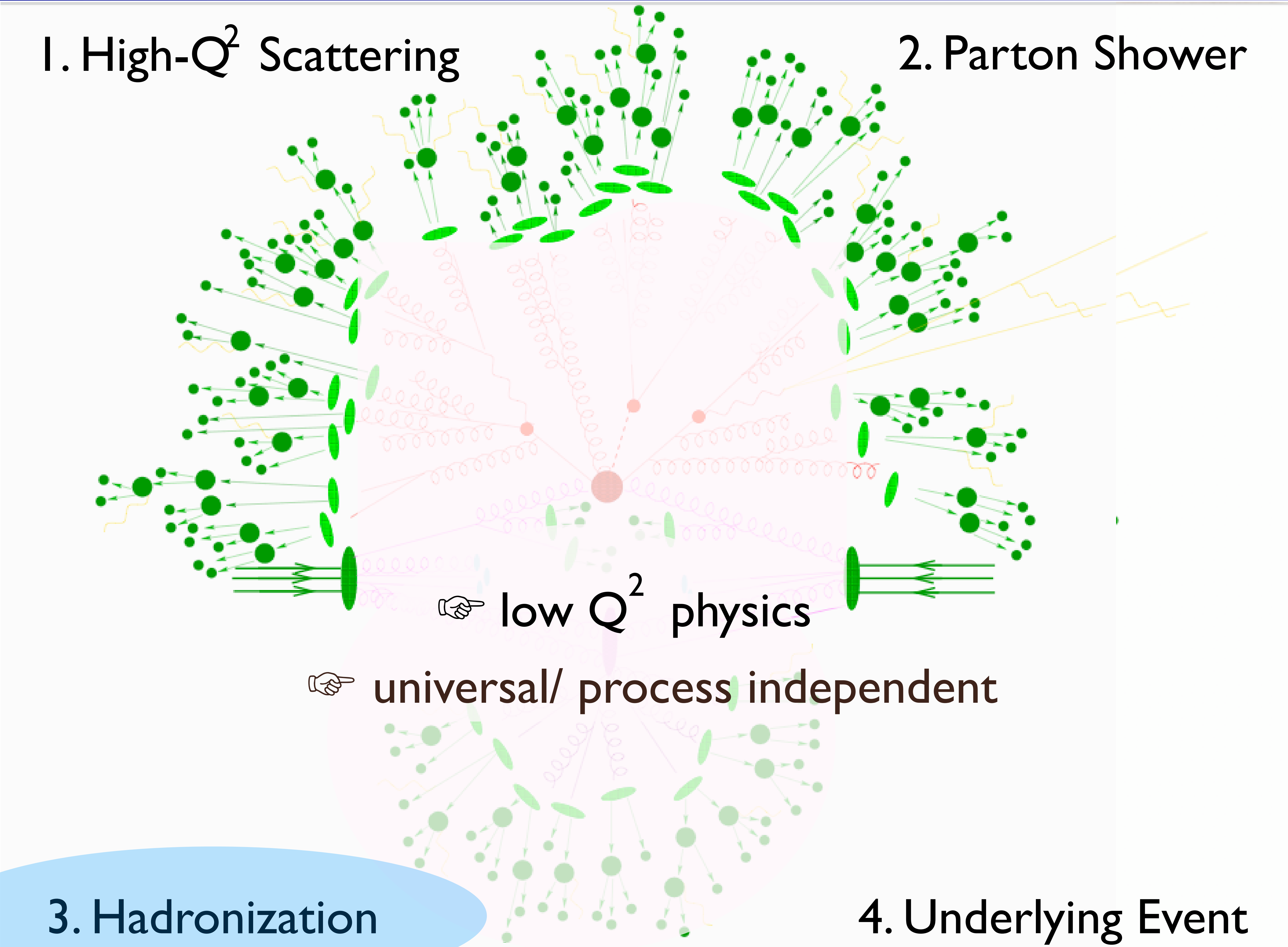
☞ universal/ process independent

☞ first principles description

3. Hadronization

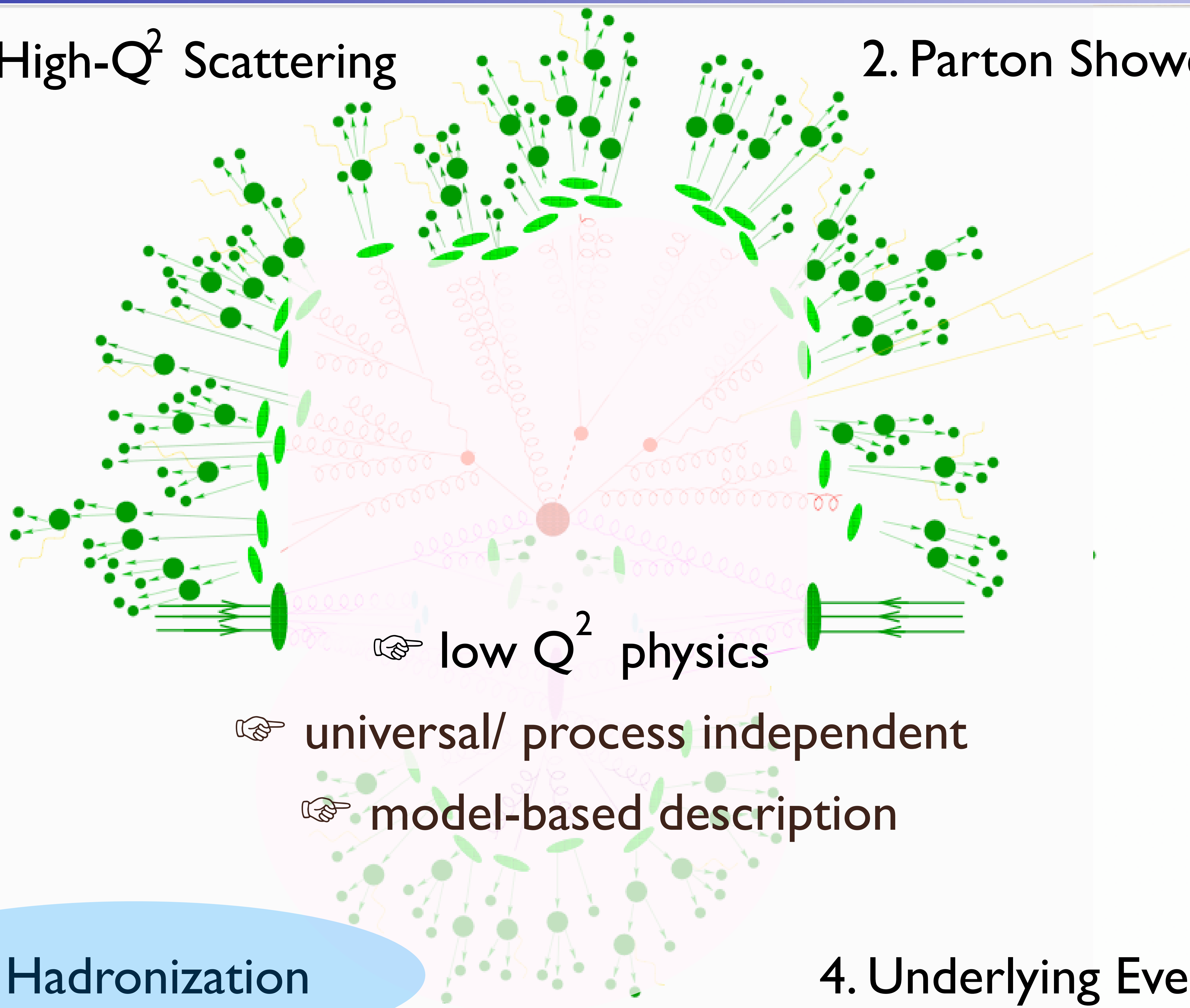
4. Underlying Event


1. High-Q² Scattering
2. Parton Shower
☞ low Q² physics
3. Hadronization
4. Underlying Event

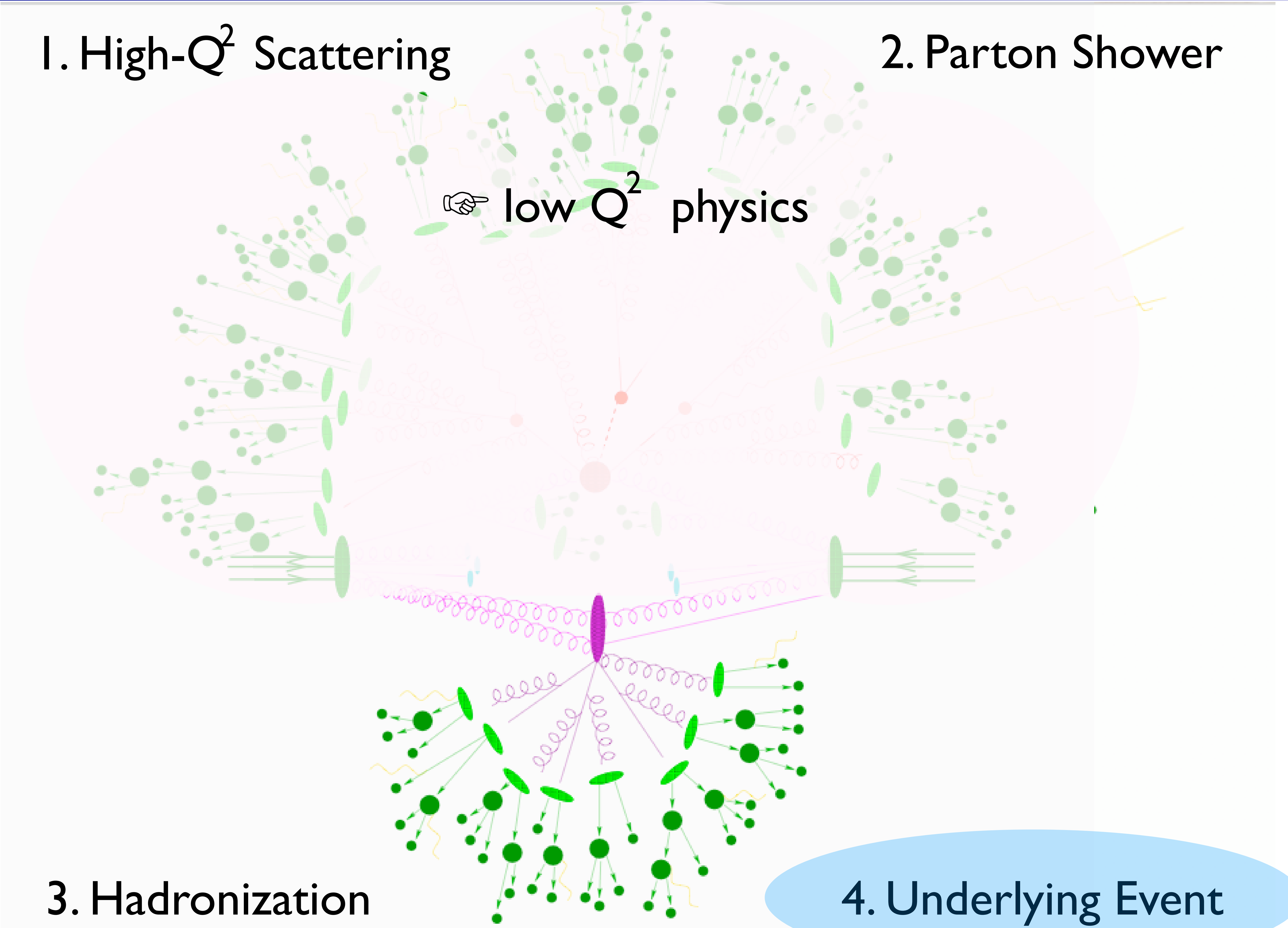


☞ low Q^2 physics

☞ universal/ process independent

