Event Generation at Hadron Colliders

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National Taiwan University

MG/FR School, Beijing, May 22-26, 2013

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

Outline of lectures

- Lecture I (Johan):
  - ➡ New Physics at hadron colliders
  - ➡ Monte Carlo integration and generation
  - ➡ Simulation of collider events
- Lecture II (Olivier):
  - ➡ Simulations with MadGraph 5
  - ➡ (and much more!)
- Lecture III (Johan):
  - ➡ MLM Matching with MadGraph and Pythia

Aims for these lectures

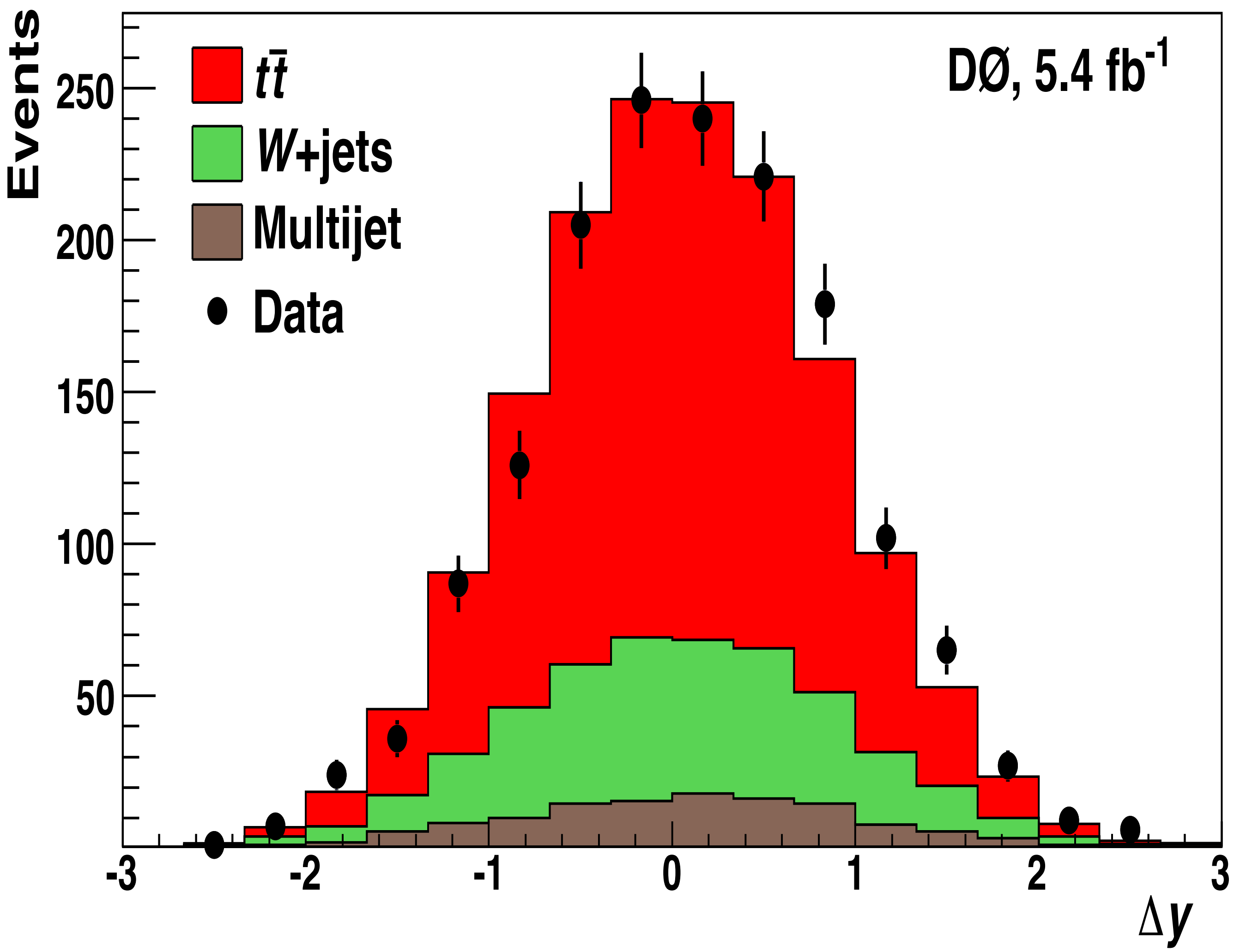
- Get you acquainted with the concepts and tools used in event simulation at hadron colliders
- Answer as many of your questions as I can (so please ask questions!)

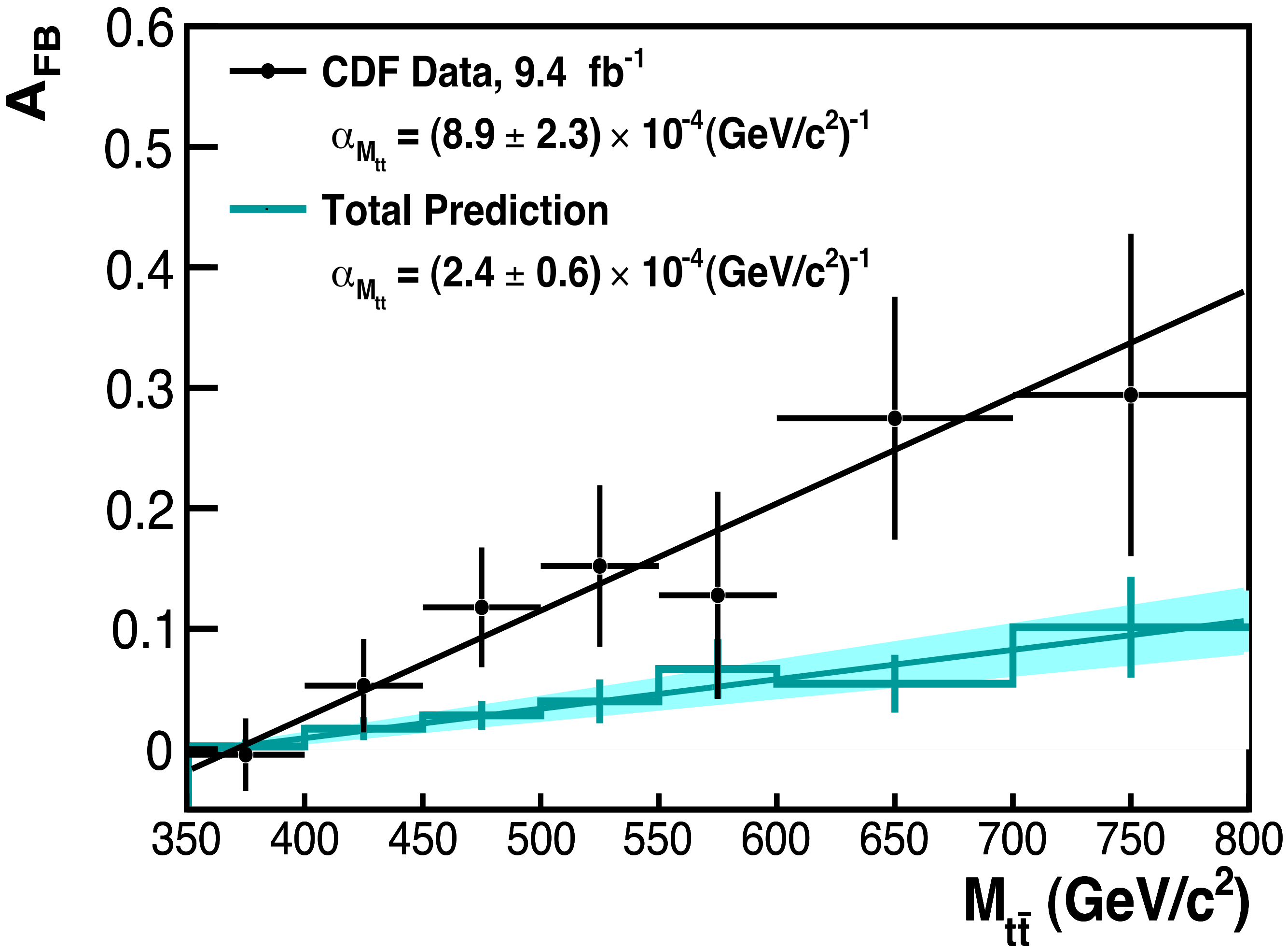
New Physics at hadron colliders

- 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 has collected 23 fb^{-1} in its 8 TeV run!
  - ➡ Allows ever-more stringent tests of the SM!
  - ➡ Found (what looks like) the Higgs boson in July 2012!
- How interpret excesses? How determine Standard Model backgrounds?
  - ➡ Monte Carlo simulation! (combined with data-driven methods)

Example: top-antitop asymmetry at Tevatron

CDF collaboration, arXiv:1211.1003, 1101.0034
DØ collaboration, arXiv: 1107.4995





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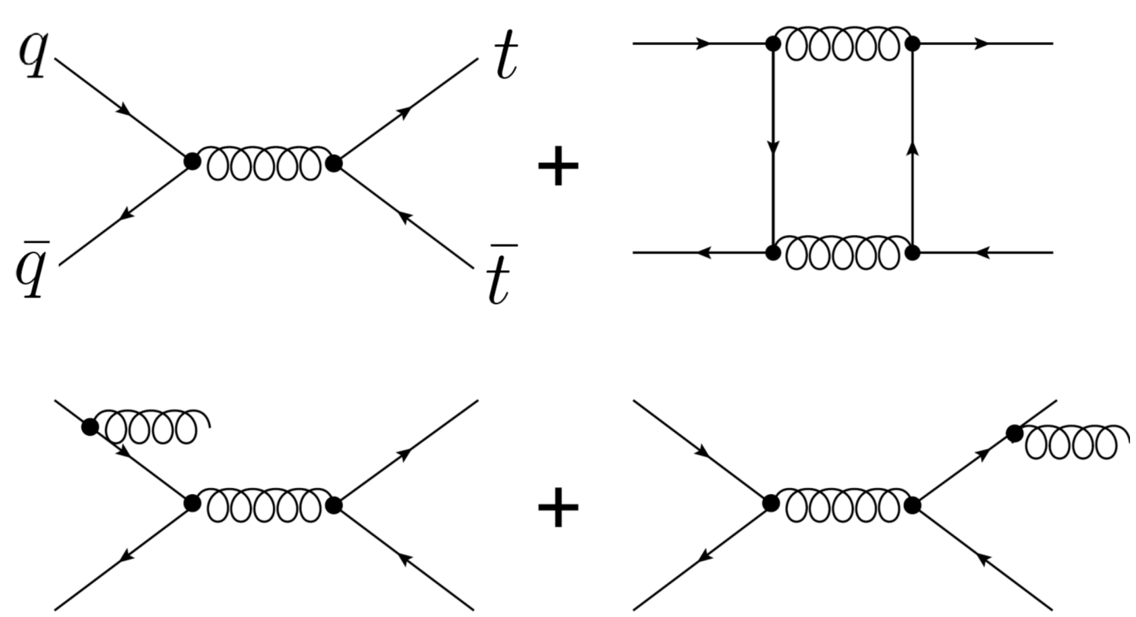

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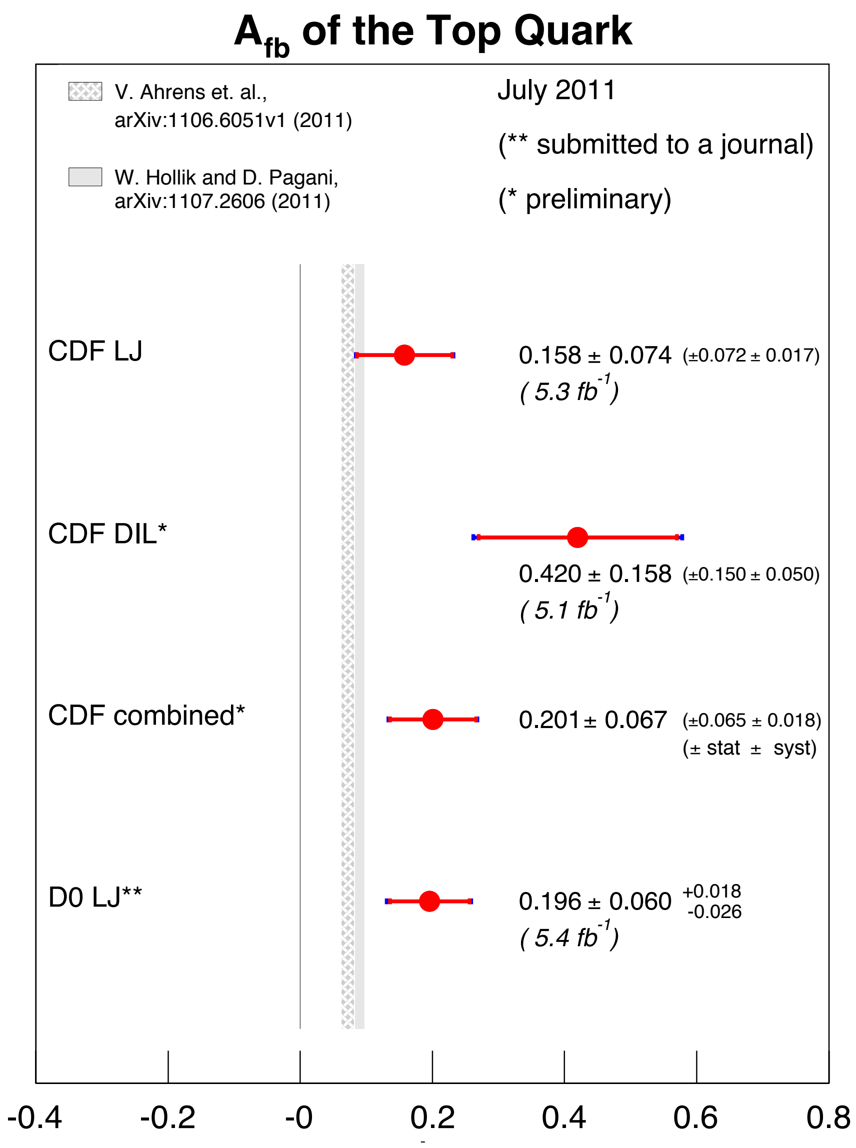

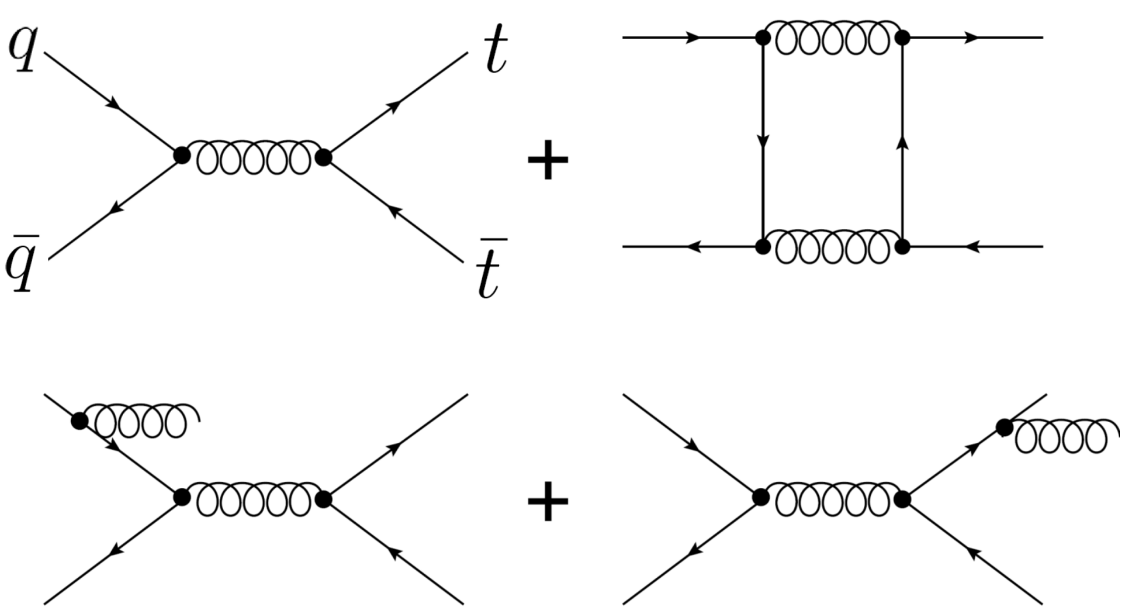

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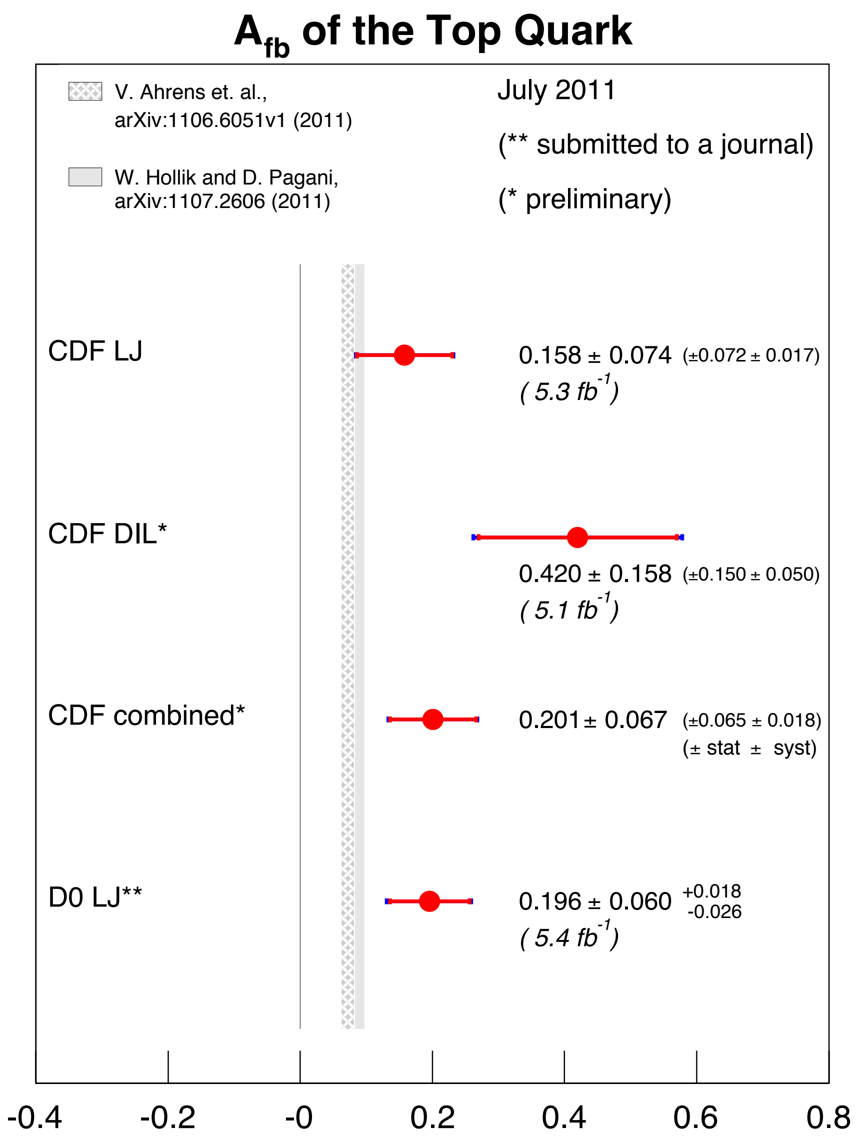

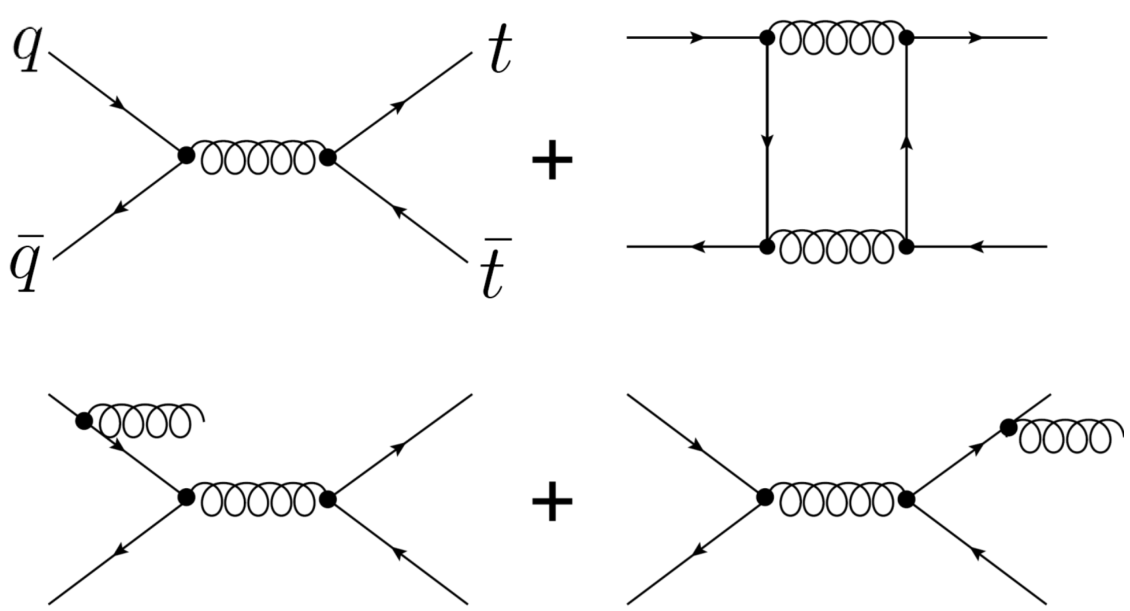

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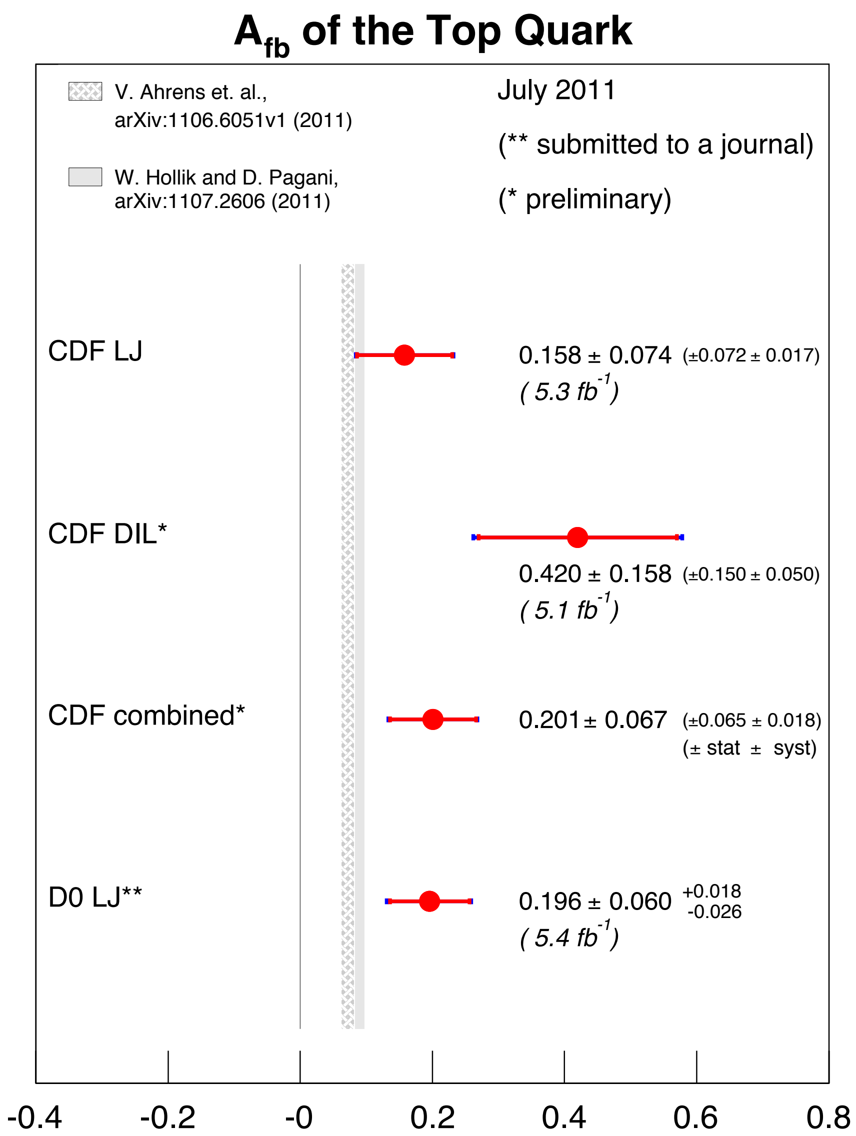

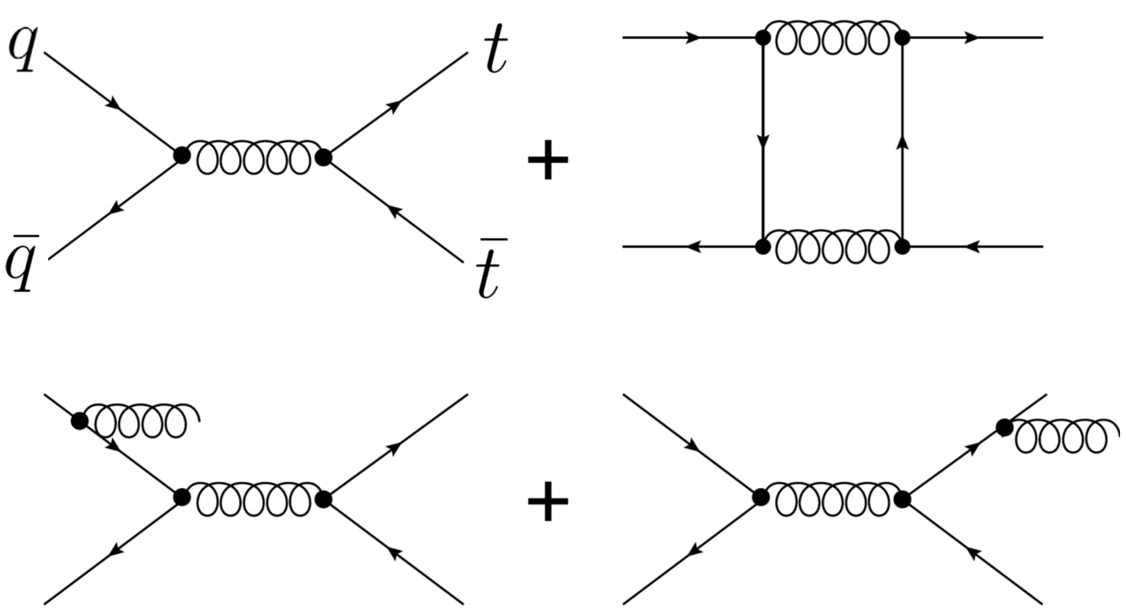

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➡ Reduces discrepancy with SM

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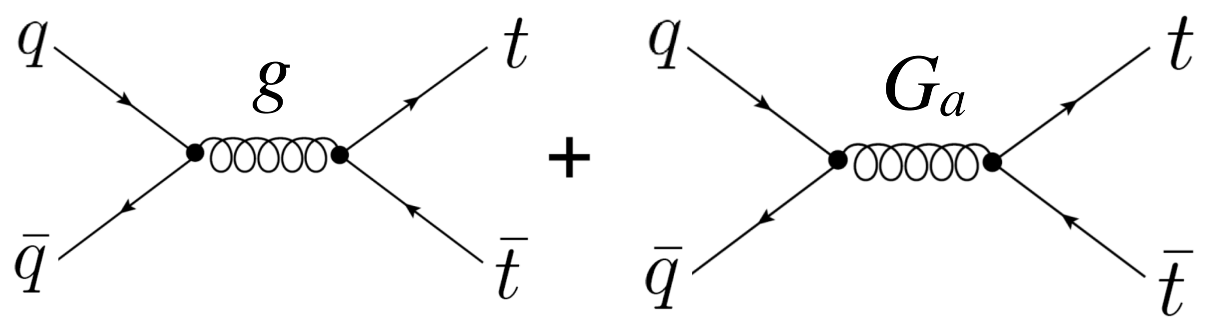
S-channel "gluon" with axial vector couplings and mass above the collider limit



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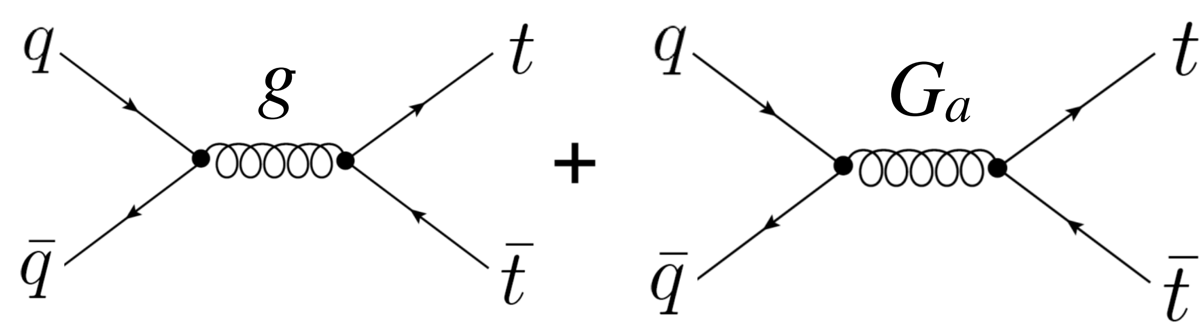

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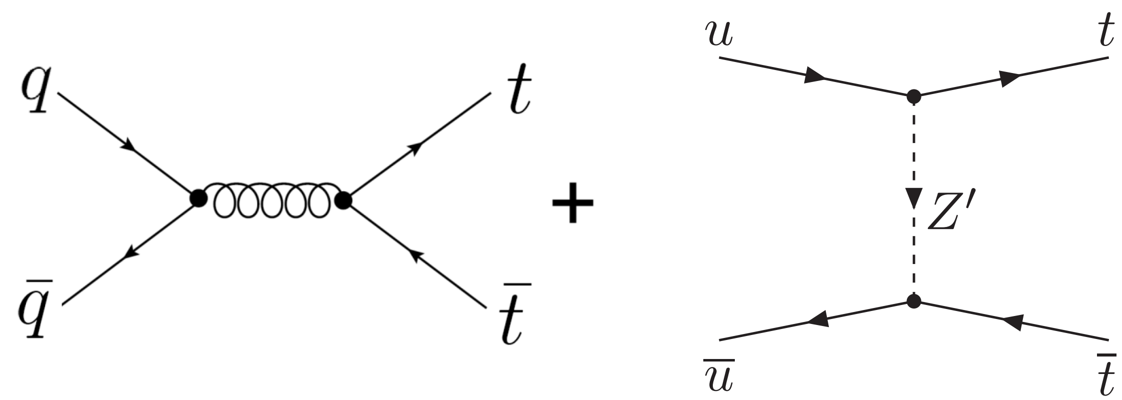
T-channel Z' with flavor-changing u-t coupling



M_Z = 350-450 GeV

Drobnak et al 1209.4354, Álvarez, Leskow 1209.4872

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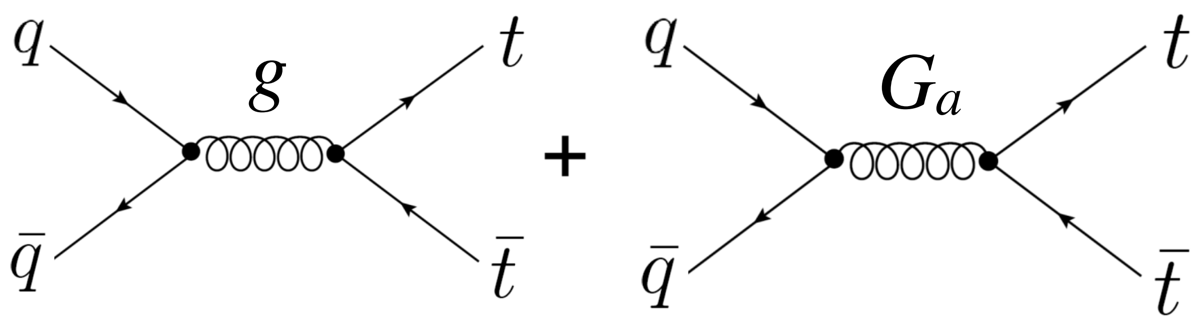

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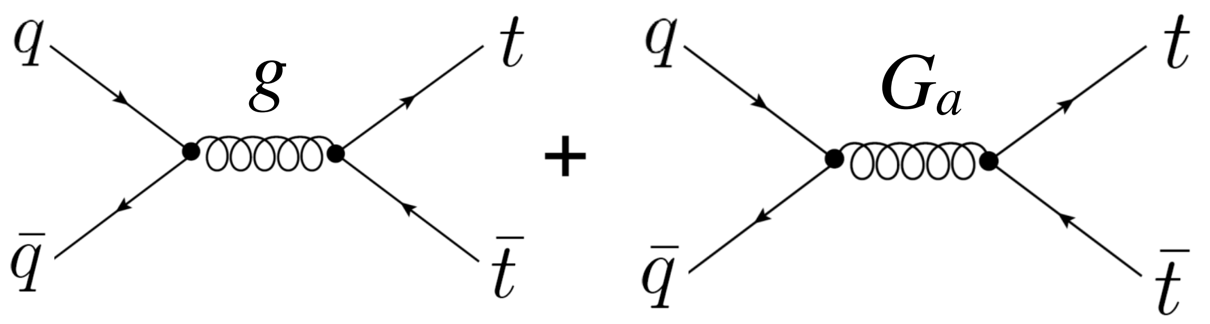

