# Monte Carlo's and Event generators for the LHC

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3. Be ready to work on the LHC data...

# Claims and (your) Aims

Several QCD and MC exercises on LHC phenomenology available at MadGraph Wiki :

(http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Physics/Zuoz)

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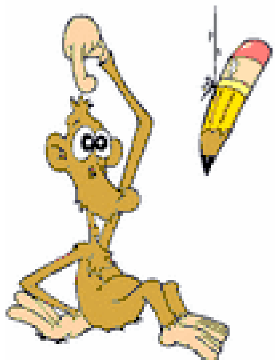

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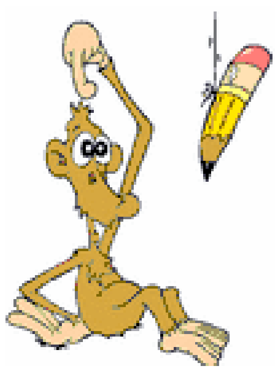

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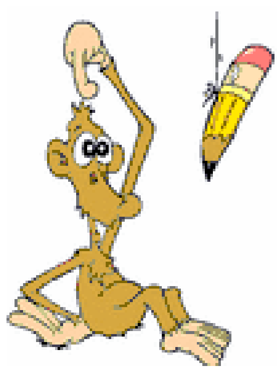

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| Score | Result | Comment |
|---|---|---|
| 5 | Addict | Always keep in mind that there are also other interesting pheno activities in the field. |
| 4 | Excellent | No problem in following these lectures. |
| 3 | Fair | Check out carefully the missed topics. |
| ≤2 | Room for improvement (not passing the Turing test) | Enroll in a MC crash course at your home institution. |
| 5 No clue | No clue |   |

# A simple plan

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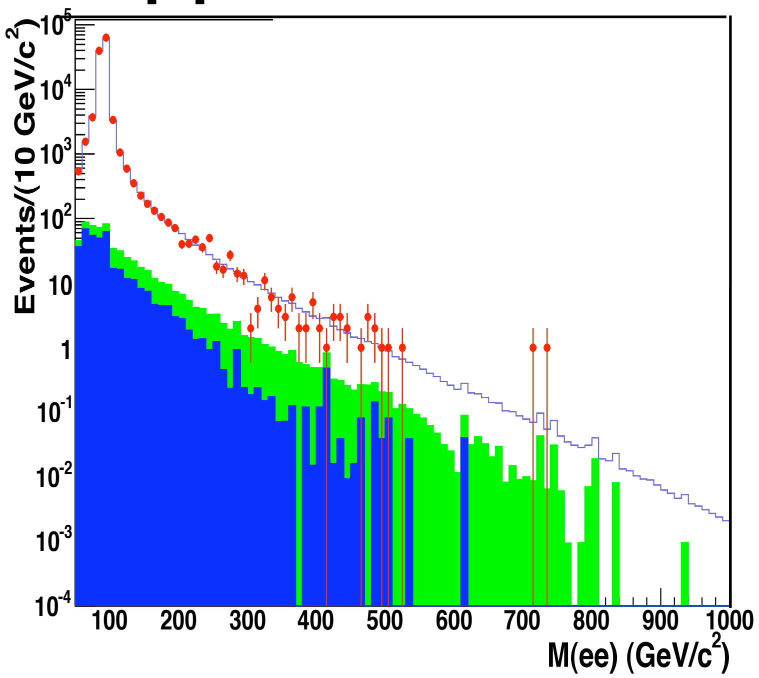
# Discoveries at hadron colliders

## peak

$pp \to Z' \to e^+e^-$

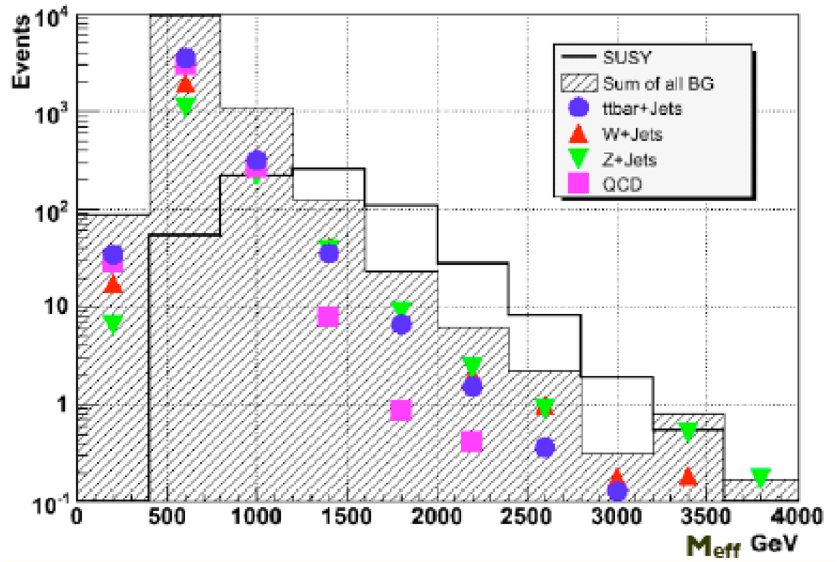



"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

## shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$

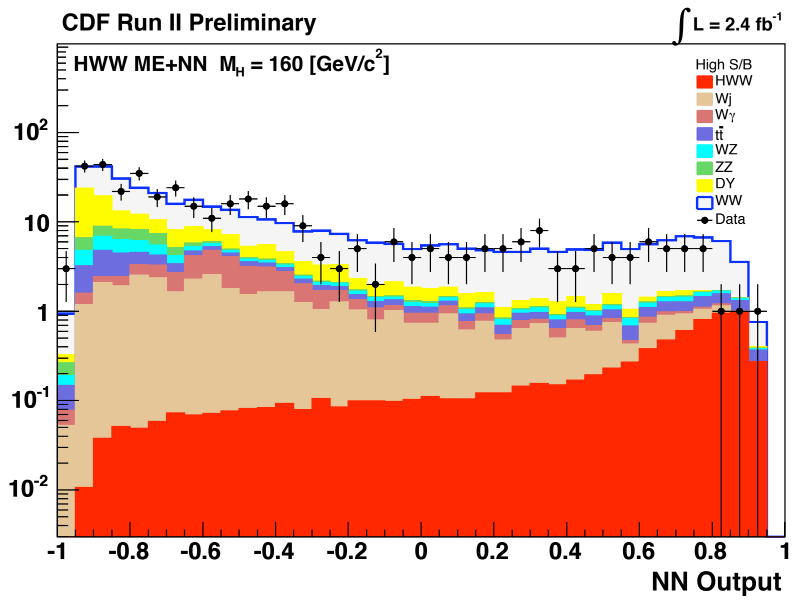



hard

Background shapes needed. Flexible MC for both signal and backgroud tuned and validated with data.

## rate

$pp \to H \to W^+W^-$

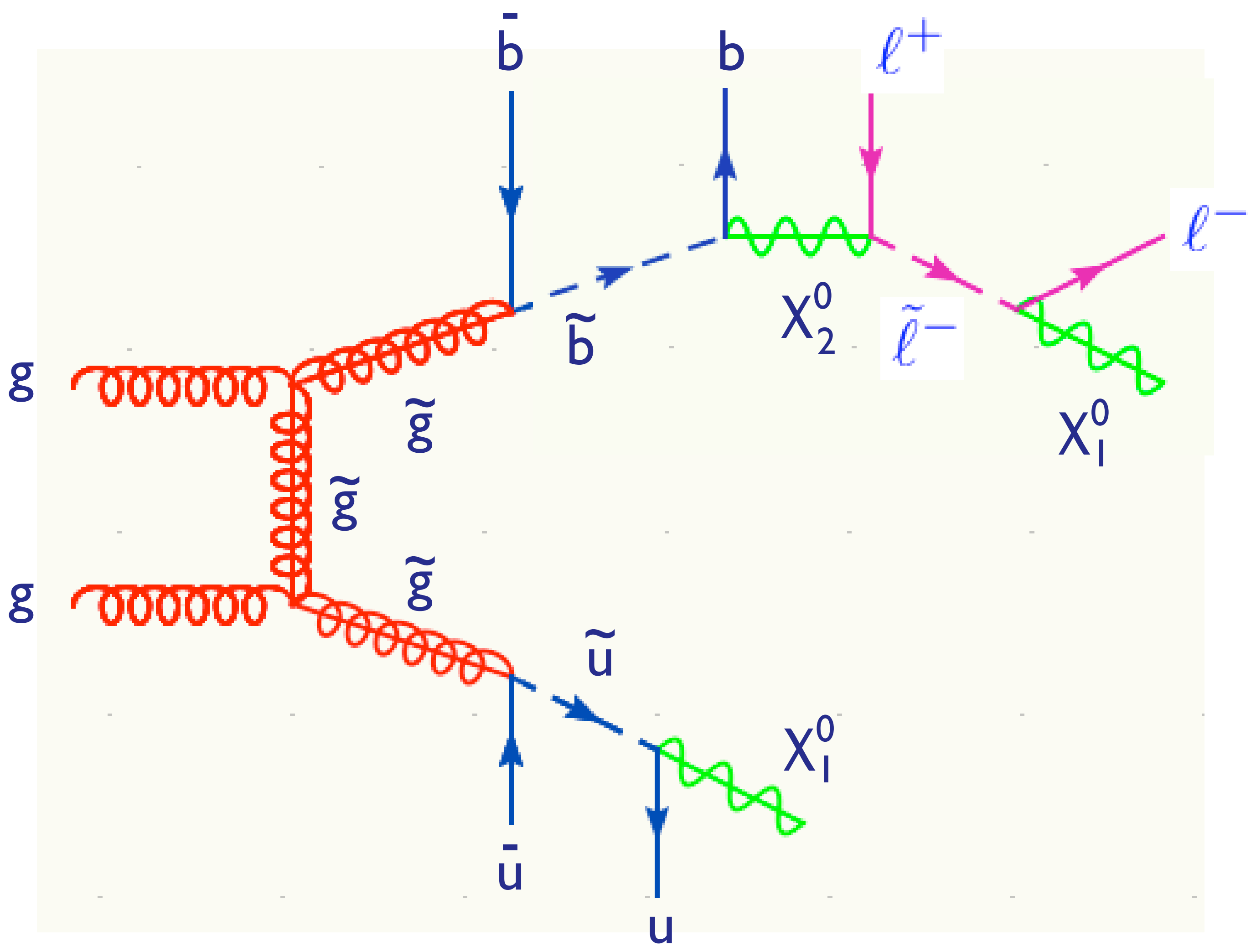



very hard

Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

# A new challenge

Consider SUSY-like inclusive searches: heavy colored states decaying through a chain into jets, leptons and missing $E_T$...