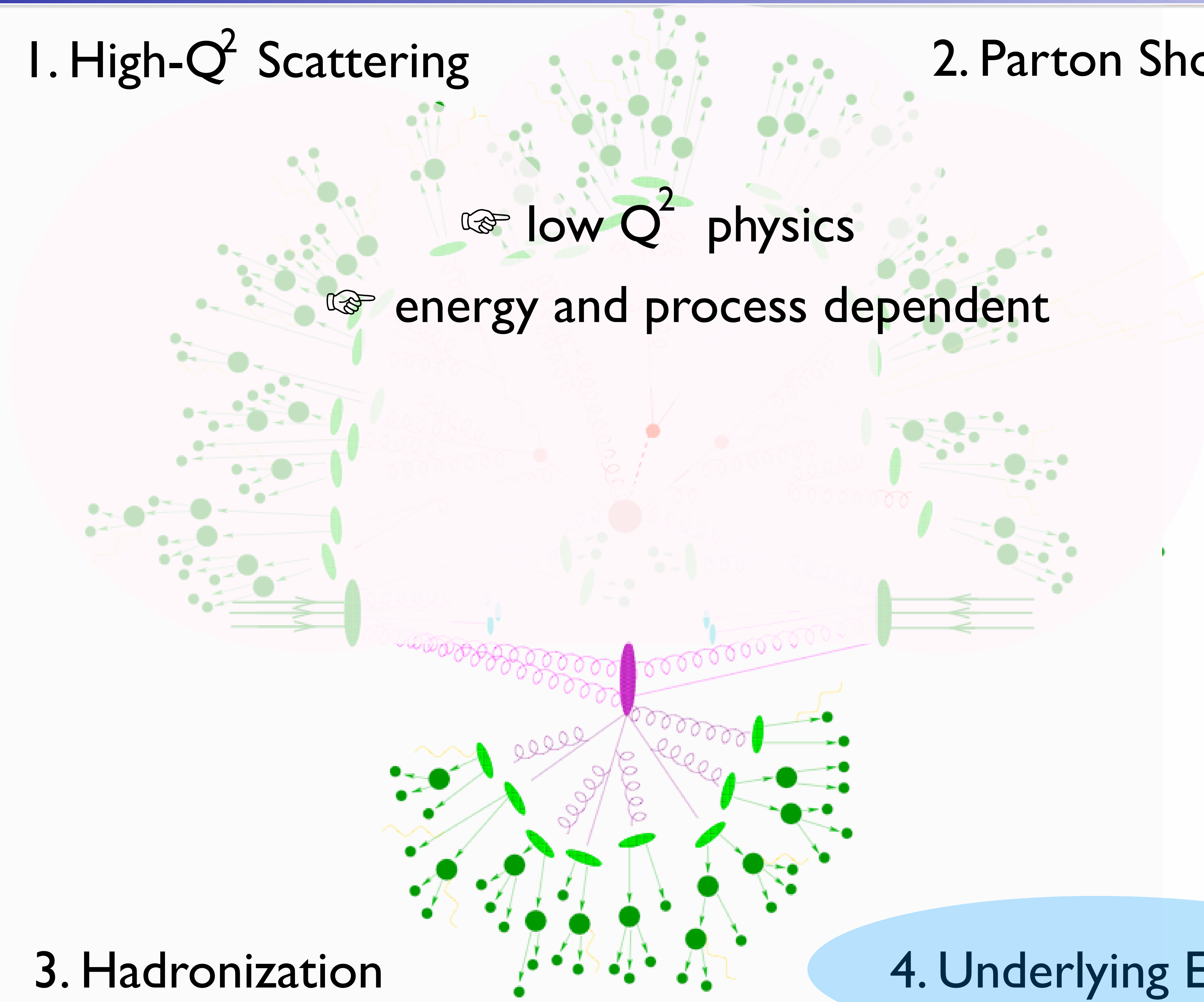


- low Q^2 physics
- universal/ process independent
- model-based description


1. High-Q^2 Scattering
2. Parton Shower
☞ low Q^2 physics
3. Hadronization
4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ low Q^2 physics

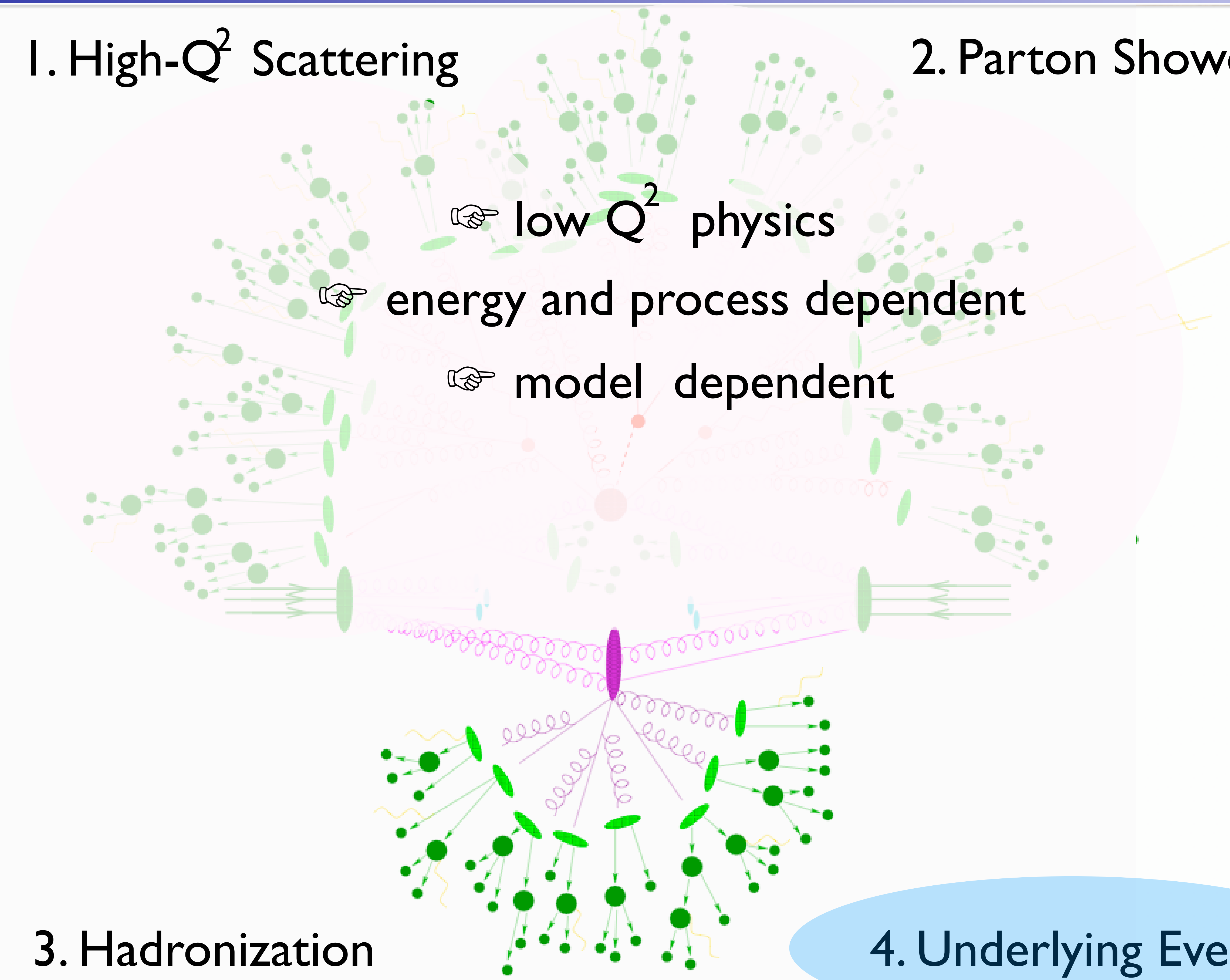
☞ energy and process dependent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