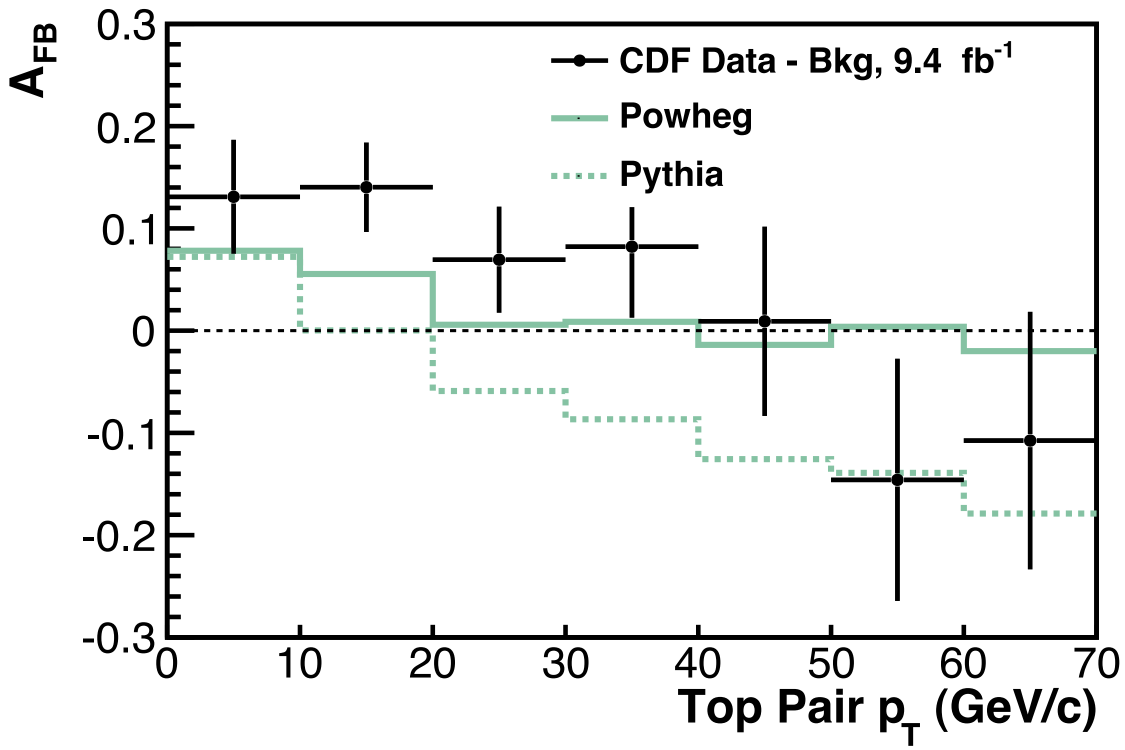

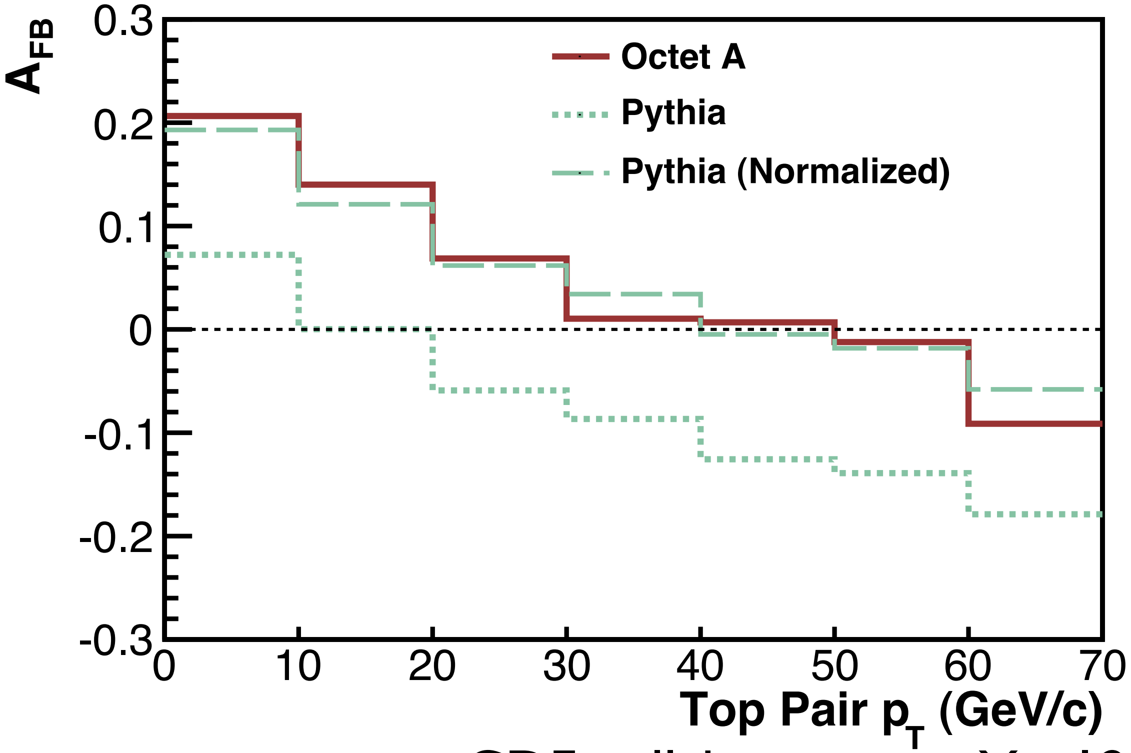

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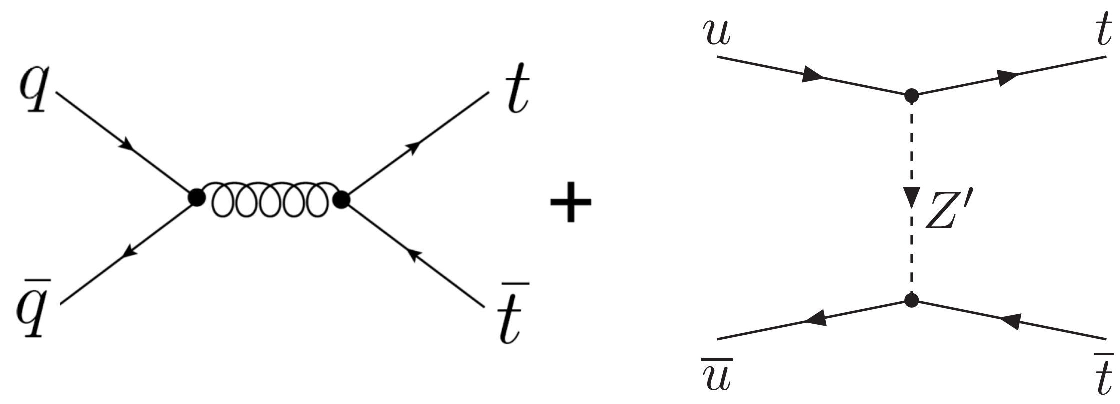

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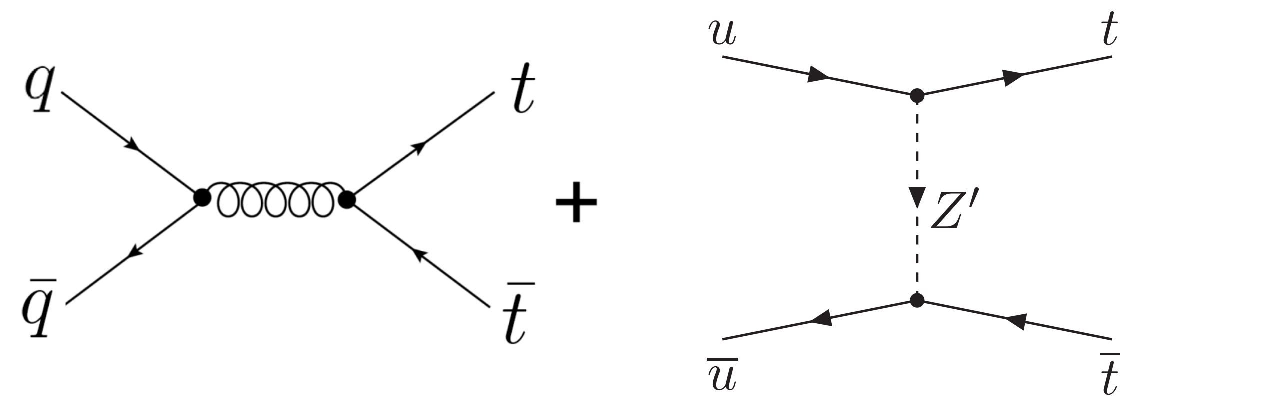
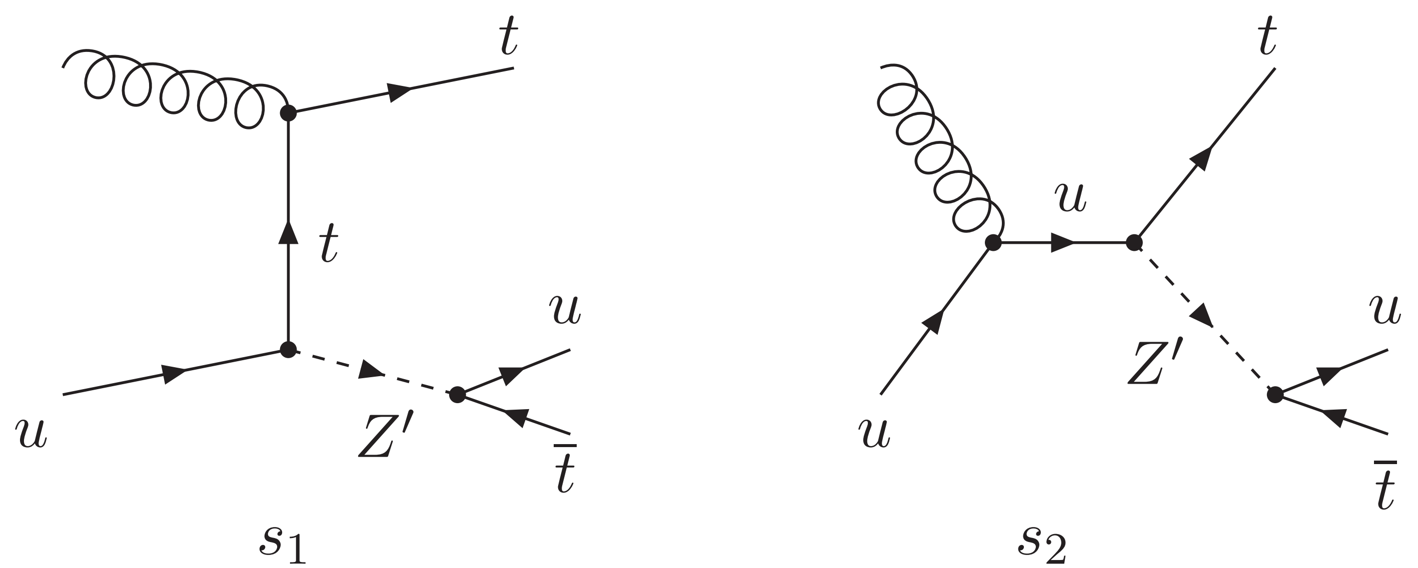


➡ Consequence:



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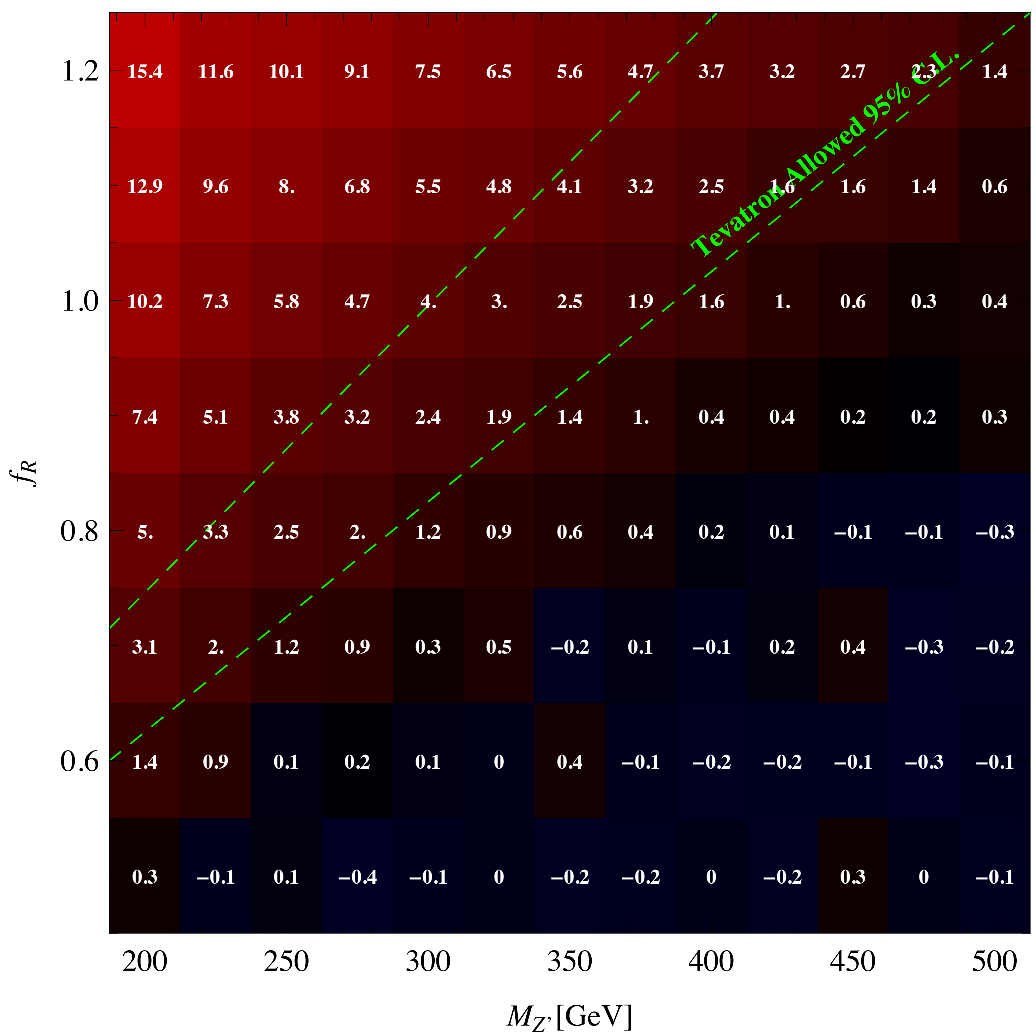
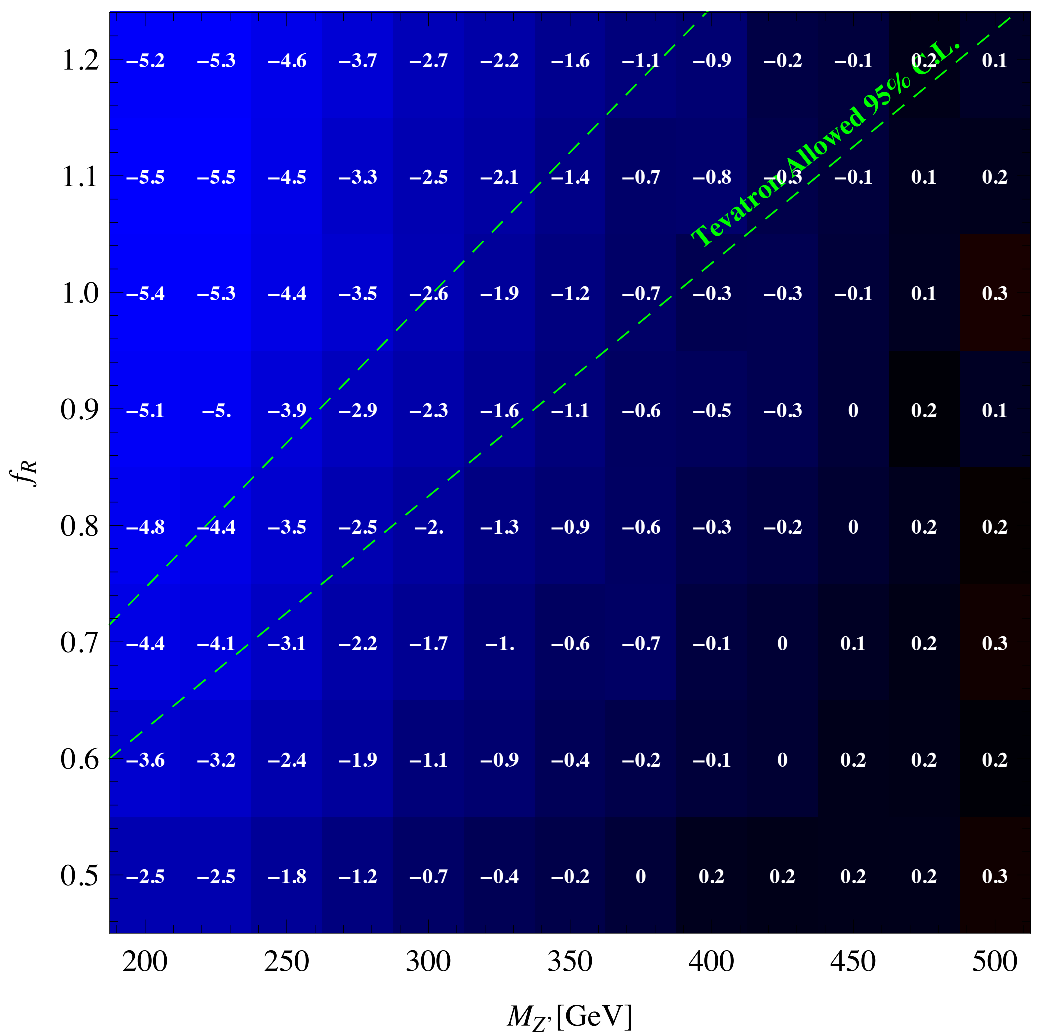


t-channel charge asymmetry



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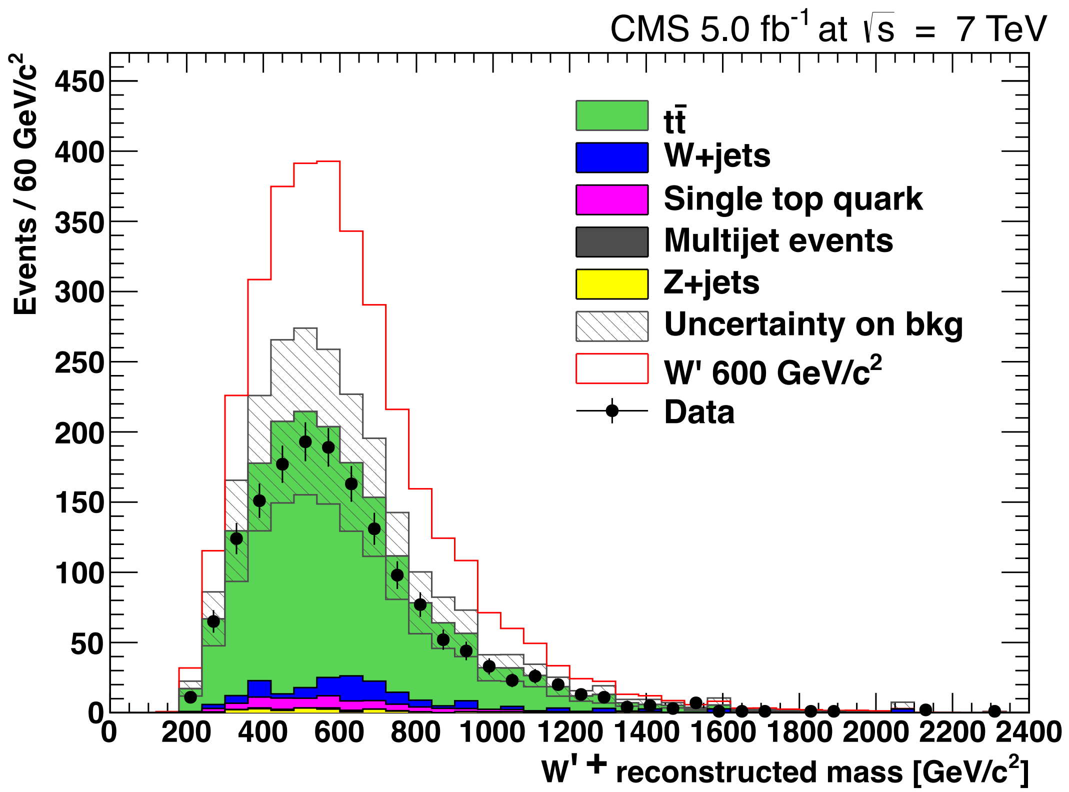
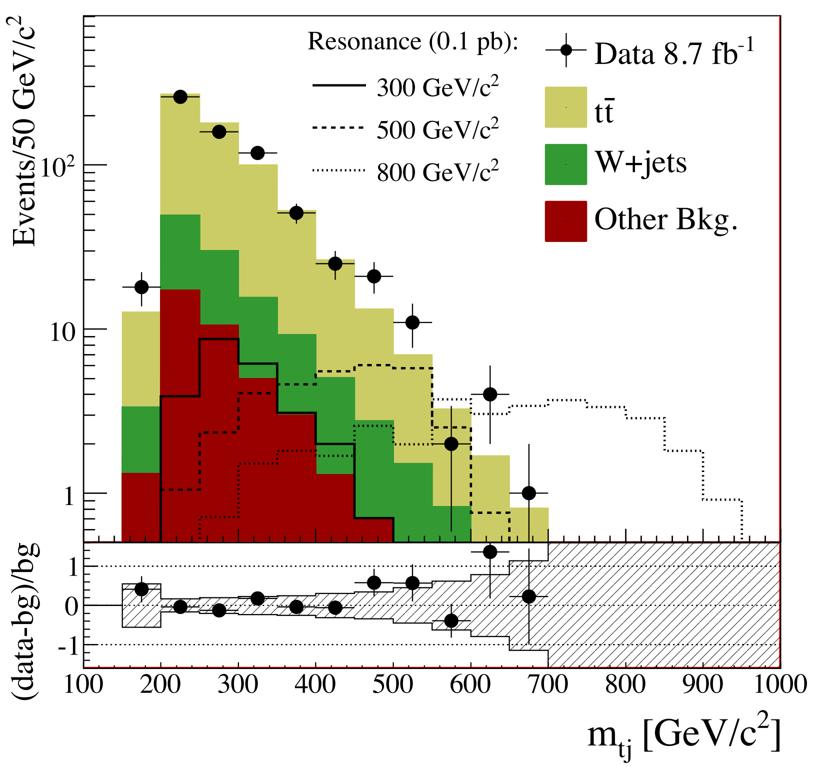


CMS collaboration, arXiv:1206.3921



CDF collaboration, arXiv:1203.3894

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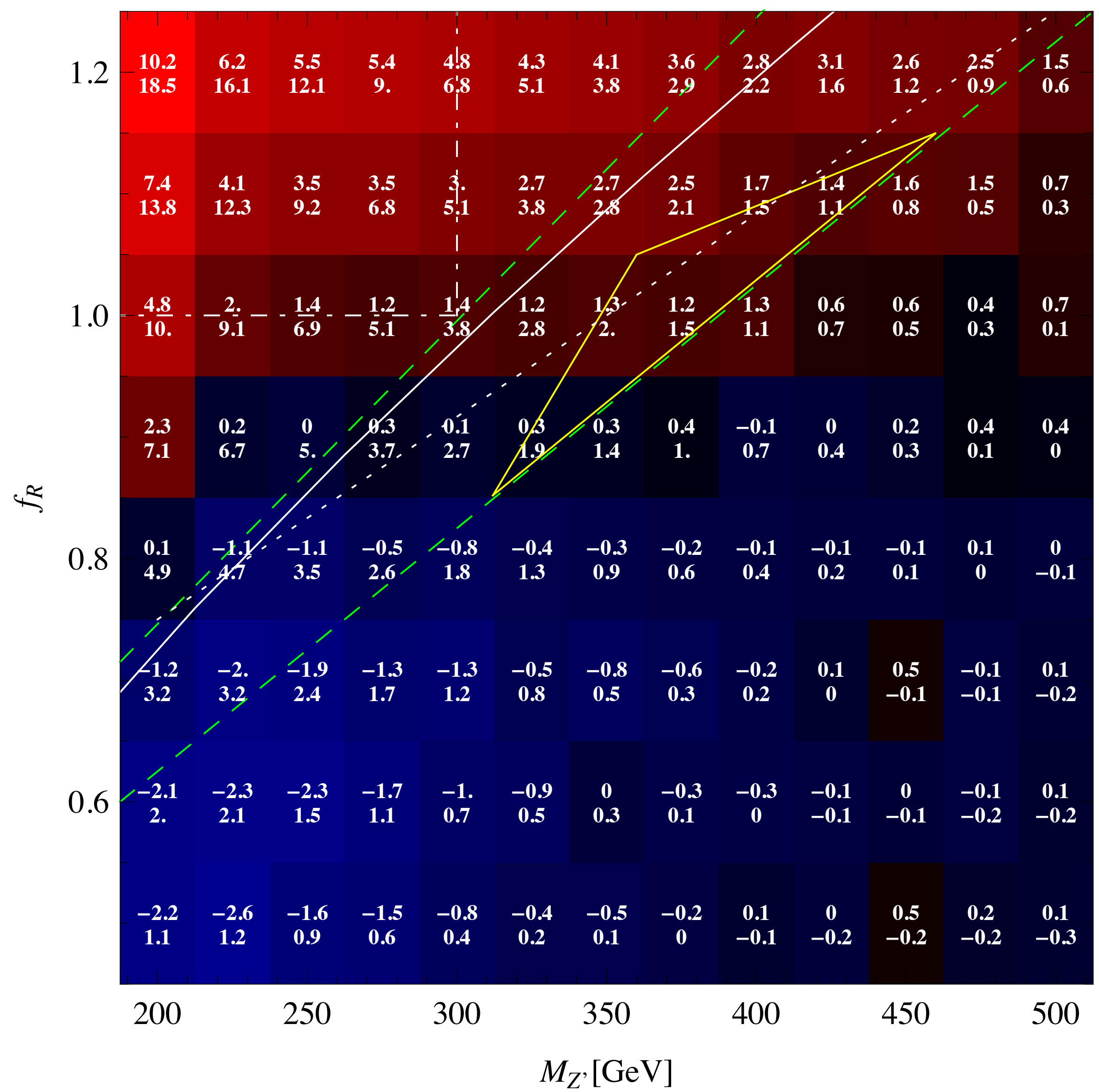

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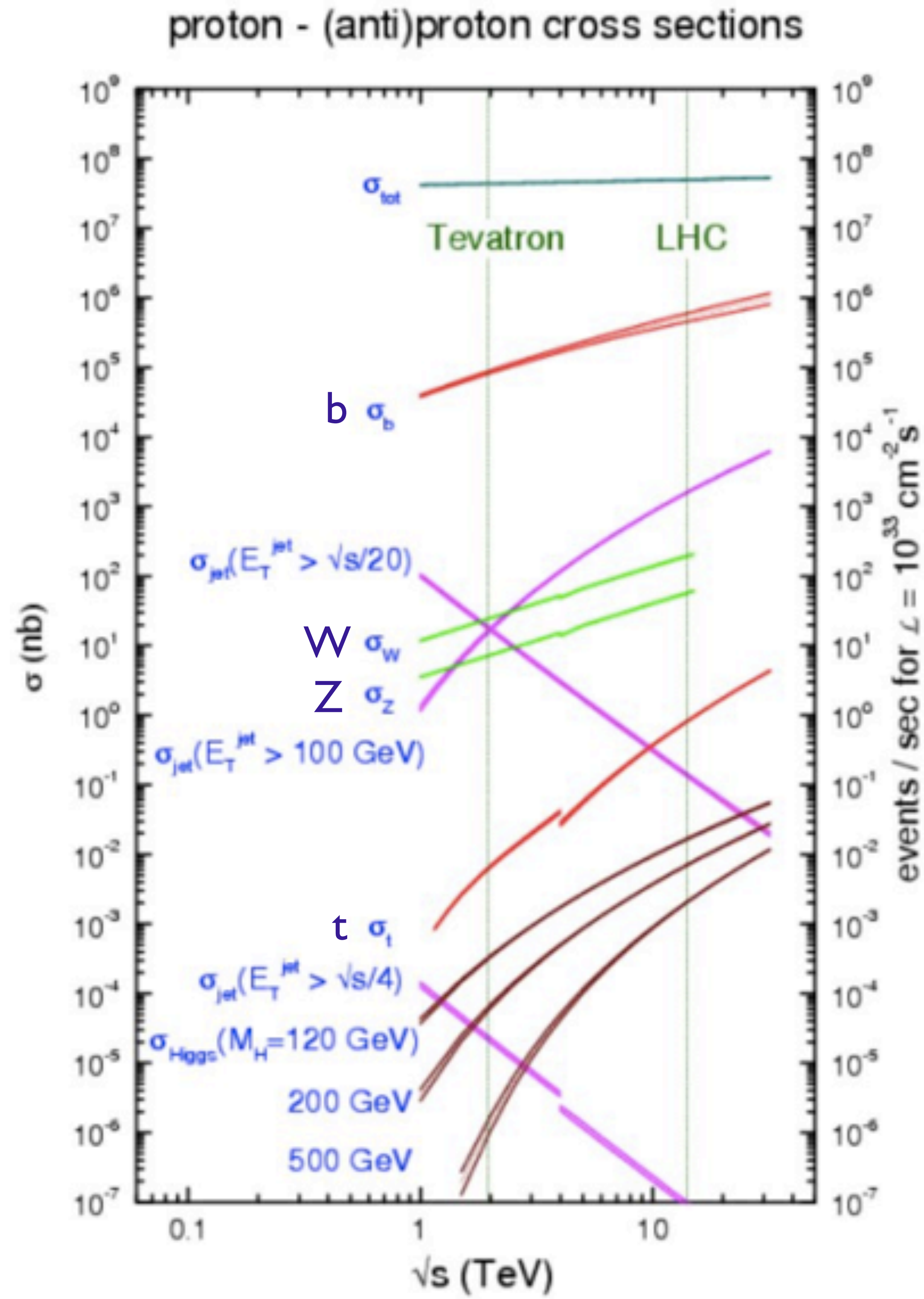
4. Find range of model parameters that can explain excess
   - ➡ Typically, using Monte Carlo simulations
5. Find other observables (collider as well as flavor/EWP/cosmology) where the explanation can be verified/falsified
   - ➡ Note that flavor/EWP/cosmology can typically be modified by additional particles in the model spectrum

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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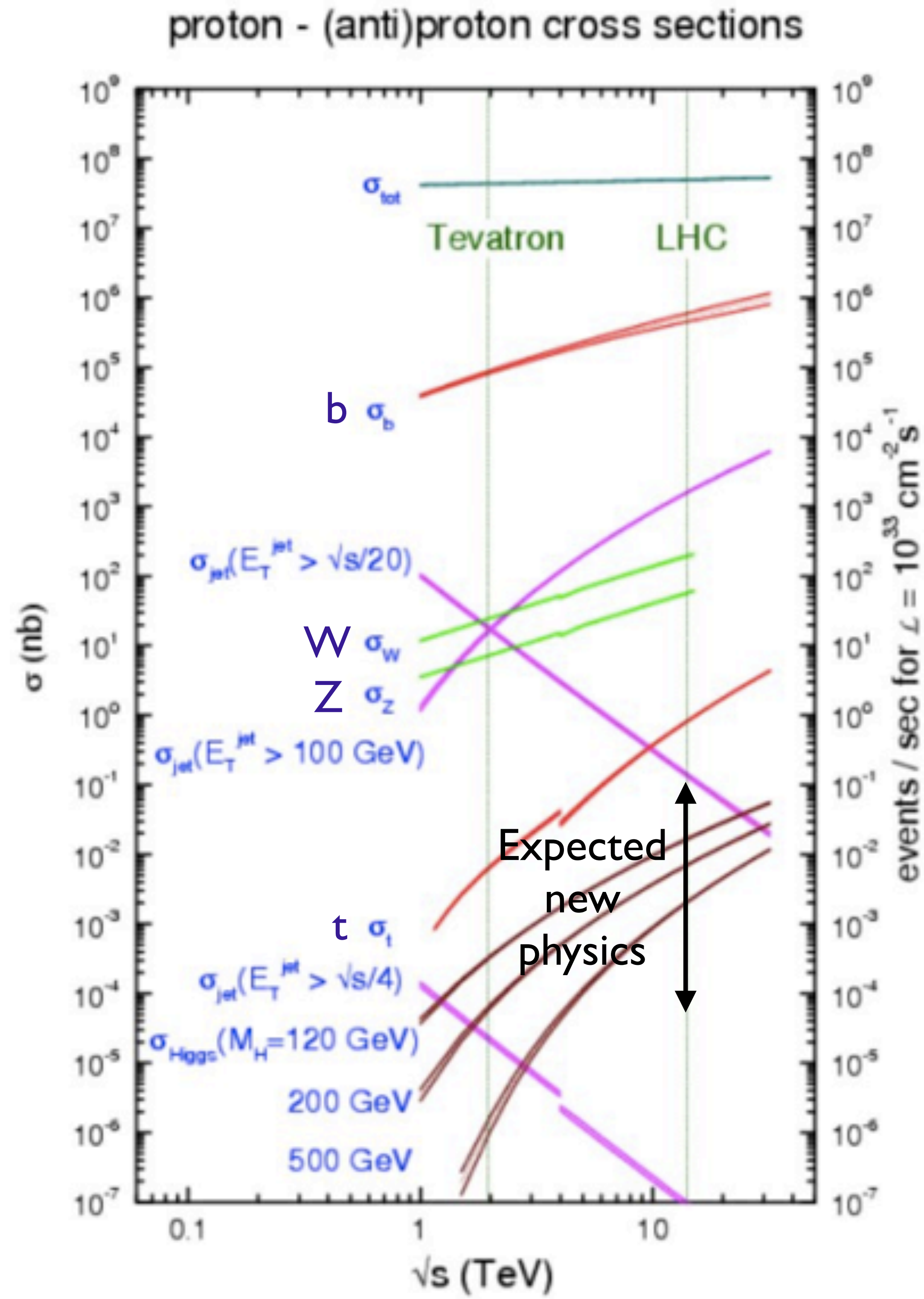

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- Parton density (or distribution) functions:
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- Difference between colliders given by parton luminocities