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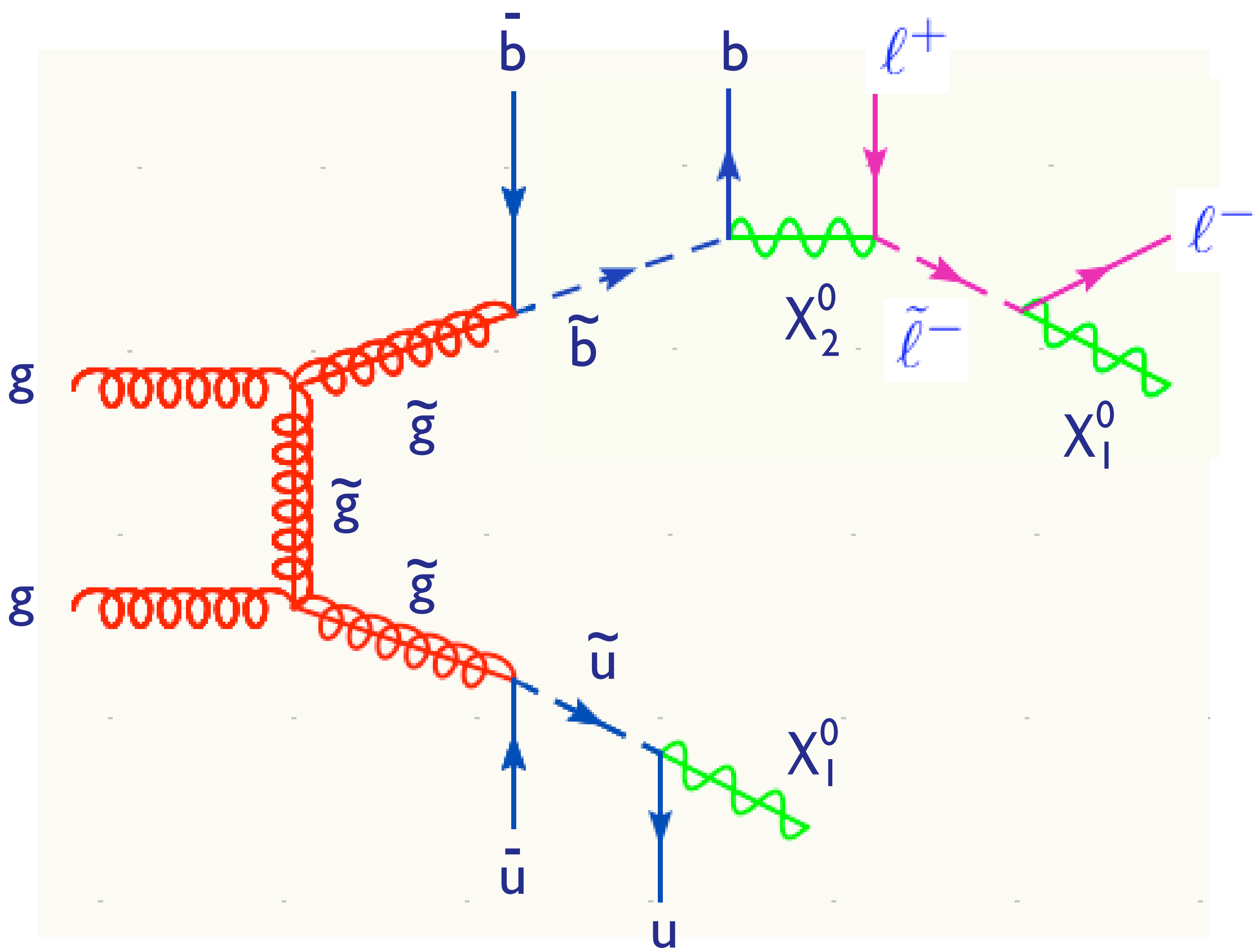
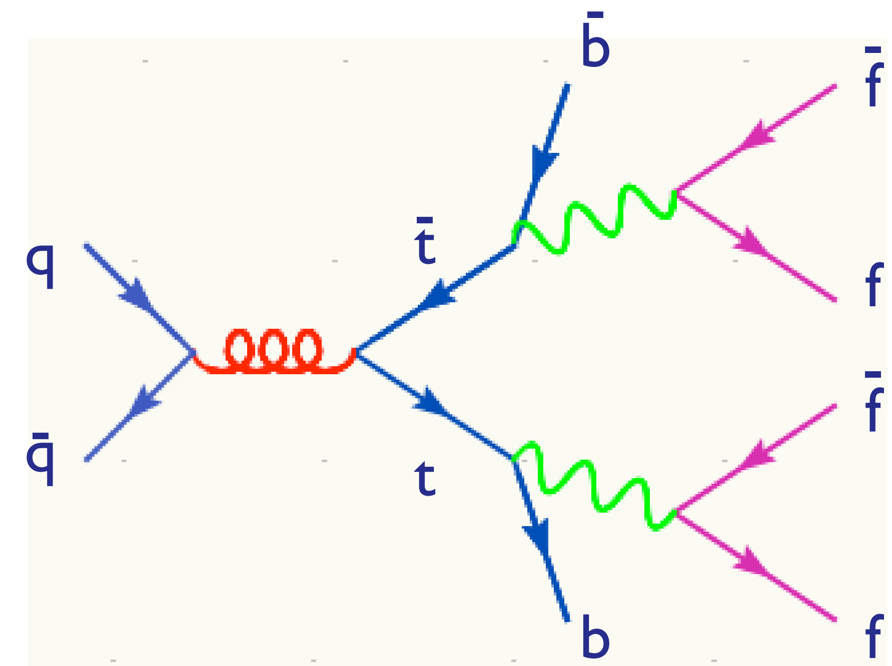



VS




Follow the same approach of CDF in 1995 to establish first evidence of an excess wrt to SM-top and then consistency with SM top production [mt=174, t→blν, σ(tt)] , works for the SM Higgs, but in general beware that...

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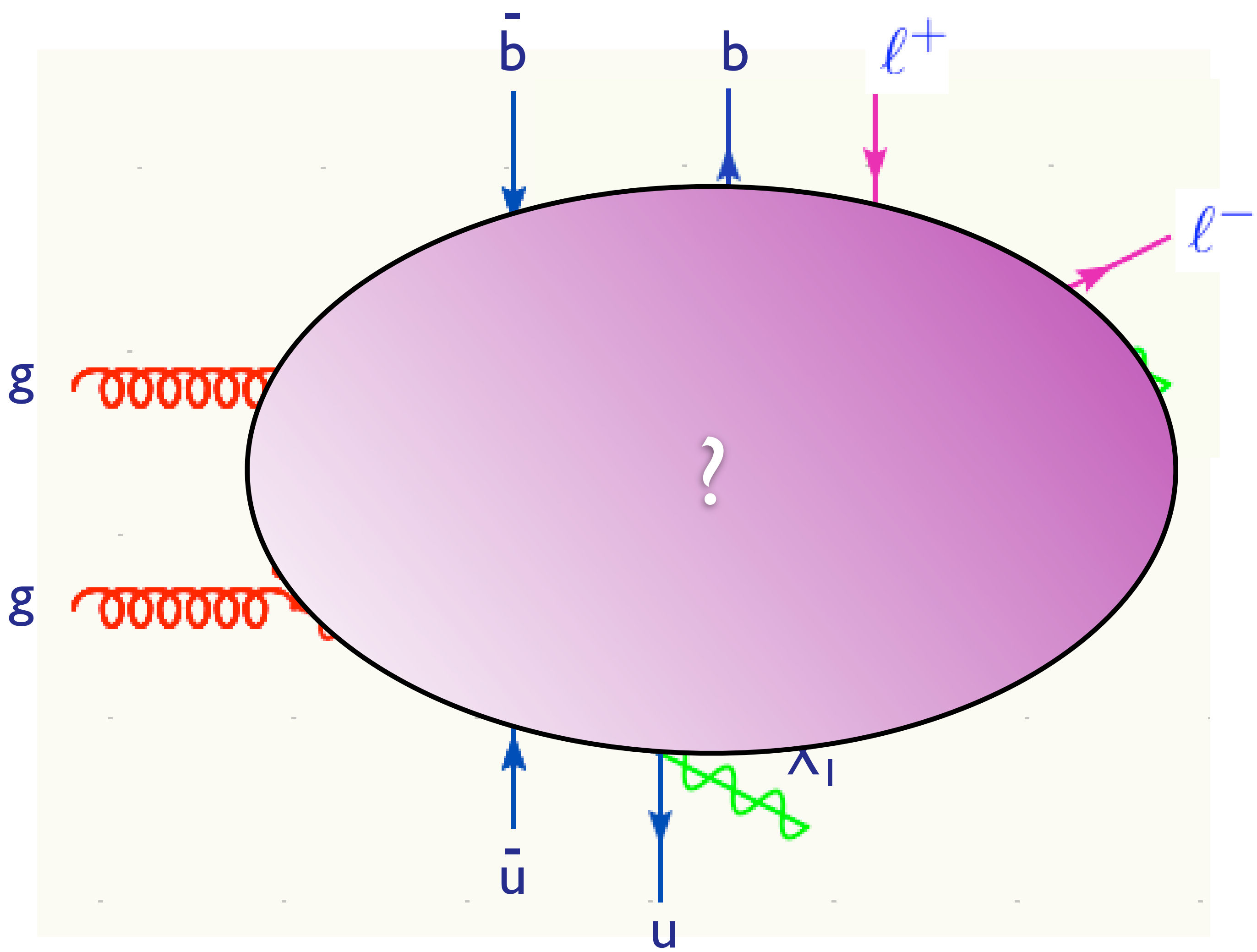


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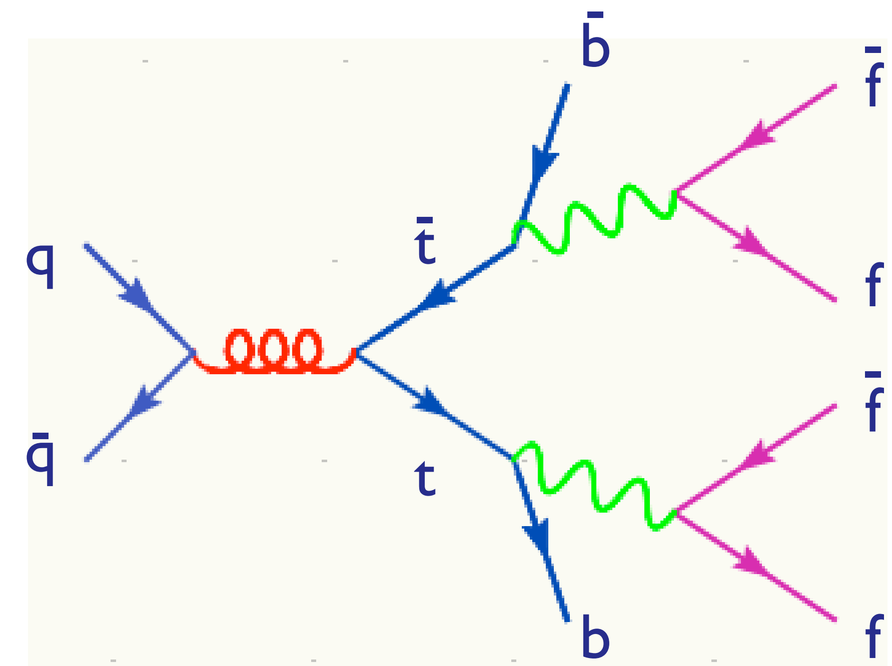
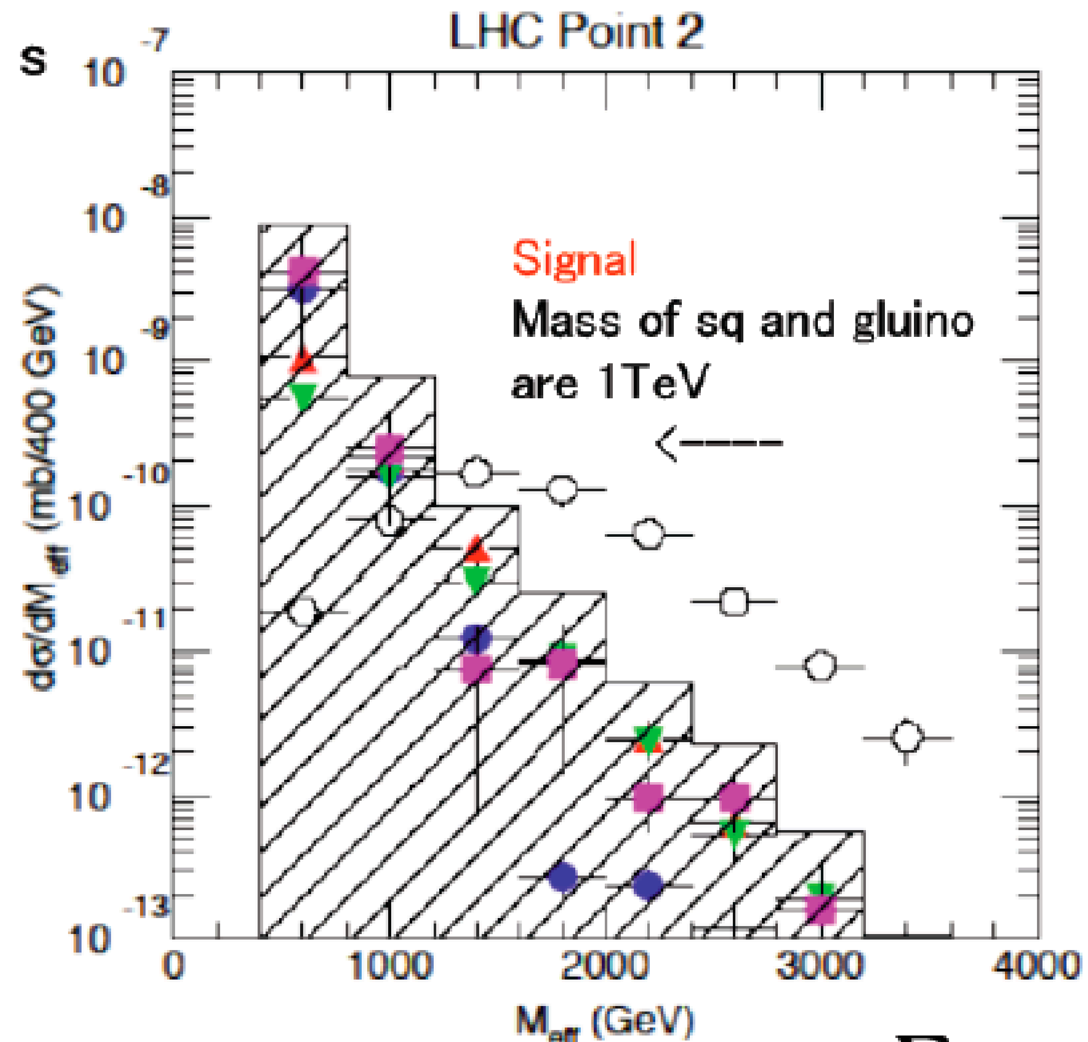



Follow the same approach of CDF in 1995 to establish first evidence of an excess wrt to SM-top and then consistency with SM top production [mt=174, t→blv, σ(tt)] , works for the SM Higgs, but in general beware that... we don't know what to expect!