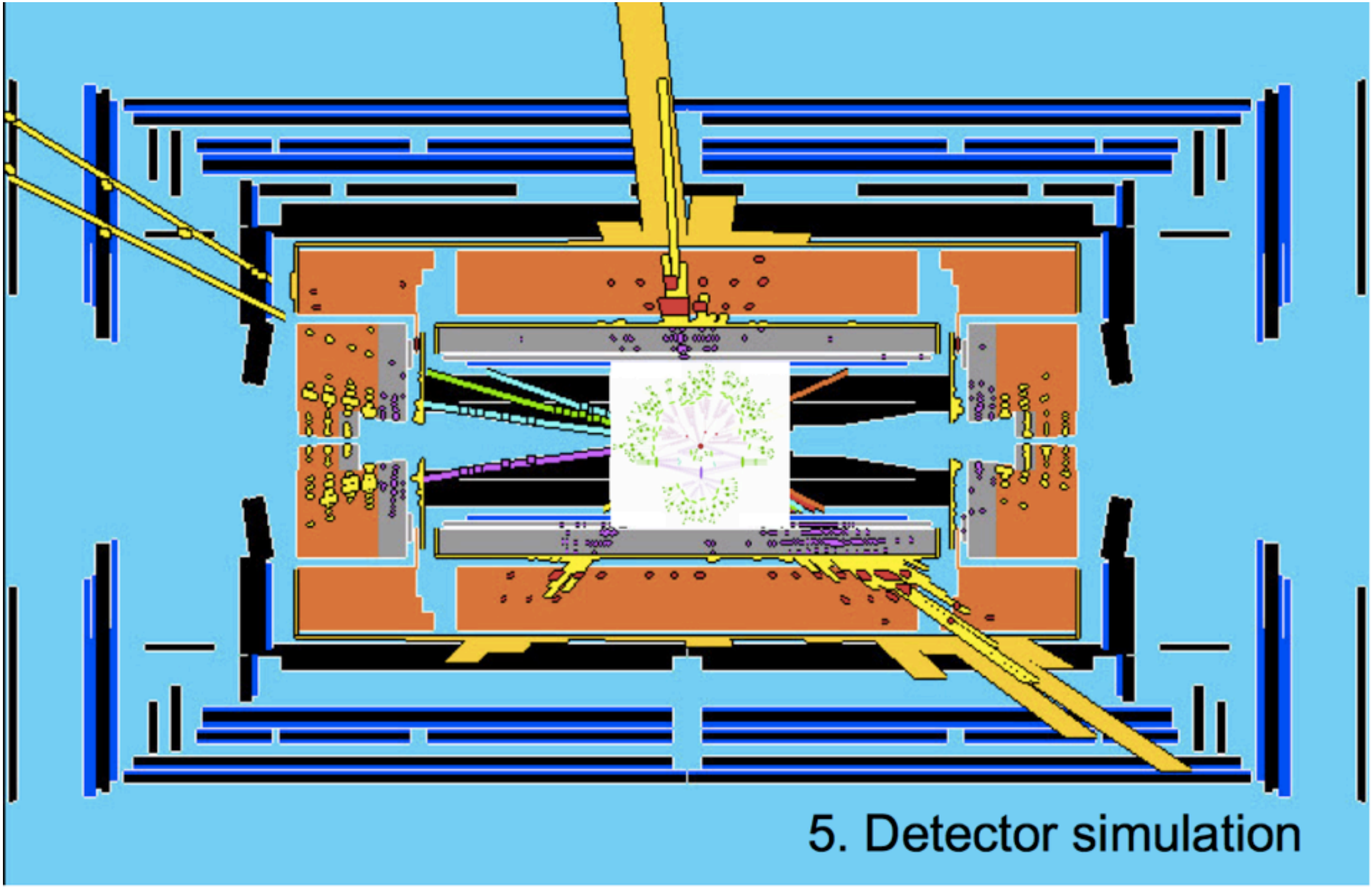
☞ low Q^2 physics

☞ energy and process dependent

☞ model dependent

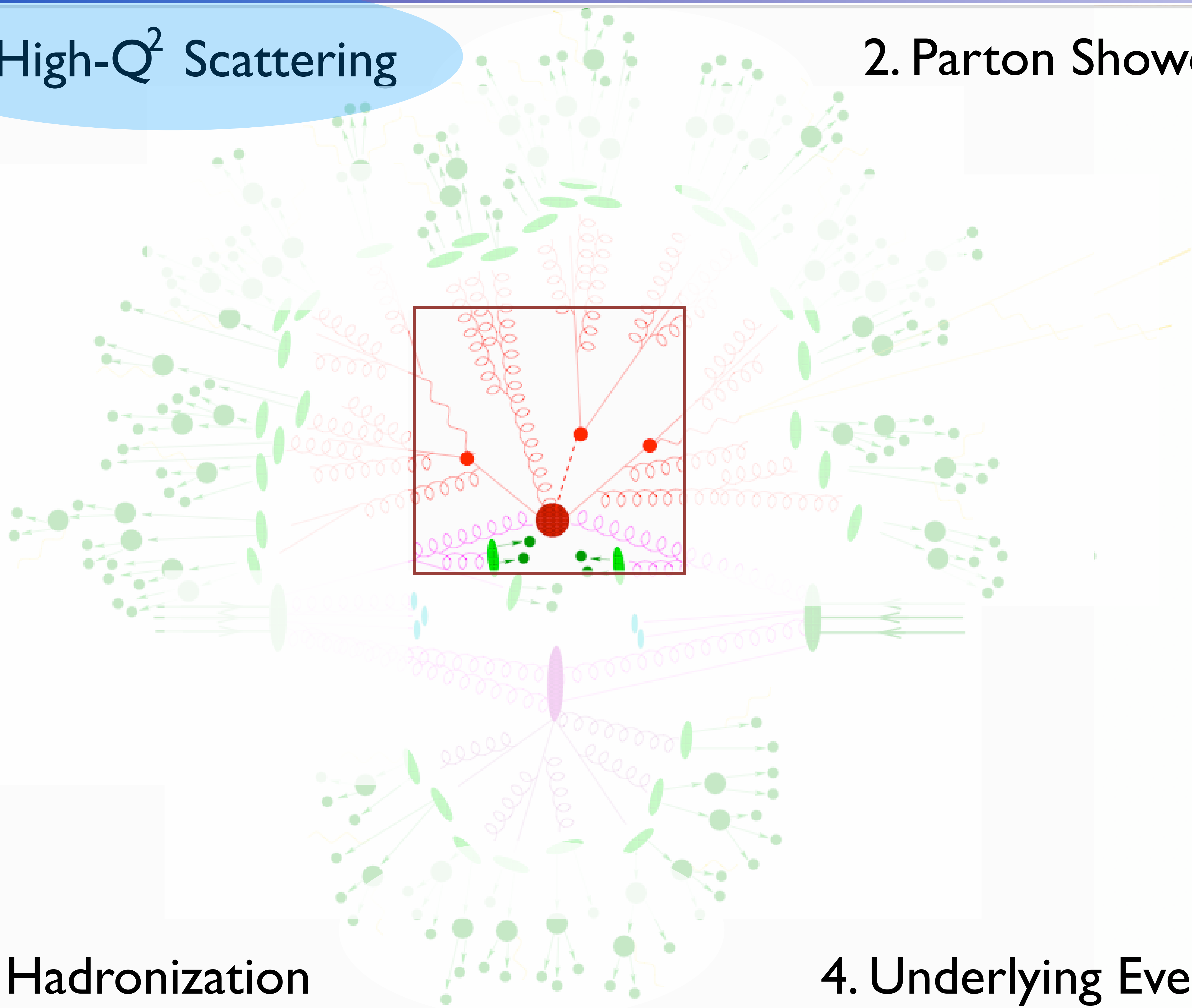
3. Hadronization

4. Underlying Event


5. Detector simulation

1. High-Q^2 Scattering

2. Parton Shower



3. Hadronization

4. Underlying Event

No.	Subprocess
	Hard QCD processes:
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
	Soft QCD processes:
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
	Prompt photons:
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
	Open heavy flavour: (also fourth generation)
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$

No.	Subprocess
	Closed heavy flavour:
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi \gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi \gamma$
421	$gg \to c\bar{c}[^3S_1^{(1)}]g$
422	$gg \to c\bar{c}[^3S_1^{(8)}]g$
423	$gg \to c\bar{c}[^1S_0^{(8)}]g$
424	$gg \to c\bar{c}[^3P_J^{(8)}]g$
425	$gq \to q c\bar{c}[^3S_1^{(8)}]$
426	$gq \to q c\bar{c}[^1S_0^{(8)}]$
427	$gq \to q c\bar{c}[^3P_J^{(8)}]$
428	$q\bar{q} \to g c\bar{c}[^3S_1^{(8)}]$
429	$q\bar{q} \to g c\bar{c}[^1S_0^{(8)}]$
430	$q\bar{q} \to g c\bar{c}[^3P_J^{(8)}]$
431	$gg \to c\bar{c}[^3P_0^{(1)}]g$
432	$gg \to c\bar{c}[^3P_1^{(1)}]g$
433	$gg \to c\bar{c}[^3P_2^{(1)}]g$
434	$gq \to q c\bar{c}[^3P_0^{(1)}]$

No.	Subprocess
435	$gq \to q c\bar{c}[^3P_1^{(1)}]$
436	$gq \to q c\bar{c}[^3P_2^{(1)}]$
437	$q\bar{q} \to g c\bar{c}[^3P_0^{(1)}]$
438	$q\bar{q} \to g c\bar{c}[^3P_1^{(1)}]$
439	$q\bar{q} \to g c\bar{c}[^3P_2^{(1)}]$
461	$gg \to b\bar{b}[^3S_1^{(1)}]g$
462	$gg \to b\bar{b}[^3S_1^{(8)}]g$
463	$gg \to b\bar{b}[^1S_0^{(8)}]g$
464	$gg \to b\bar{b}[^3P_J^{(8)}]g$
465	$gq \to q b\bar{b}[^3S_1^{(8)}]$
466	$gq \to q b\bar{b}[^1S_0^{(8)}]$
467	$gq \to q b\bar{b}[^3P_J^{(8)}]$
468	$q\bar{q} \to g b\bar{b}[^3S_1^{(8)}]$
469	$q\bar{q} \to g b\bar{b}[^1S_0^{(8)}]$
470	$q\bar{q} \to g b\bar{b}[^3P_J^{(8)}]$
471	$gg \to b\bar{b}[^3P_0^{(1)}]g$
472	$gg \to b\bar{b}[^3P_1^{(1)}]g$
473	$gg \to b\bar{b}[^3P_2^{(1)}]g$
474	$gq \to q b\bar{b}[^3P_0^{(1)}]$
475	$gq \to q b\bar{b}[^3P_1^{(1)}]$
476	$gq \to q b\bar{b}[^3P_2^{(1)}]$
477	$q\bar{q} \to g b\bar{b}[^3P_0^{(1)}]$
478	$q\bar{q} \to g b\bar{b}[^3P_1^{(1)}]$
479	$q\bar{q} \to g b\bar{b}[^3P_2^{(1)}]$