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
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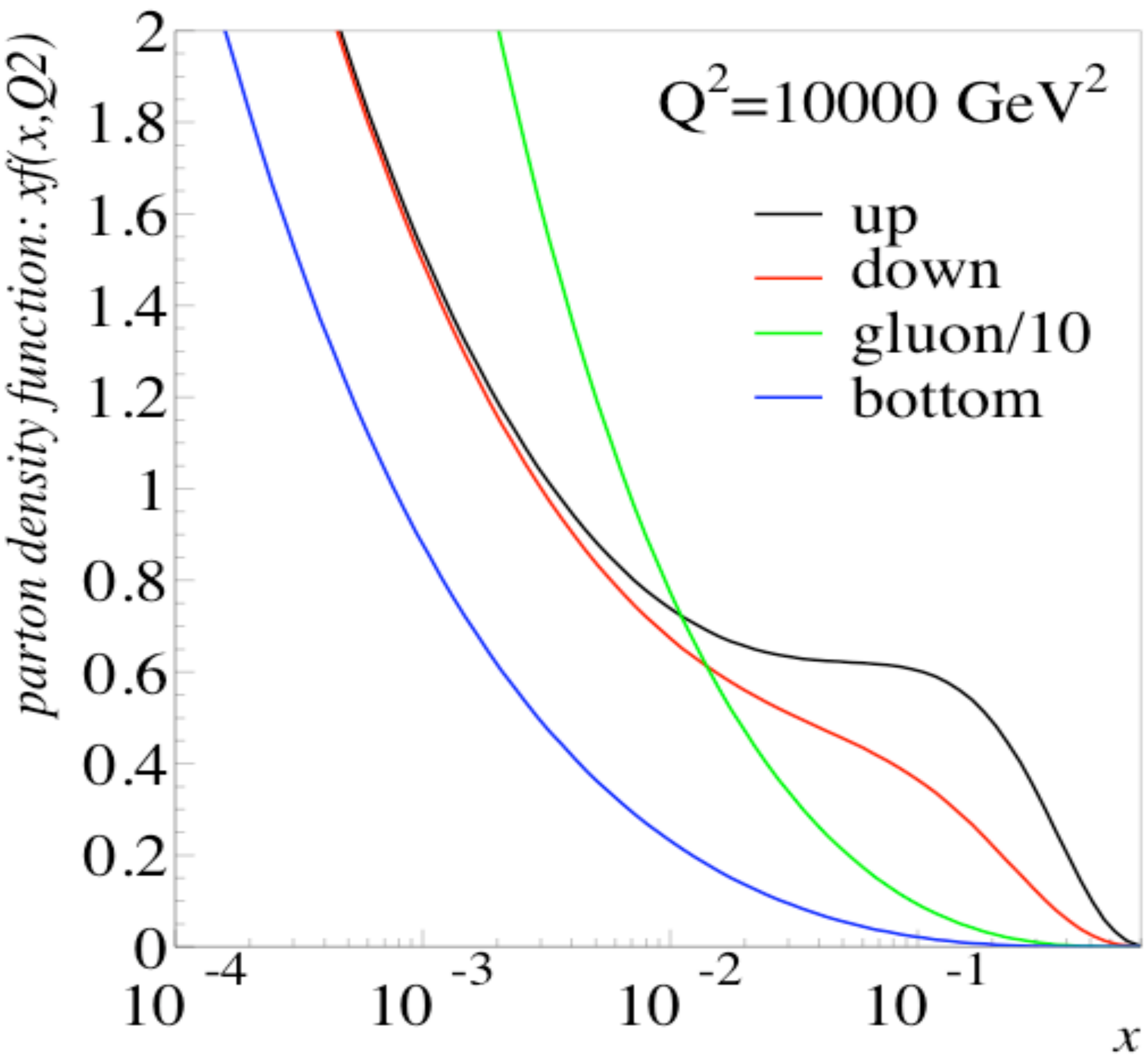
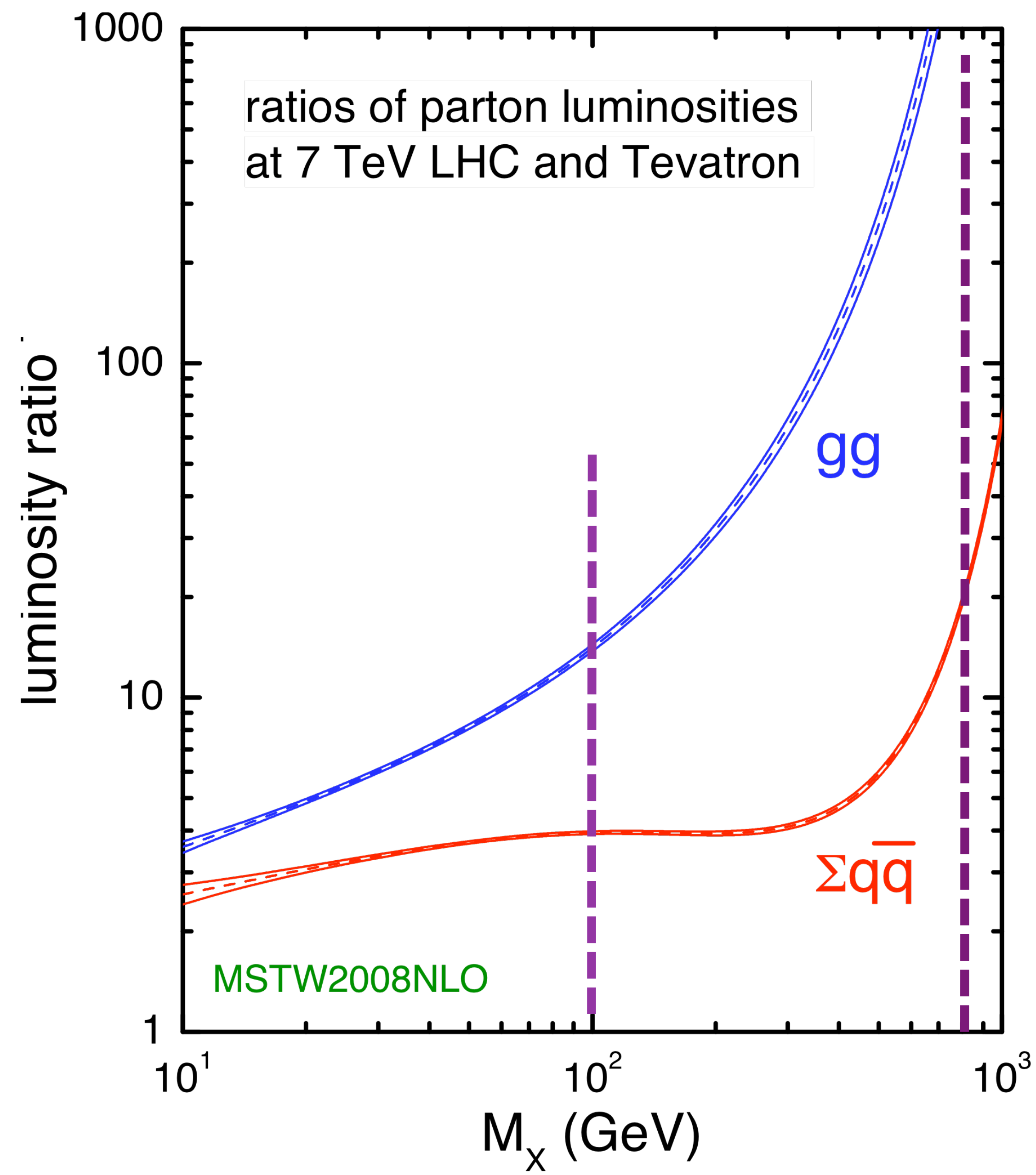
Parton densities

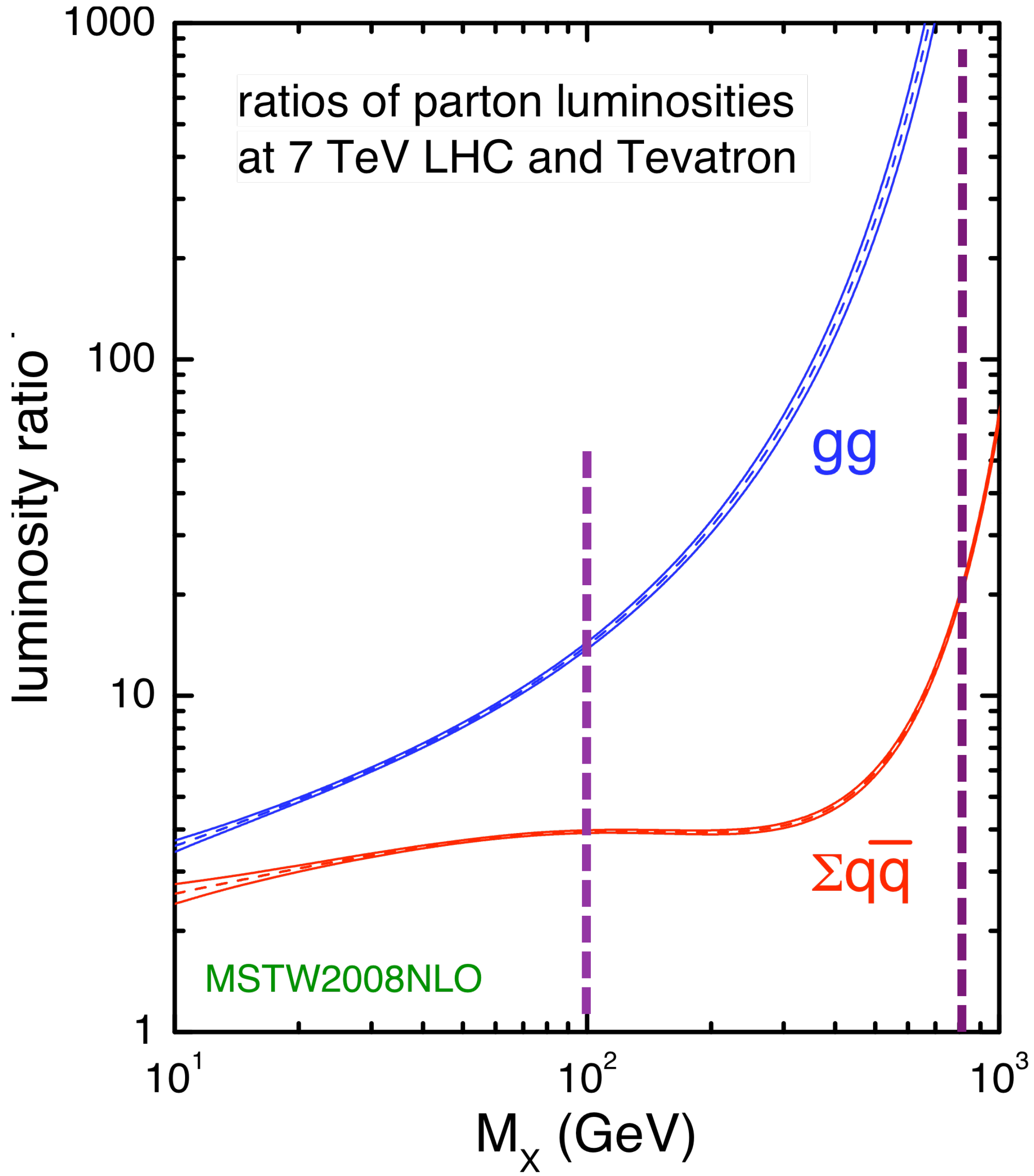


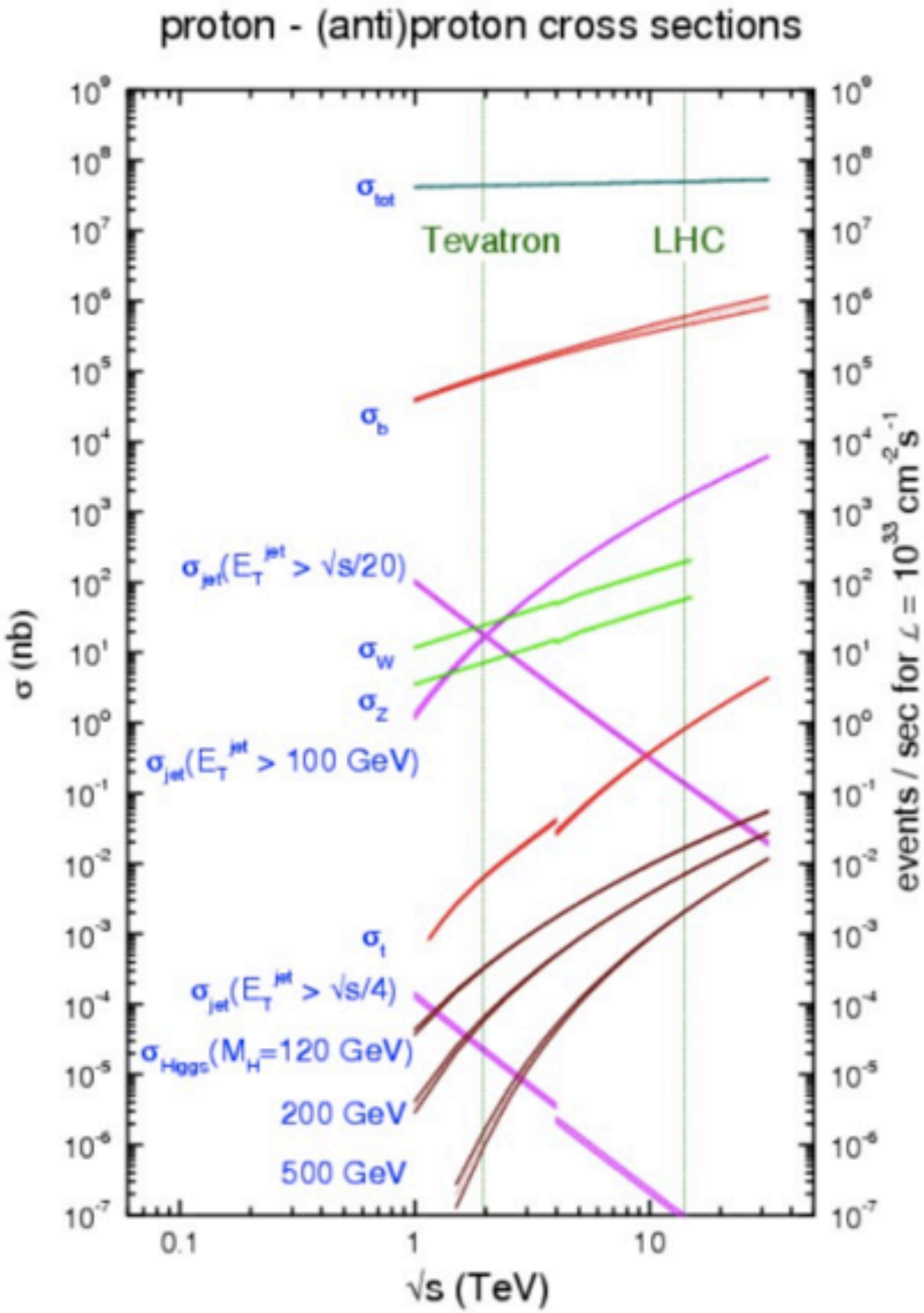
At small x (small $\hat{s}$), gluon domination.
At large x valence quarks



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

Back to the processes





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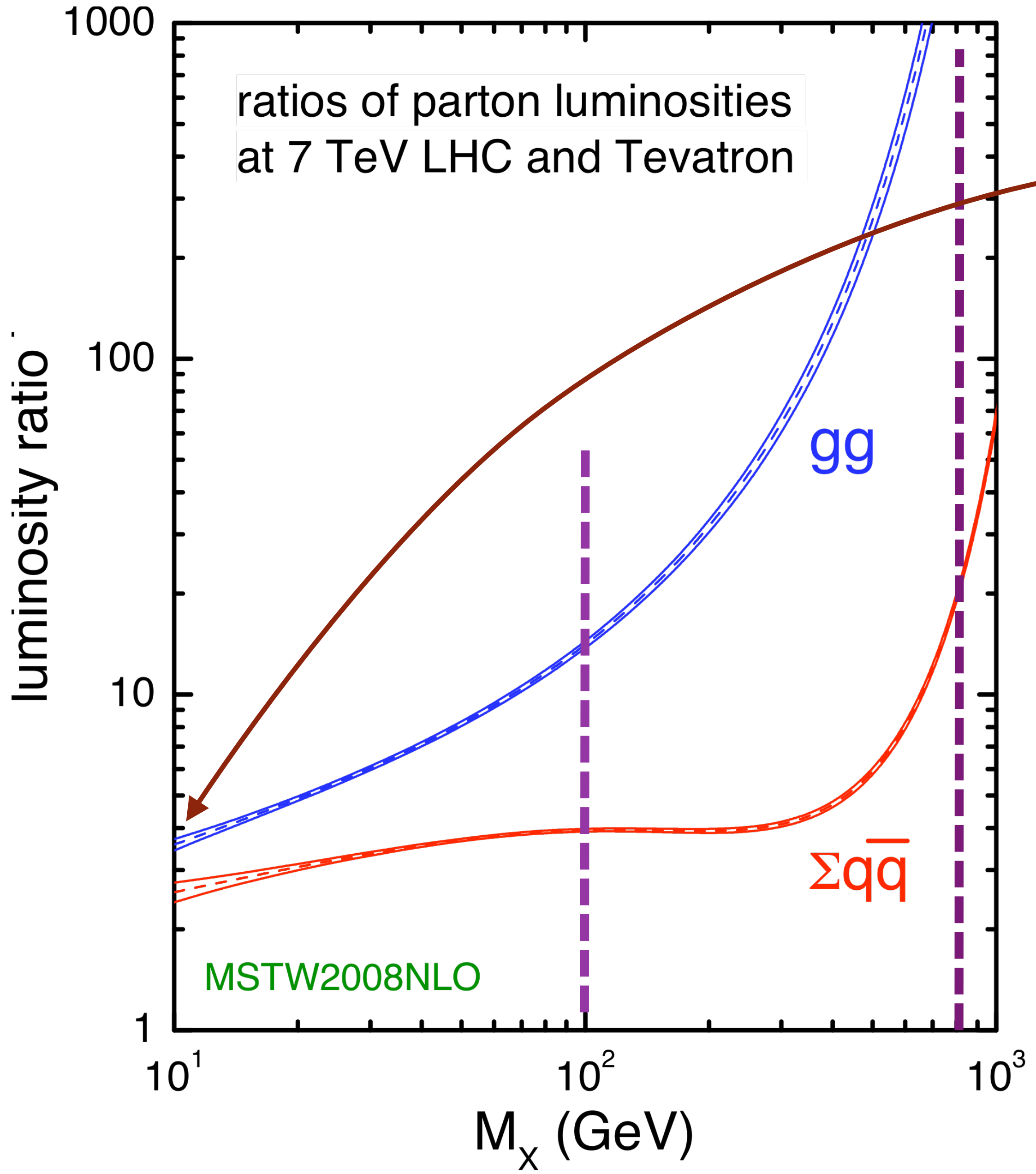

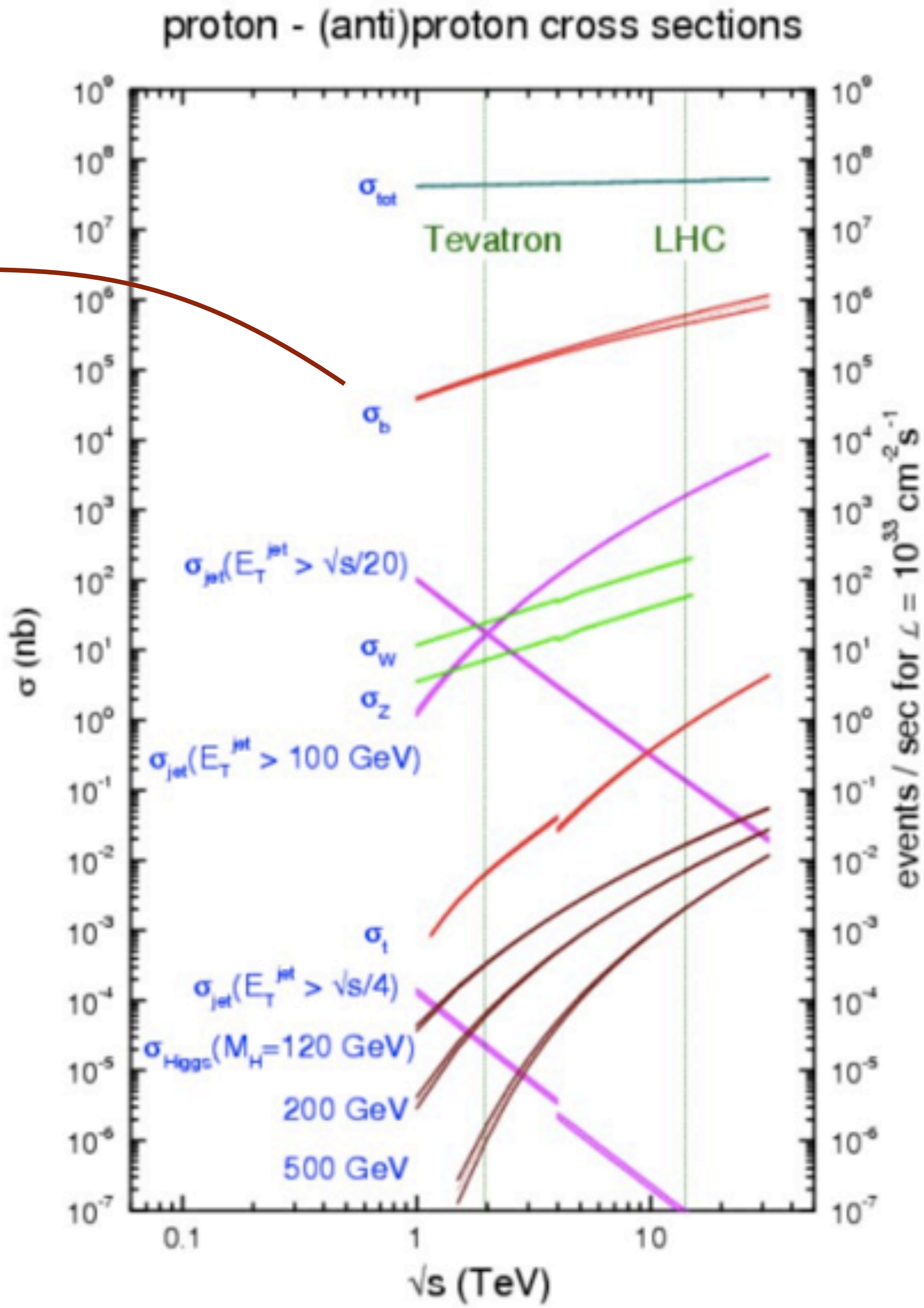

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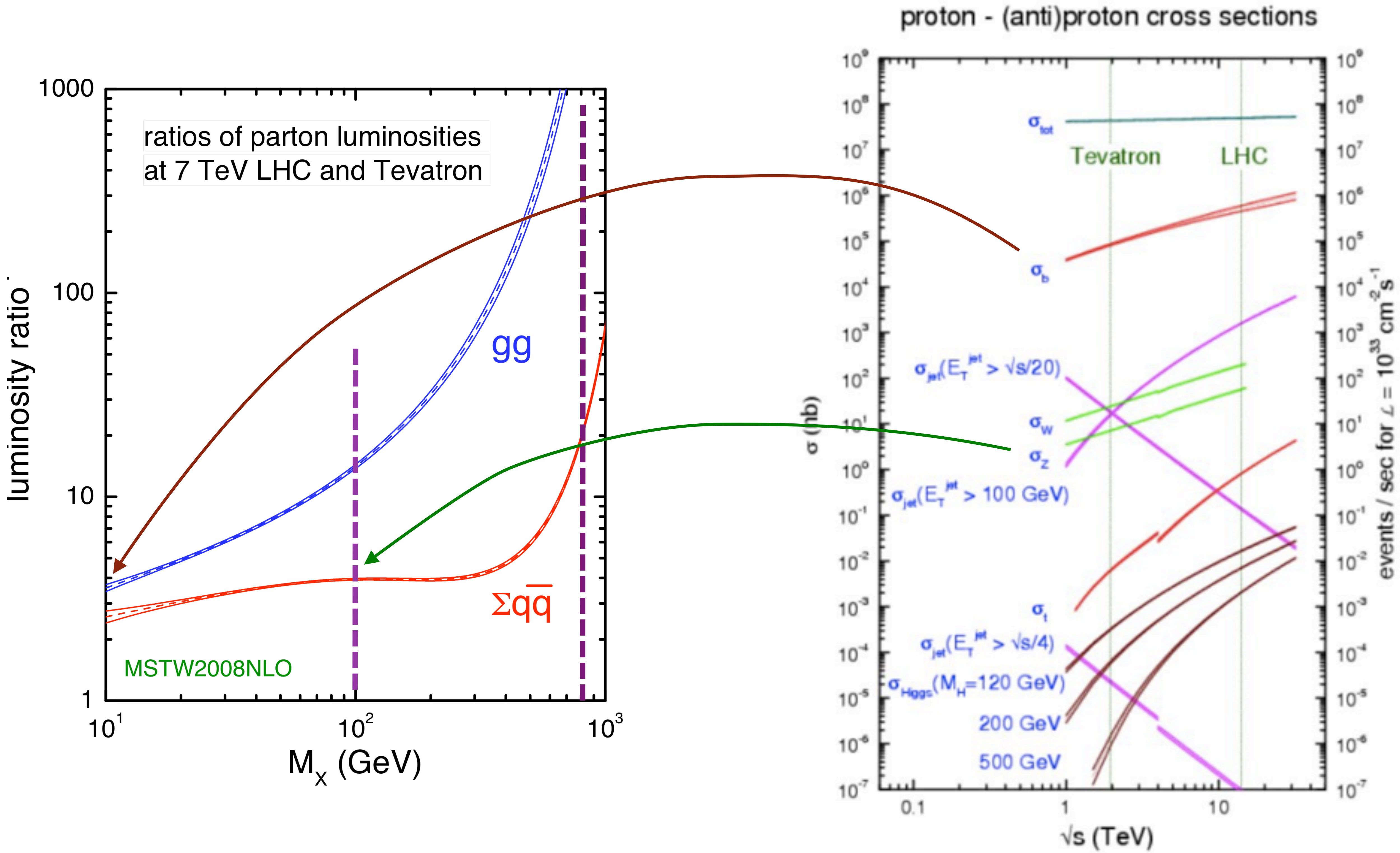

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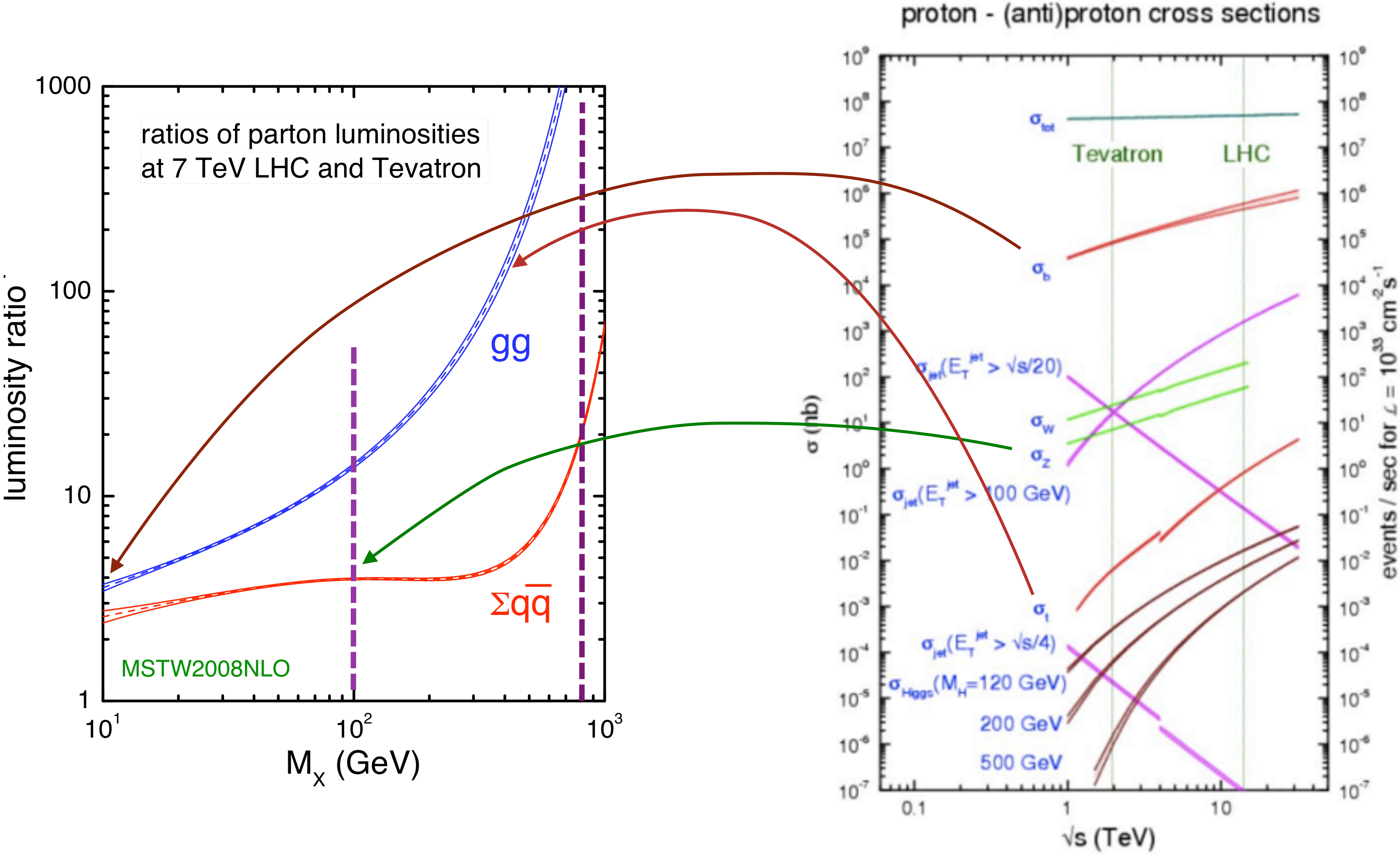

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General and flexible method is needed

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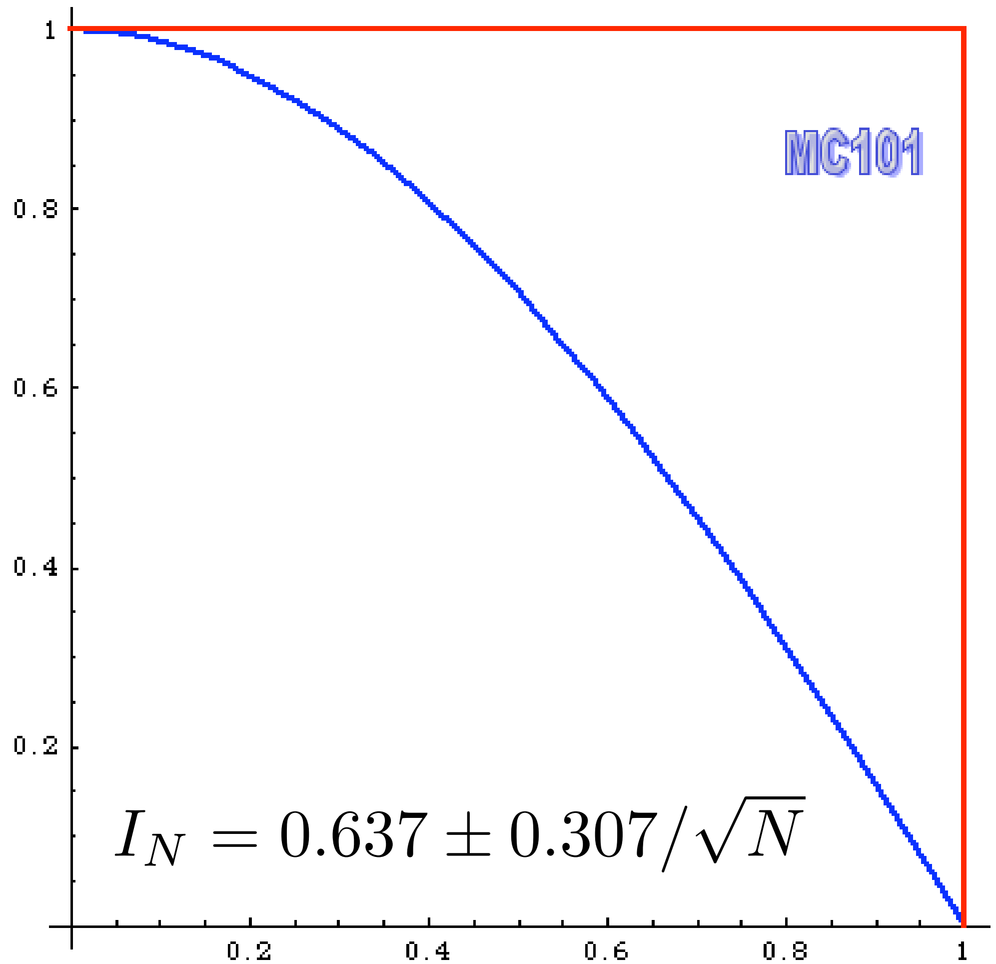
- ☞ Convergence is slow but it can be easily estimated
- ☞ Error does not depend on # of dimensions!
- ☞ Improvement by minimizing V_N.
- ☞ Optimal/Ideal case: $f(x)=C \Rightarrow V_N=0$