# Example: early discovery SuperSymmetry at the LHC




$= \not{E}_T + \sum P_T$

"Old MC"

Background: t tbar+jets,(Z,W)+jets, jets. Very difficult to estimate theoretically: many parton calculation (2 → 8 gluons = 10 millions Feynman diagrams diagrams!!). Now MC's for this are available...

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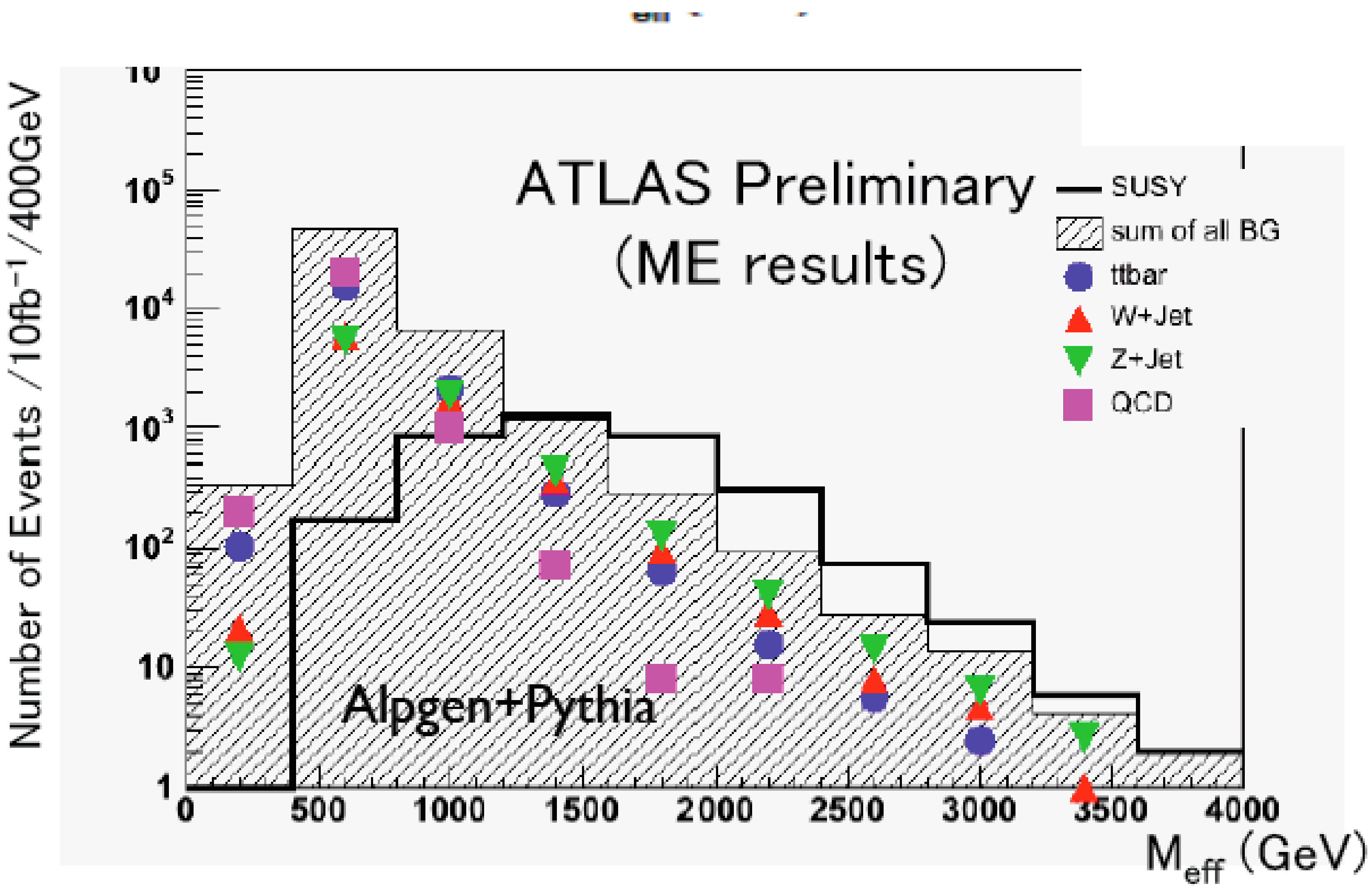


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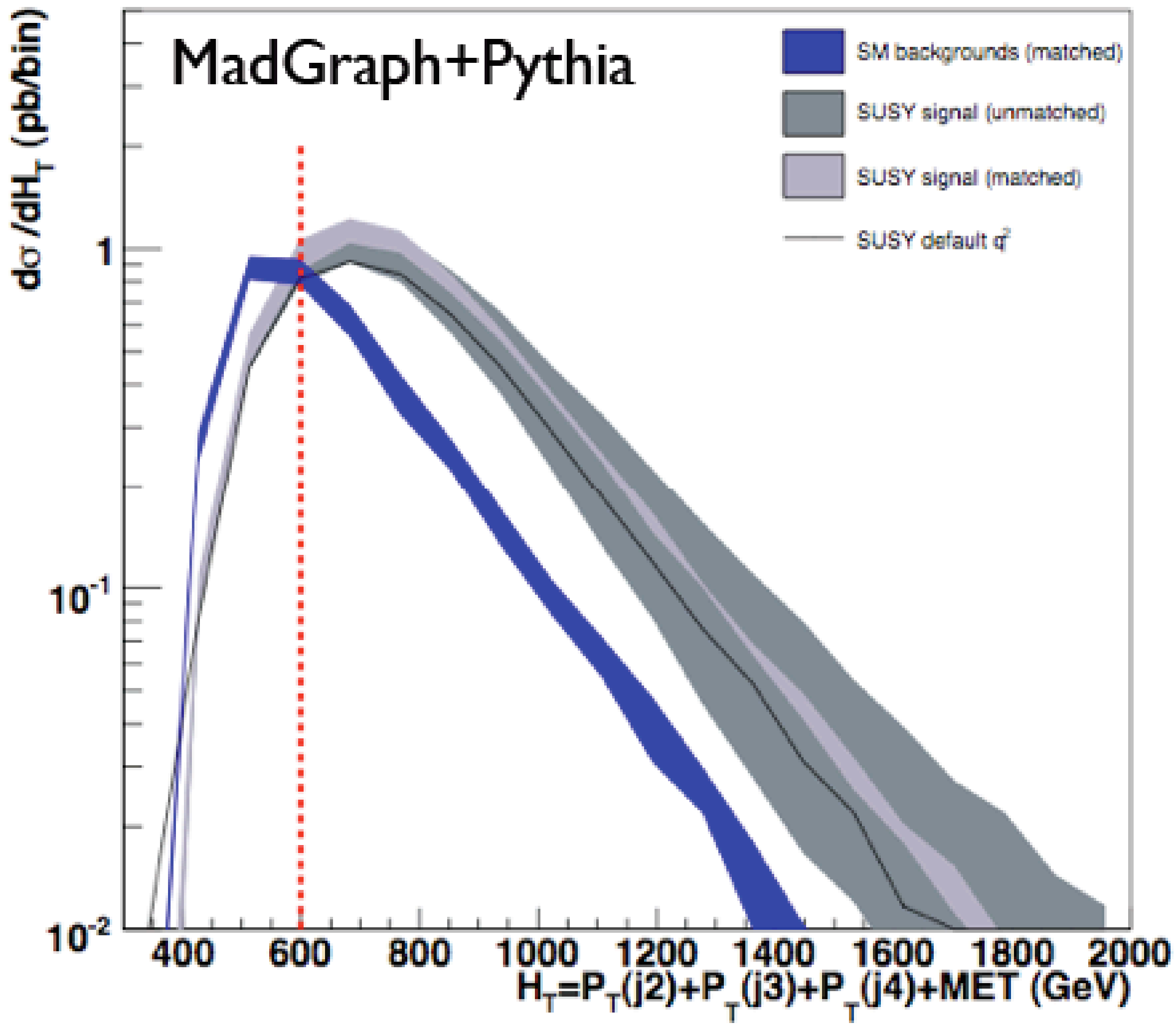


"New MC for Signal & BKG"

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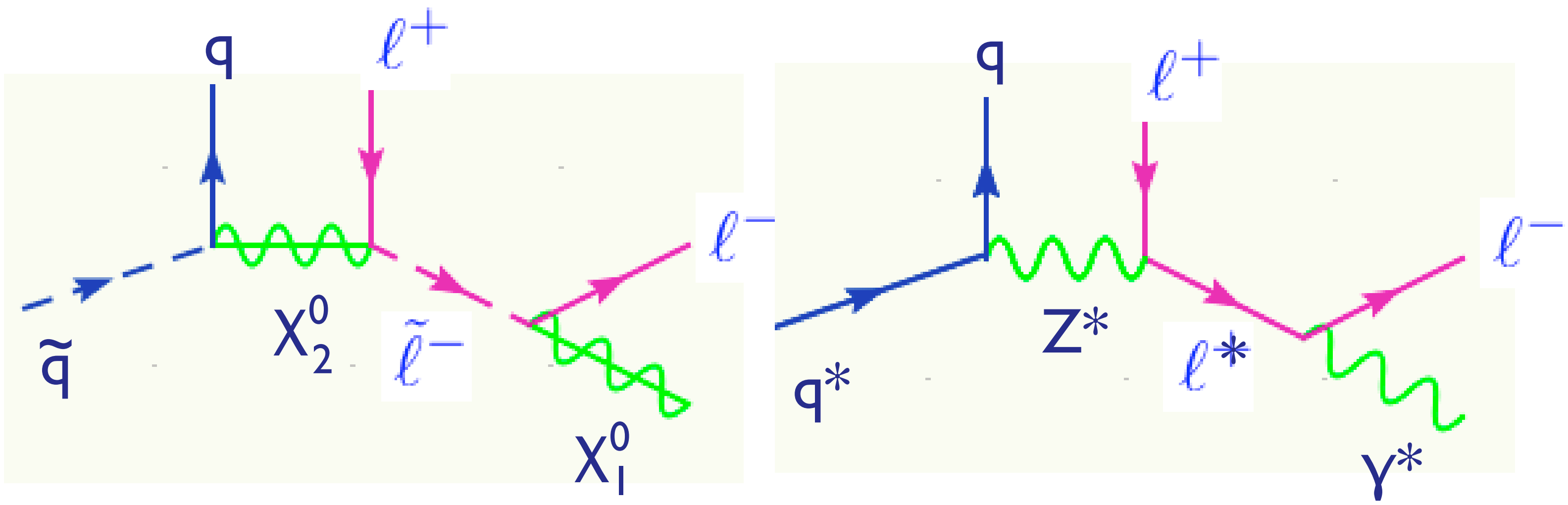
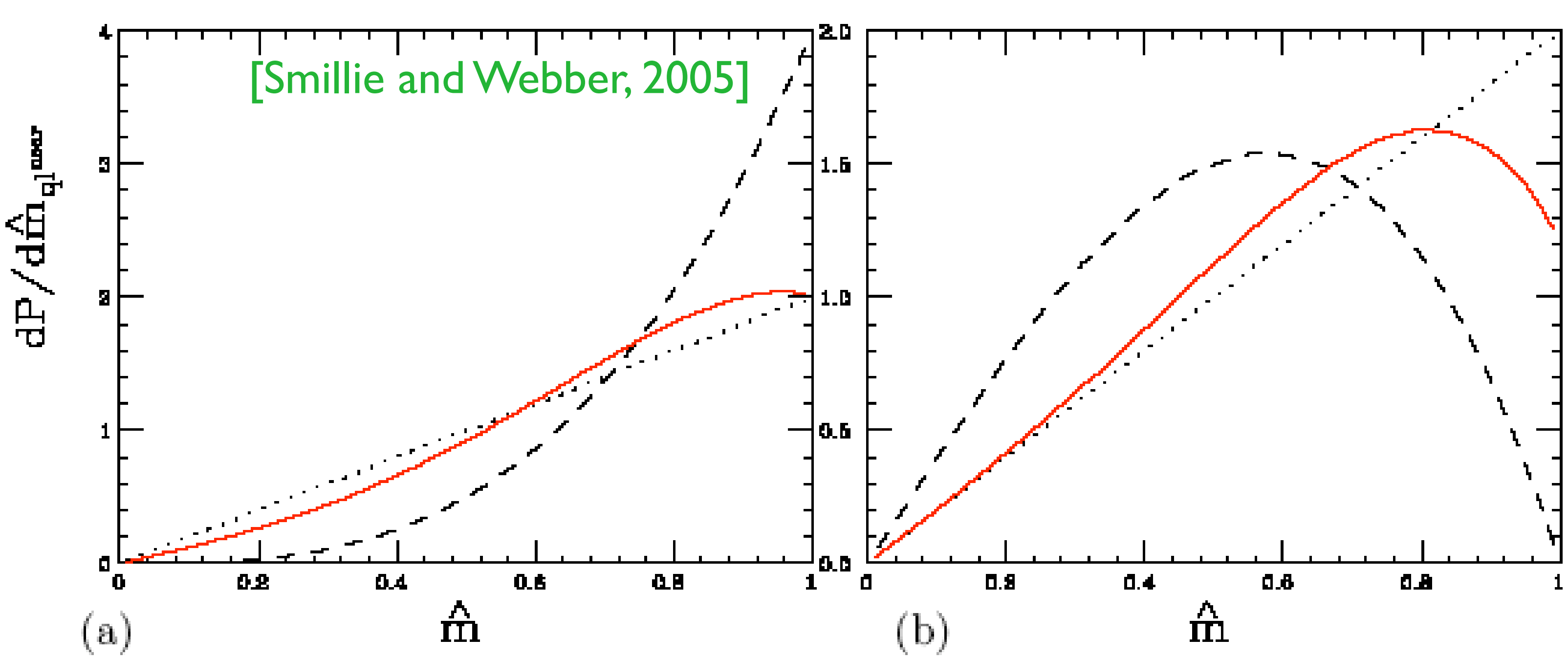
Texte: signal matched ME+PS. Predictability improved. Same theoretical status as the background.