No.	Subprocess
	Deeply Inel. Scatt.:
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
	Photon-induced:
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g\gamma^*_T \to f_i \bar{f}_i$
136	$g\gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
	W/Z production:
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$

No.	Subprocess
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
	Light SM Higgs:
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$
	Heavy SM Higgs:
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$

No.	Subprocess
	BSM Neutral Higgs:
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$

No.	Subprocess
	Charged Higgs:
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t}bH^+$
402	$q\bar{q} \to \bar{t}bH^+$
	Higgs pairs:
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
	New gauge bosons:
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
	Leptoquarks:
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$

No.	Subprocess
	Technicolor:
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W^+_L W^-_L$
362	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
	Compositeness:
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
	Left-right symmetry:
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$
	Extra Dimensions:
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$

No.	Subprocess
	SUSY:
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_L$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}^*_R$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}^*_R +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_L$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}^*_R$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}^*_R +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_1$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}^*_2$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}^*_2 +$
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}^*_\ell +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}^*_\tau +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}^*_\tau +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}^*_\ell$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}^*_\tau$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$

No.	Subprocess
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_1$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}^\pm_2$
243	$f_i \bar{f}_i \to \tilde{g}\tilde{g}$
244	$gg \to \tilde{g}\tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$
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253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}^\pm_2$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_1$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}^*_2$

No.	Subprocess
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
264	$gg \to \tilde{t}_1 \tilde{t}^*_1$
265	$gg \to \tilde{t}_2 \tilde{t}^*_2$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jL}$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}^*_{jR}$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}^*_{jR} +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}^*_{jL}$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}^*_{jR}$
279	$gg \to \tilde{q}_{iL} \tilde{q}^*_{iL}$
280	$gg \to \tilde{q}_{iR} \tilde{q}^*_{iR}$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} + \tilde{b}_2 \tilde{q}_{iL}$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iL}$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}^*_{iR}$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}^*_{iR} + \tilde{b}_2 \tilde{q}^*_{iL}$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}^*_1$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}^*_2$
289	$gg \to \tilde{b}_1 \tilde{b}^*_1$
290	$gg \to \tilde{b}_2 \tilde{b}^*_2$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}^*_2 +$

List of processes implemented in Pythia (by hand!)

Automatized Matrix Element Generators

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- High-Q2 scattering processes: In principle infinite number of processes for innumerable models

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- Implementation by hand time-consuming, labor intensive and error prone (bad use of PhD student time!)
- Instead: Automatized matrix element generators
  - ➡ Use Feynman rules to build diagrams

Automatized Matrix Element Generators

- Automatic matrix element generators:
  - ➡ CalcHep / CompHep
  - ➡ MadGraph
  - ➡ AMEGIC++ (Sherpa)
  - ➡ Whizard
- Standard Model only, with faster matrix elements:
  - ➡ AlpGen
  - ➡ HELAC
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See more later!

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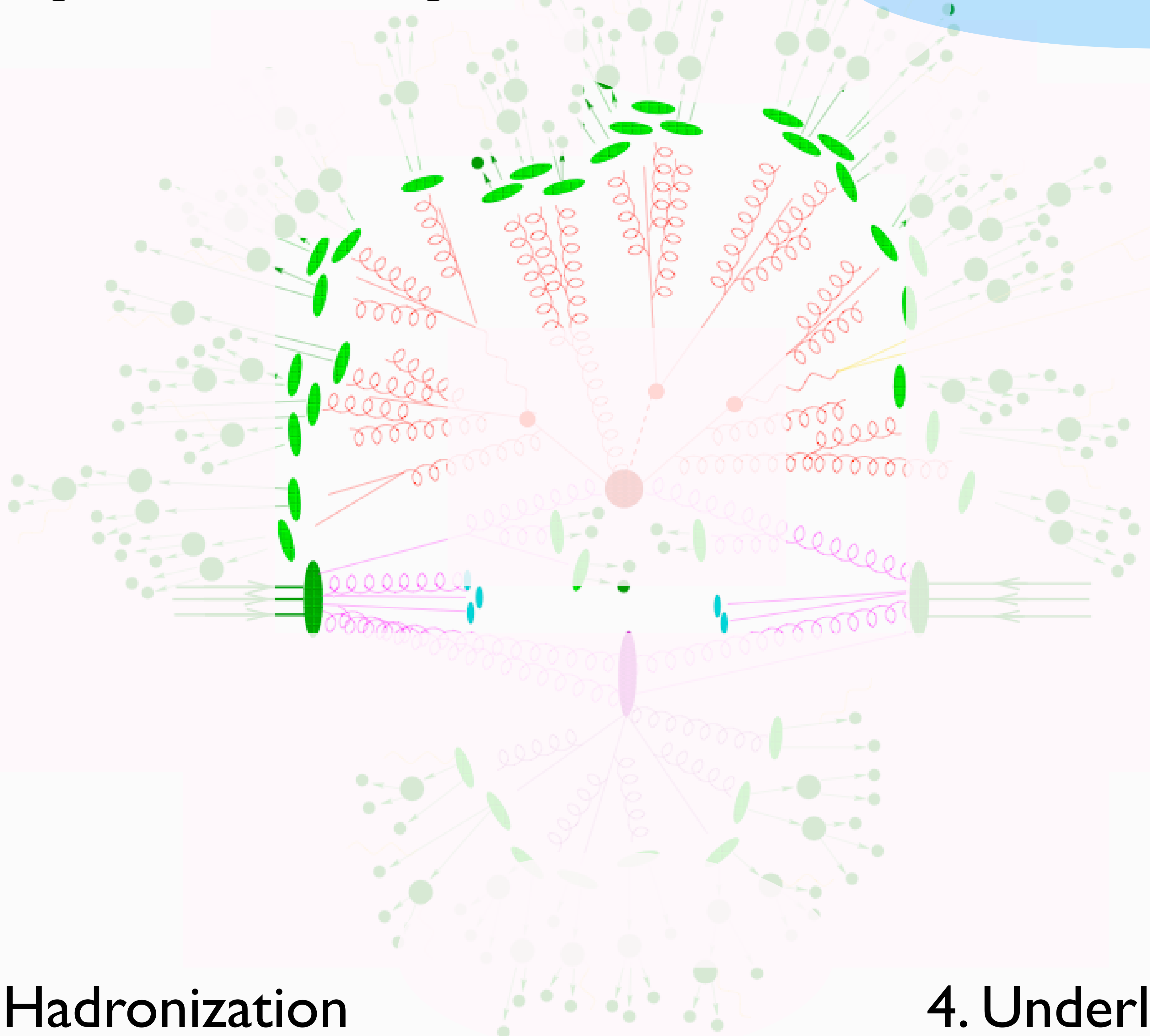
1. High-Q^2 Scattering

2. Parton Shower



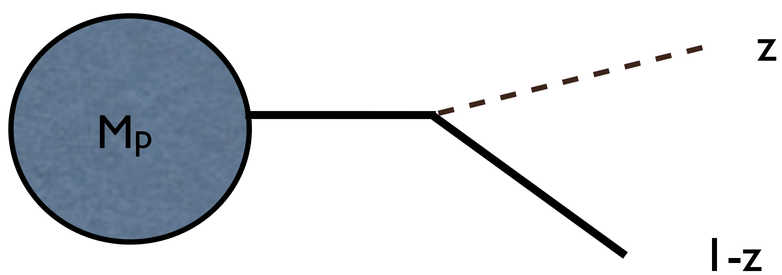
3. Hadronization

4. Underlying Event

Parton Shower MC event generators

Matrix elements involving q →q g (or g → gg) are strongly enhanced when the final state particles are close in the phase space:

$$\frac{1}{(p_q + p_g)^2} \simeq \frac{1}{2E_qE_g(1-\cos\theta)}$$



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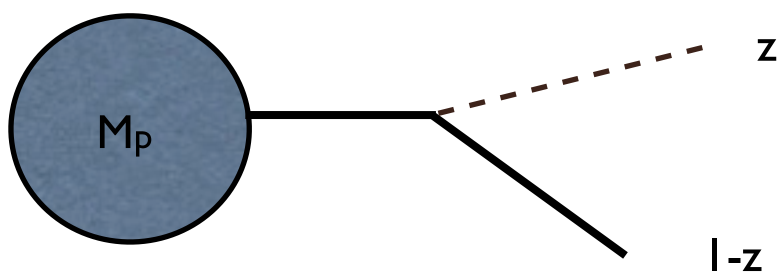

Soft

Parton Shower MC event generators

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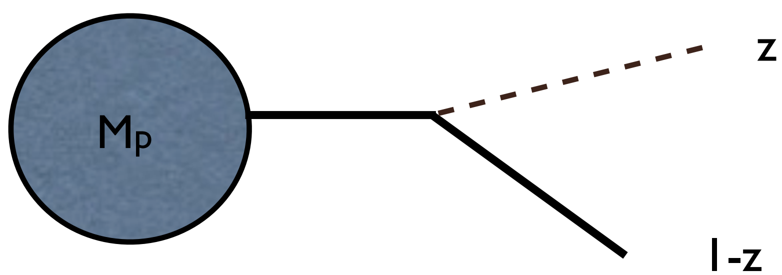


Soft and collinear divergences!