Importance Sampling



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

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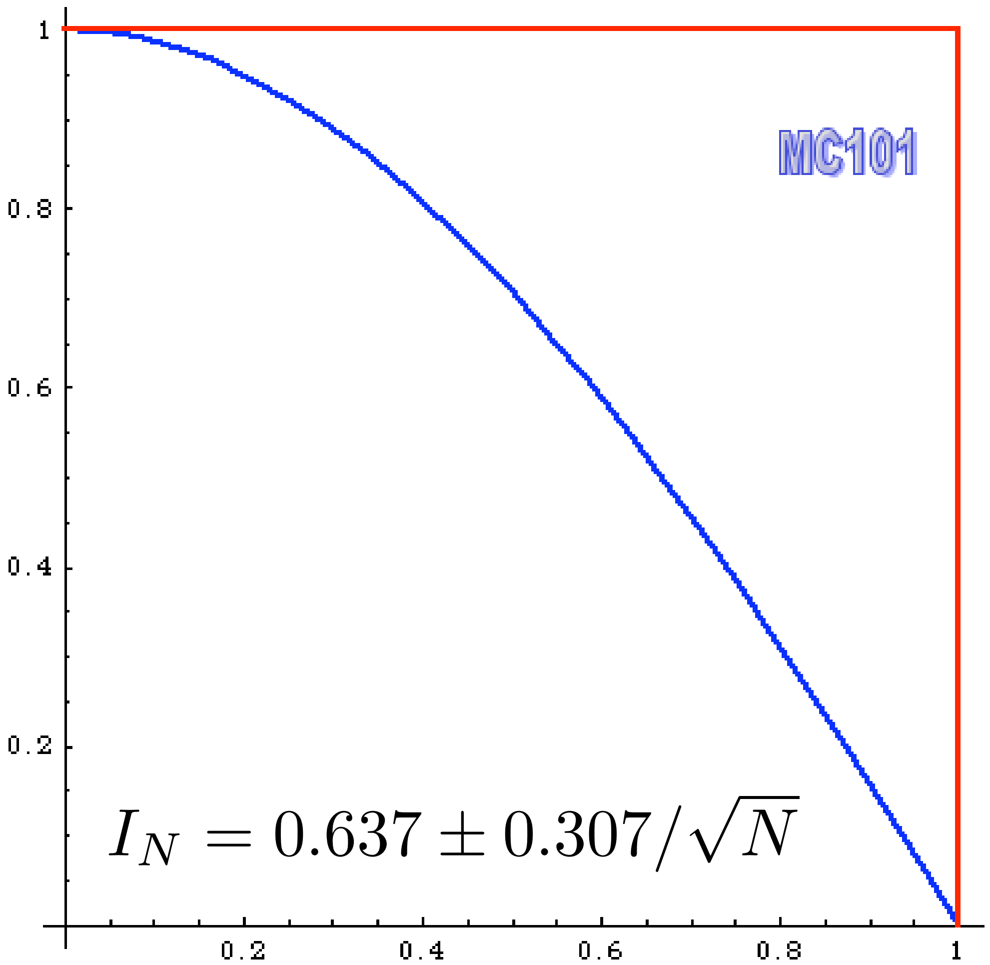

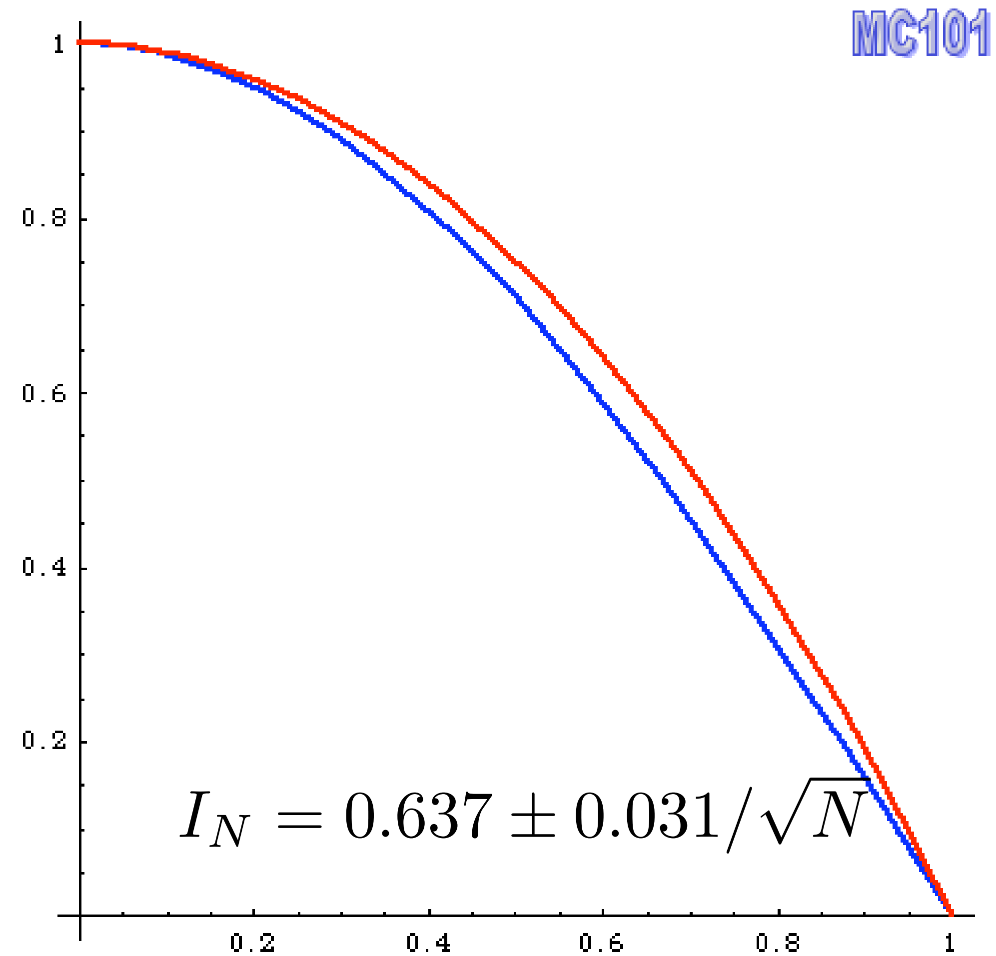

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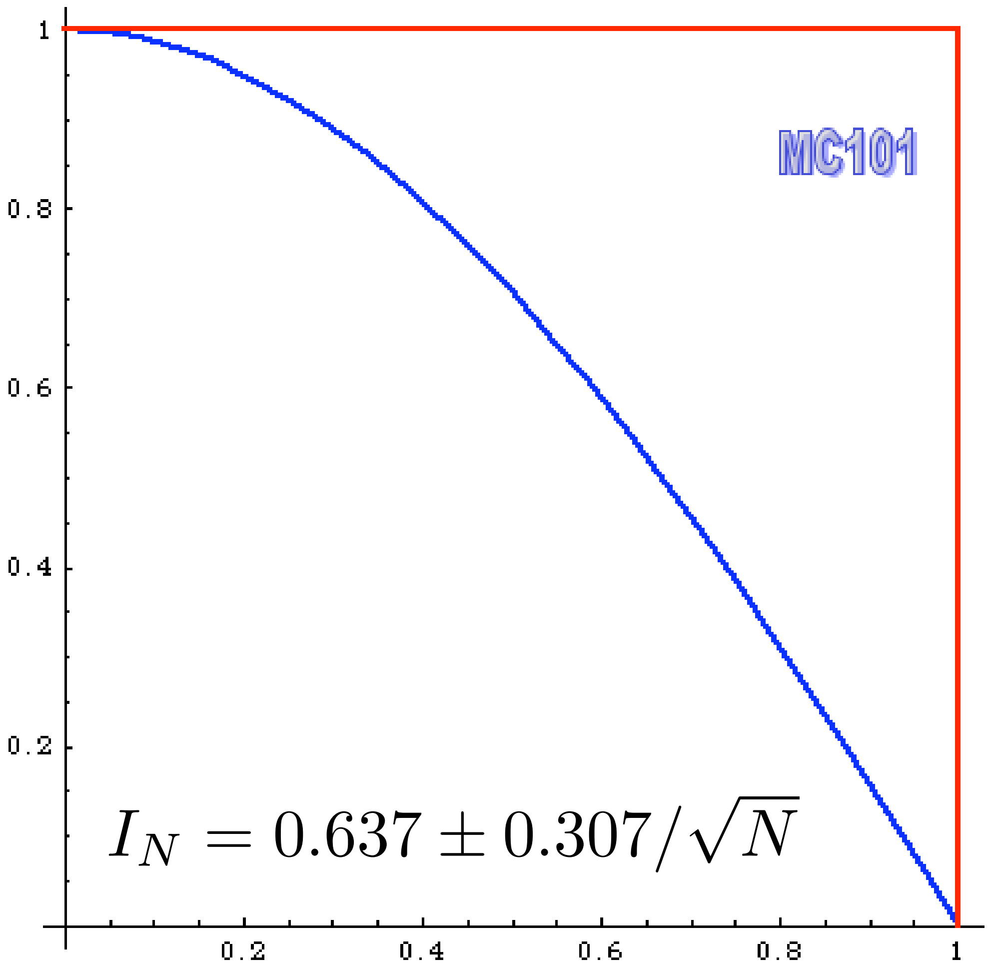

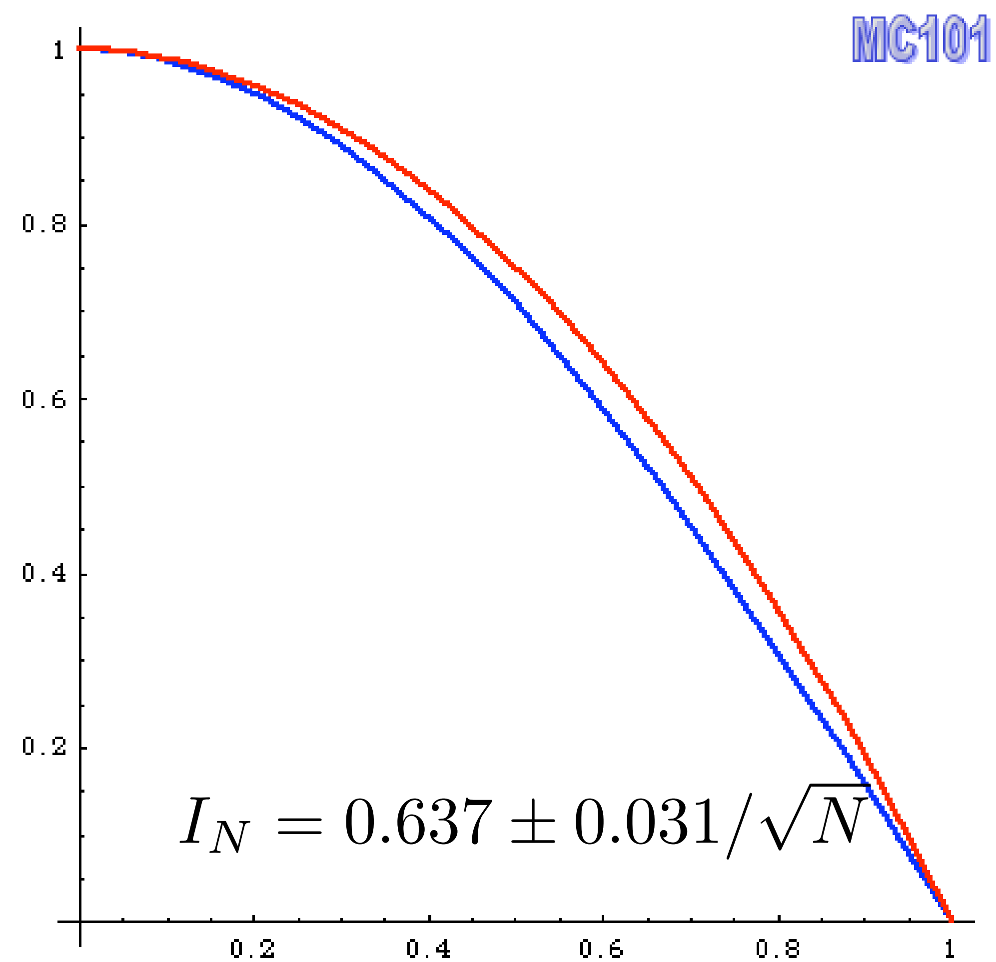

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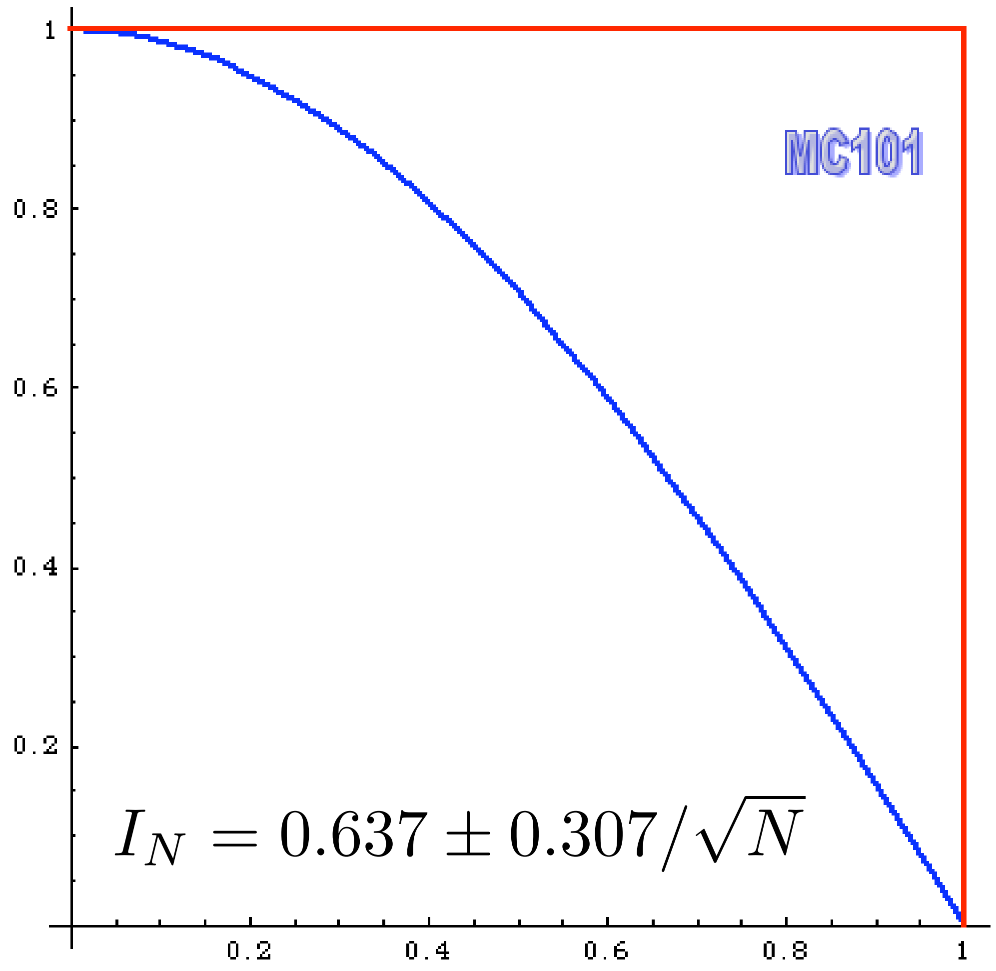

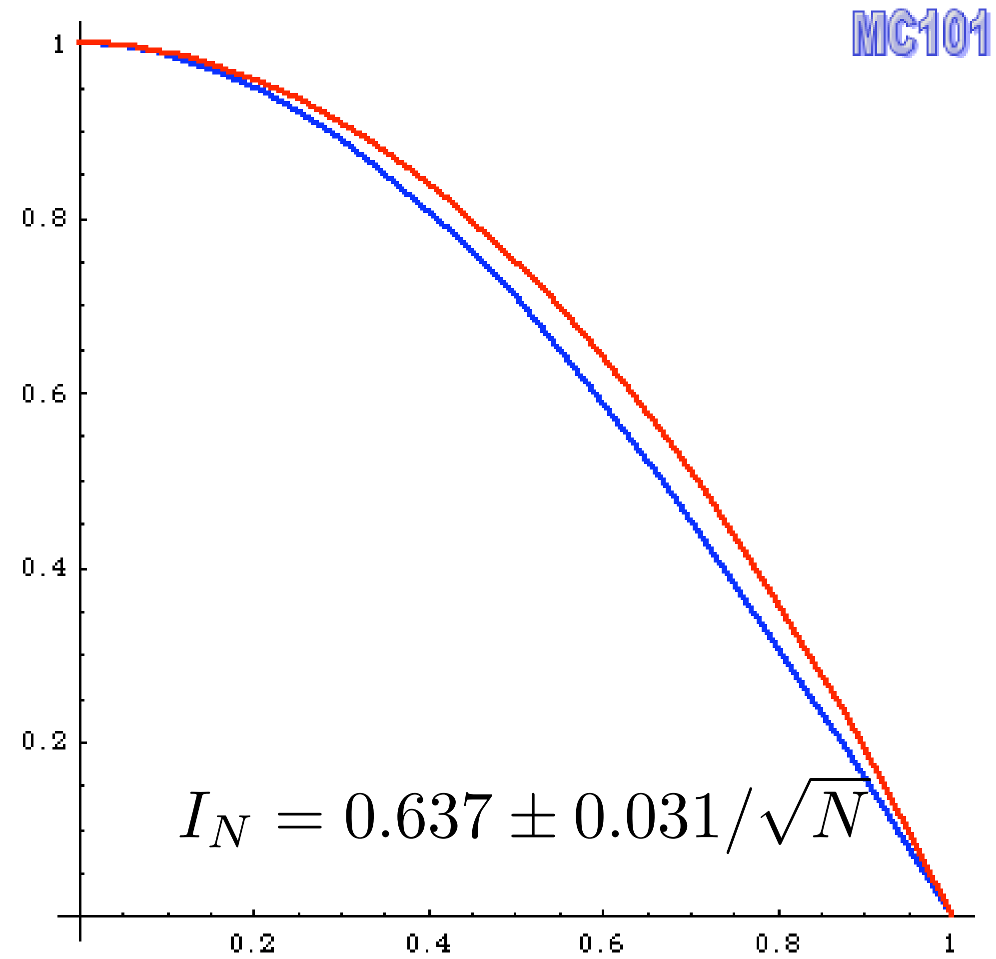

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Alternative: learn during the run and build a step-function approximation p(x) of f(x) ⇒ VEGAS

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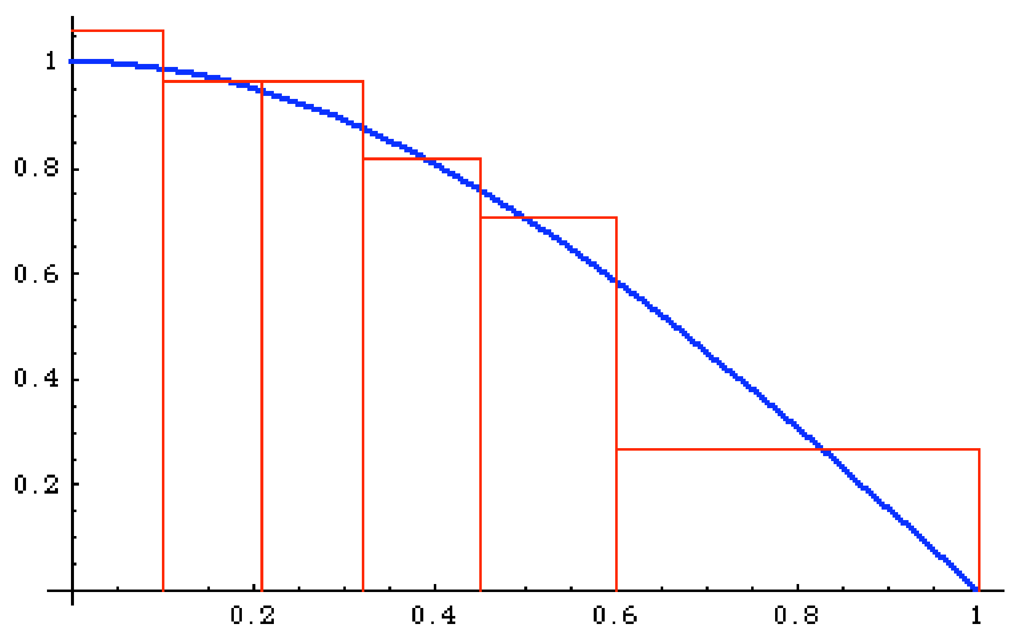
MC101



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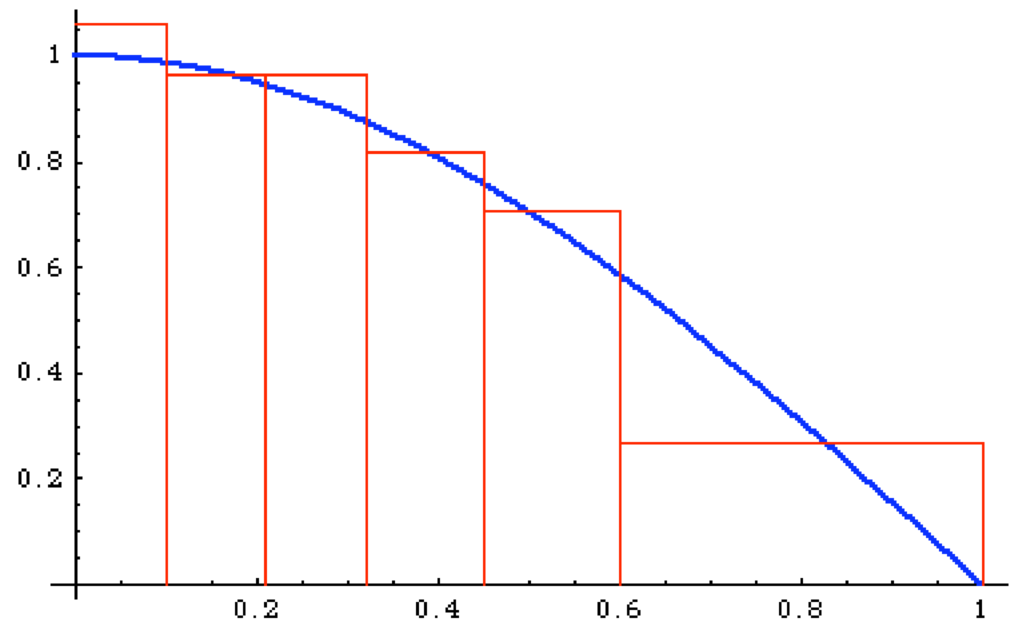

many bins where f(x) is large

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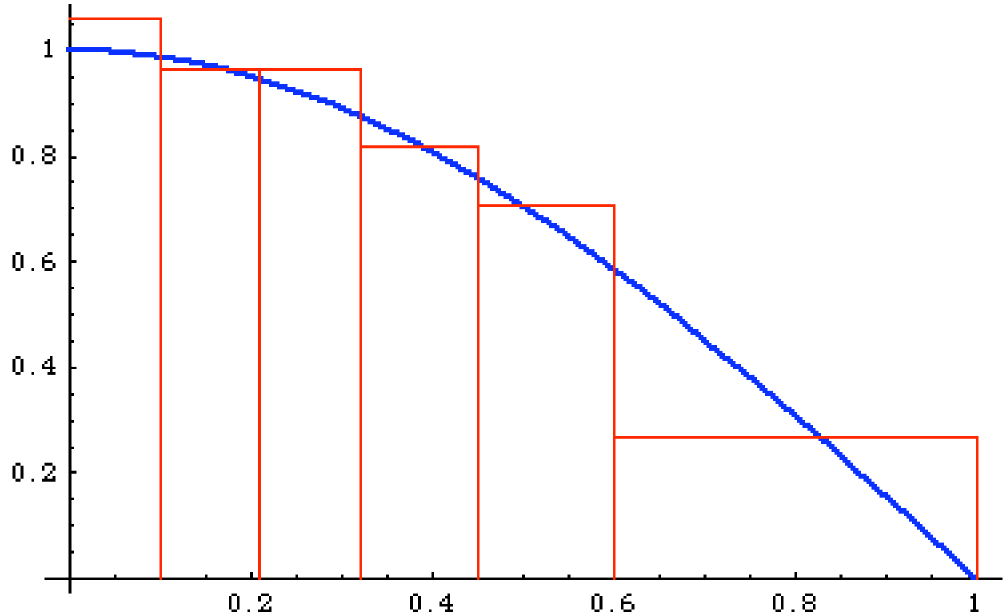
MC101



many bins where f(x) is large

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

Importance Sampling

can be generalized to n dimensions:

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

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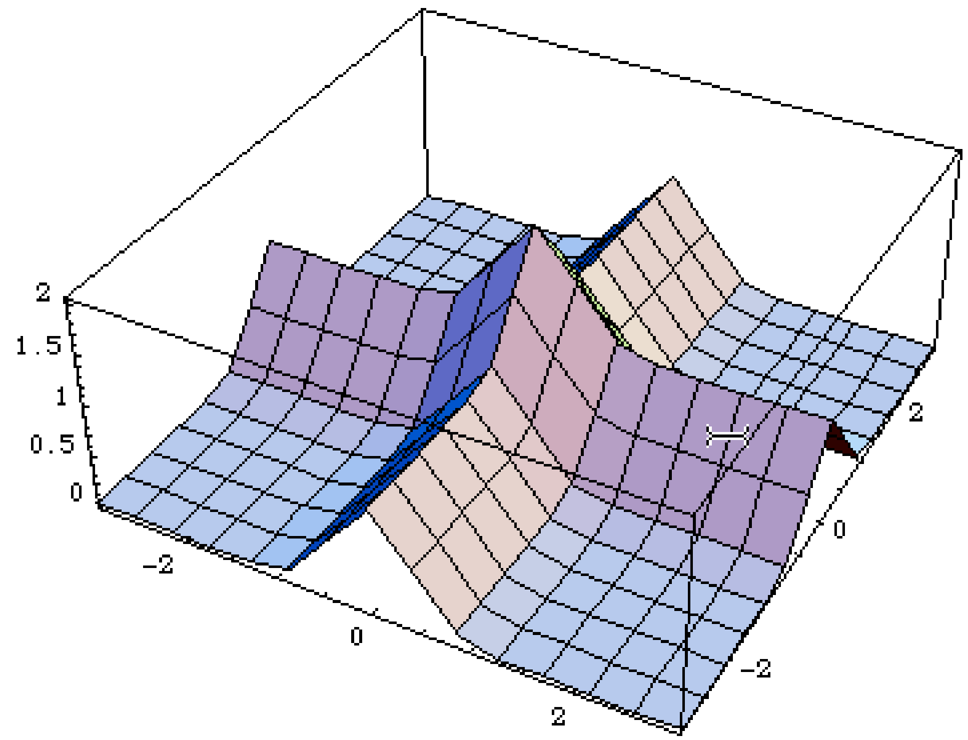

This is ok...

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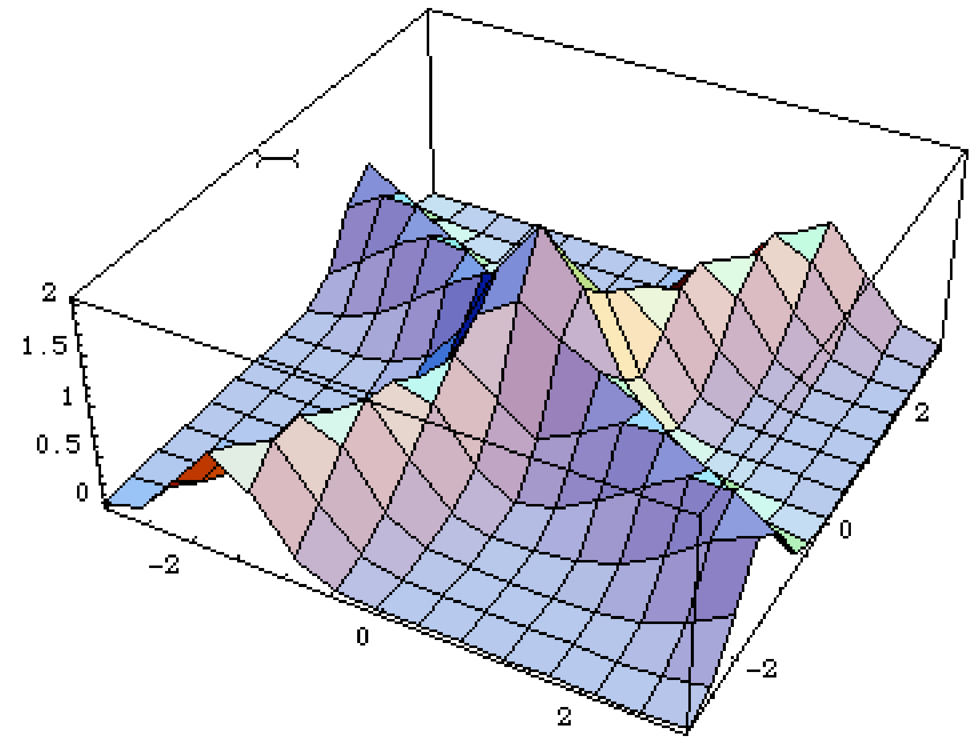

This is not ok...

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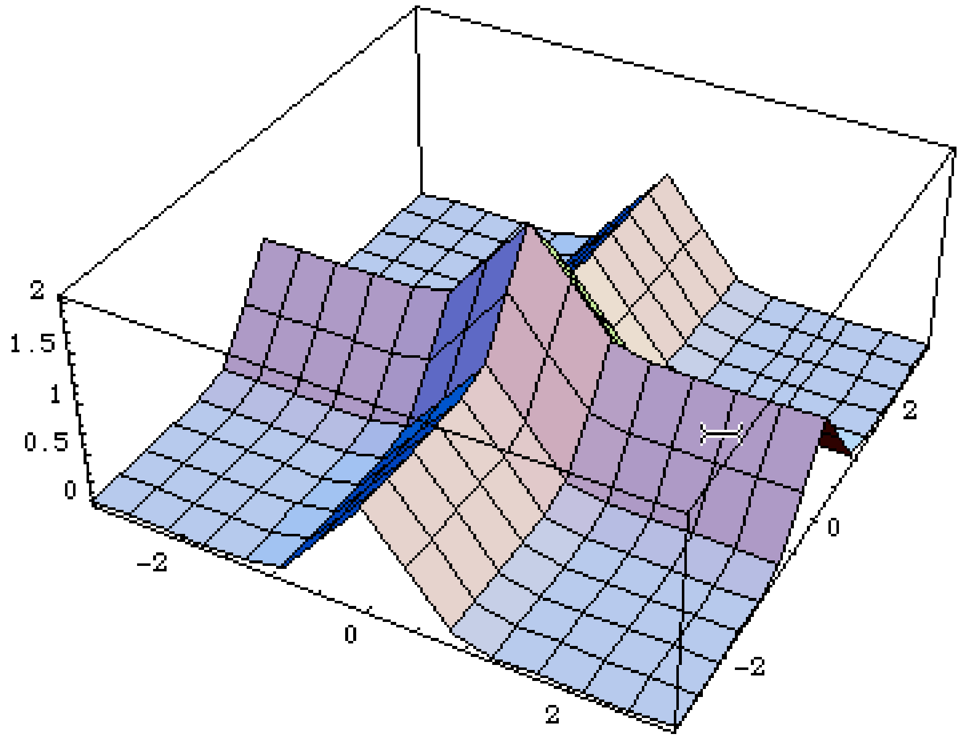
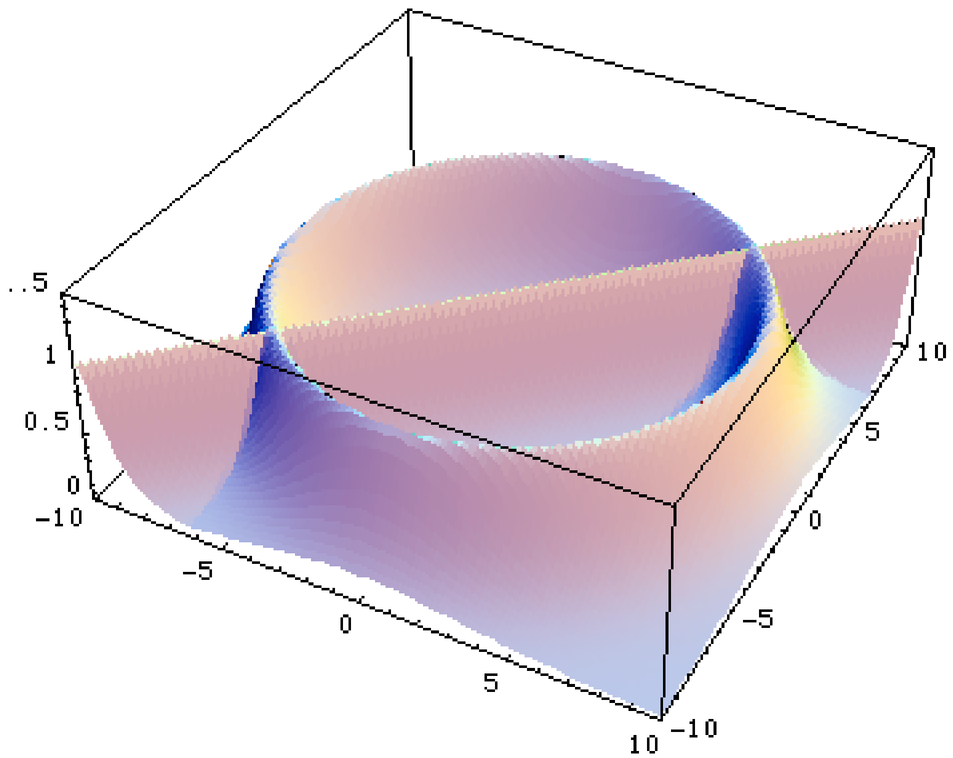


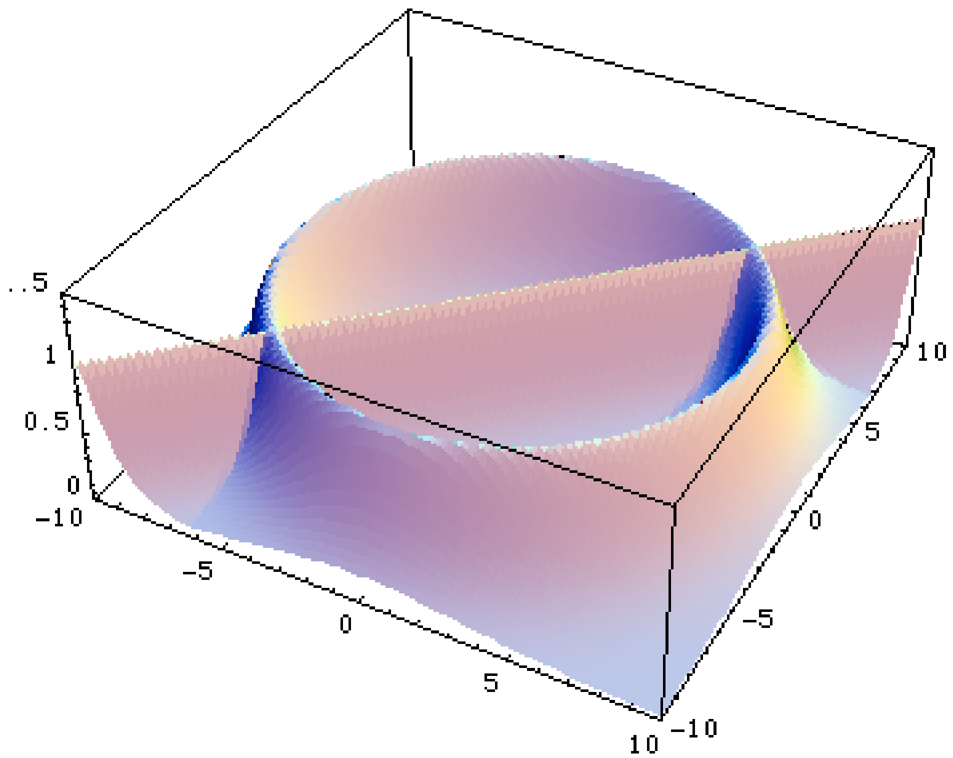
but it is sufficient to make a change of variables!