# Example: SUSY vs UED

Information on the mass of the intermediate states can be obtained through the study of kinemetical edges. The shape of the edges can give information on the spin of the intermediate states. Compare for instance SUSY and UED:



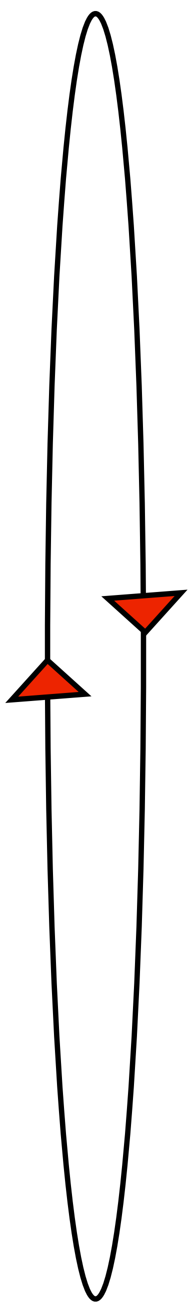

Beware that most of the MC's make some of or all the following simplifications:

1. production and decay are factorized.
2. Spin is ignored.
3. Chains proceed only through 1→2 decays.
4. The narrow width approximation is employed.
5. Non-resonant diagrams are ignored.

Flexible and powerful ME tools are needed to check and in case go beyond the above approximations!

# The path towards discoveries

LHC physics = QCD + $\epsilon$



1. Rediscover the known SM at the LHC (top's, W's, Z's) + jets.

New regime for QCD. Exclusive description for rich and energetic final states with flexible MC to be validated and tuned to control samples. Shapes for multi-jet final states and normalization for key process important. Accurate predictions (NLO,NNLO) needed only for standard candle cross sections.

2. Identify excess(es) over SM

Importance of a good theoretical description depends on the nature of the physics discovered: from none (resonances) to fundamental (inclusive SUSY).

3. Identify the nature of BSM: from coarse information to measurements of mass spectrum, quantum numbers, couplings.

Not fully worked out strategy. Several approaches proposed (MARMOSET, VISTA,...). Only in the final phase accurate QCD predictions and MC tools for SM as well as for the BSM signals will be needed.

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No QCD $\Rightarrow$ No Party

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# The QCD Lagrangian

By direct inspection and by using the form non-abelian covariant derivation, we can check that indeed non-abelian gauge symmetry implies self-interactions. This is not surprising since the gluon itself is charged (In QED the photon is not!)

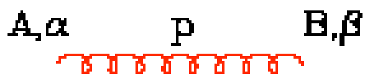
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \sum_f \bar{\psi}_i^{(f)} (i\partial\!\!\!/ - m_f) \psi_i^{(f)} - \bar{\psi}_i^{(f)} (g_s t^a_{ij} A\!\!\!/_a) \psi_j^{(f)}$$

Gauge Fields and their interact.

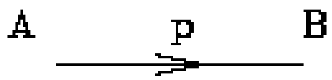
Matter

Interaction

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




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

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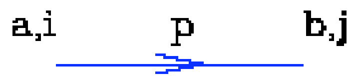
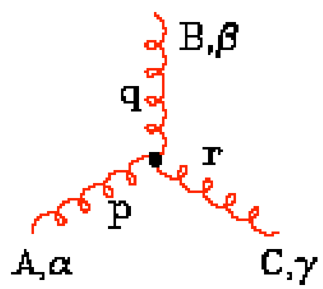
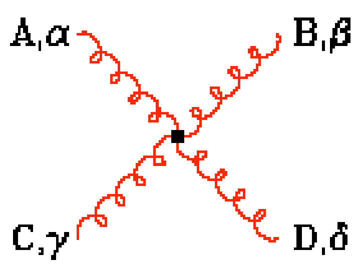



$$\delta^{ab}\frac{i}{(\not{p}-m+i\epsilon)_{ji}}$$

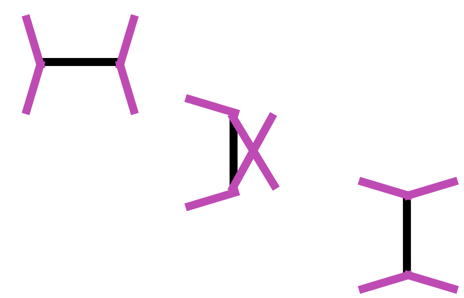


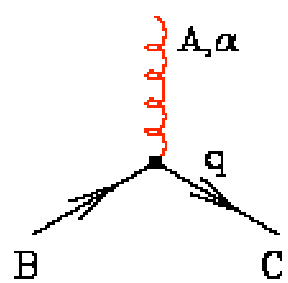

$$-g\ f^{ABC}[(p-q)^{\gamma}g^{\alpha\beta}+(q-r)^{\alpha}g^{\beta\gamma}+(r-p)^{\beta}g^{\gamma\alpha}]$$

(all momenta incoming)

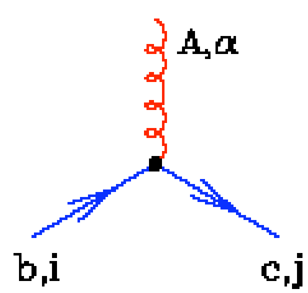



$$-ig^{2}\ f^{XAC}f^{XBD}\ [g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$
$$-ig^{2}\ f^{XAD}f^{XBC}\ [g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\gamma}g^{\beta\delta}]$$
$$-ig^{2}\ f^{XAB}f^{XCD}\ [g^{\alpha\gamma}g^{\beta\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$





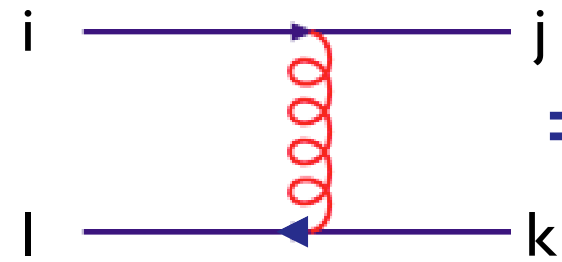

$$g\ f^{ABC}q^{\alpha}$$




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

# The importance of color

$$t^a_{ij}t^a_{kl} = \frac{1}{2}(\delta_{il}\delta_{kj} - \frac{1}{N_c}\delta_{ij}\delta_{kl})$$

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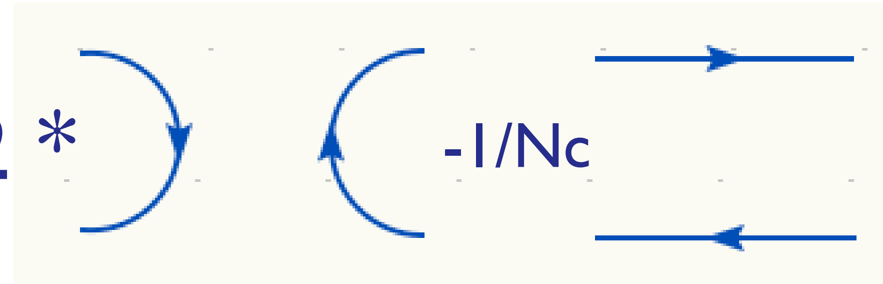

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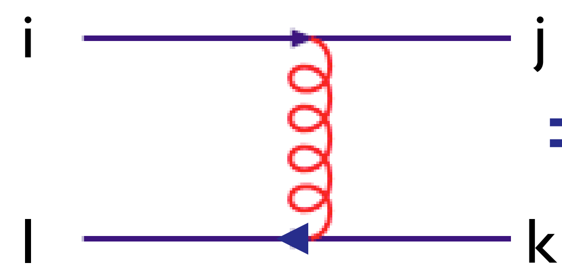


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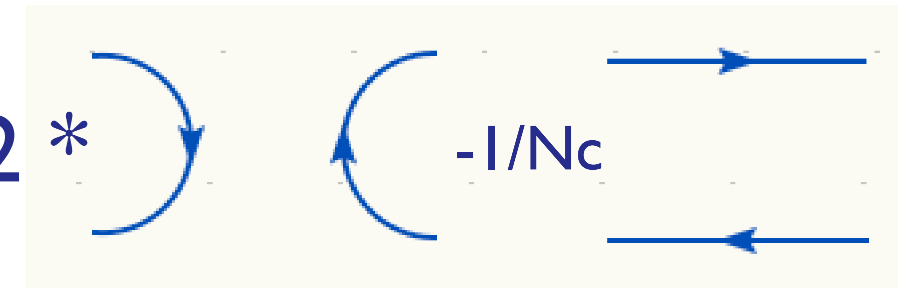


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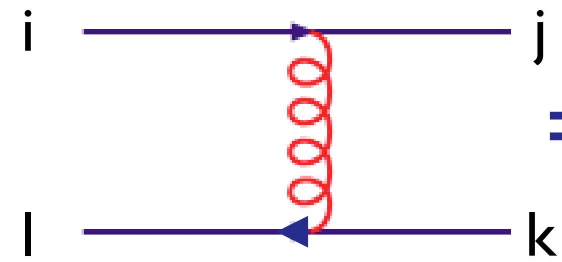


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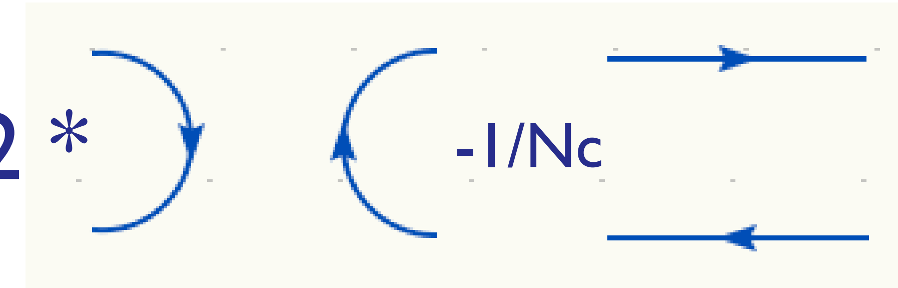