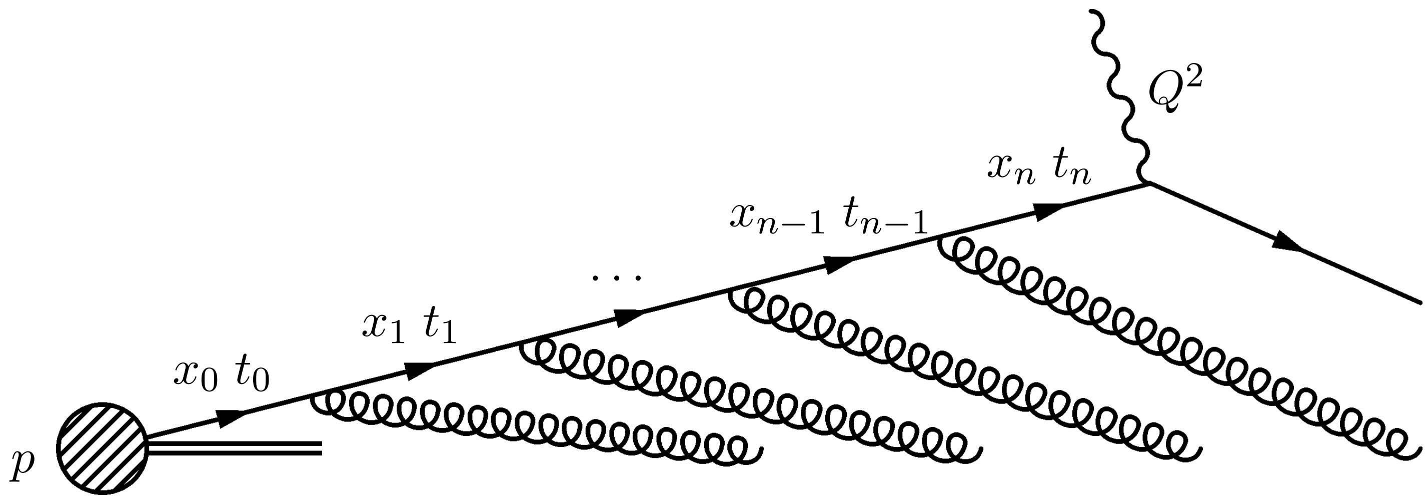
Parton Shower MC event generators

Collinear factorization:

$$|M_{p+1}|^2 d\Phi_{p+1} \simeq |M_p|^2 d\Phi_p \frac{dt}{t} \frac{\alpha_S}{2\pi} P(z) dz d\phi$$

Allows for a step-by-step (Markov process) evolution:

“Parton shower”



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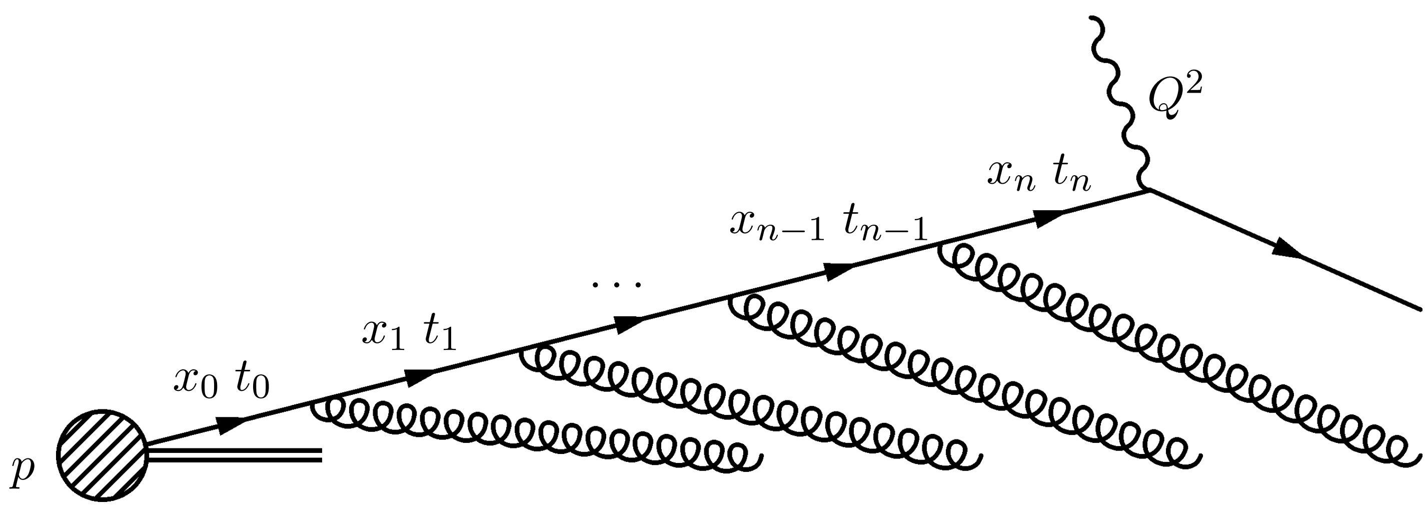

See lectures on PS by me and Grigory for (much) more details!

Parton Shower MC event generators

- General-purpose tools
- Complete exclusive description of the events: hard scattering, showering, hadronization, underlying event
- Reliable and well tuned to experimental data.

most famous: PYTHIA, HERWIG, SHERPA

- Significant and intense progress in the development of new showering algorithms with the final aim to go at NLO in QCD [Nagy, Soper, 2005; Giele, Kosower, Skands, 2007; Krauss, Schumman, 2007]

Detector simulation

- Detector simulation
  - ➡ Fast general-purpose detector simulators: Delphes, PGS ("Pretty good simulations"), AcerDet
  - ➡ Specify parameters to simulate different experiments
- Experiment-specific fast simulation
  - ➡ Detector response parameterized
  - ➡ Run time ms-s/event
- Experiment-specific full simulation
  - ➡ Full tracking of particles through detector using GEANT
  - ➡ Run time several minutes/event

Matrix Elements vs. Parton Showers (teaser)

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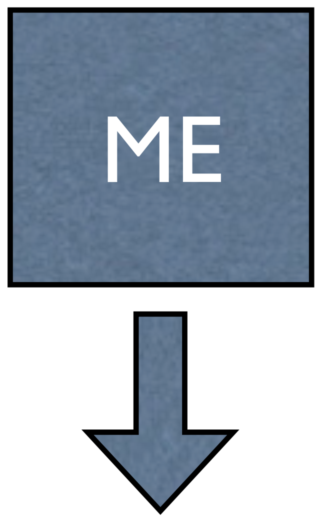

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2. Computationally expensive
3. Limited number of particles
4. Valid when partons are hard and well separated
5. Quantum interference correct
6. Needed for multi-jet description

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Shower MC

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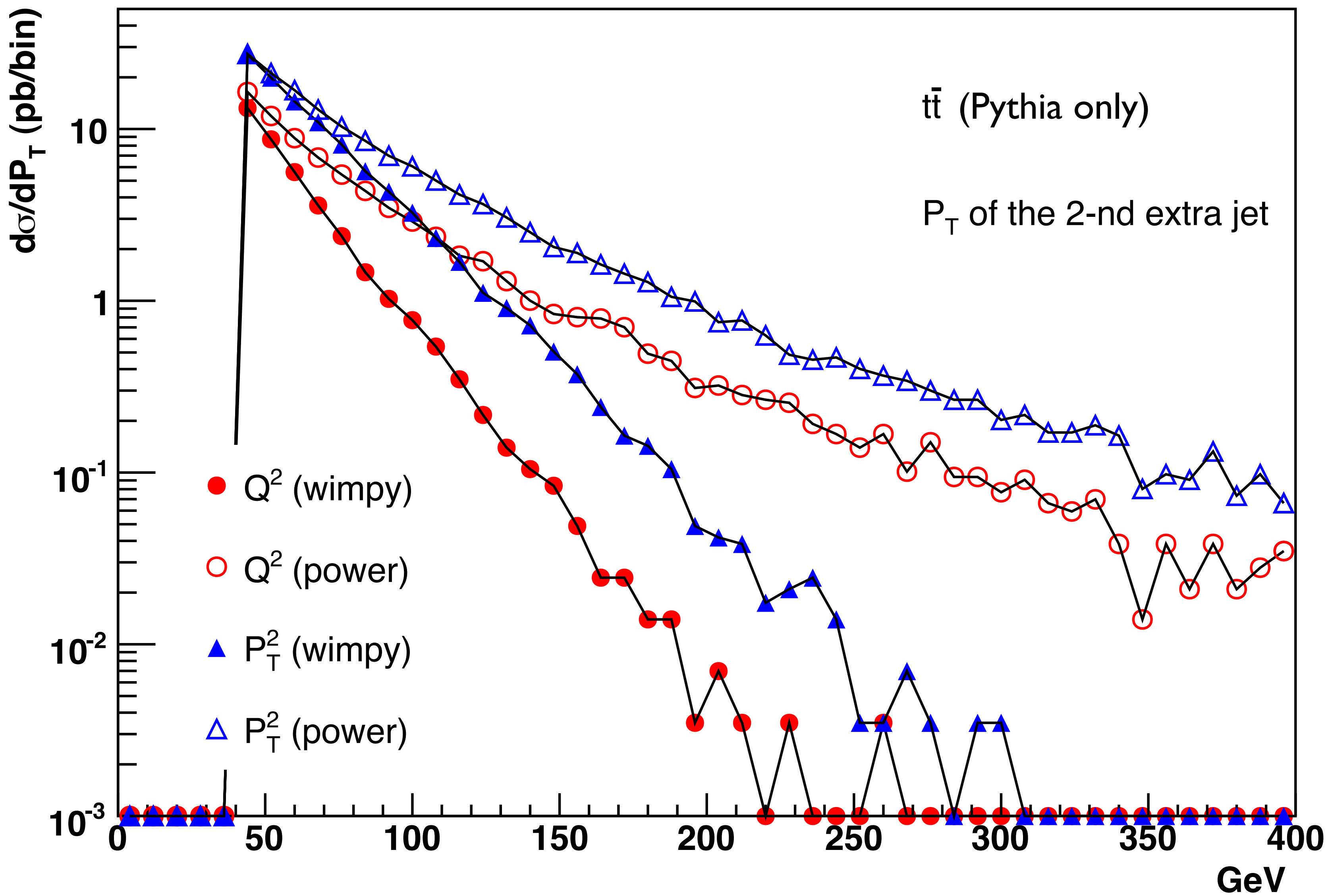
Approaches are complementary: merge them!