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



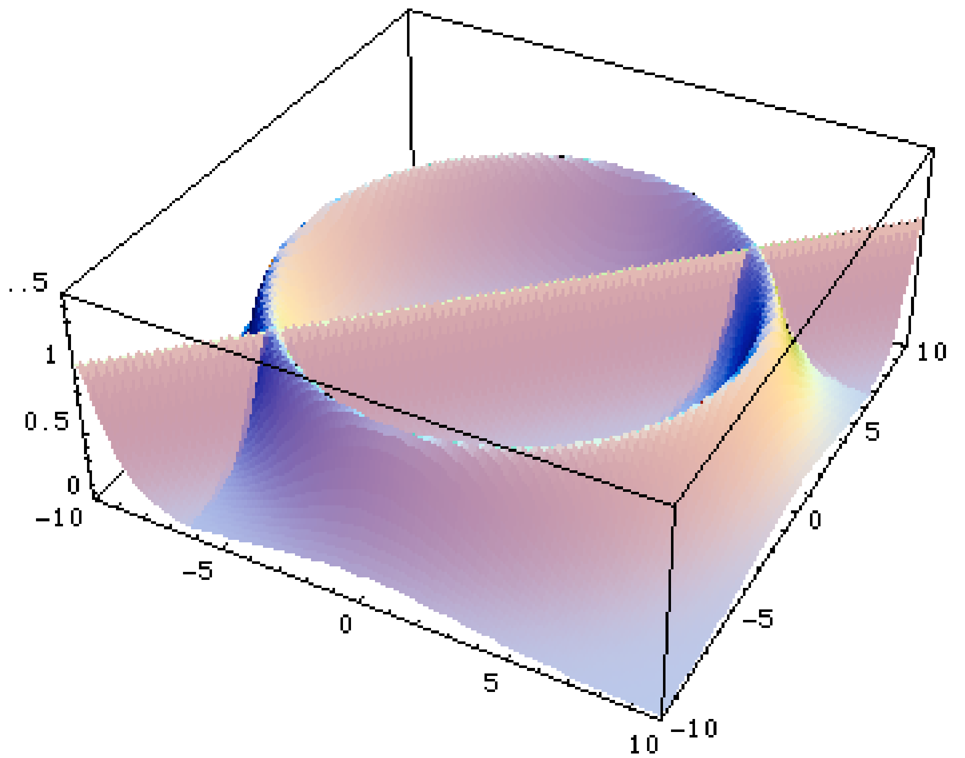
What do we do if there is no transformation that aligns all integrand peaks to the chosen axes? Vegas is bound to fail!

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

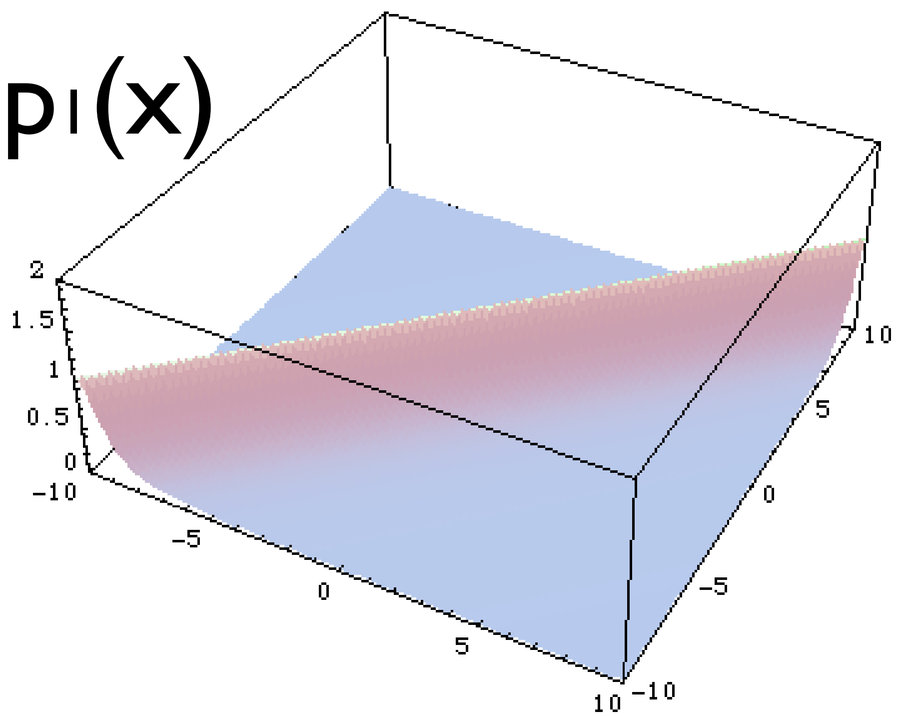
Multi-channel



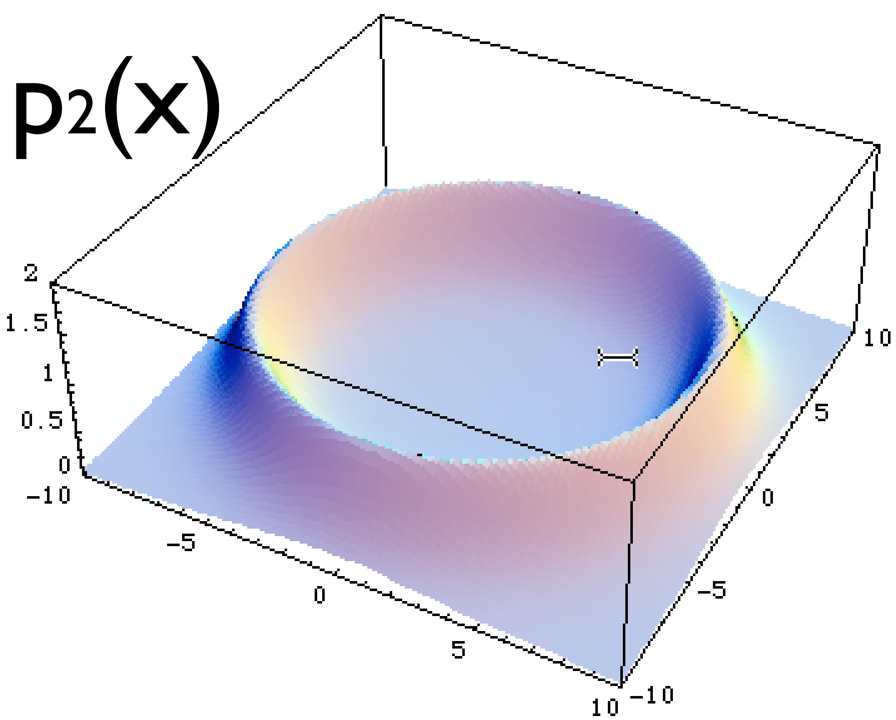
$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x)$$

with
$$\sum_{i=1}^{n} \alpha_i = 1$$

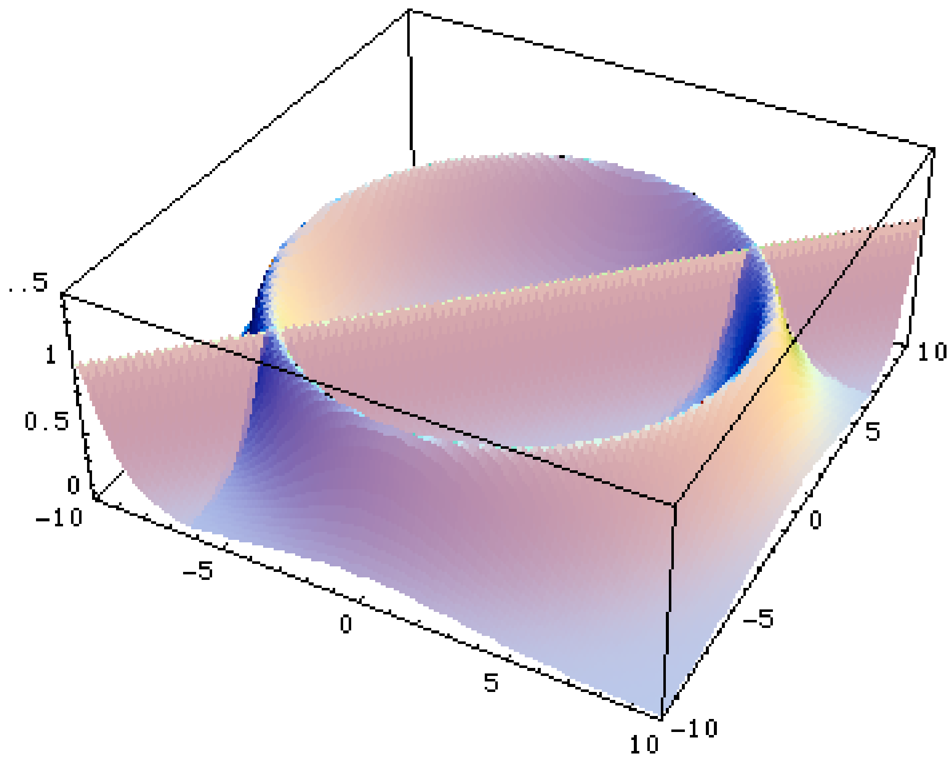
$p_1(x)$



$p_2(x)$



Multi-channel



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

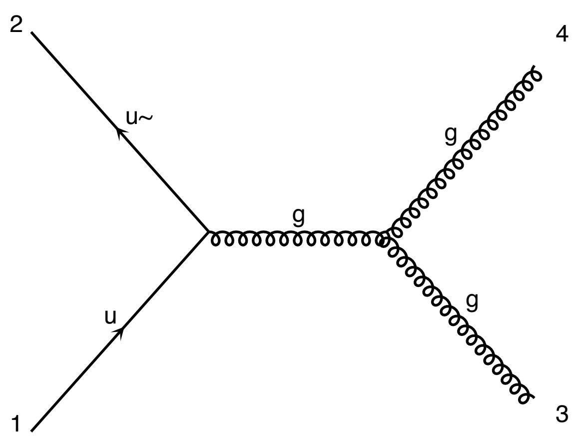
with

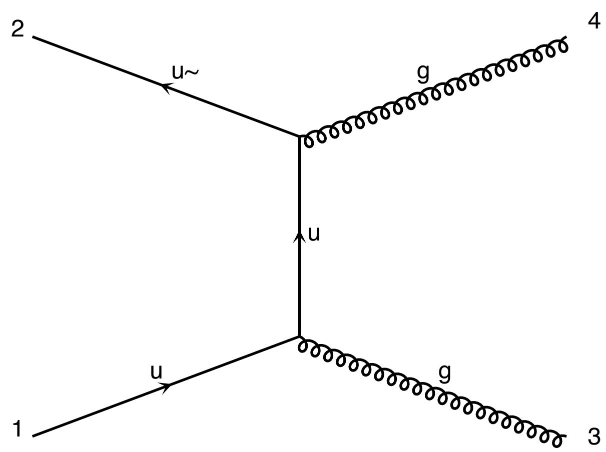
$$\sum_{i=1}^{n} \alpha_i = 1$$

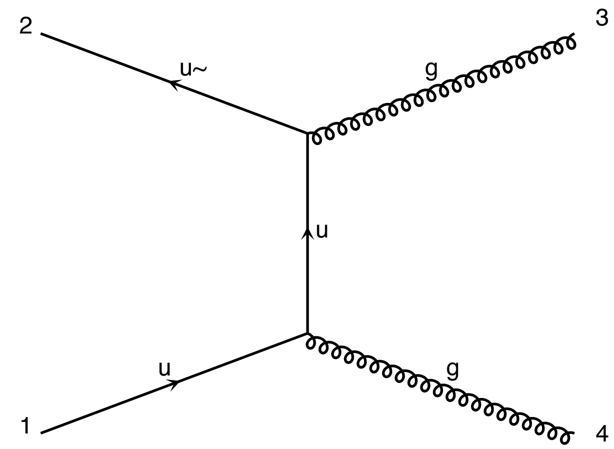
Then,

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

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 tree level which many contributing diagrams. We would like to have 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,

giving us the combined integral

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

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Does such a basis exist?

Multi-channel based on single diagrams*

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

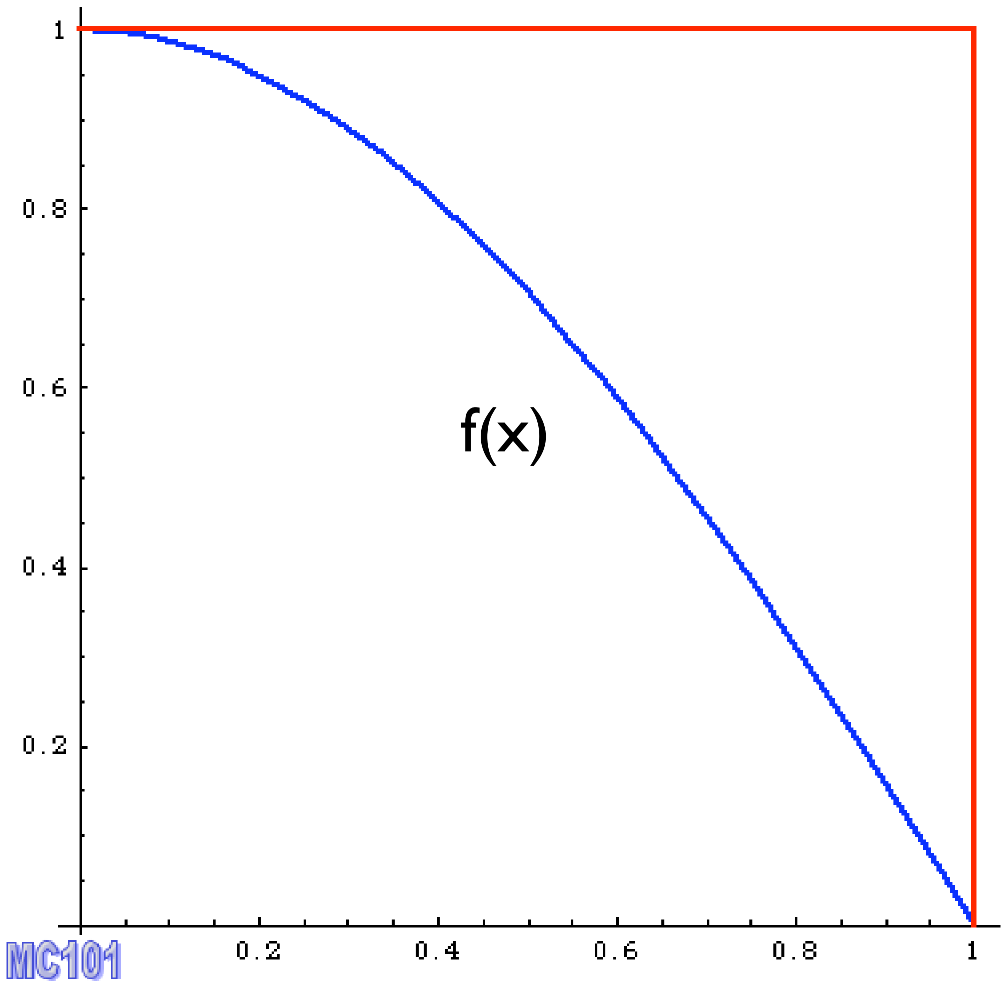
Multi-channel based on single diagrams*

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

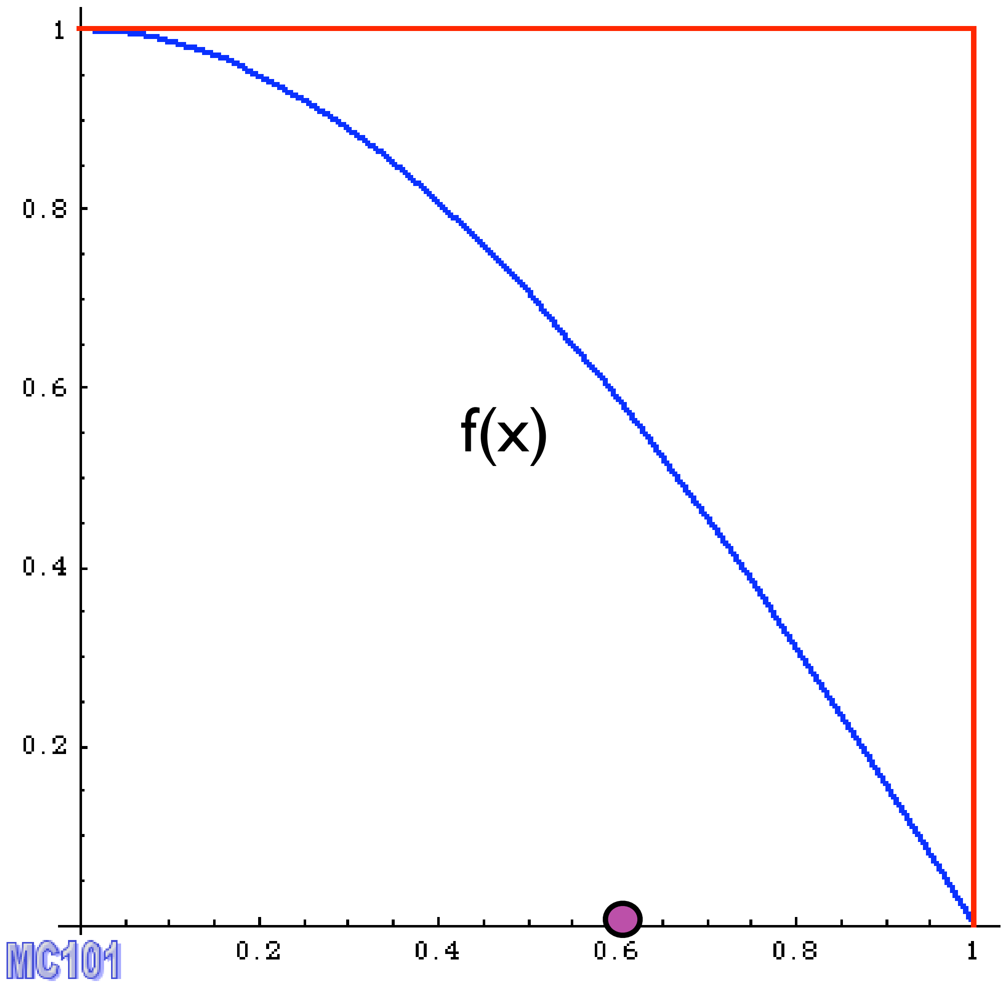
- Key Idea
  - Any single diagram is "easy" to integrate (pole structures/ suitable integration variables known from the propagators)
  - Divide integration into pieces, based on diagrams
  - All other peaks taken care of by denominator sum
- Get N independent integrals
  - Errors add in quadrature so no extra cost
  - "Weight" functions already calculated during $|M|^2$ calculation
  - Parallel in nature
- What about interference?
  - Never creates "new" peaks, so we're OK!

*Method used in MadGraph

Monte Carlo Event Generation

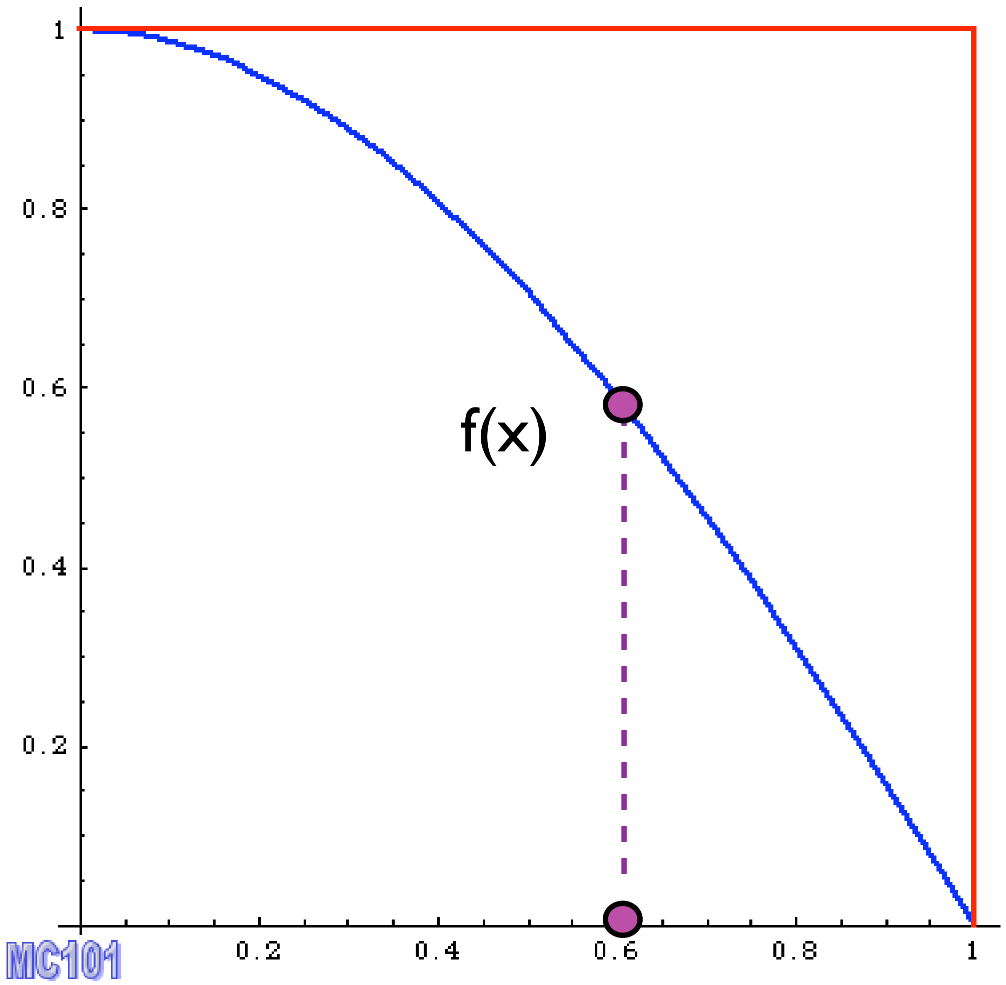


Monte Carlo Event Generation



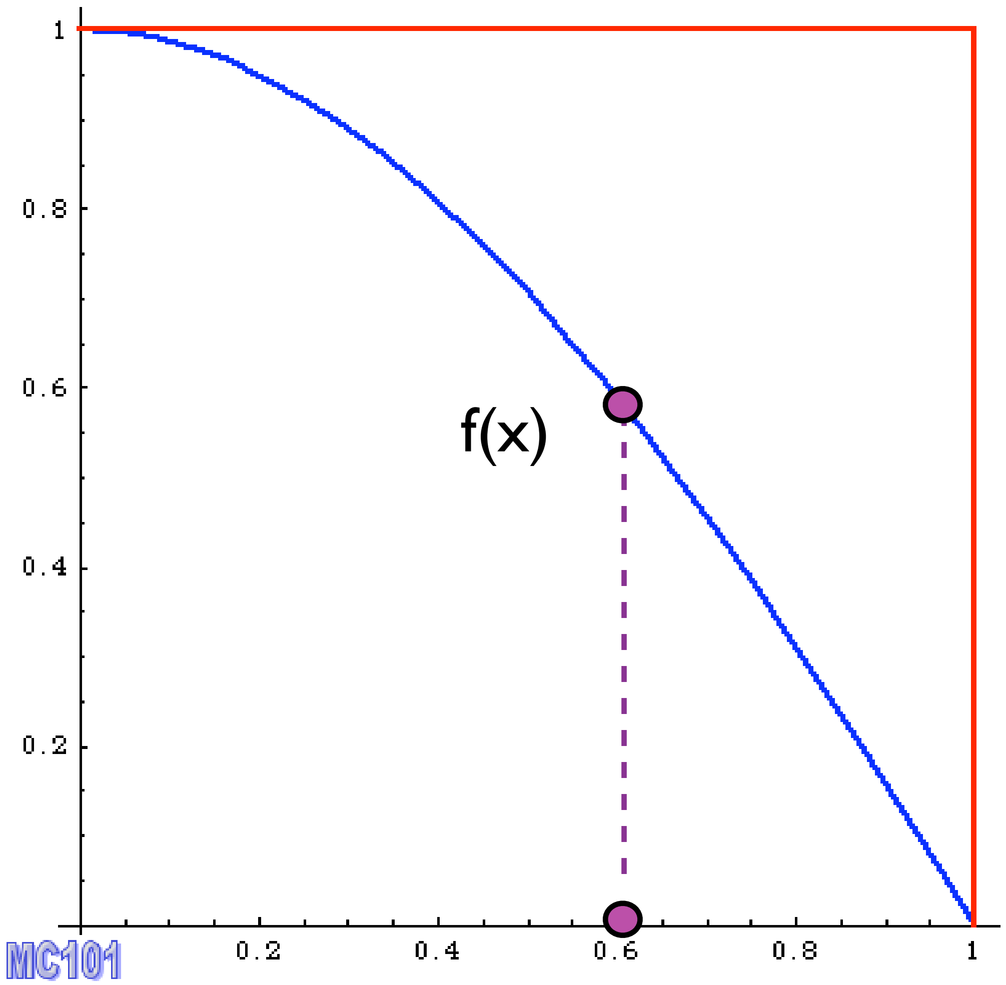
1. pick x

Monte Carlo Event Generation



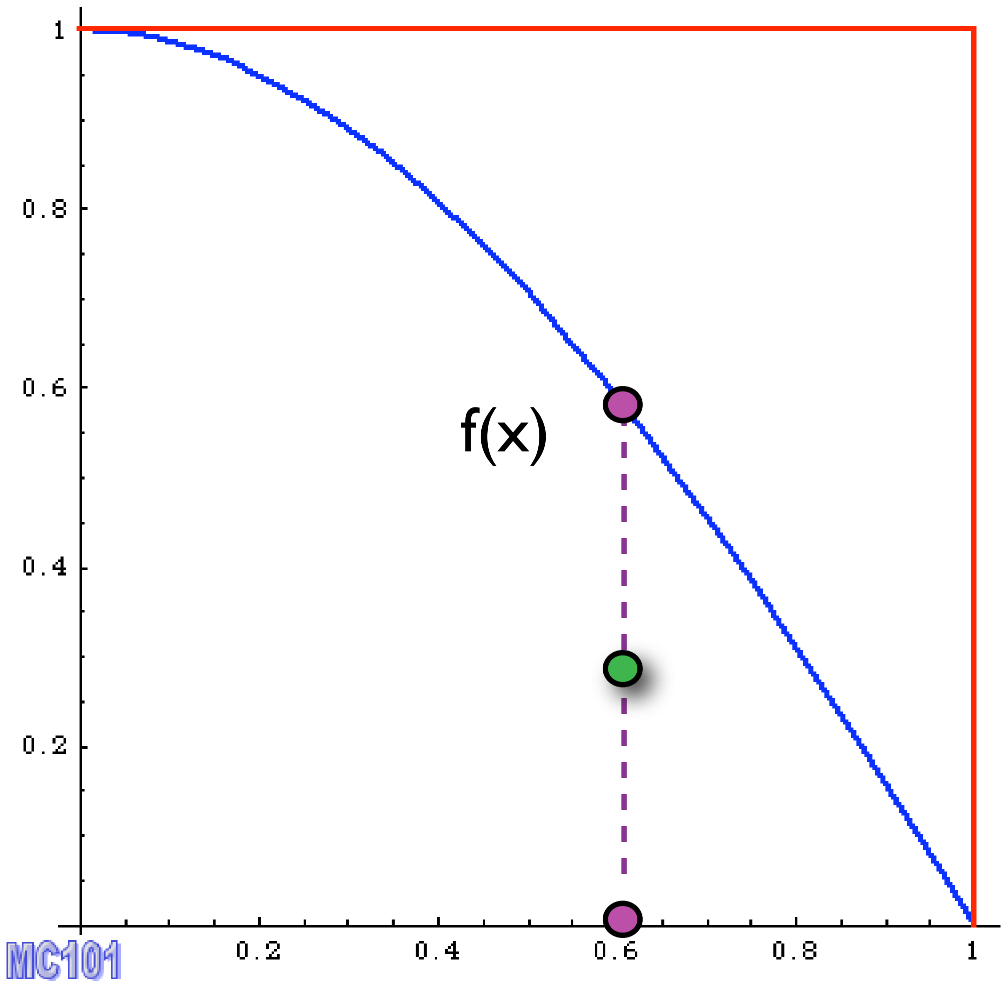
1. pick x
2. calculate f(x)

Monte Carlo Event Generation



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

Monte Carlo Event Generation



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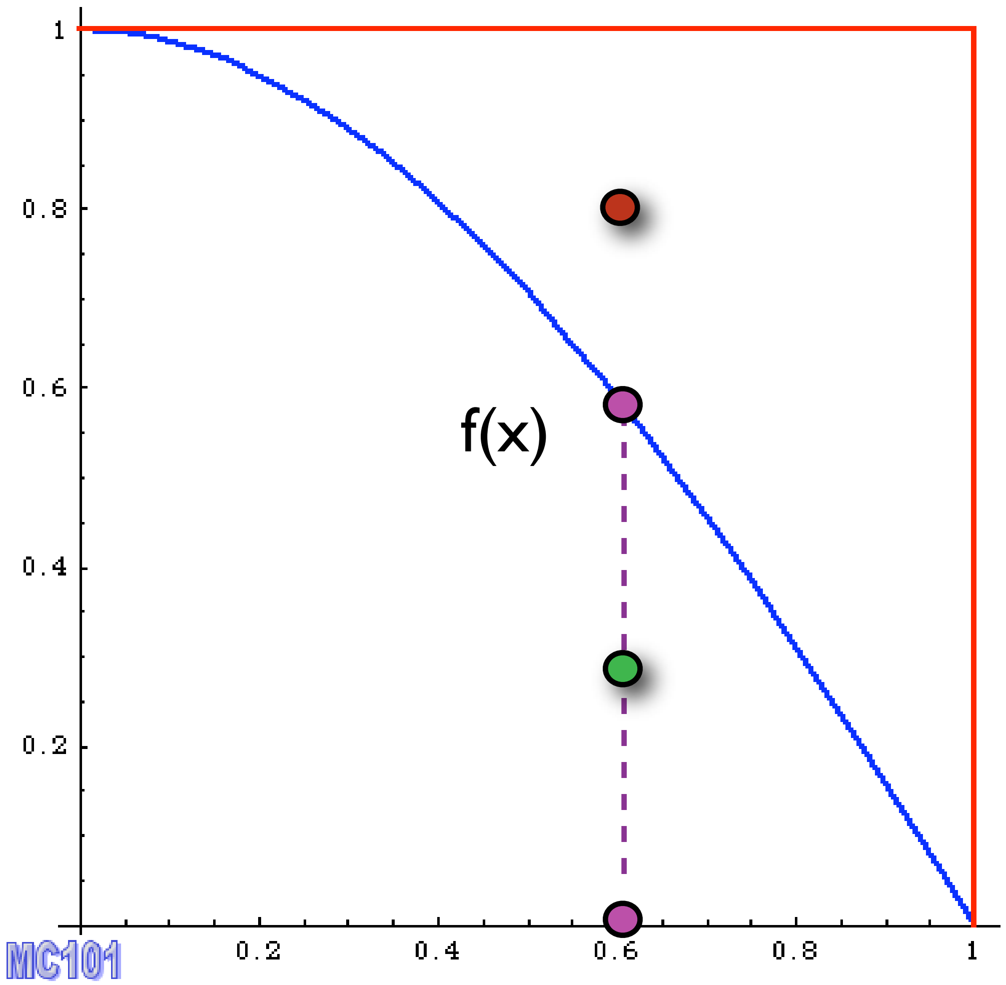
3. pick 0<y<fmax
4. Compare:
   if f(x)>y accept event,