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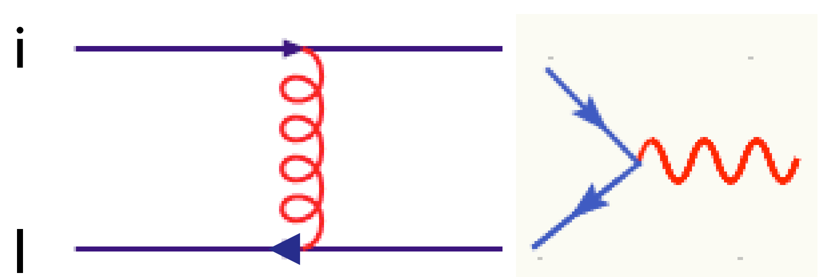
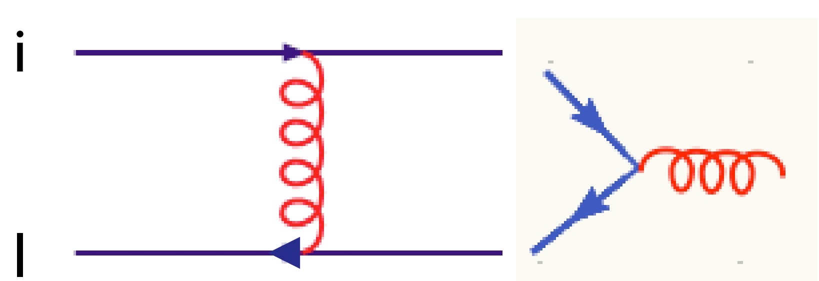
Solution: a q qb pair can be in a singlet state (photon) or in octet (gluon) : $3 \otimes \bar{3} = 1 \oplus 8$




$$\frac{1}{2}(\delta_{ik}\delta_{lj} - \frac{1}{N_c}\delta_{ij}\delta_{lk})\delta_{ki} = \frac{1}{2}\delta_{lj}(N_c - \frac{1}{N_c}) = C_F\delta_{lj}$$




$$\frac{1}{2}(\delta_{ik}\delta_{lj} - \frac{1}{N_c}\delta_{ij}\delta_{lk})t^a_{ki} = -\frac{1}{2N_c}t^a_{lj}$$

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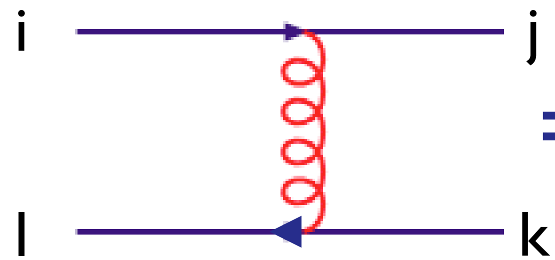


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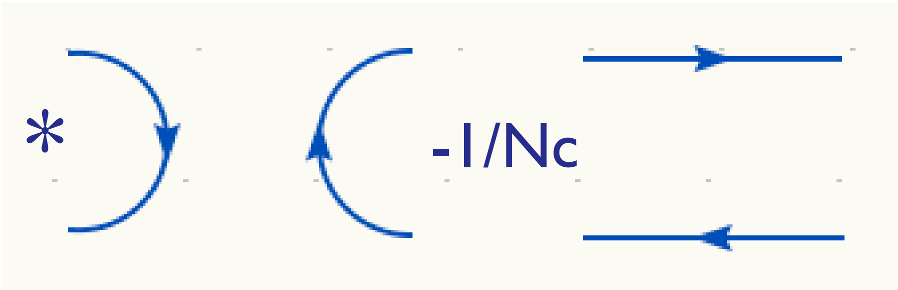


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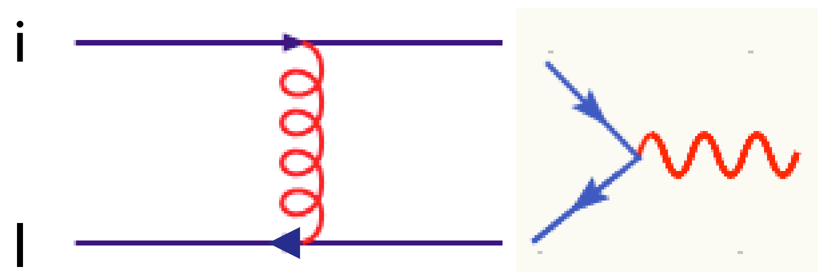
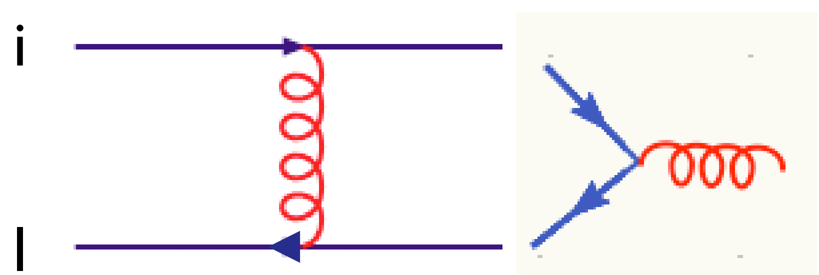
Solution: a q qb pair can be in a singlet state (photon) or in octet (gluon) : $3 \otimes \bar{3} = 1 \oplus 8$




$$\frac{1}{2}\left(\delta_{ik}\delta_{lj} - \frac{1}{N_c}\delta_{ij}\delta_{lk}\right)\delta_{ki} = \frac{1}{2}\delta_{lj}\left(N_c - \frac{1}{N_c}\right) = C_F\delta_{lj}$$

>0, attractive




$$\frac{1}{2}\left(\delta_{ik}\delta_{lj} - \frac{1}{N_c}\delta_{ij}\delta_{lk}\right)t^a_{ki} = -\frac{1}{2N_c}t^a_{lj}$$

<0, repulsive

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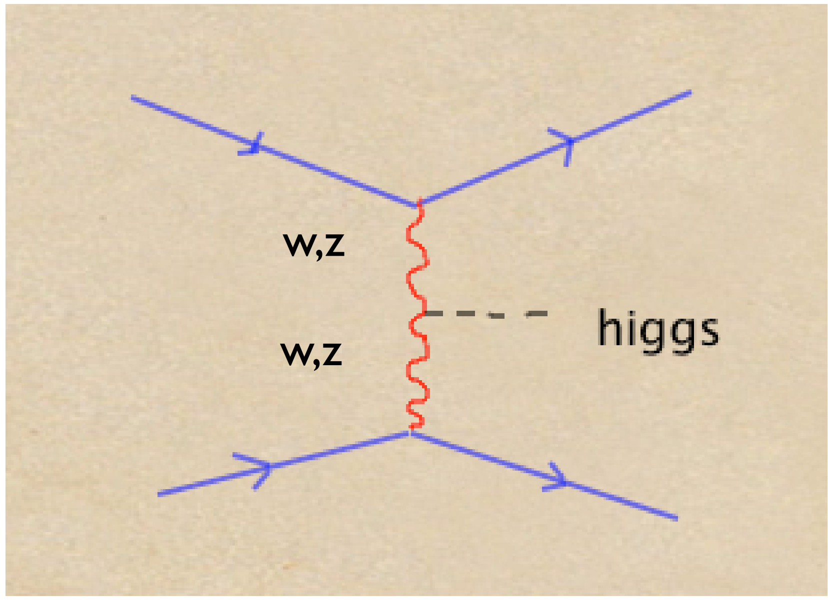

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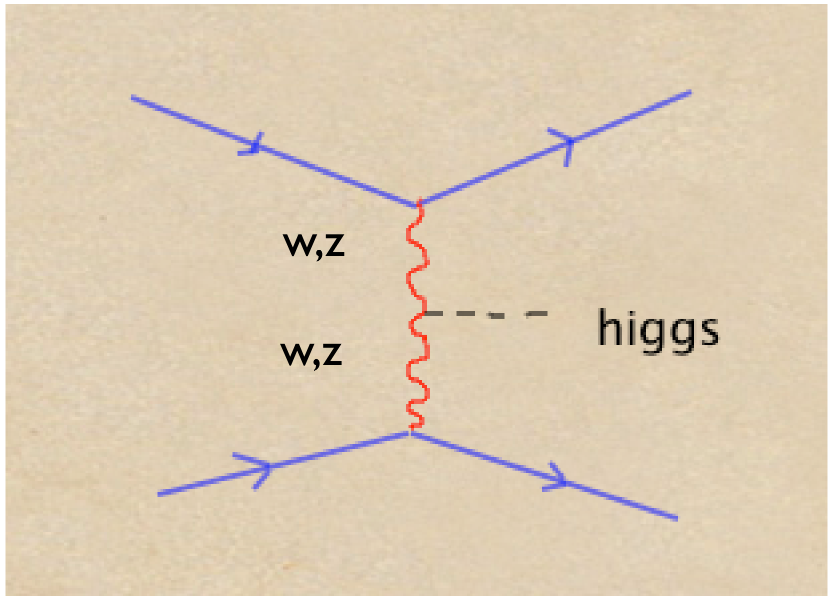


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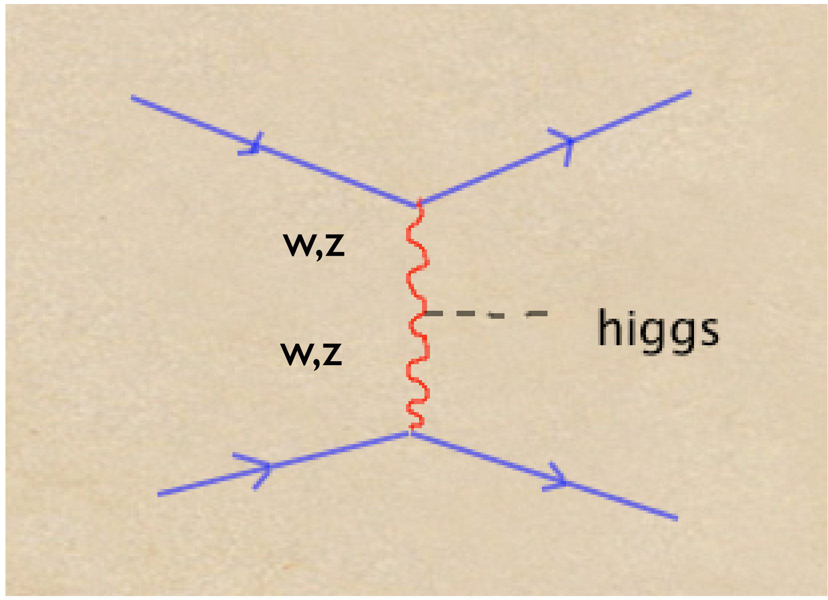


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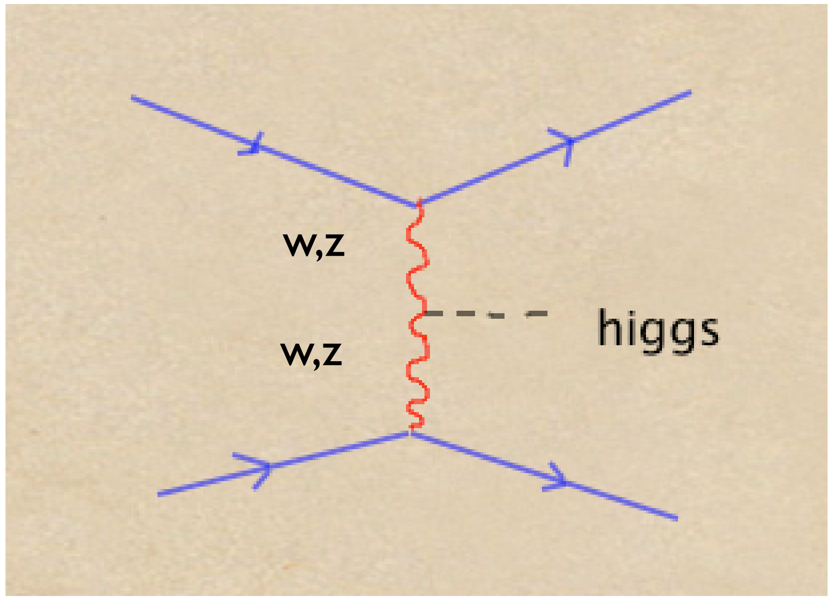