Difficulty: avoid double counting, ensure smooth distributions

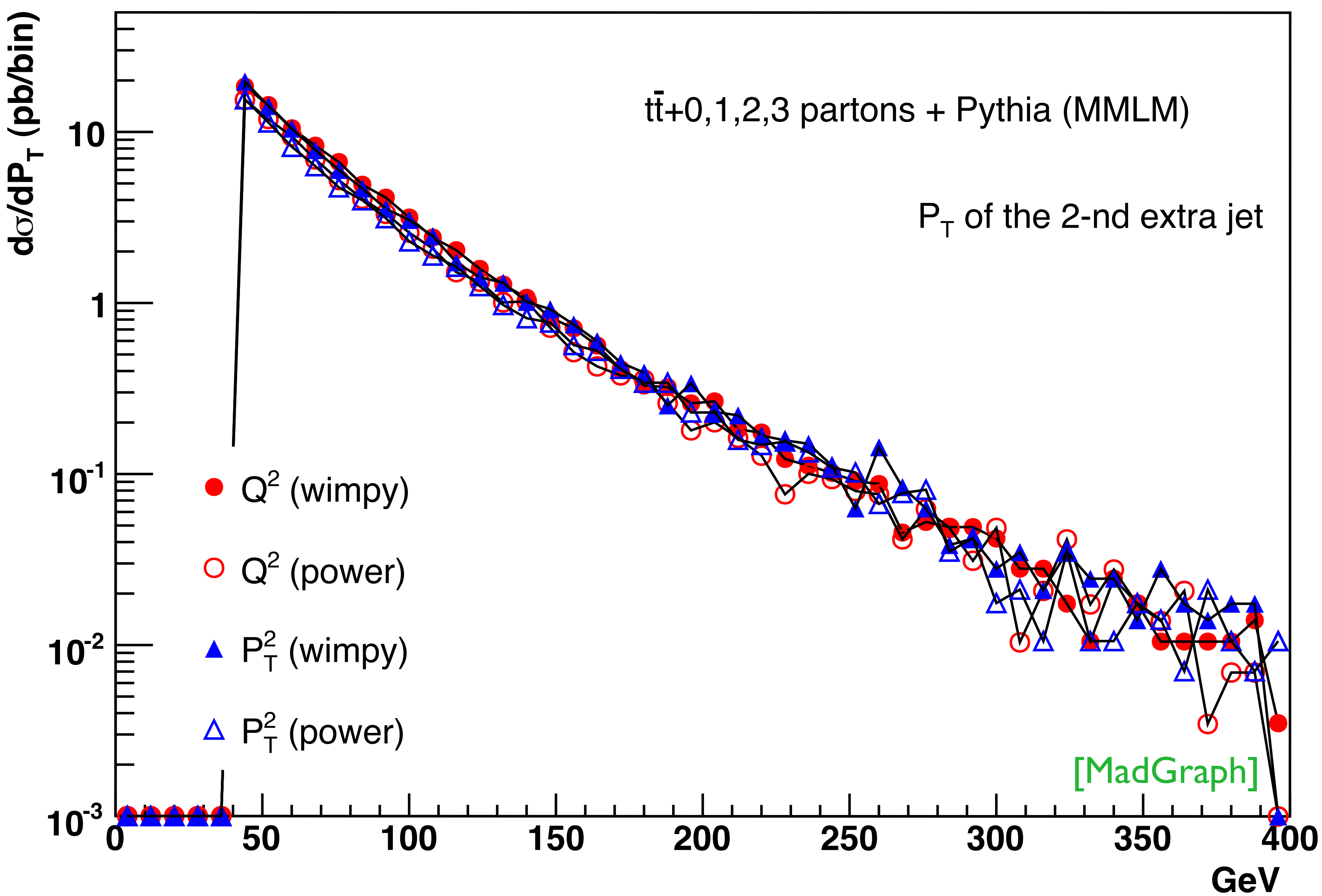
PS alone vs matched samples

In the soft-collinear approximation of Parton Shower MCs, parameters are used to tune the result ⇒ Large variation in results (small prediction power)



PS alone vs matched samples

In a matched sample these differences are irrelevant since the behavior at high pt is dominated by the matrix element.

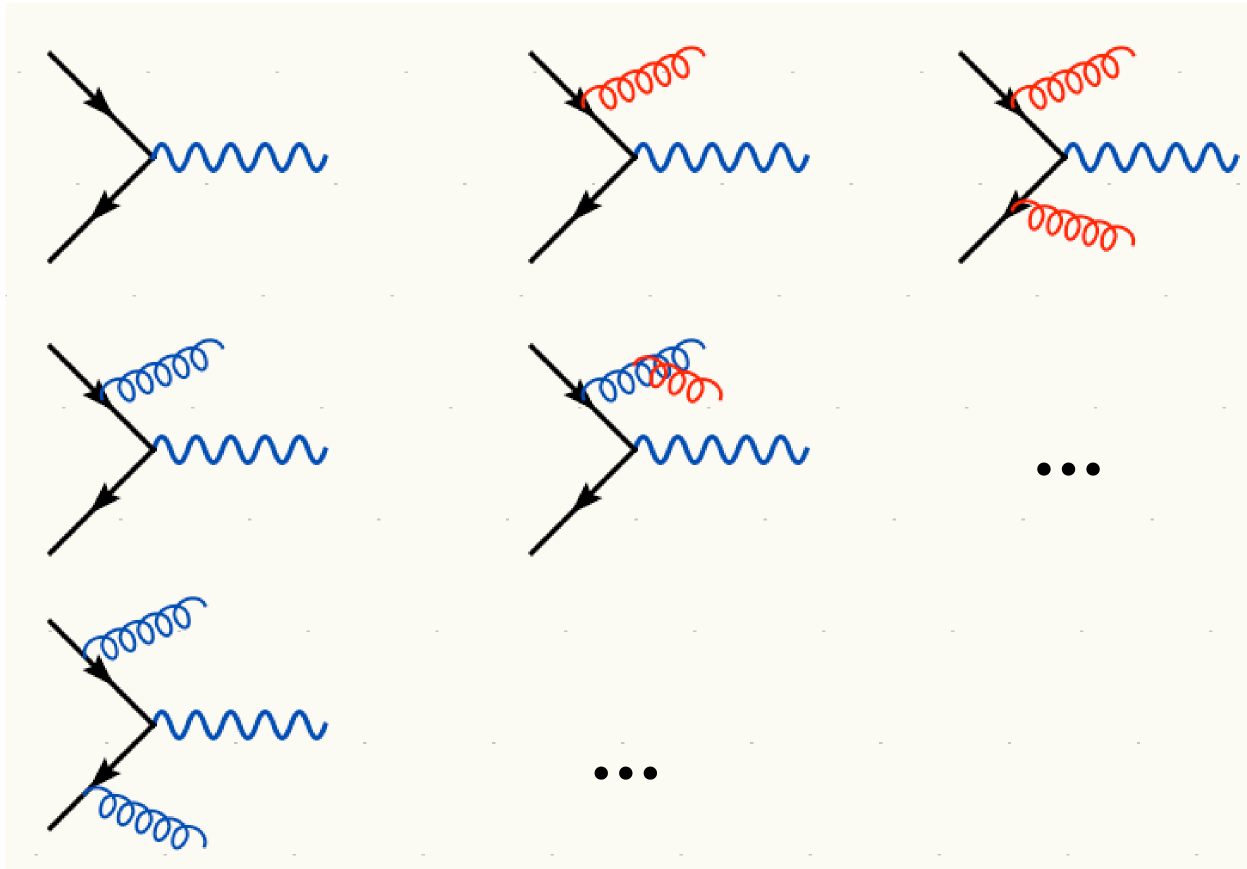


Merging ME with PS

[Mangano]
[Catani, Krauss, Kuhn, Webber]

PS →

ME ↓



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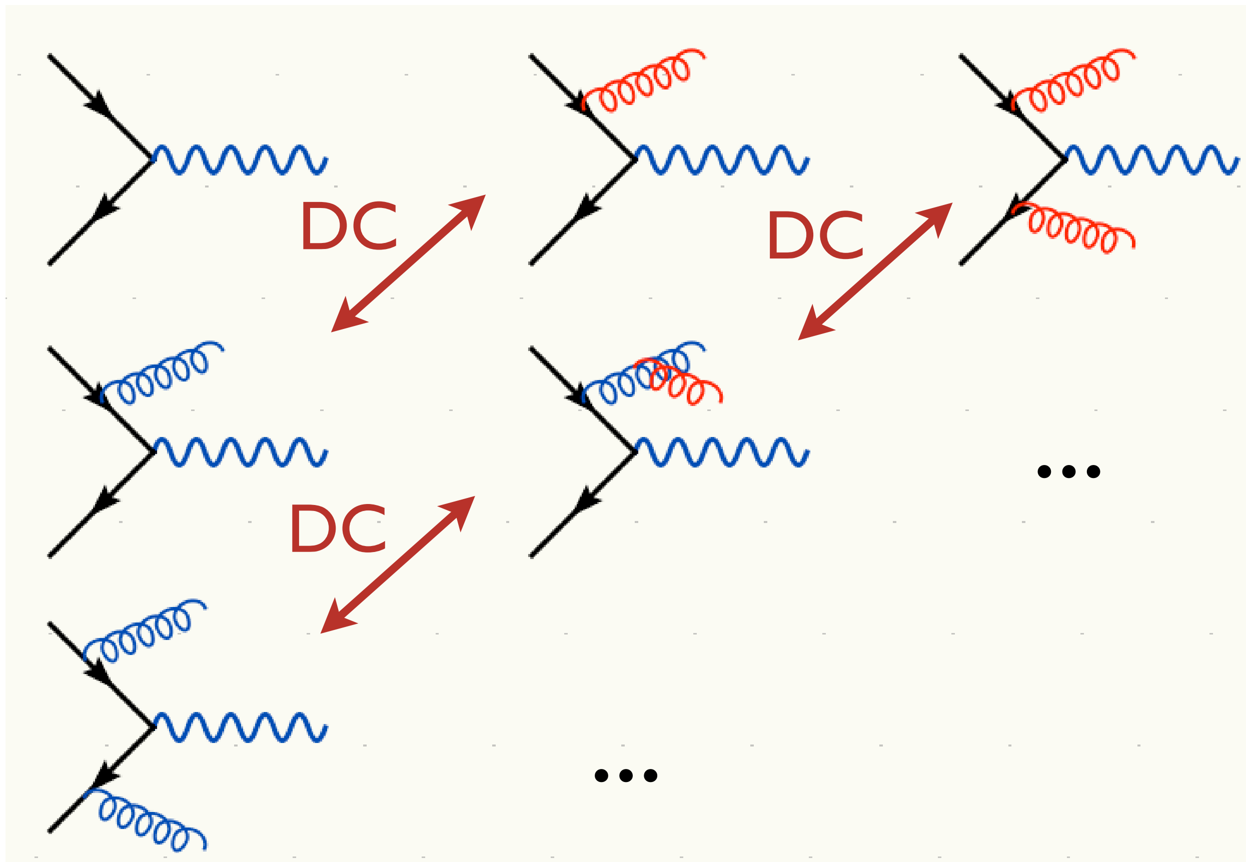