Monte Carlo Event Generation



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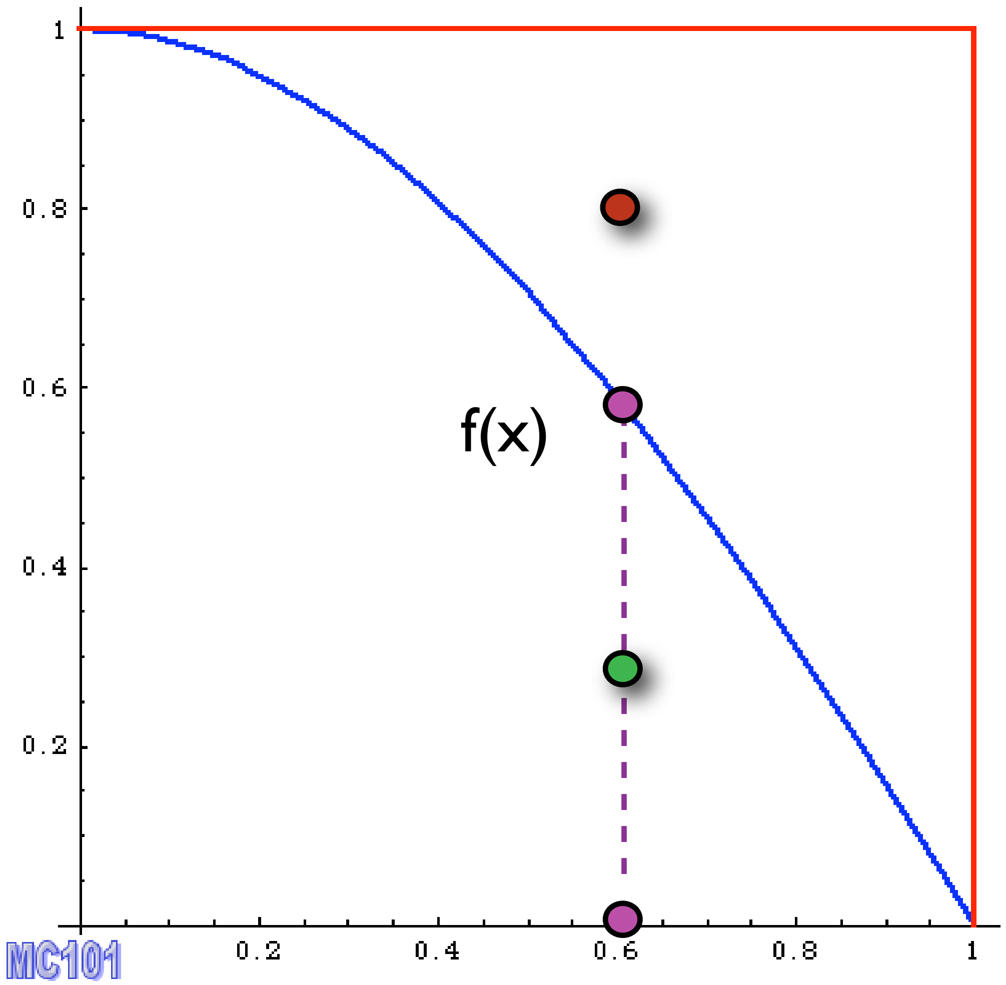

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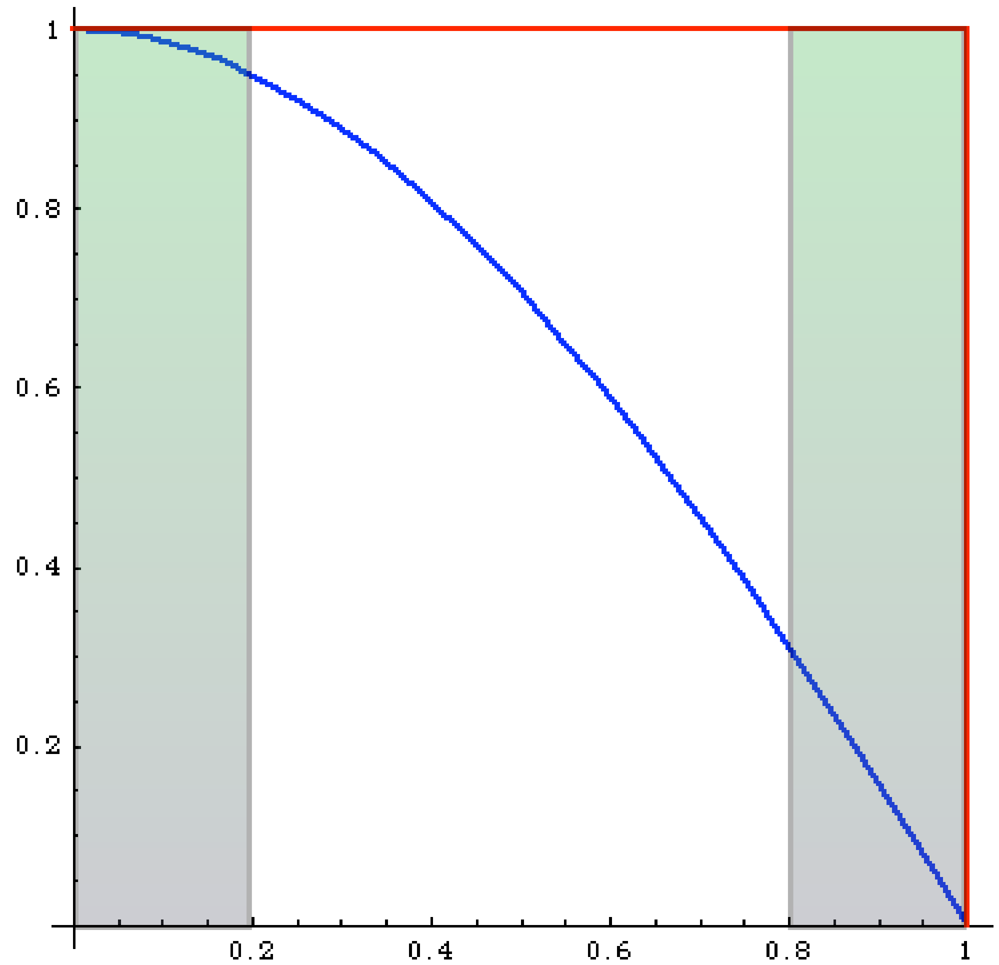
$$I = \frac{\text{accepted}}{\text{total tries}} = \text{efficiency}$$

Event generation

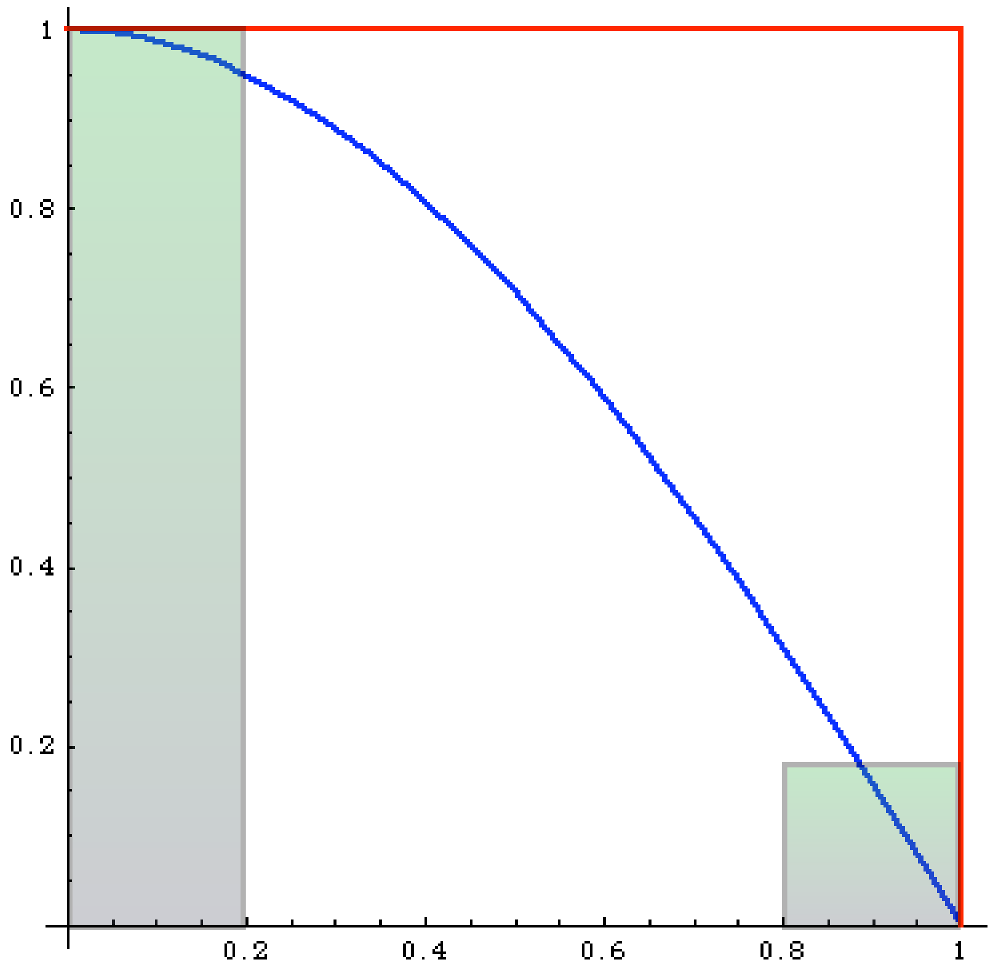


What's the difference between weighted and unweighted?

Weighted:

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

Event generation



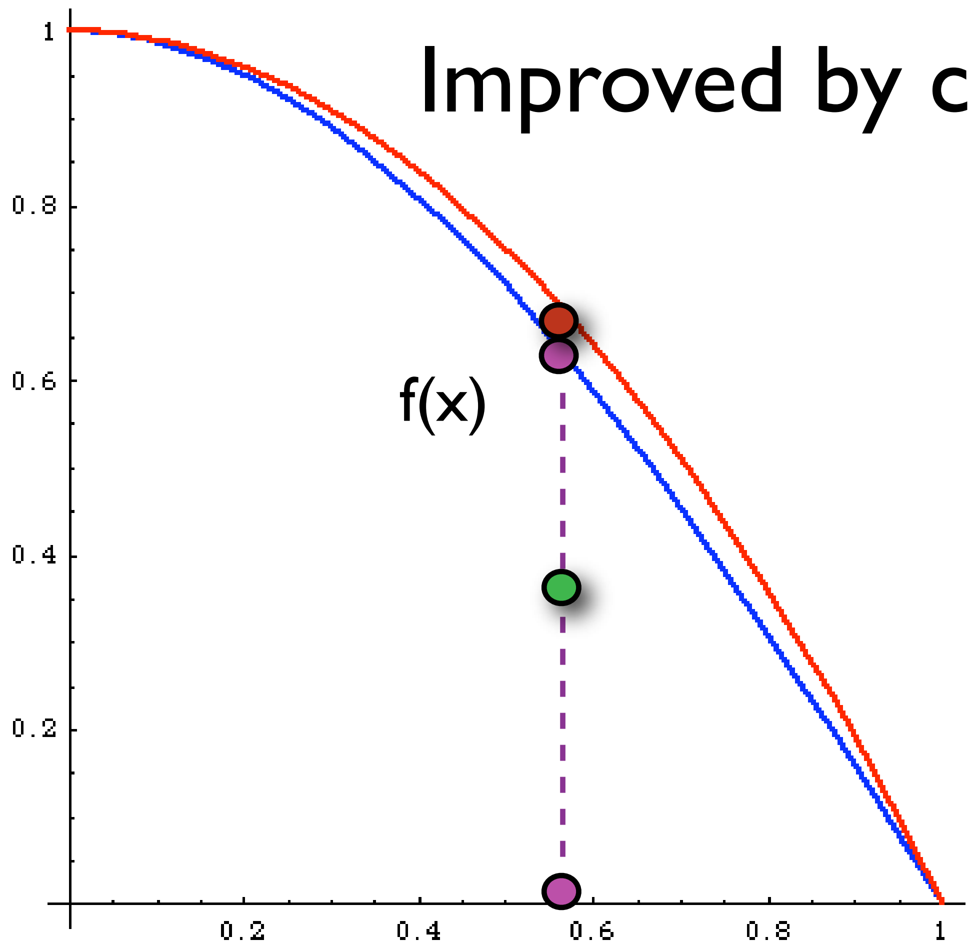
What's the difference between weighted and unweighted?

Unweighted:

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.

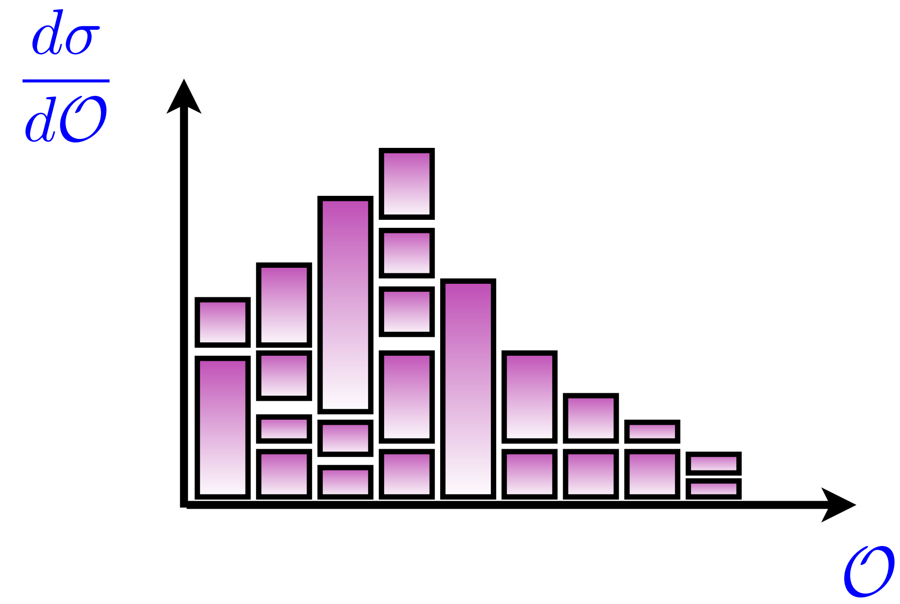
much better efficiency!!!

Event generation

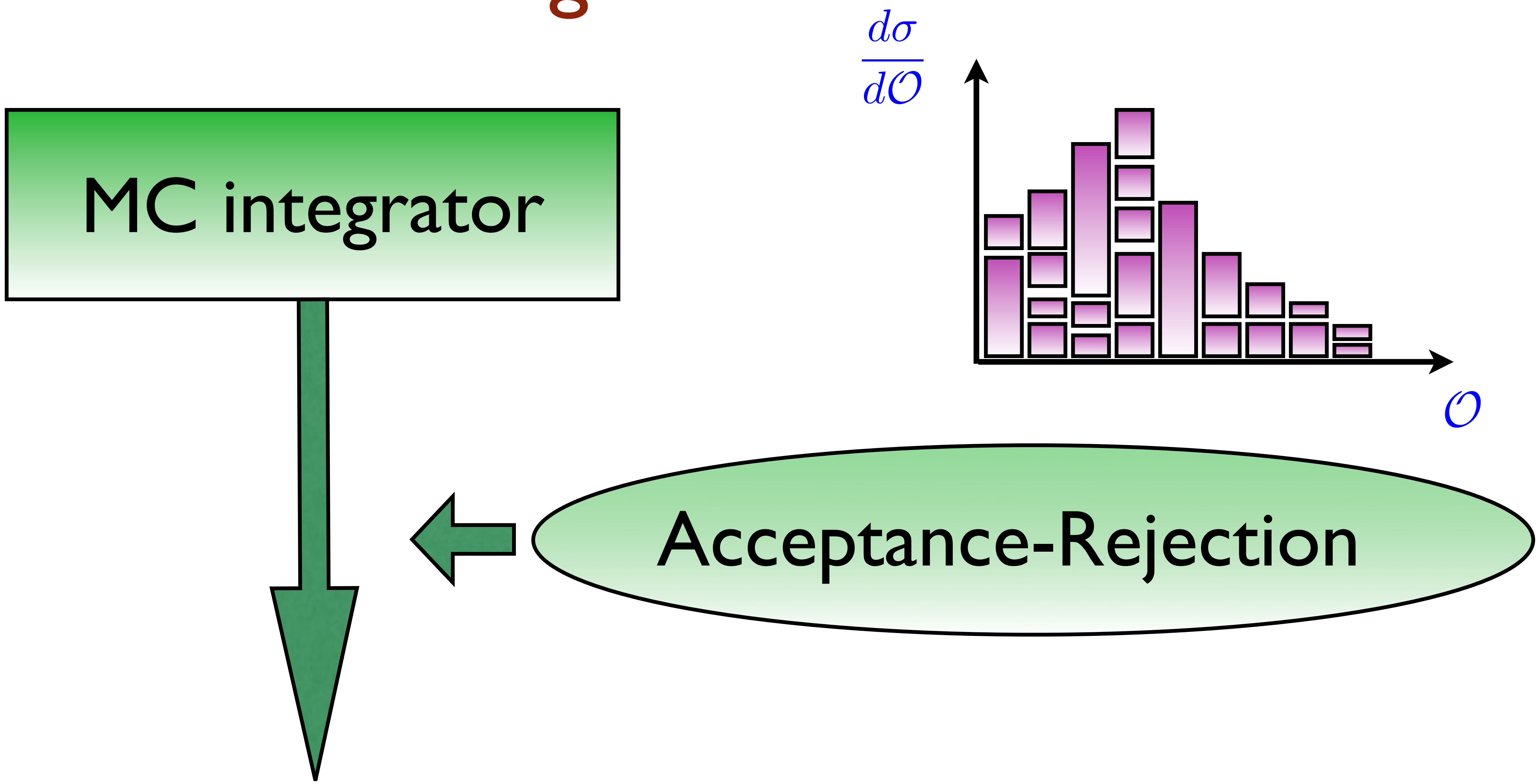
MC integrator

Event generation

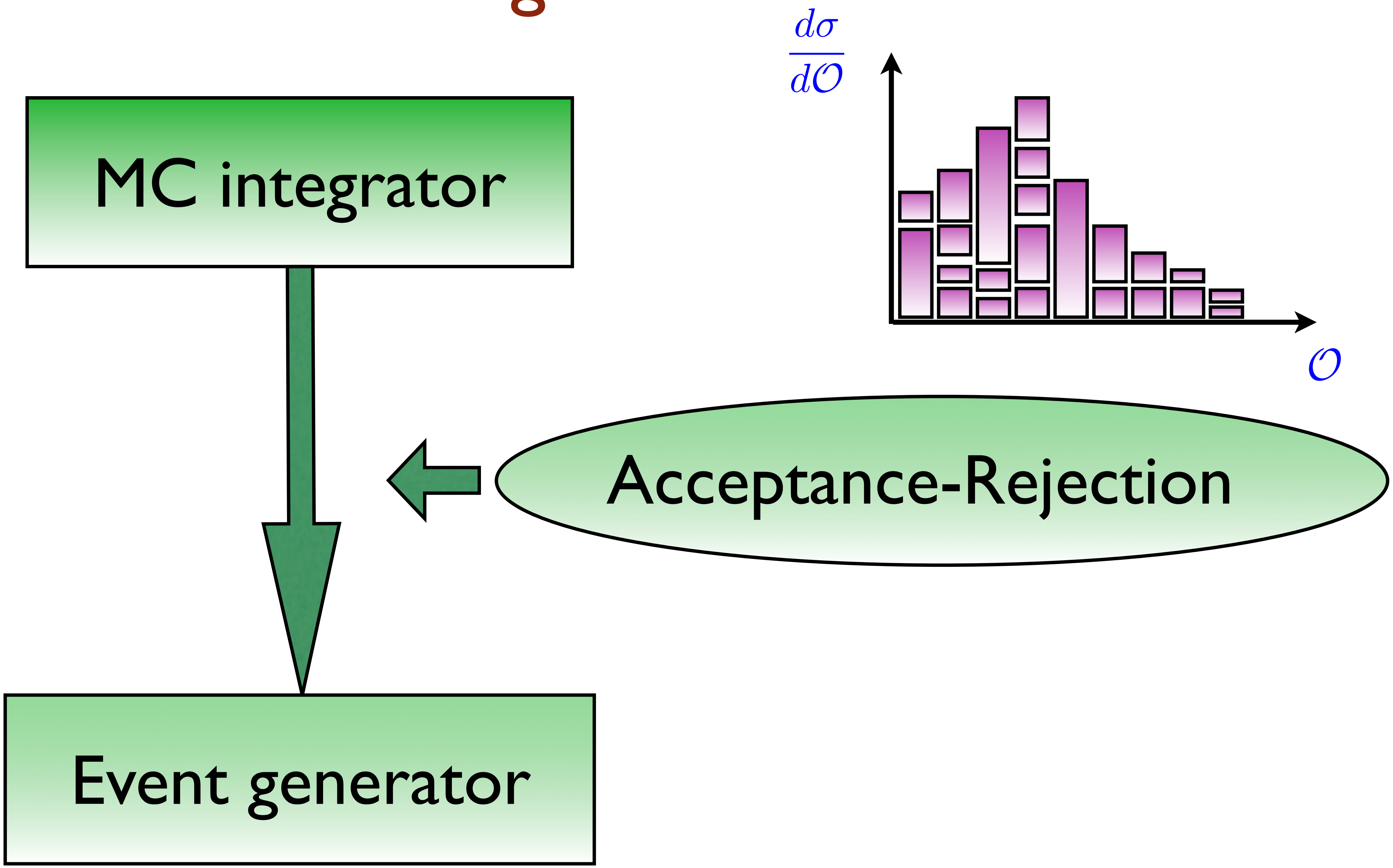
MC integrator



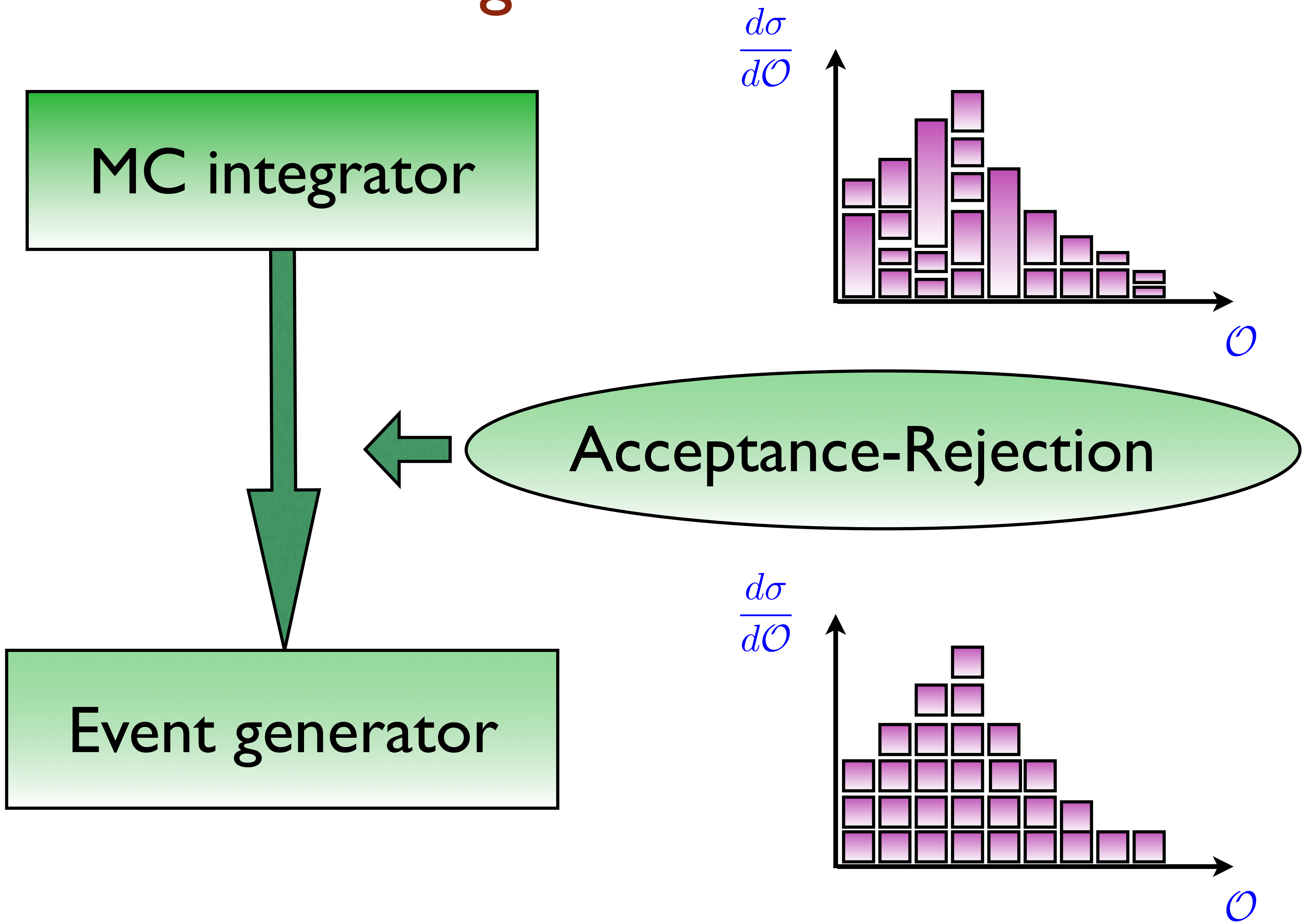
Event generation



Event generation



Event generation



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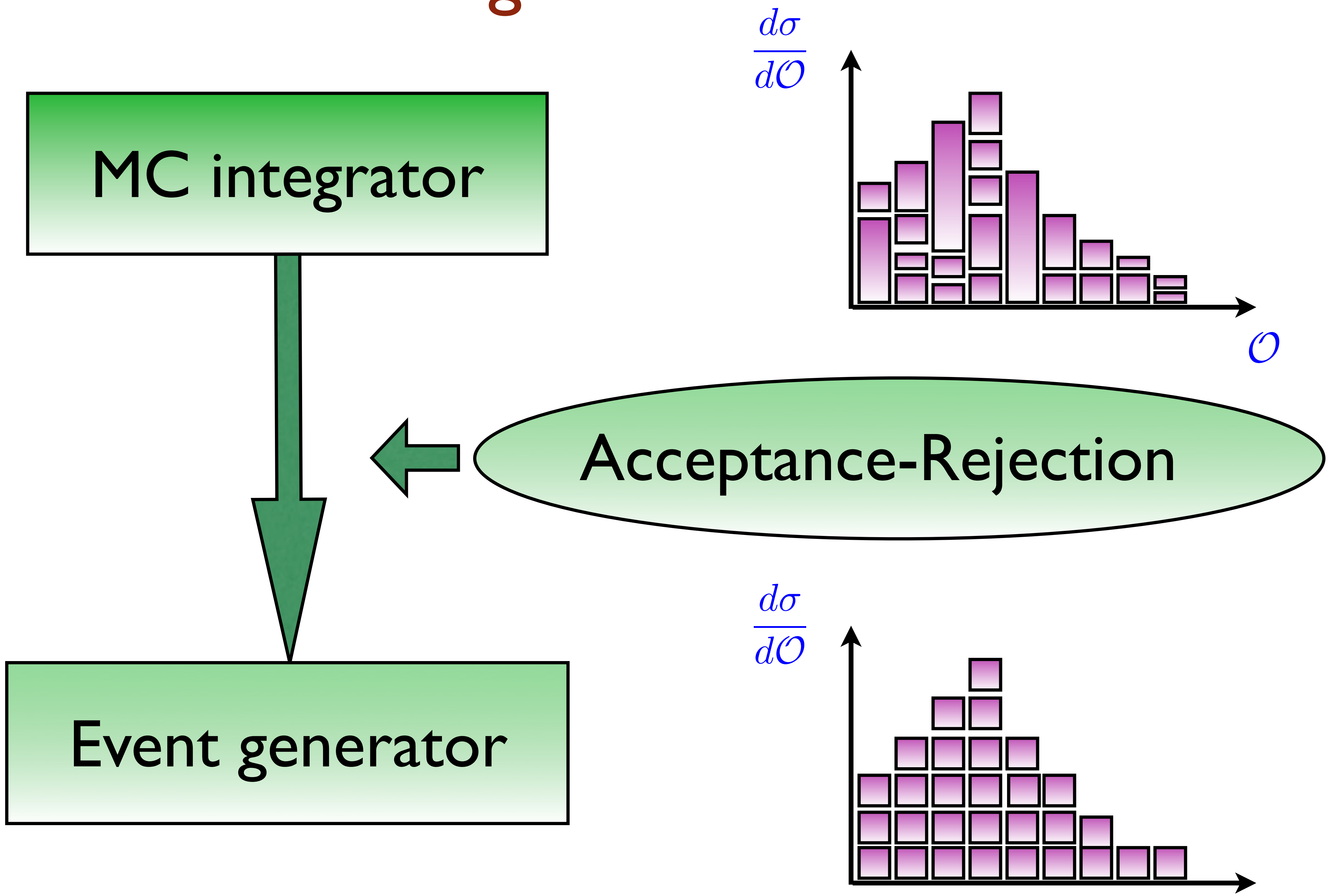
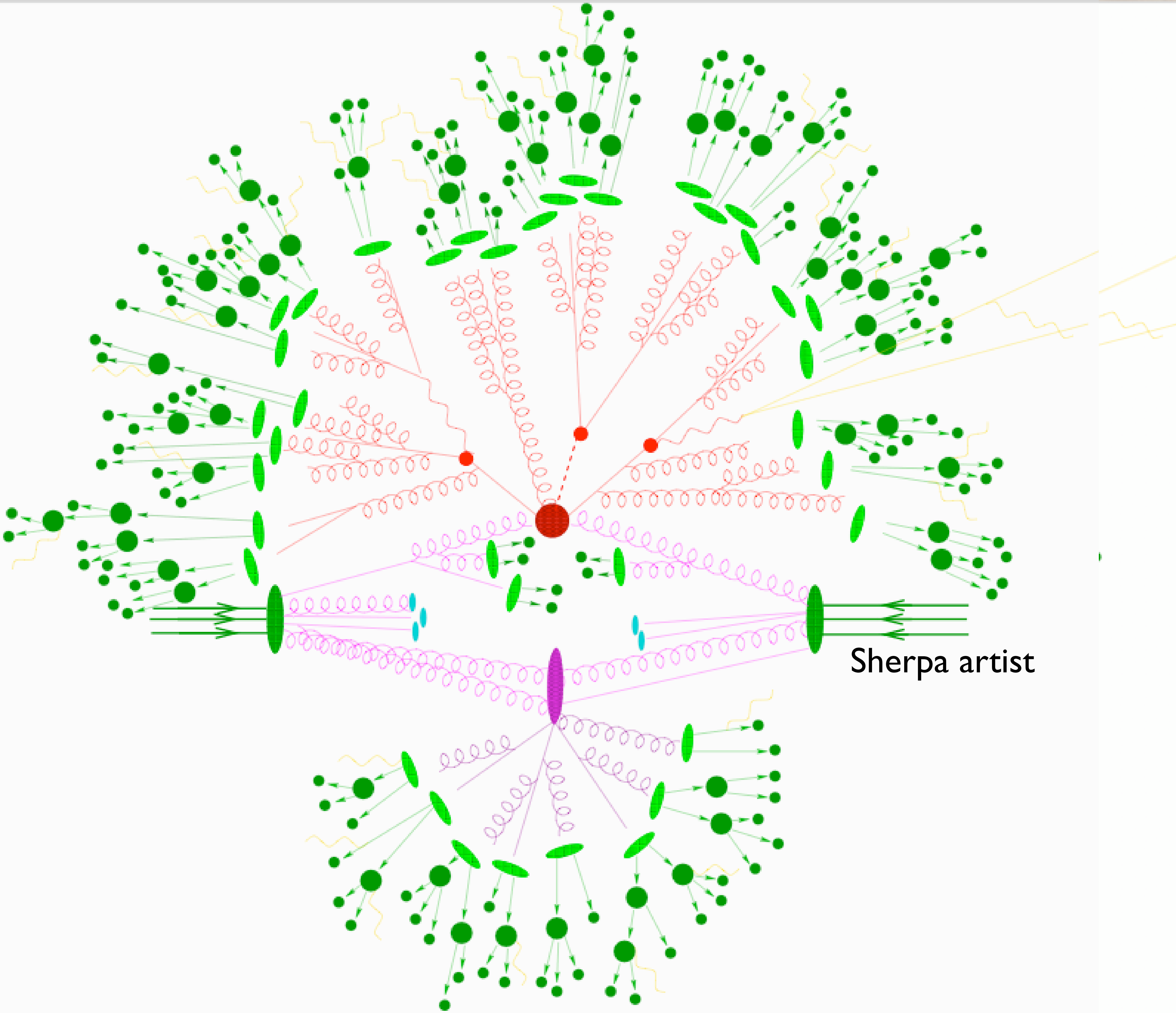