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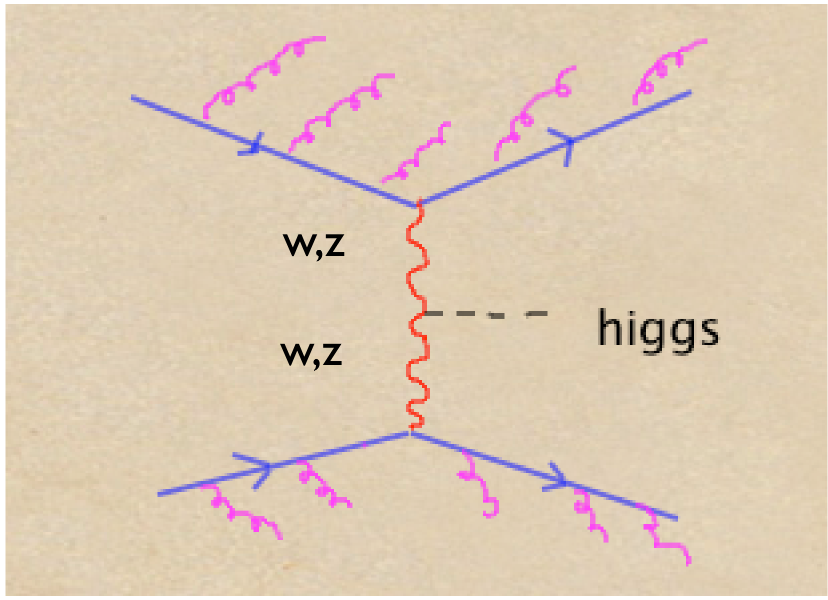


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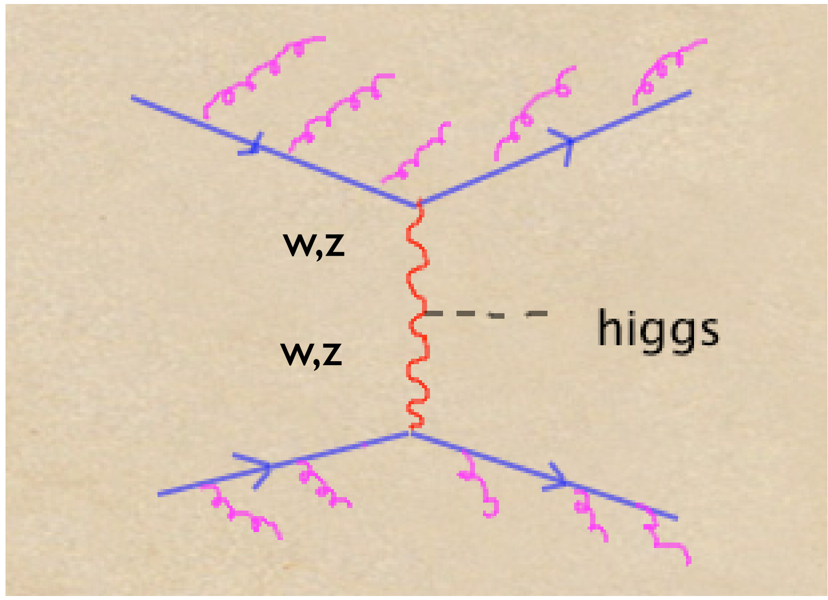


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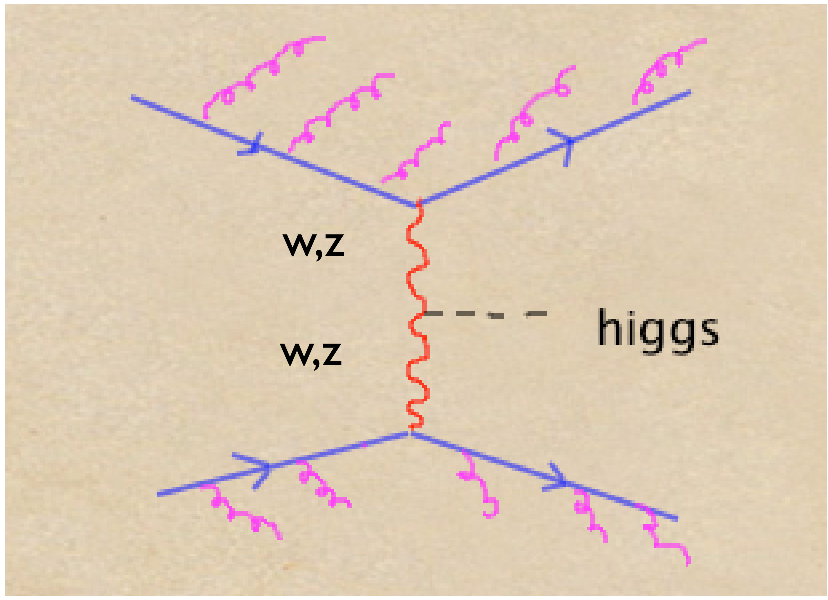


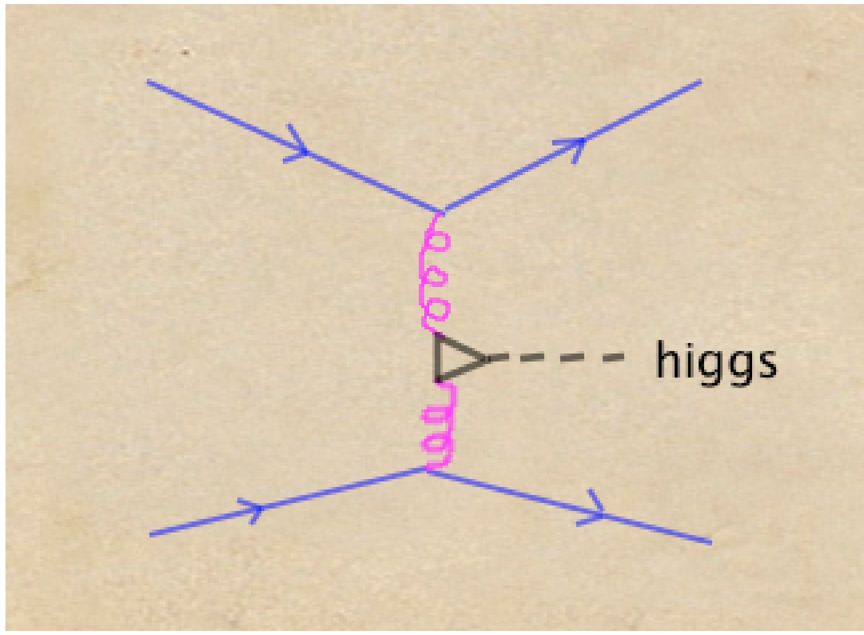


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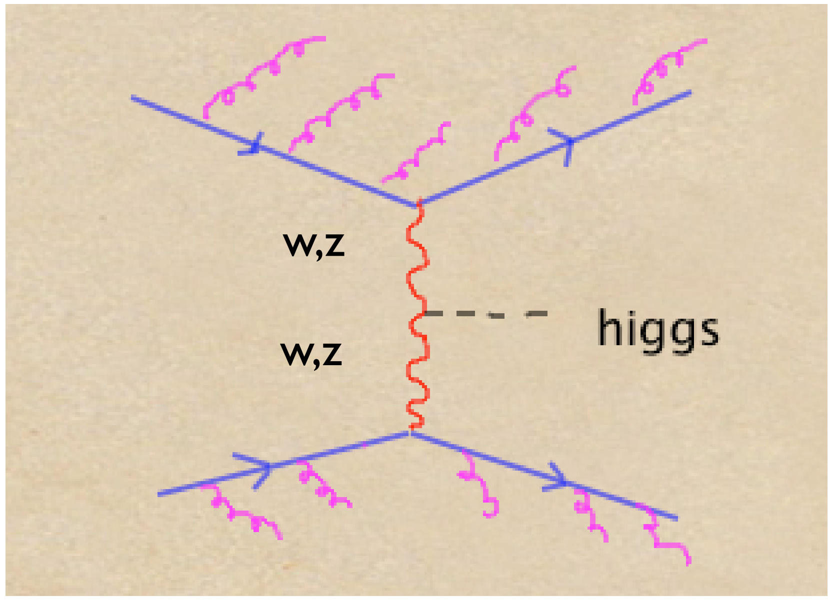


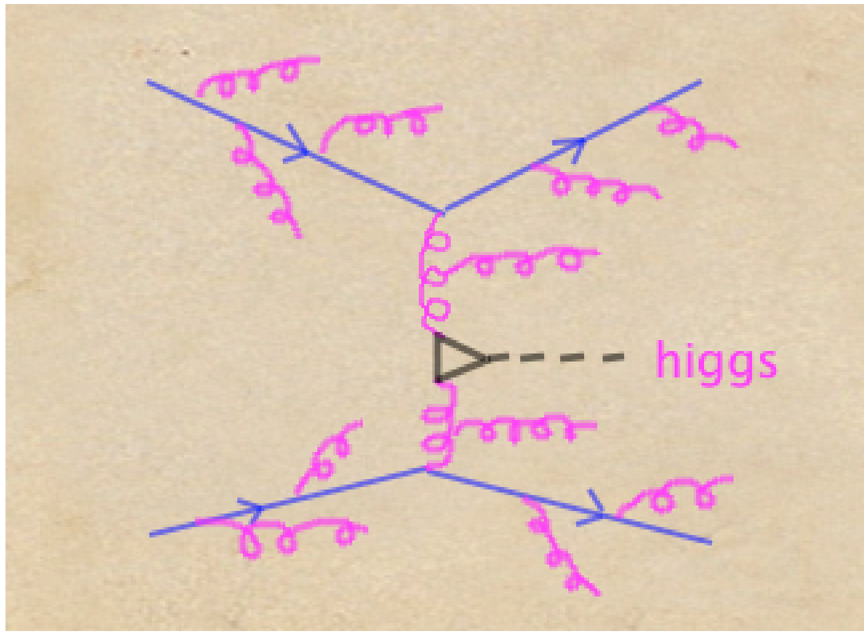


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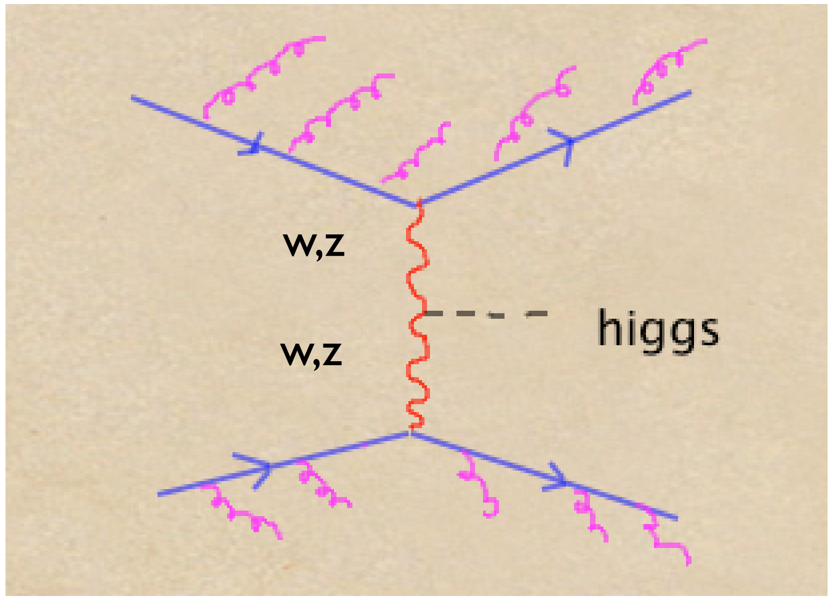