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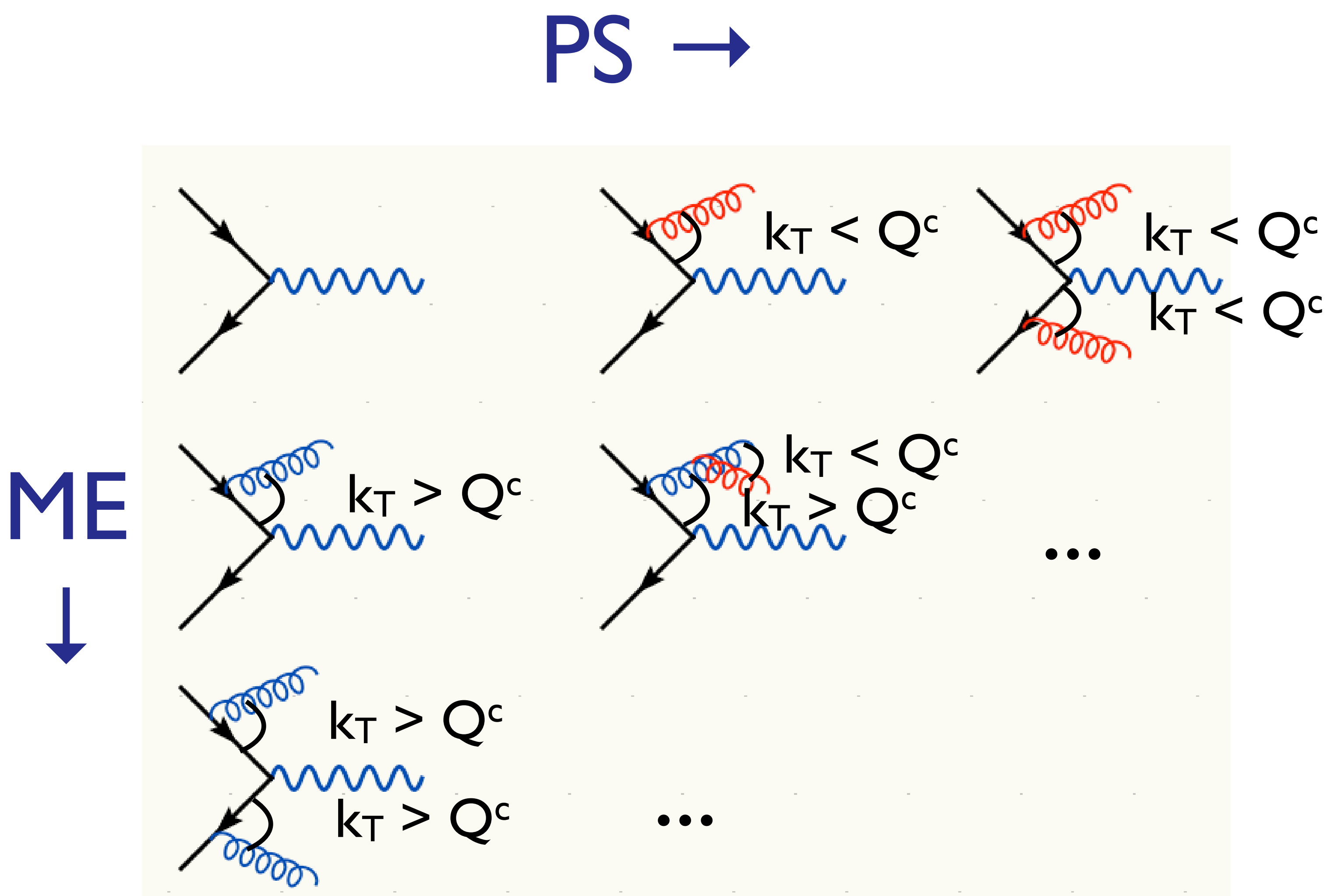

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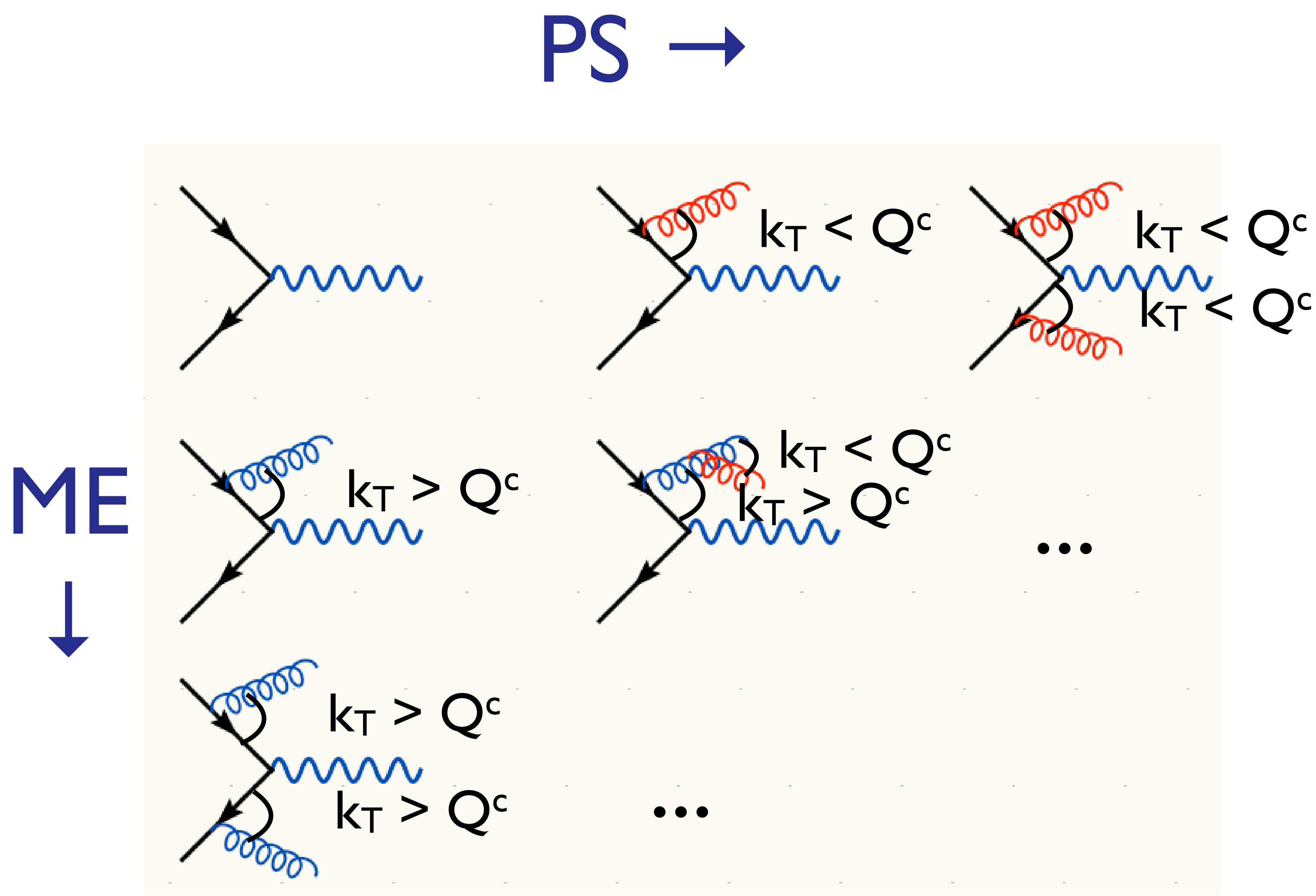

Double counting between ME and PS avoided using phase space cut between the two: PS below cutoff, ME above cutoff. Resulting events exclusive and can be added together into an inclusive sample. Smoothness of distributions achieved by careful treatment of ME samples to match PS.

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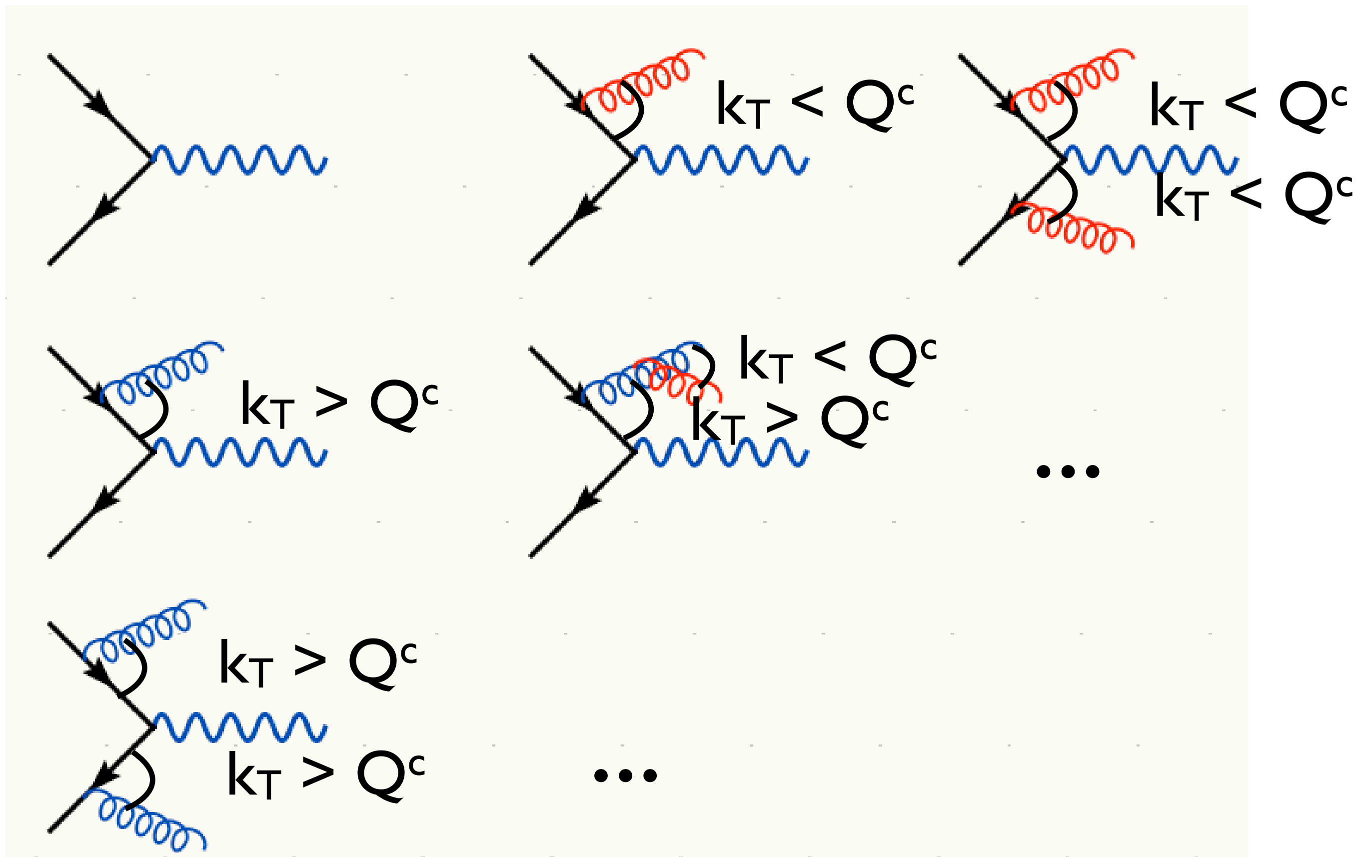