☞ **This is possible only if f(x)<∞ AND has definite sign!** $\mathcal{O}$

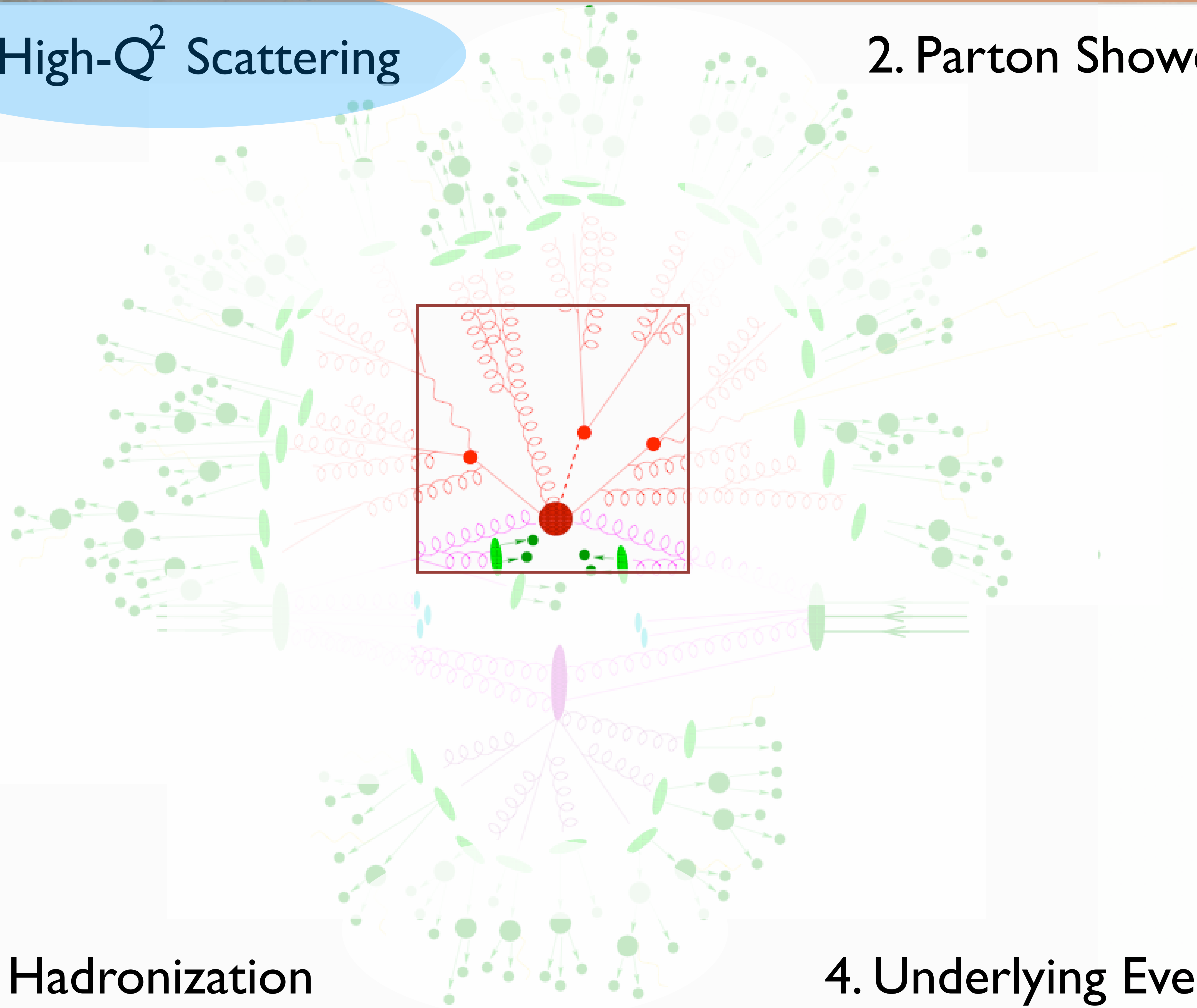
Simulation of collider events



Sherpa artist

1. High-Q^2 Scattering

2. Parton Shower



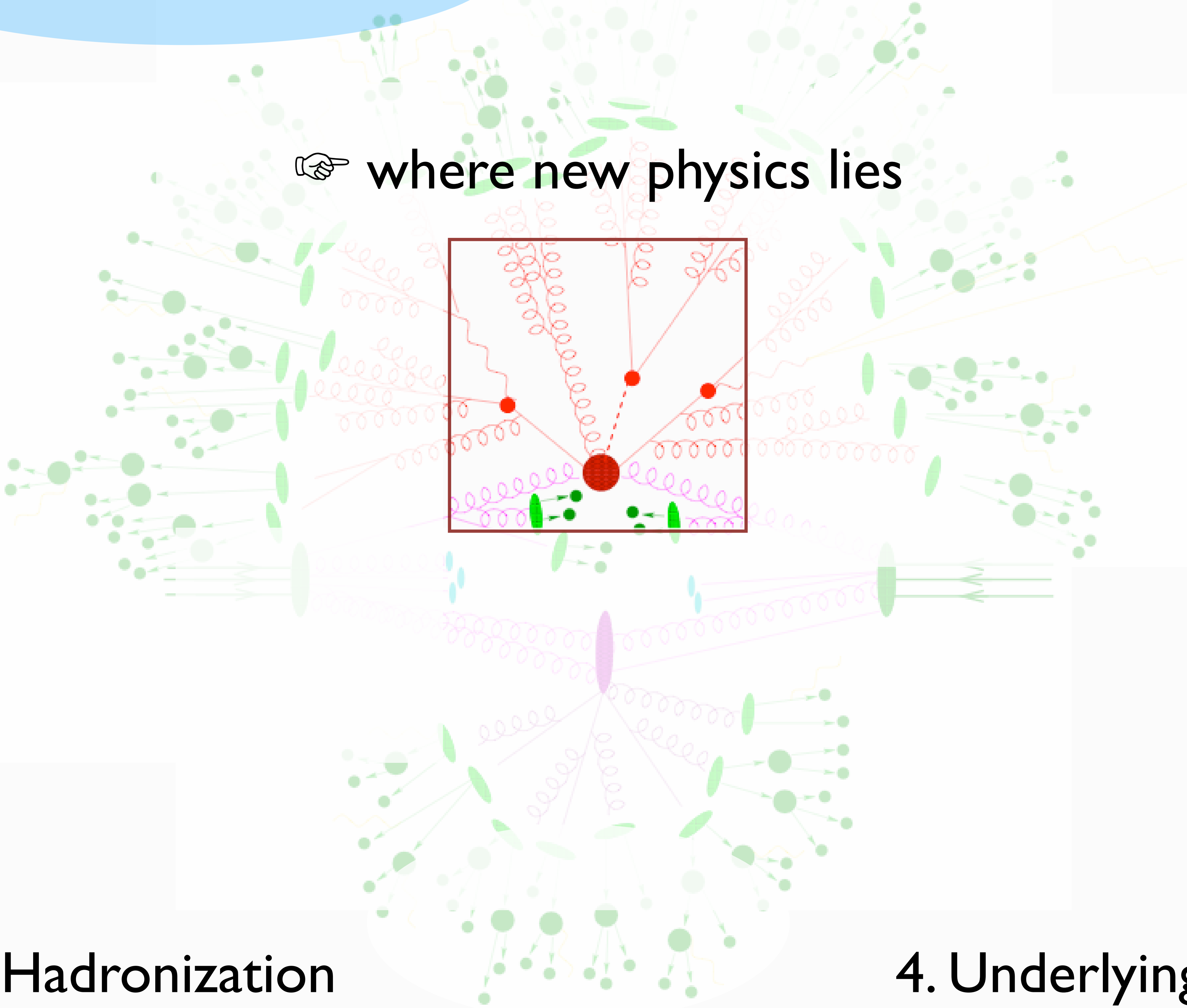
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



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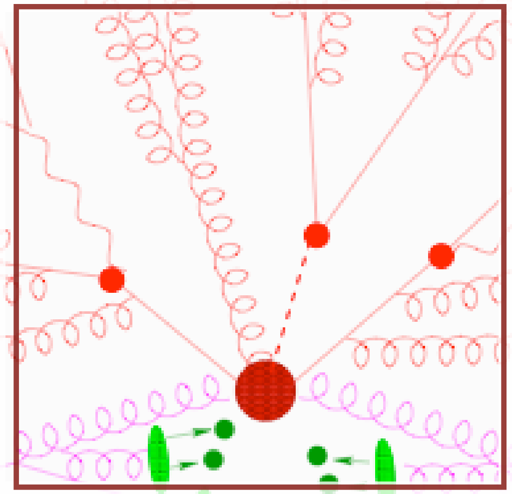

☞ process dependent

3. Hadronization

4. Underlying Event

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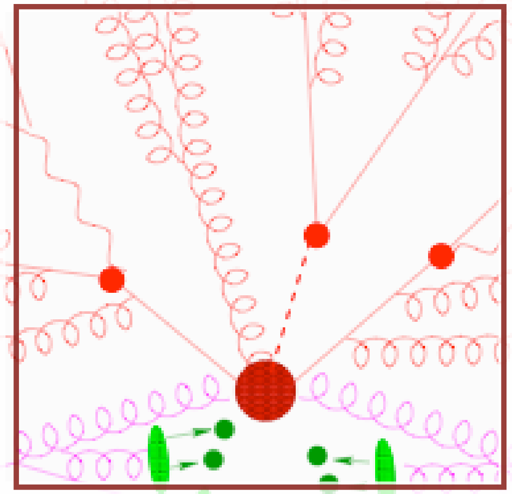

☞ process dependent

☞ first principles description

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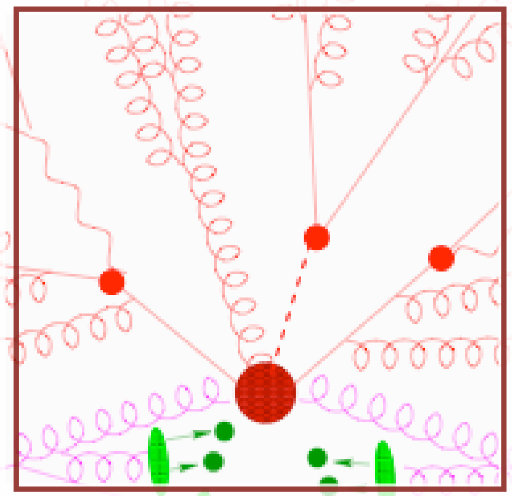

☞ process dependent

☞ first principles description

☞ it can be systematically improved

3. Hadronization

4. Underlying Event

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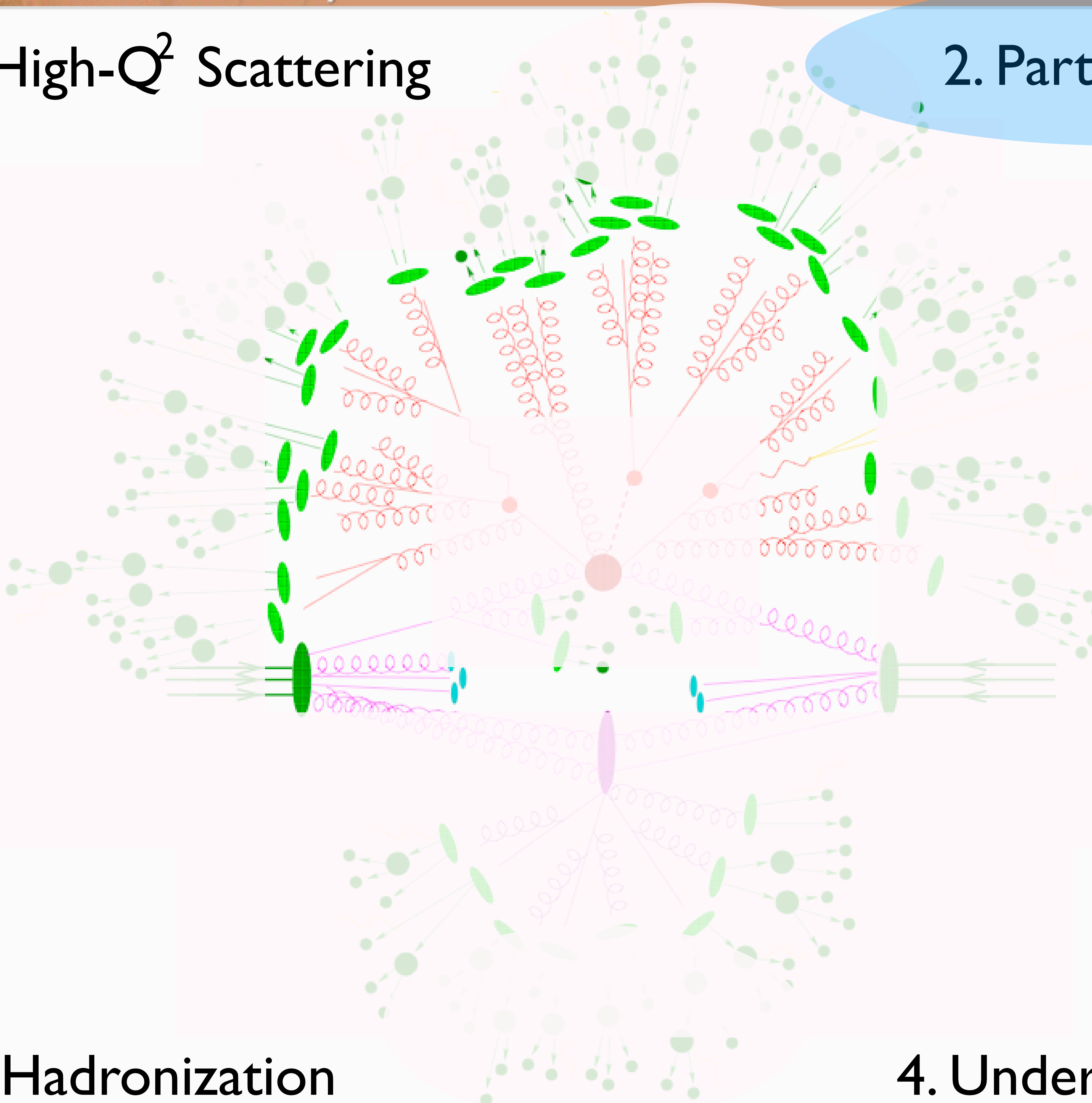
2. Parton Shower



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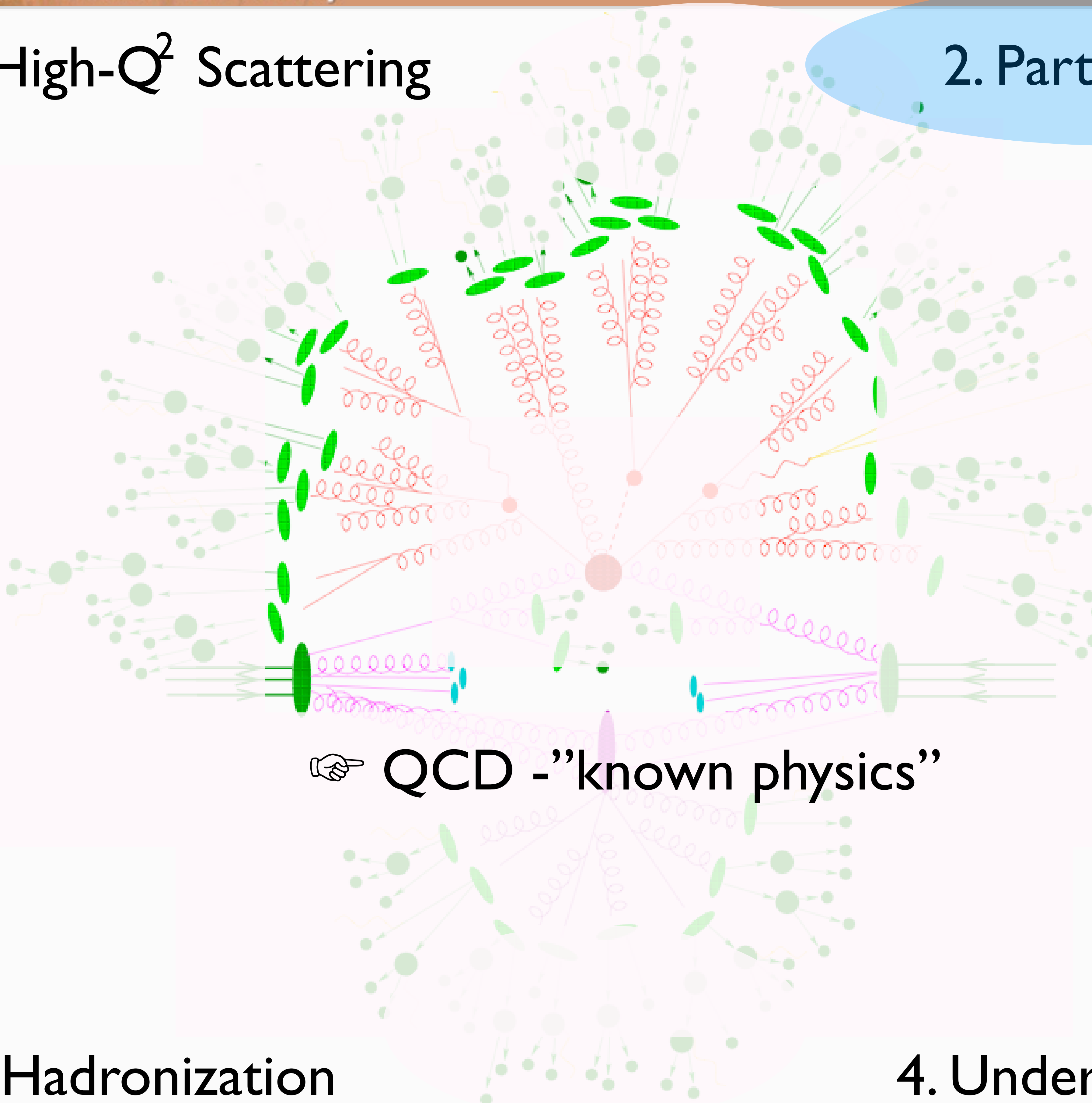

☞ QCD -"known physics"

3. Hadronization

4. Underlying Event

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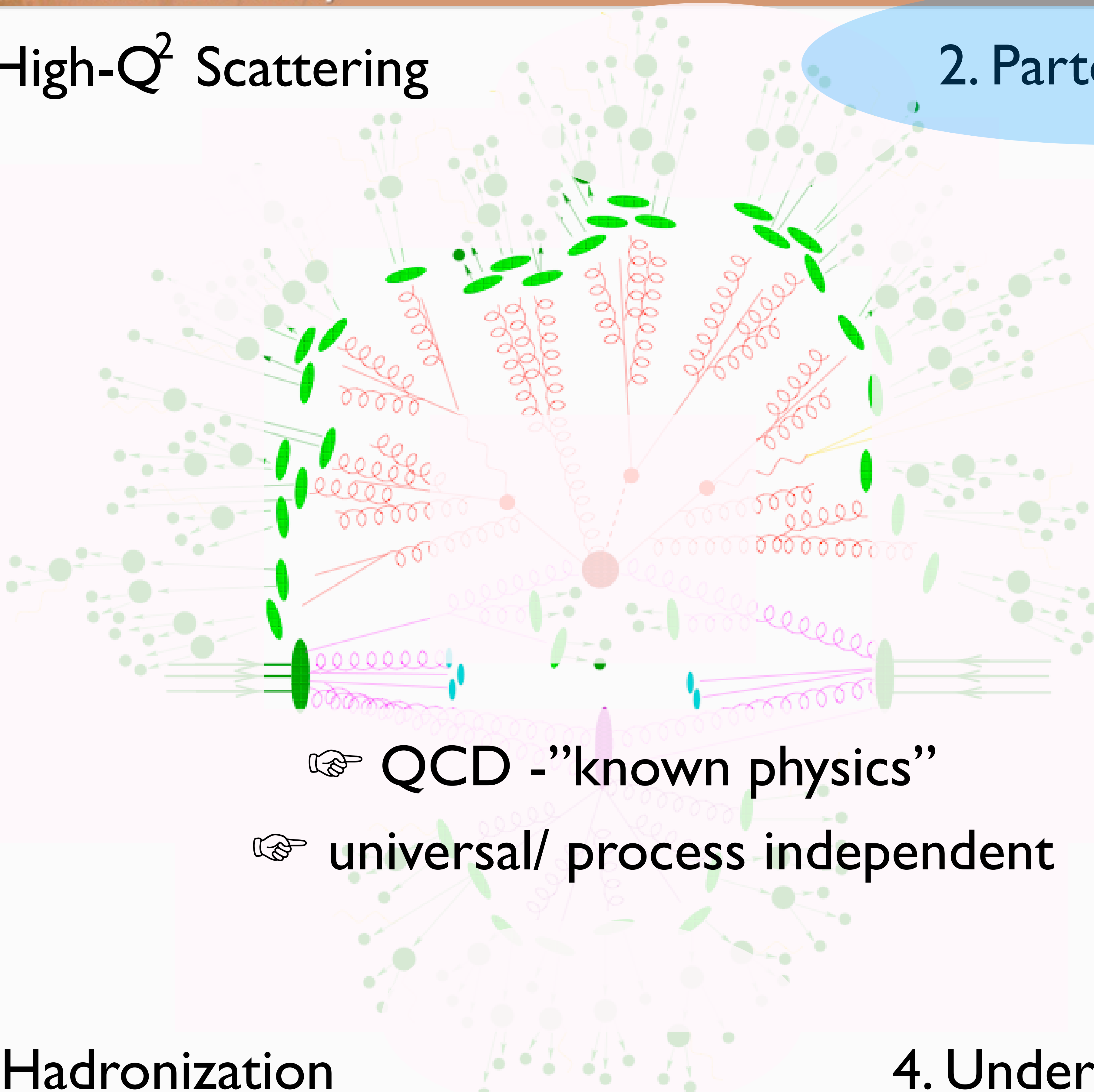

☞ QCD -"known physics"

☞ universal/ process independent

3. Hadronization

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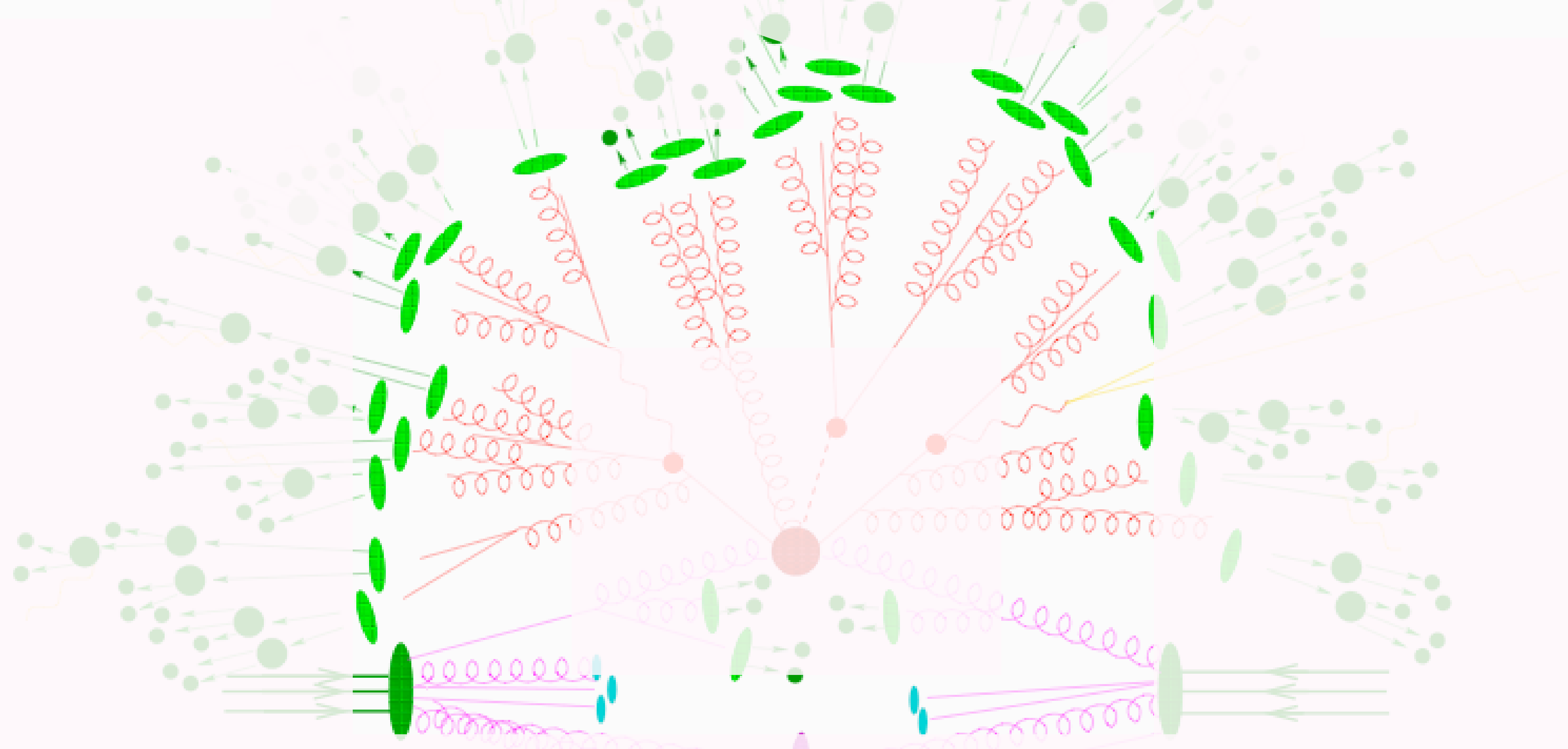
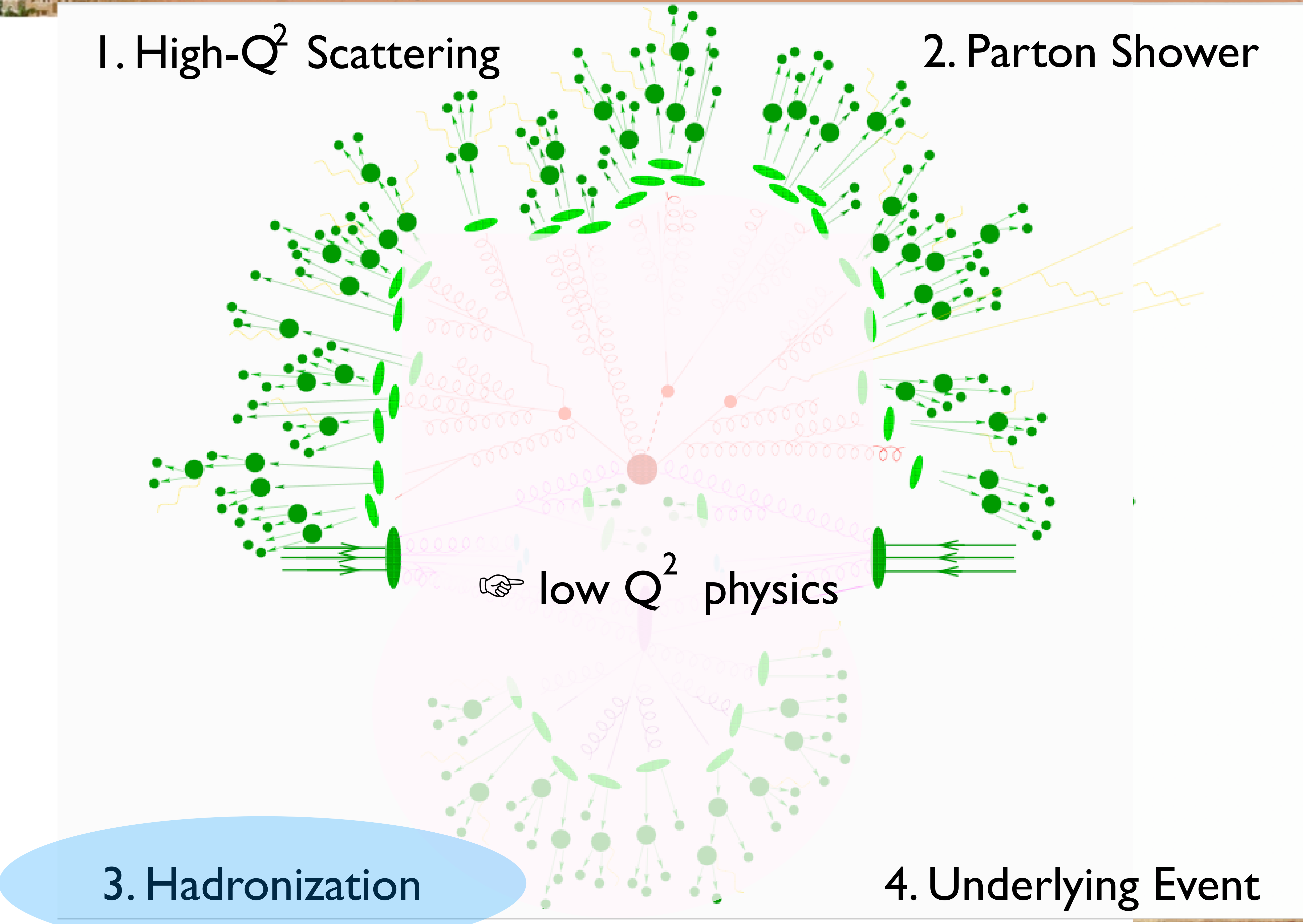


- ☞ QCD -"known physics"
- ☞ universal/ process independent
- ☞ first principles description