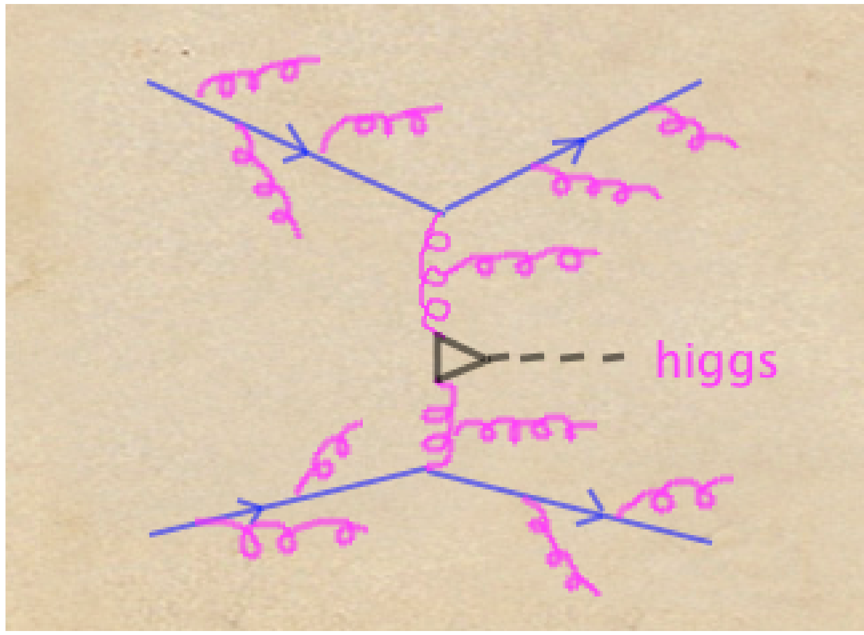


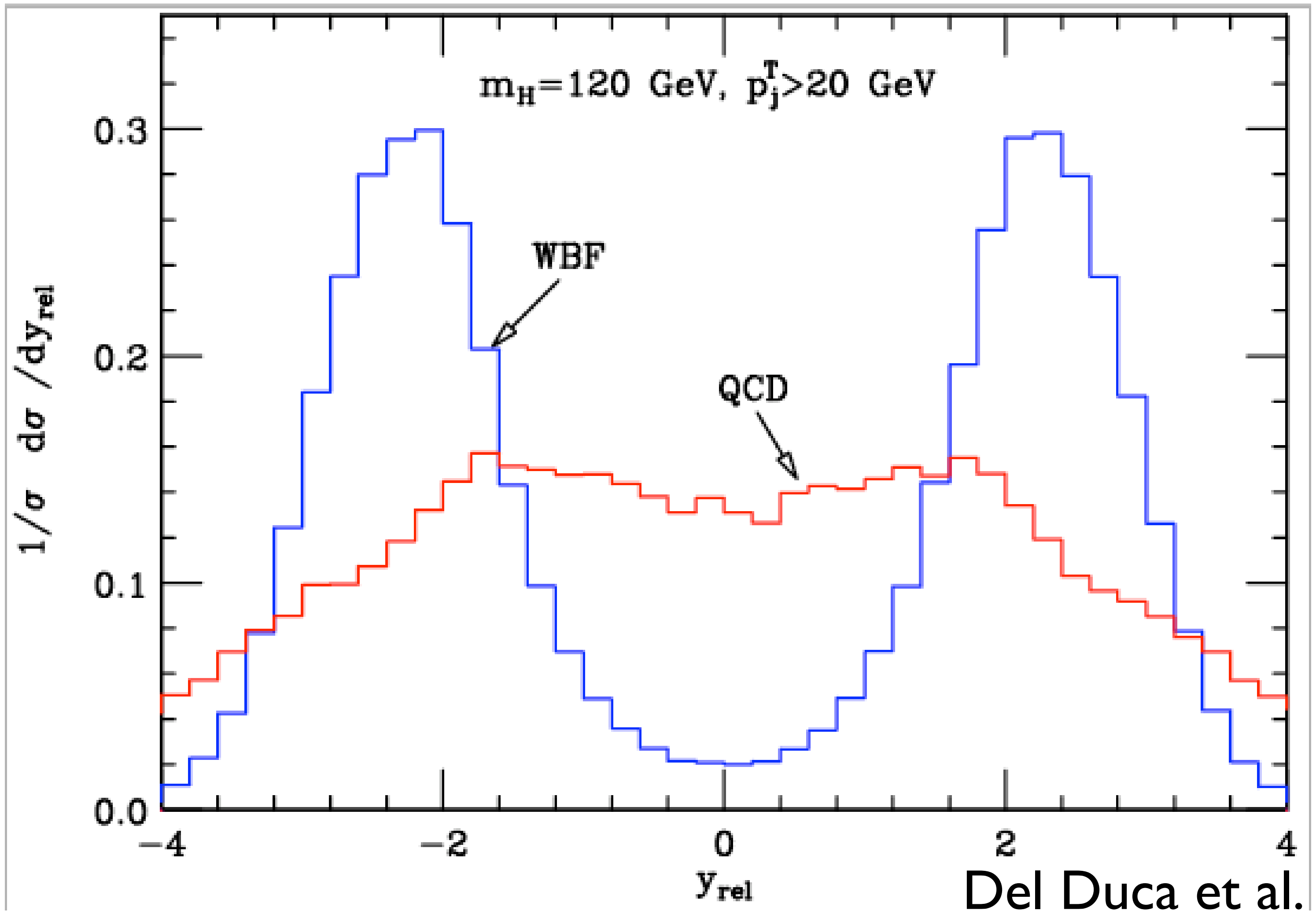


Del Duca et al.

Third jet distribution

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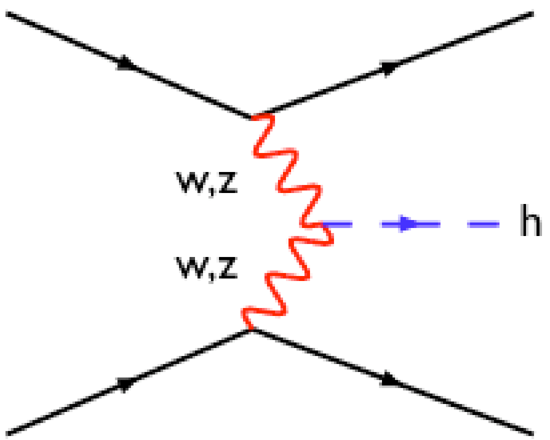


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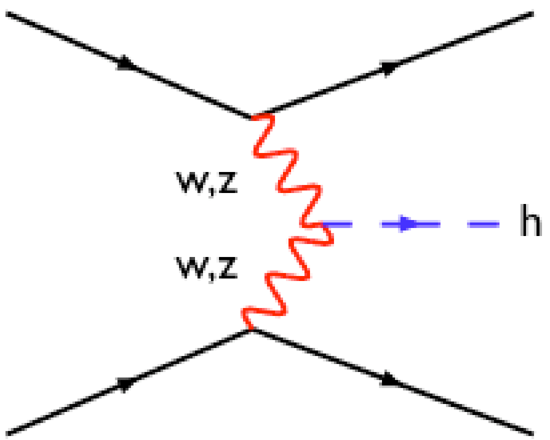


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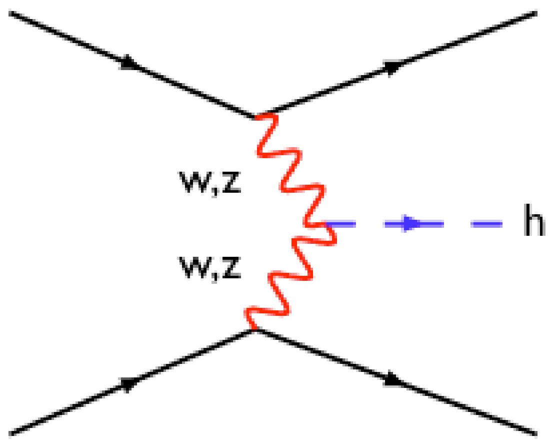

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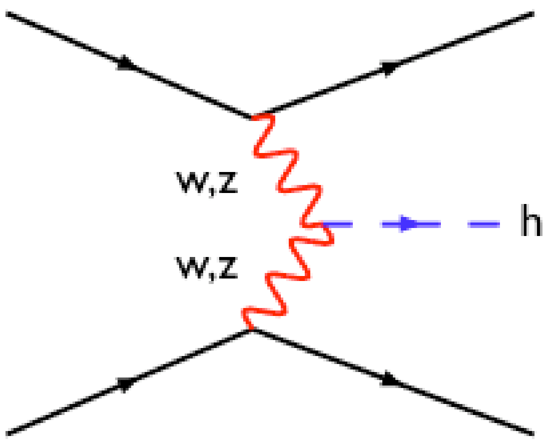


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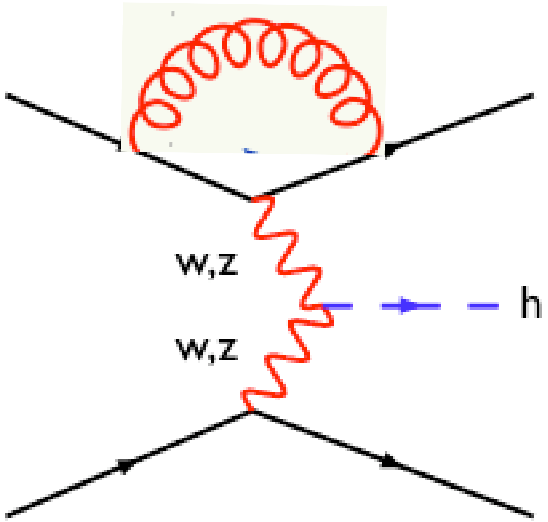

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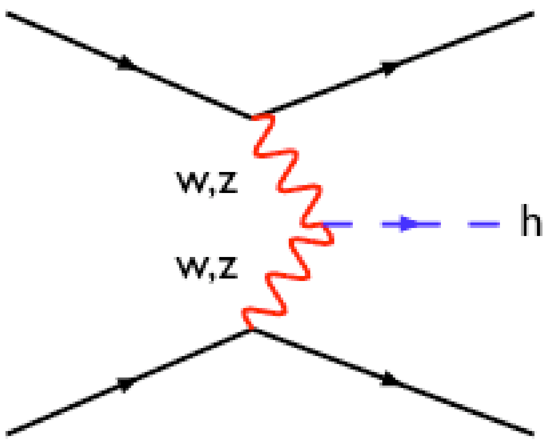


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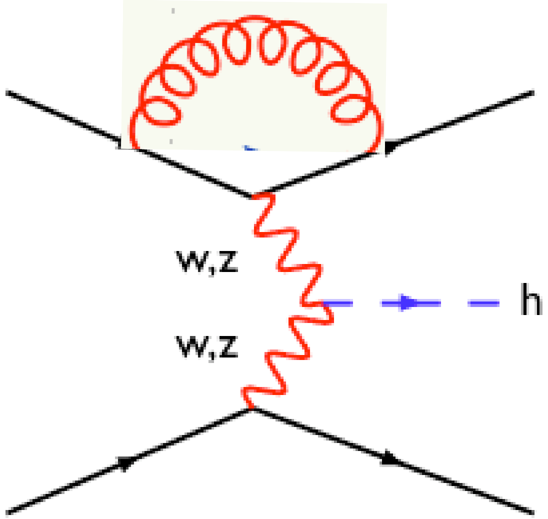


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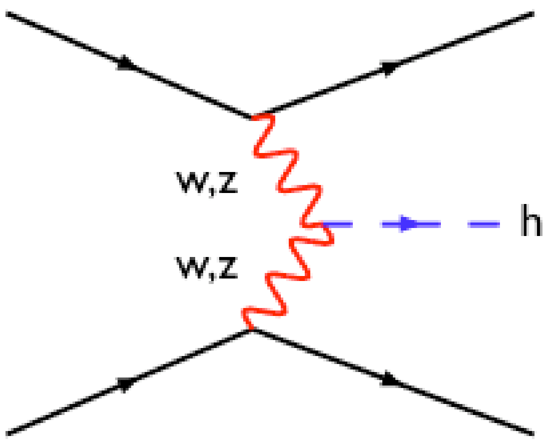


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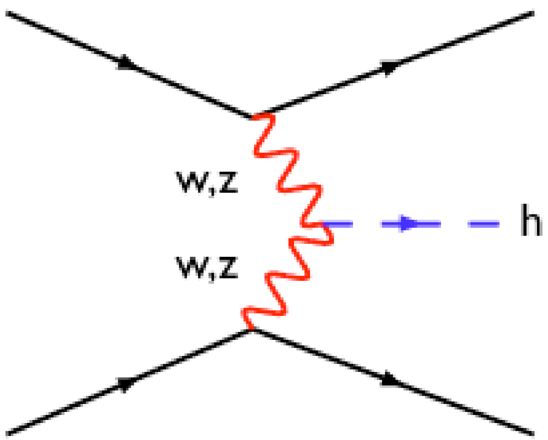