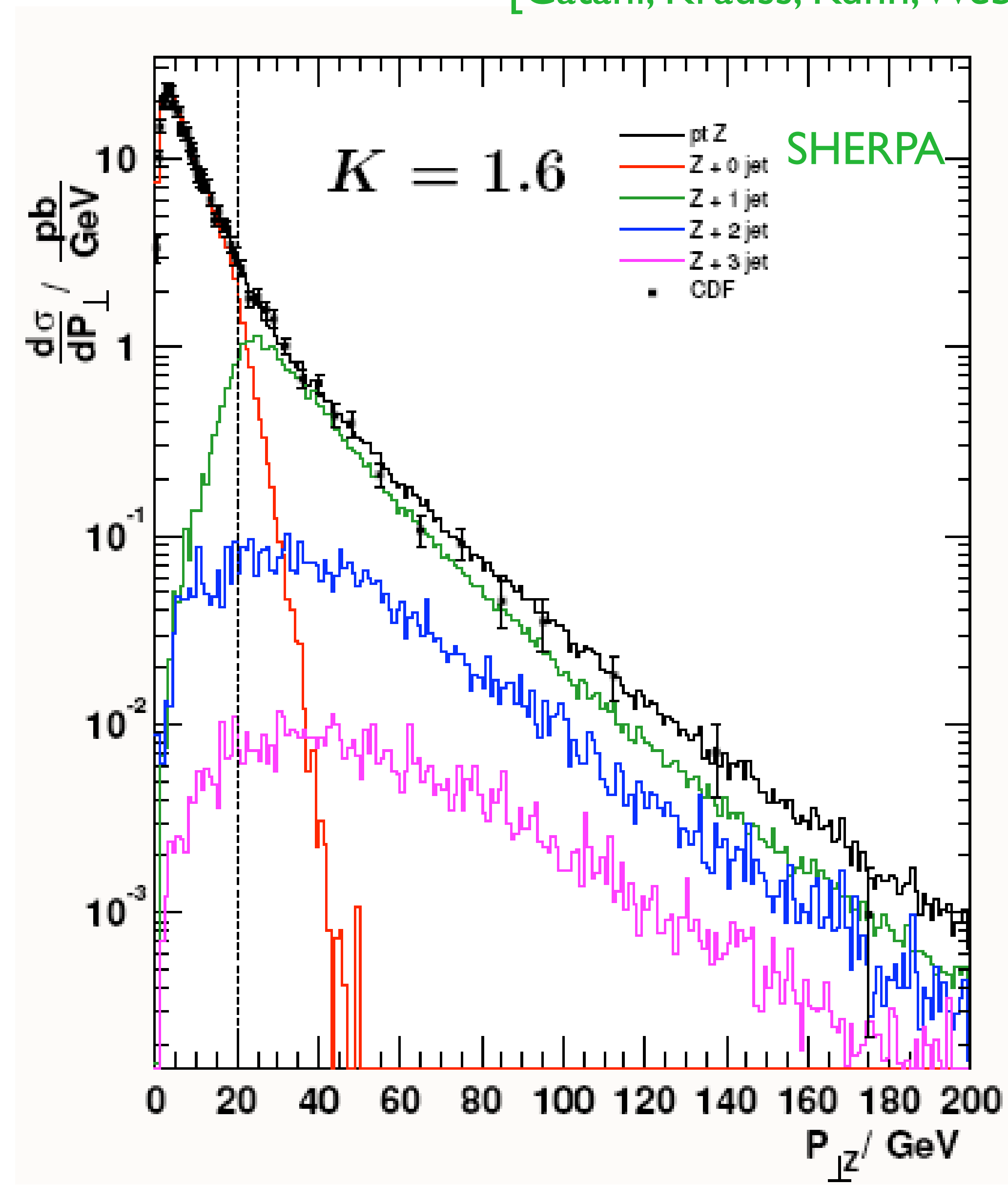

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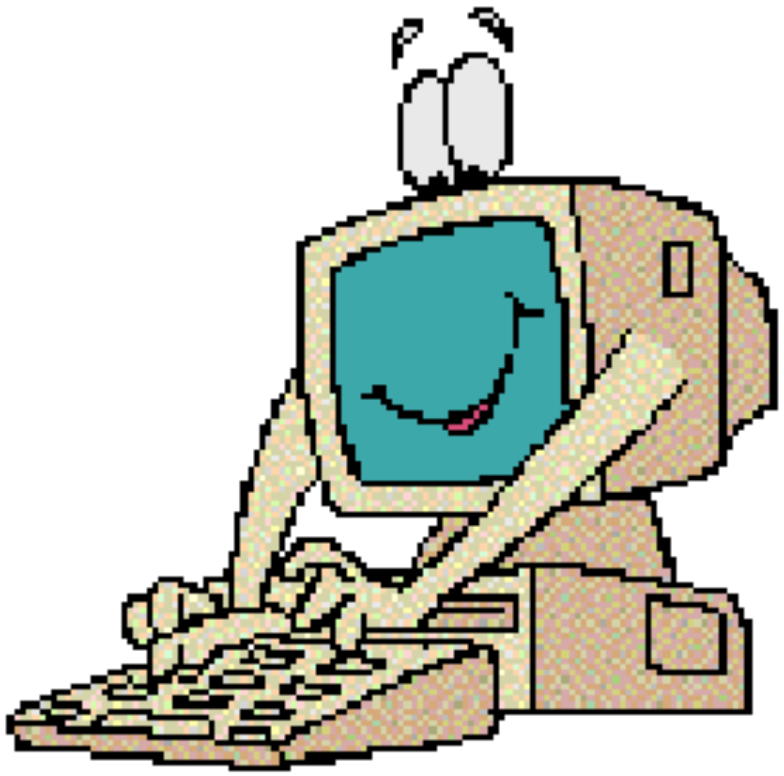
Event simulation in practice
Using MadGraph

Using MadGraph on the Web!

To generate matrix elements using MadGraph:

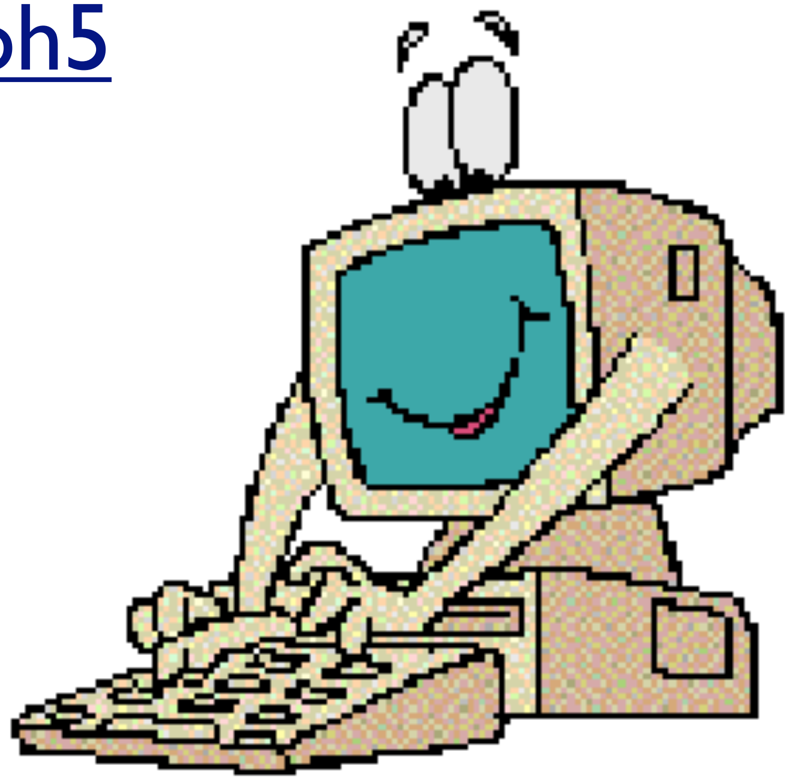
- Go to http://madgraph.hep.uiuc.edu/ (or google for MadGraph)
- Register
- Write your process
- Press Submit
- Download the tar file or generate events directly online on our clusters!



Using MadGraph on your computer!

To generate matrix elements and events:

- Download MadGraph 5 from https://launchpad.net/madgraph5
- Untar and run bin/mg5
- Write "generate *process*"
- Write "output"
- Write "launch"



Sounds easy? It is! Let me show you!

Examples shown

- p p > t t~
  This gives only (the dominant) QCD vertices, and ignores (the negligible) QED vertices.
- p p > t t~ QED=2
  This gives both QED and QCD vertices.
- p p > w+ j j, w+ > l+ vl
  More complicated example.

More syntax examples

- p p > t t~ j QED=2: Generate all combinations of processes for particles defined in multiparticle labels p / j, including up to two QED vertices (and unlimited QCD vertices)
- p p > t t~, (t > b w+, w+ > l+ vl), t~ > b~ j j :
  - Only diagrams compatible with given decay
  - Only t / t~ and W+ close to mass shell in event generation
- p p > w+ w- / h : Exclude any diagrams with h
- p p > w+ w- $ h : Exclude on-shell h in event generation (but retain interference effects)

Thanks for listening!

And now over to Olivier...