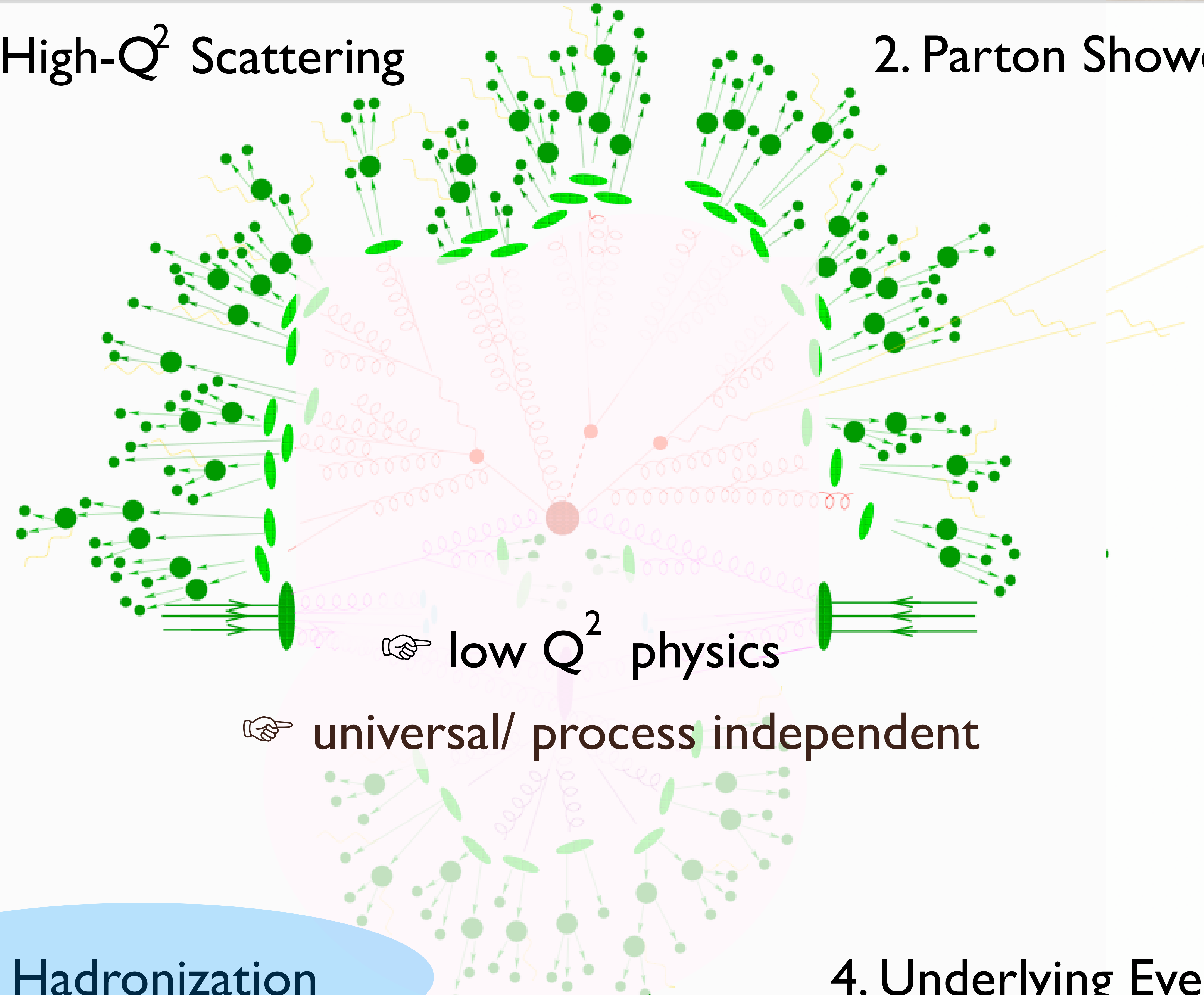
3. Hadronization

4. Underlying Event


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

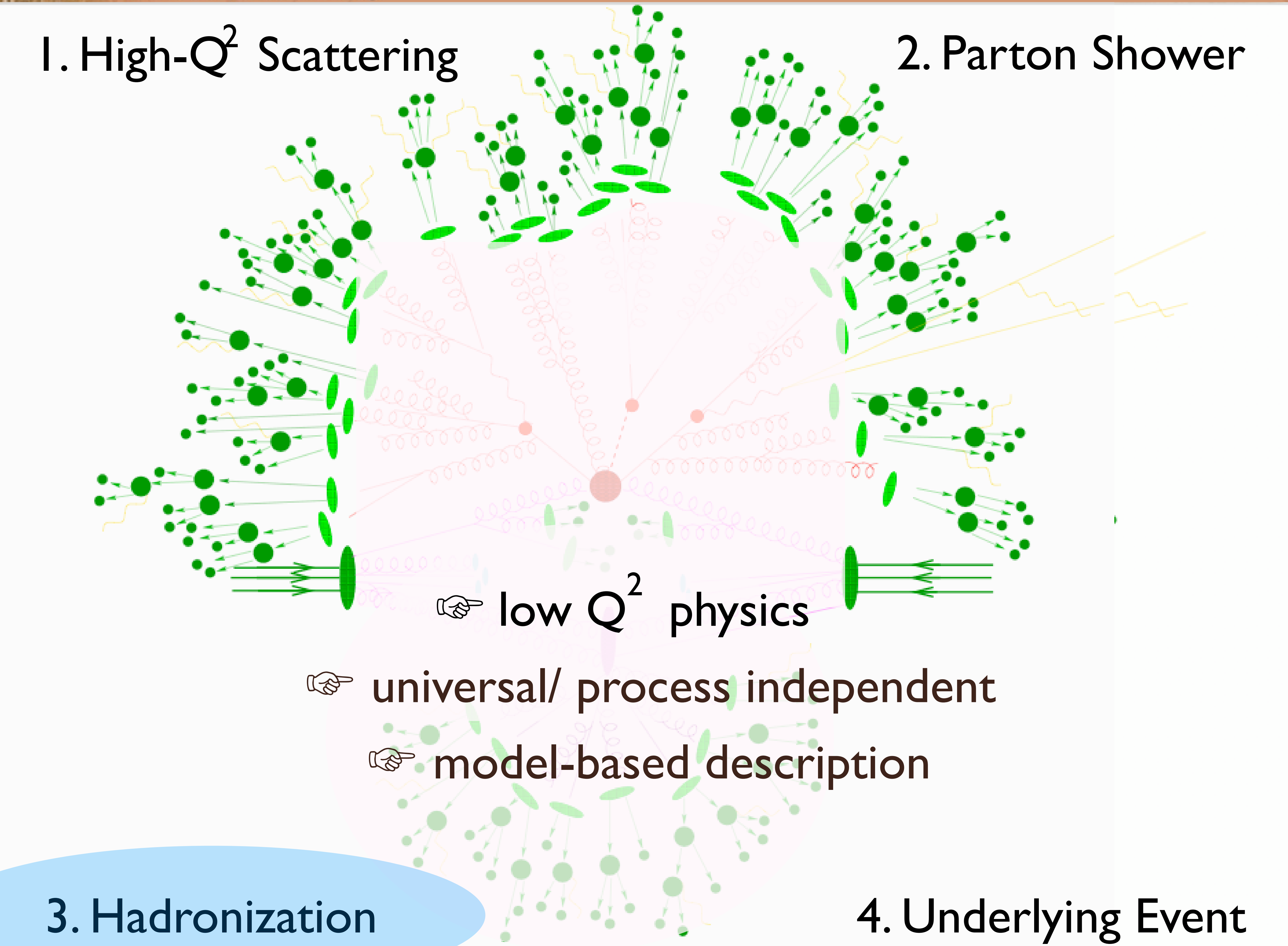


☞ low Q^2 physics

☞ universal/ process independent

3. Hadronization

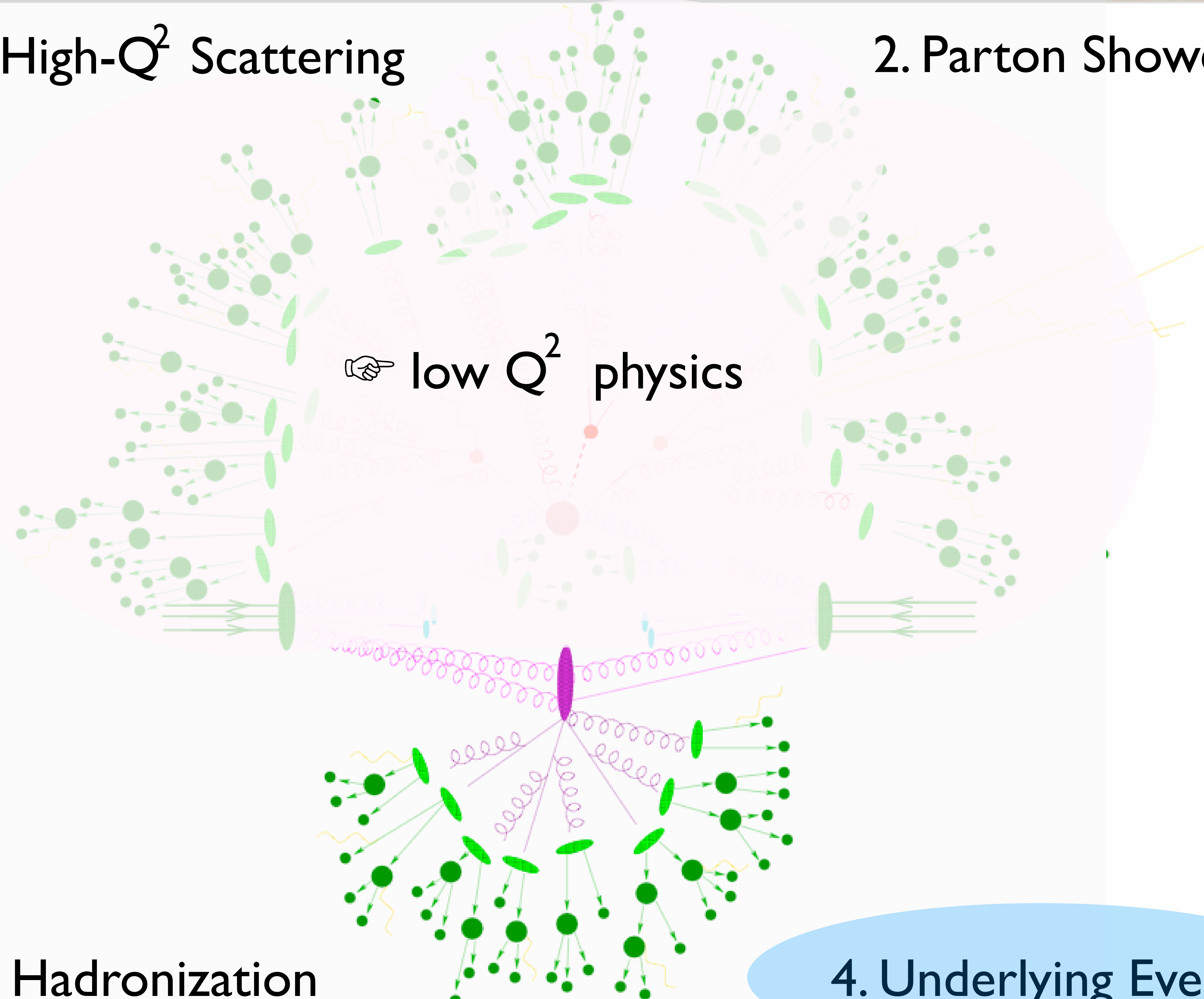
4. Underlying Event



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

1. High-Q^2 Scattering

2. Parton Shower



3. Hadronization

4. Underlying Event

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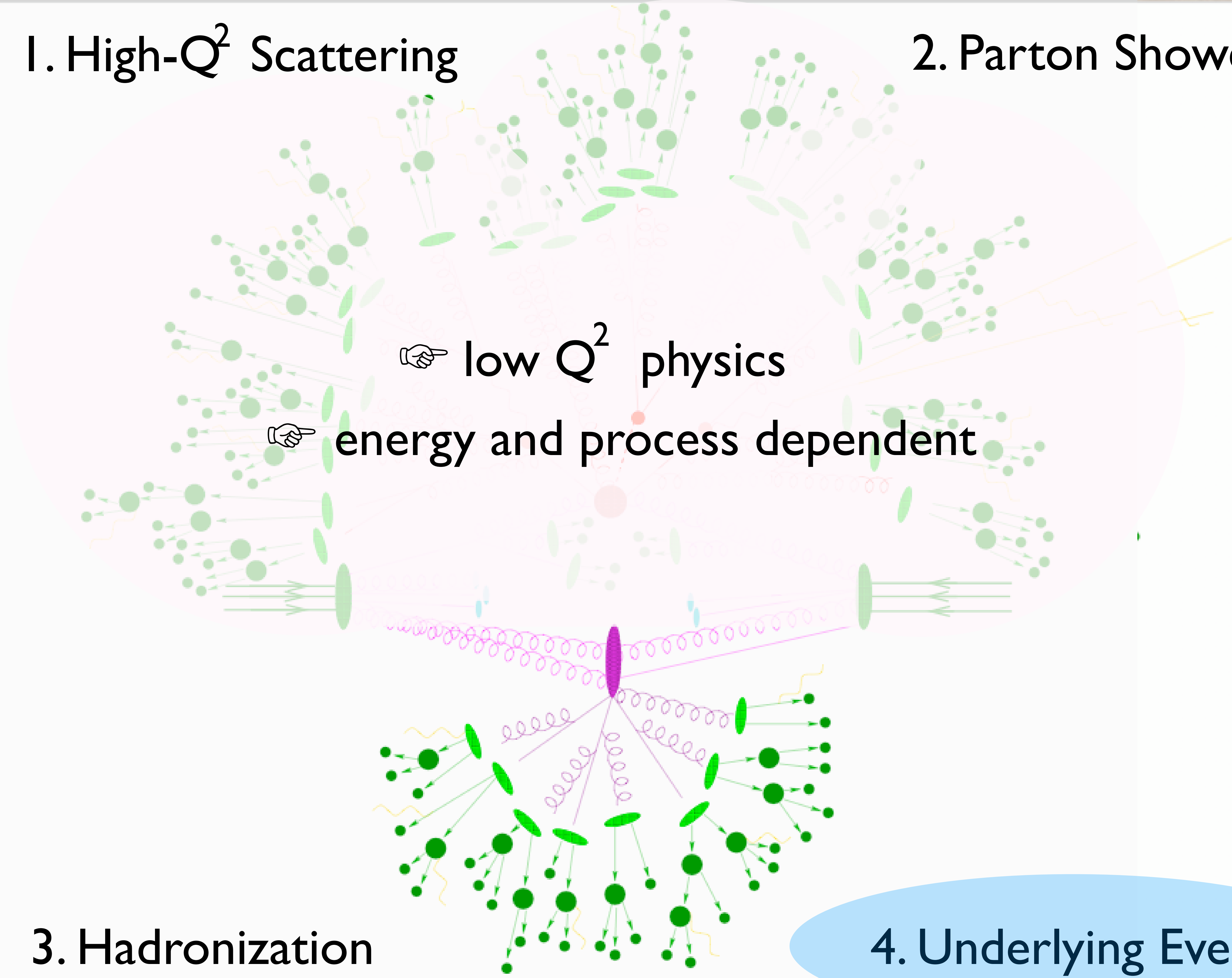


☞ low Q^2 physics

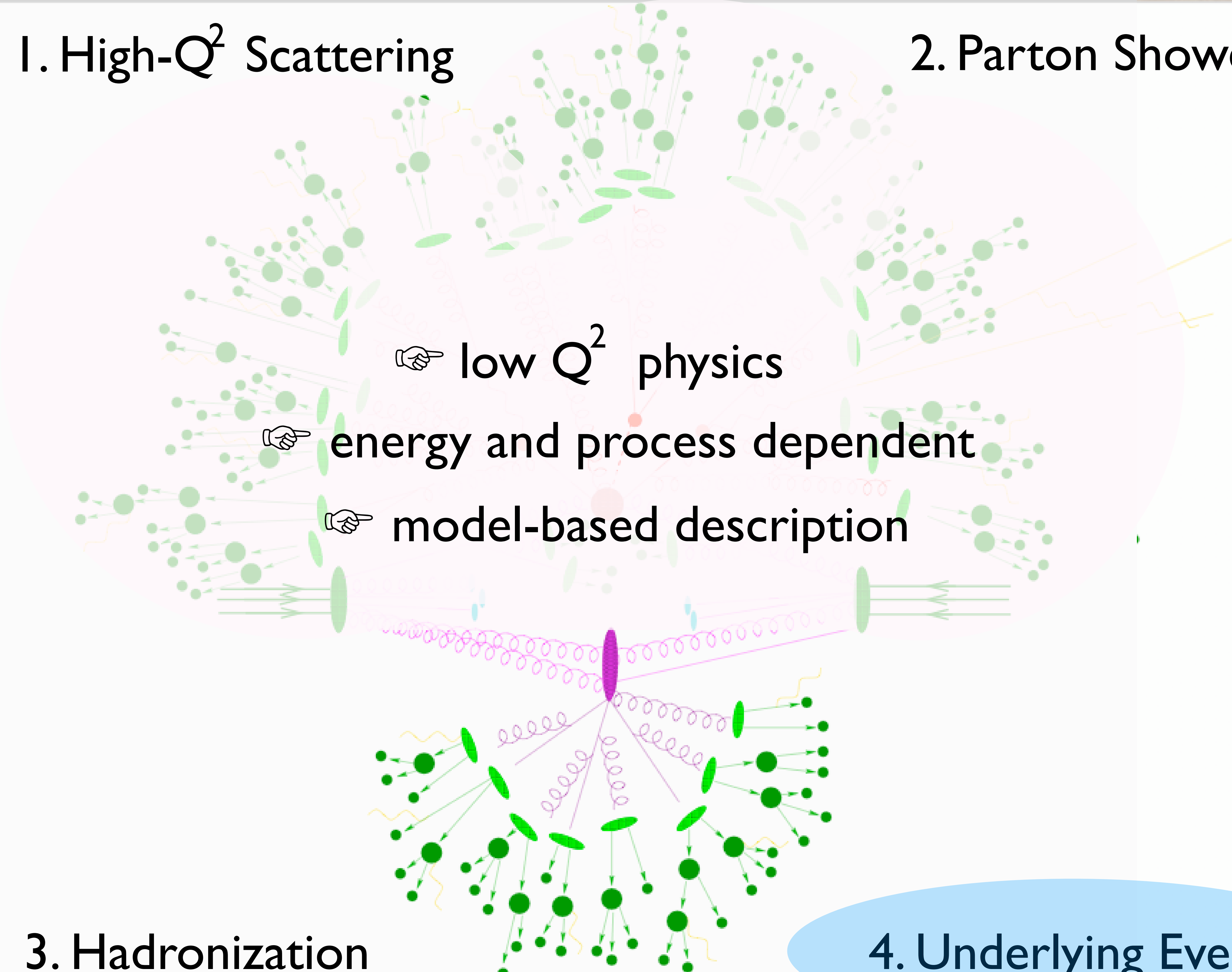
☞ energy and process dependent

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

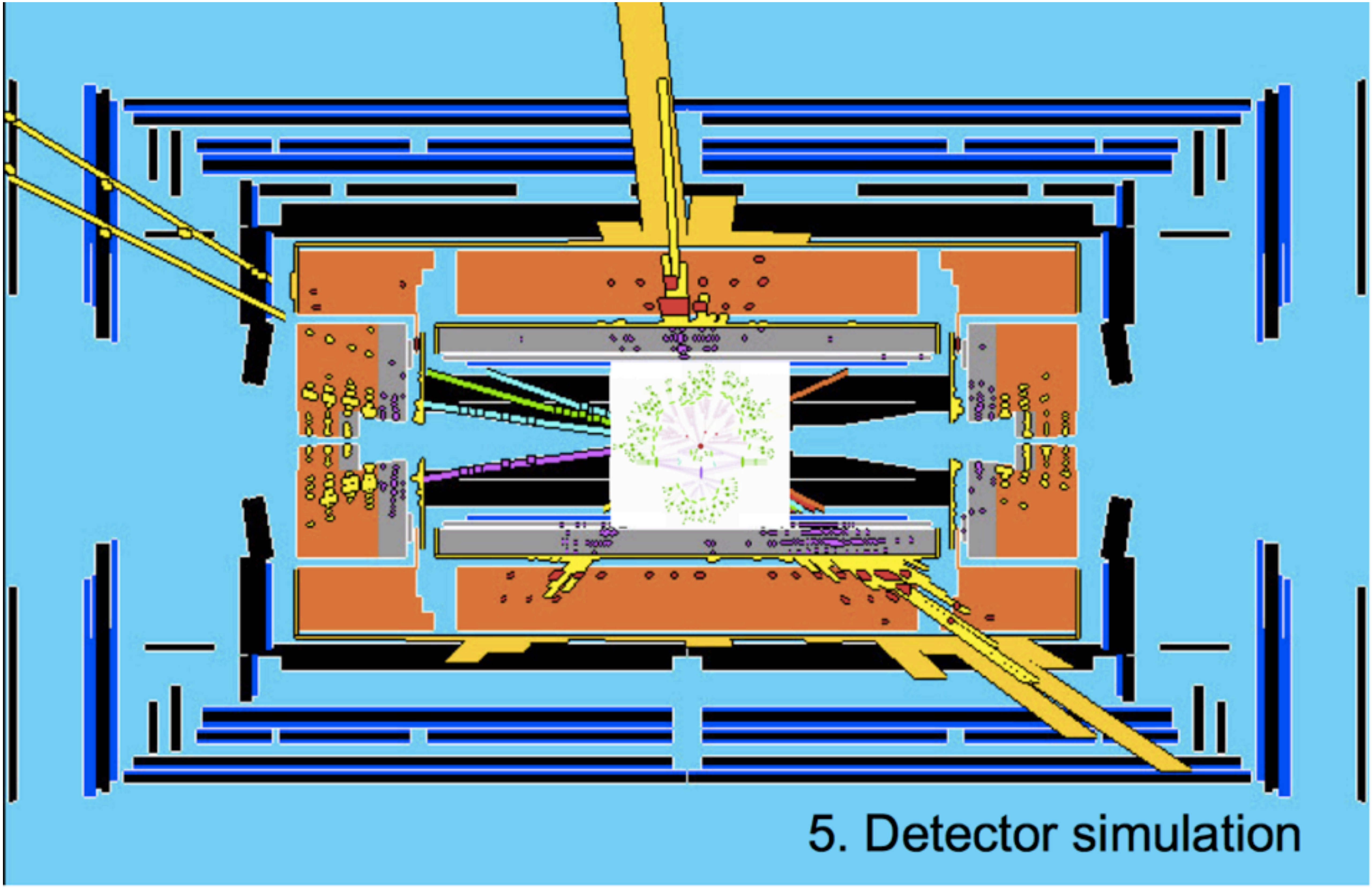
2. Parton Shower



- ☞ low Q^2 physics
- ☞ energy and process dependent
- ☞ model-based description

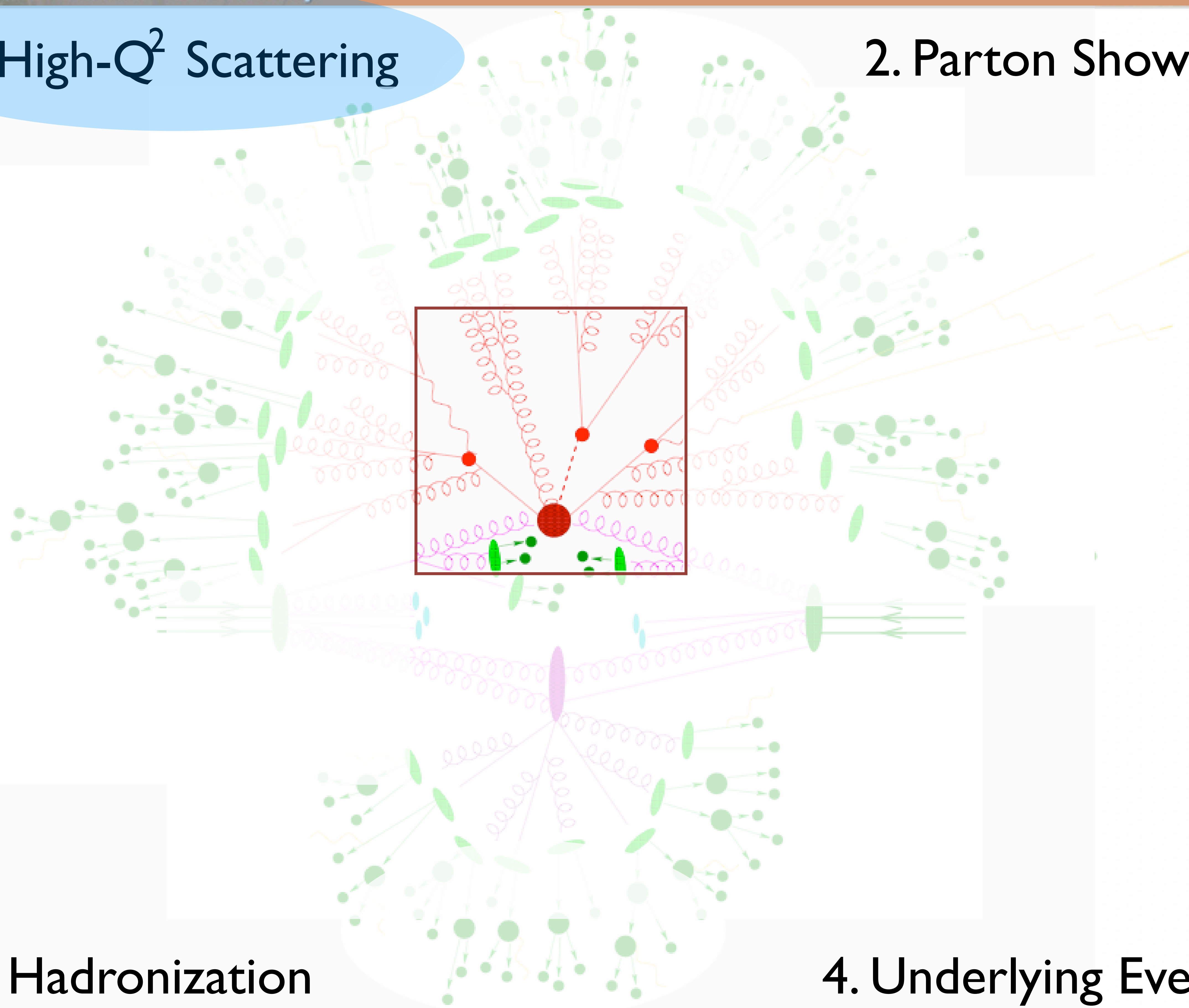
3. Hadronization

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	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$
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	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
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!)

Automated Matrix Element Generators

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

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  - ➡ Use Feynman rules to build diagrams

Automated Matrix Element Generators

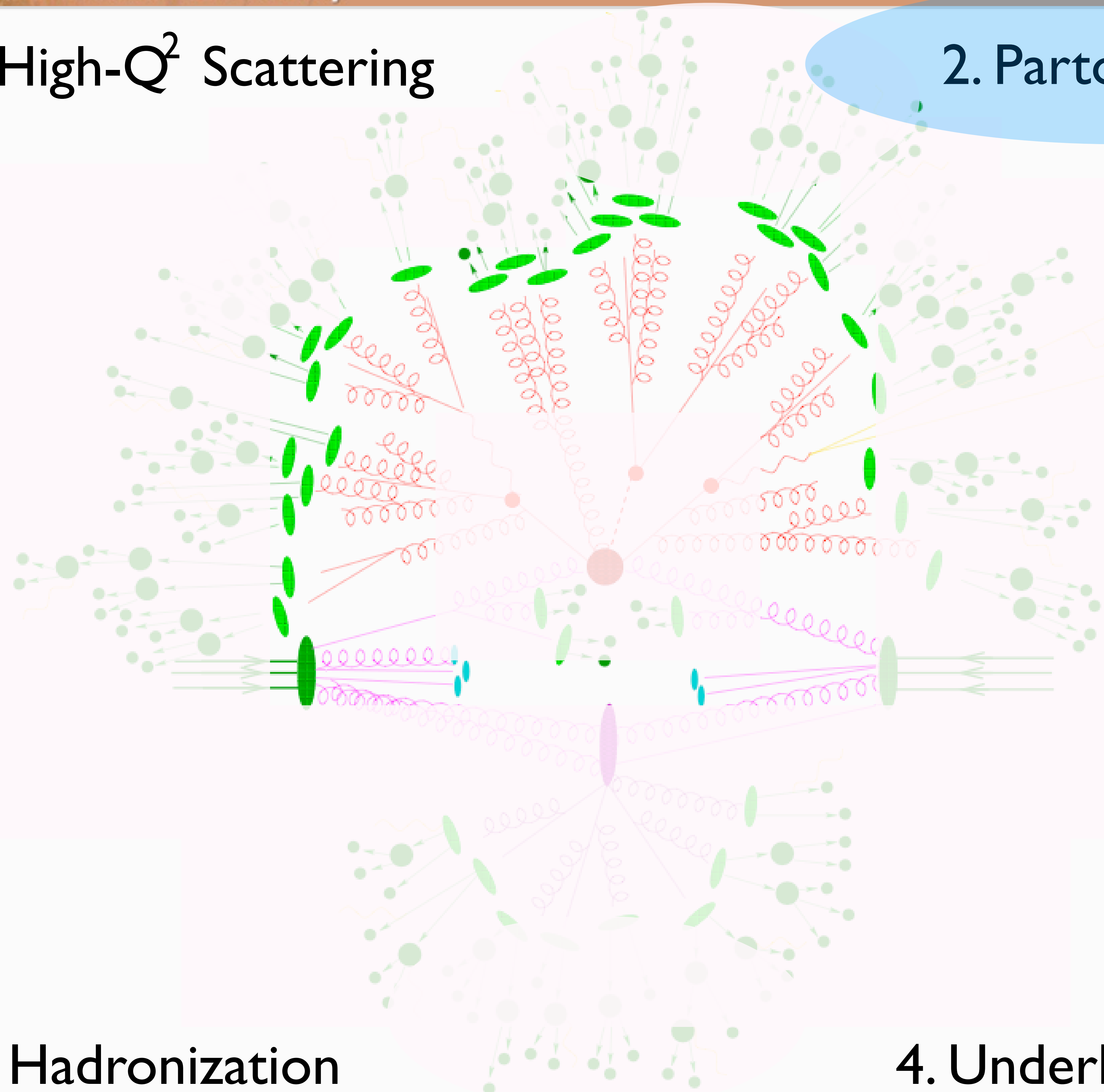
- High-Q2 scattering processes: In principle infinite number of processes for innumerable number of models
- Implementation by hand time-consuming, labor intensive and error prone
- Instead: Automated matrix element generators
  - ➡ Use Feynman rules to build diagrams
- Given files defining the model content: particles, parameters and interactions, allows to generate any process for a given model!

Automated Matrix Element Generators

- Automatic matrix element generators:
  - ➡ CalcHep / CompHep
  - ➡ MadGraph
  - ➡ AMEGIC++ (Sherpa)
  - ➡ Whizard
- Standard Model only, with fast matrix elements for high parton multiplicity final states:
  - ➡ AlpGen
  - ➡ HELAC
  - ➡ COMIX (Sherpa)

1. High-Q^2 Scattering

2. Parton Shower



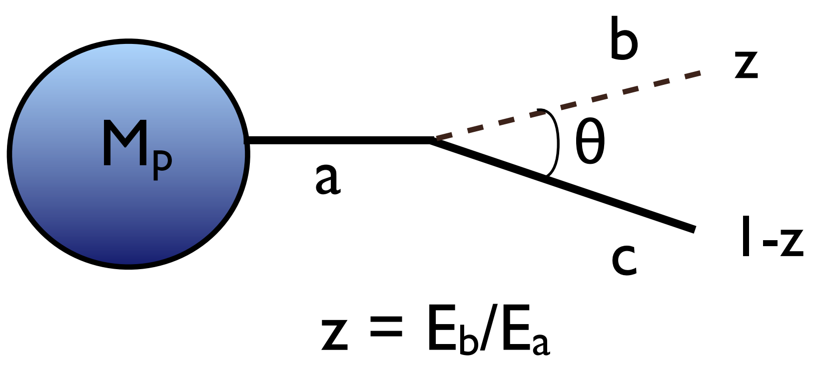
3. Hadronization

4. Underlying Event

Parton Shower basics

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

$$\frac{1}{(p_b+p_c)^2} \simeq \frac{1}{2E_bE_c(1-\cos\theta)} = \frac{1}{t}$$



soft and collinear divergencies

Collinear factorization:

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

when θ is small.

Parton showers

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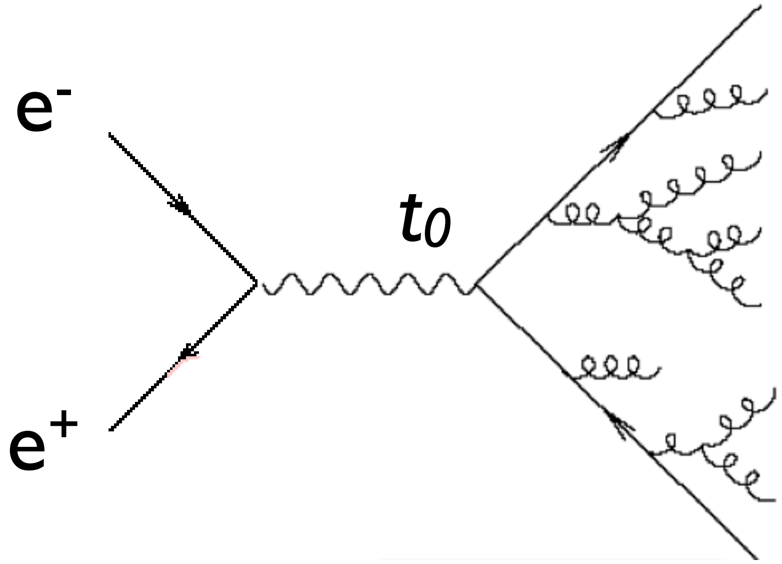

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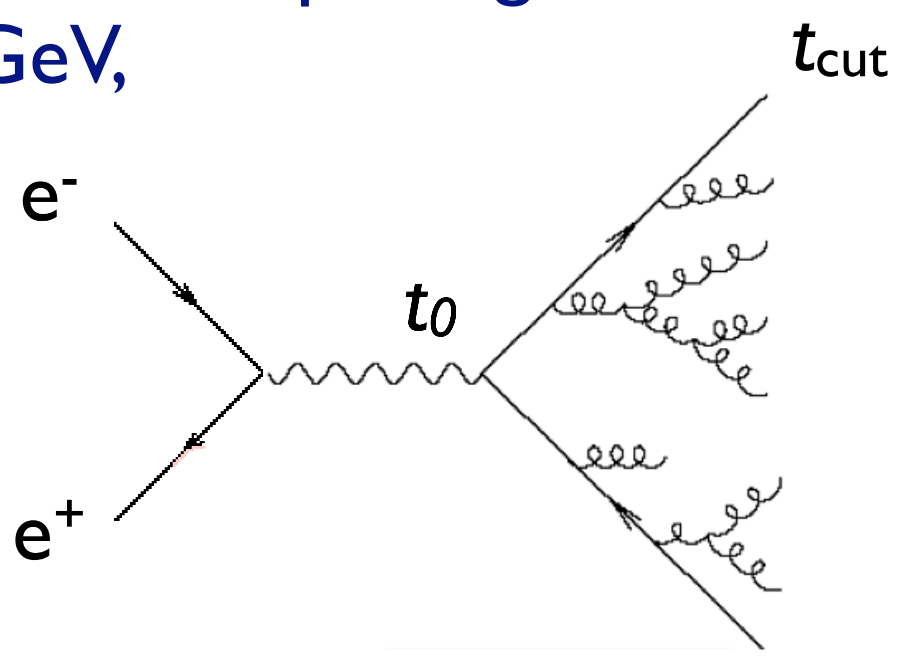
- The procedure stops when the scale of the splitting is below some t_{cut} , usually close to 1 GeV, the scale where non-perturbative effects start dominating over the perturbative parton shower.



Parton showers

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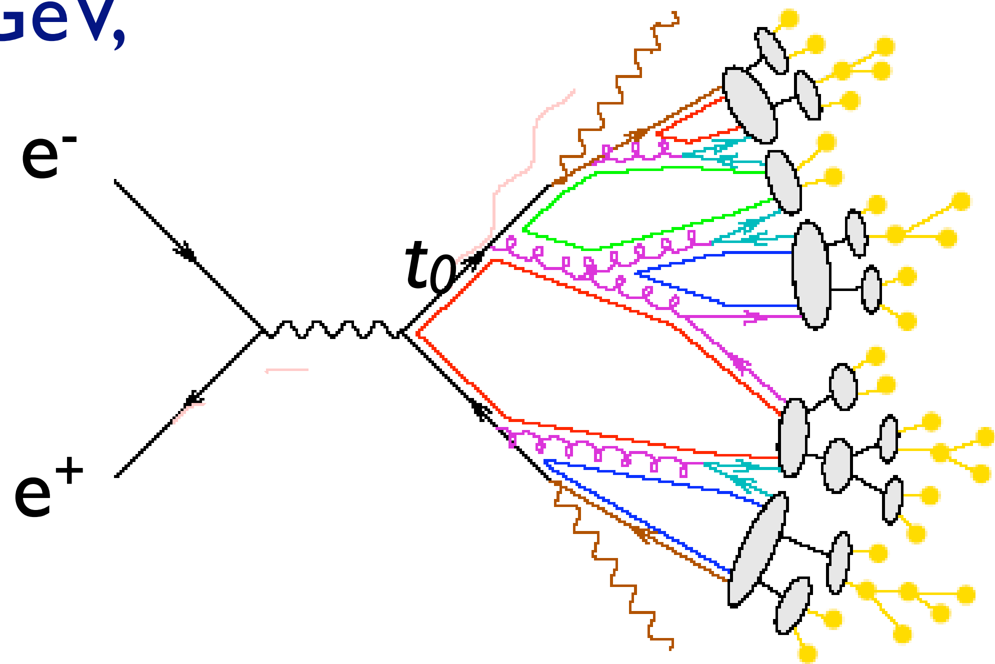
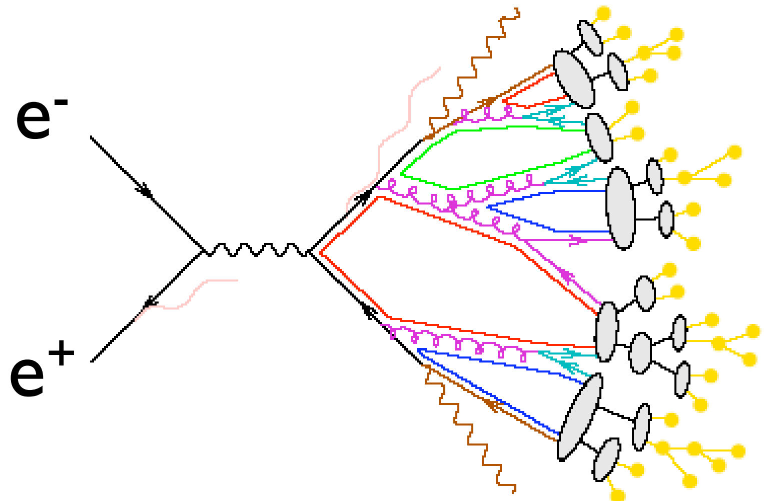
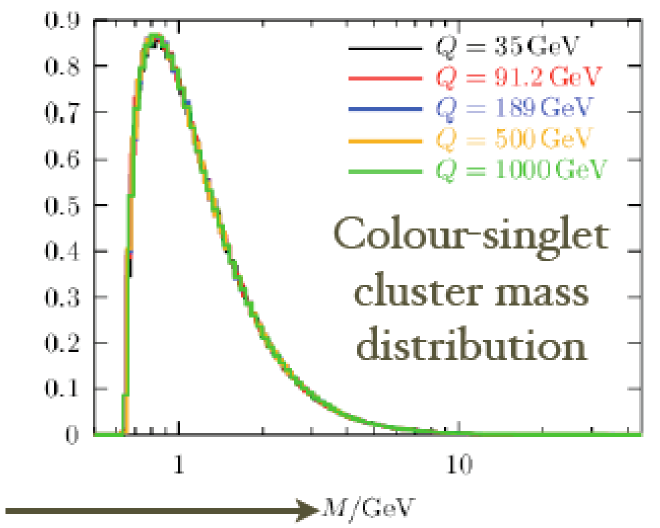
- At this point, phenomenological models are used to simulate how the partons turn into color-neutral hadrons.



From Parton Showers to Hadronization

- The parton shower evolves the hard scattering down to the scale of O(1GeV).
- At this scale, QCD is no longer perturbative. some hadronization model is used to describe the transition from the perturbative PS region to the non-perturbative hadronization region.
- Main hadronization models:
  - ➡ String hadronization (Pythia) [Andersson,Gustafson,Ingelman,Sjöstrand (1983)]
  - ➡ Cluster hadronization (Herwig) [Webber (1984)]
- Hadronization only acts locally, not sensitive to high-q^2 scattering.





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 well-known: PYTHIA, HERWIG, SHERPA

- You will hear much more about Parton Showers in coming lectures, including recent progress in taking PS to NLO in QCD

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

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- Next lecture: Simulations with MadGraph 5