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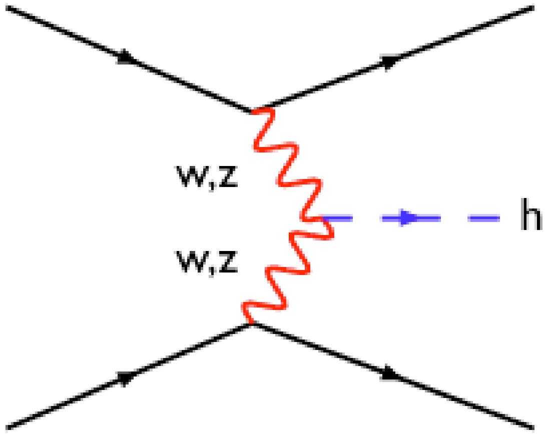


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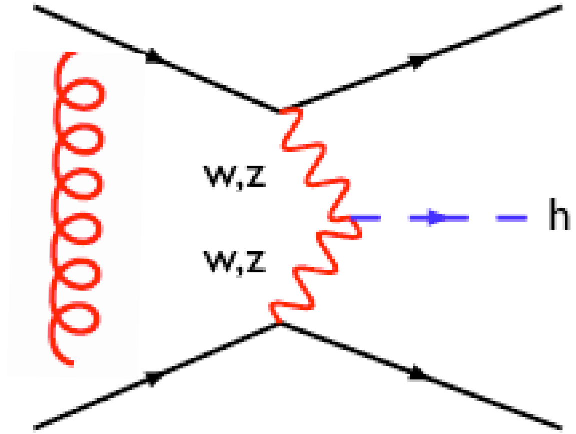


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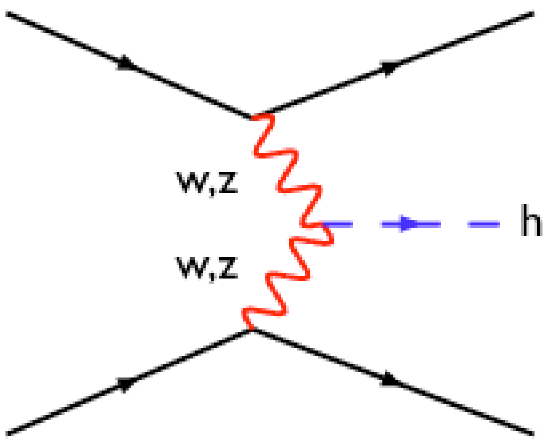


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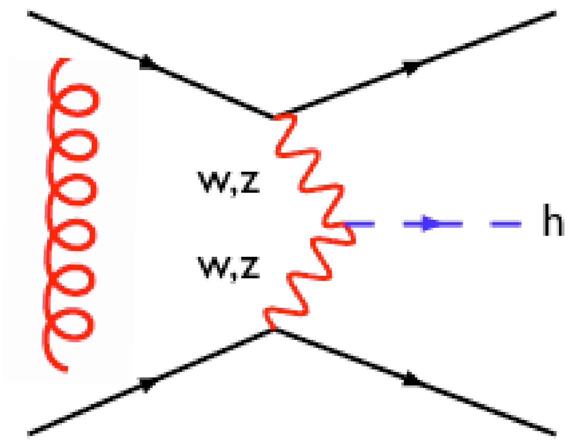


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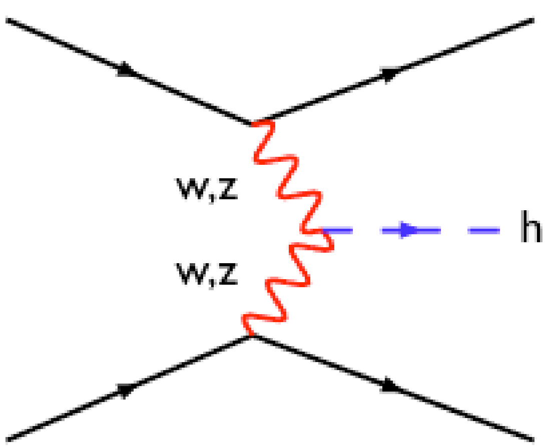


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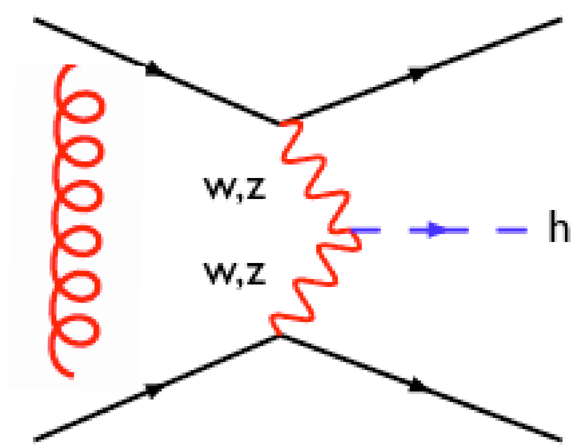


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Also at NLO there is no color exchange! With one little exception....

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# Beware of the factorial growth

| n | full Amp | partial Amp | BG |
|---|---|---|---|
| 4 | 4 | 3 | 3 |
| 5 | 25 | 10 | 10 |
| 6 | 220 | 36 | 35 |
| 7 | 2485 | 133 | 70 |
| 8 | 34300 | 501 | 126 |
| 9 | 559405 | 1991 | 210 |
| 10 | 10525900 | 7335 | 330 |
| 11 | 224449225 | 28199 | 495 |
| 12 | 5348843500 | 108280 | 715 |

$(2n)!$ $3.8^n$ $n^4$

Note: one always needs to (MC) sum over colors at the end, something that is intrinsically factorial.

- Complexity of plain vanilla Feynman calculations grows factorially
- "Old techniques" based on calculating simpler guauge invariant objects by a recursive techniques are much more powerful.
- In any case the calculation through partial amplitudes is not as efficient as the direct calculation of the full amplitude at fixed color through numerical recursive relations [ALPGEN, Moretti, Caravaglios, Mangano, Pittau, 1998; HELAC, Draggiotis, Kleiss, Papadopoulos, 1998], which has only an exponential growth.
- New twistor tree-level BCF or CSW, without or with color, relations don't improve on the "old" Berends-Giele recursive relations. [Dinsdale, Wernick, Weinzierl, 2006; Duhr, Hoeche, FM, 2006].

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General and flexible method is needed

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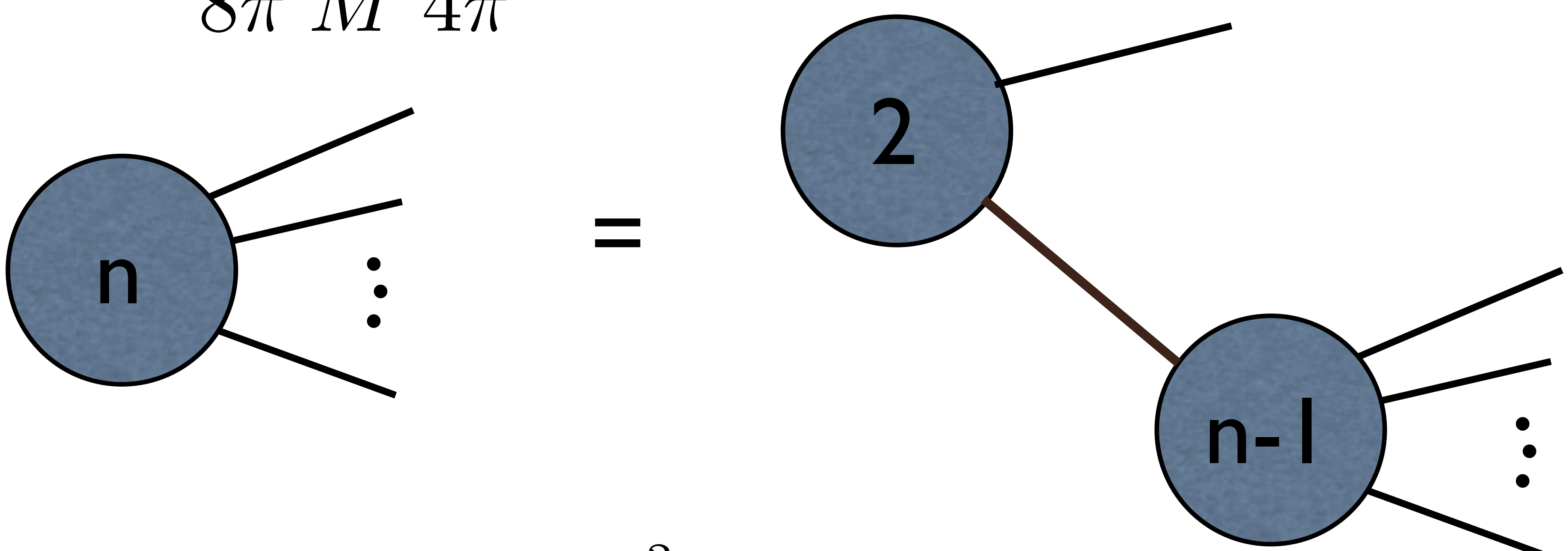


$$d\Phi_n(M) = \frac{1}{2\pi} \int_0^{(M-\mu)^2} d\mu^2 d\Phi_2(M) d\Phi_{n-1}(\mu)$$

# Integrals as averages

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

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

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

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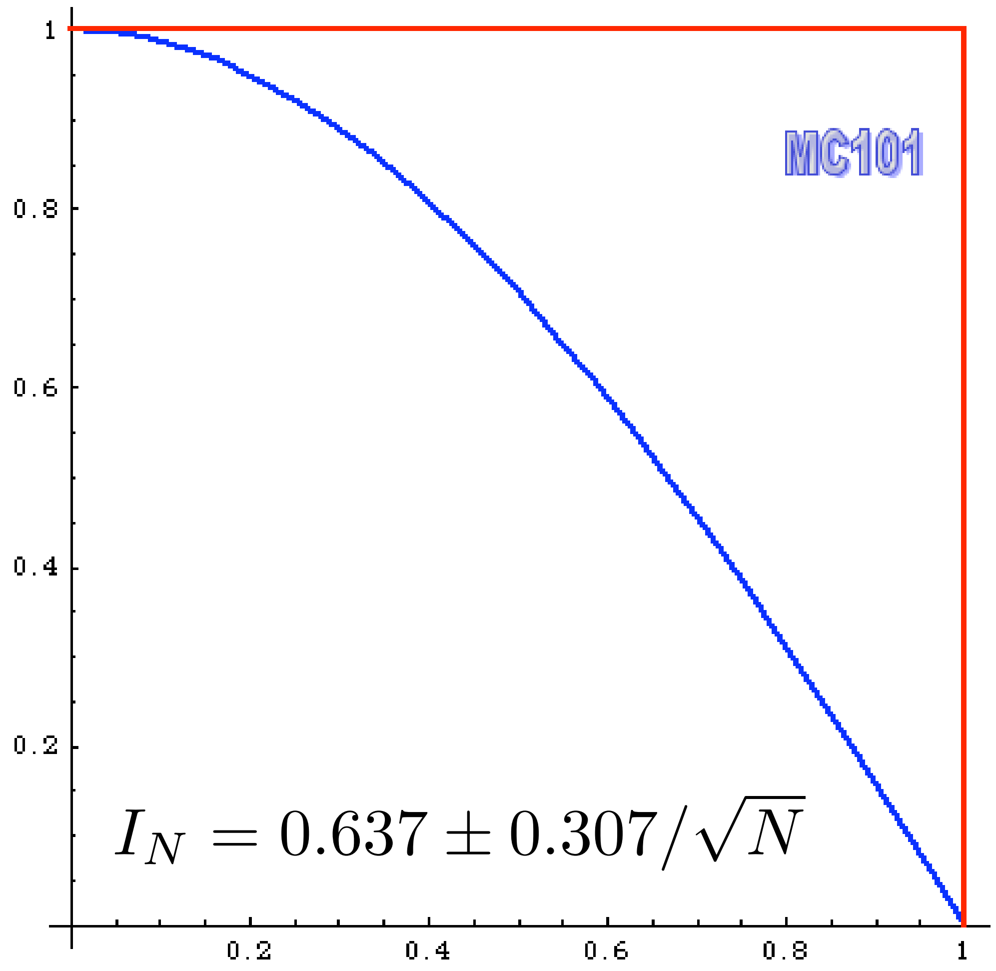


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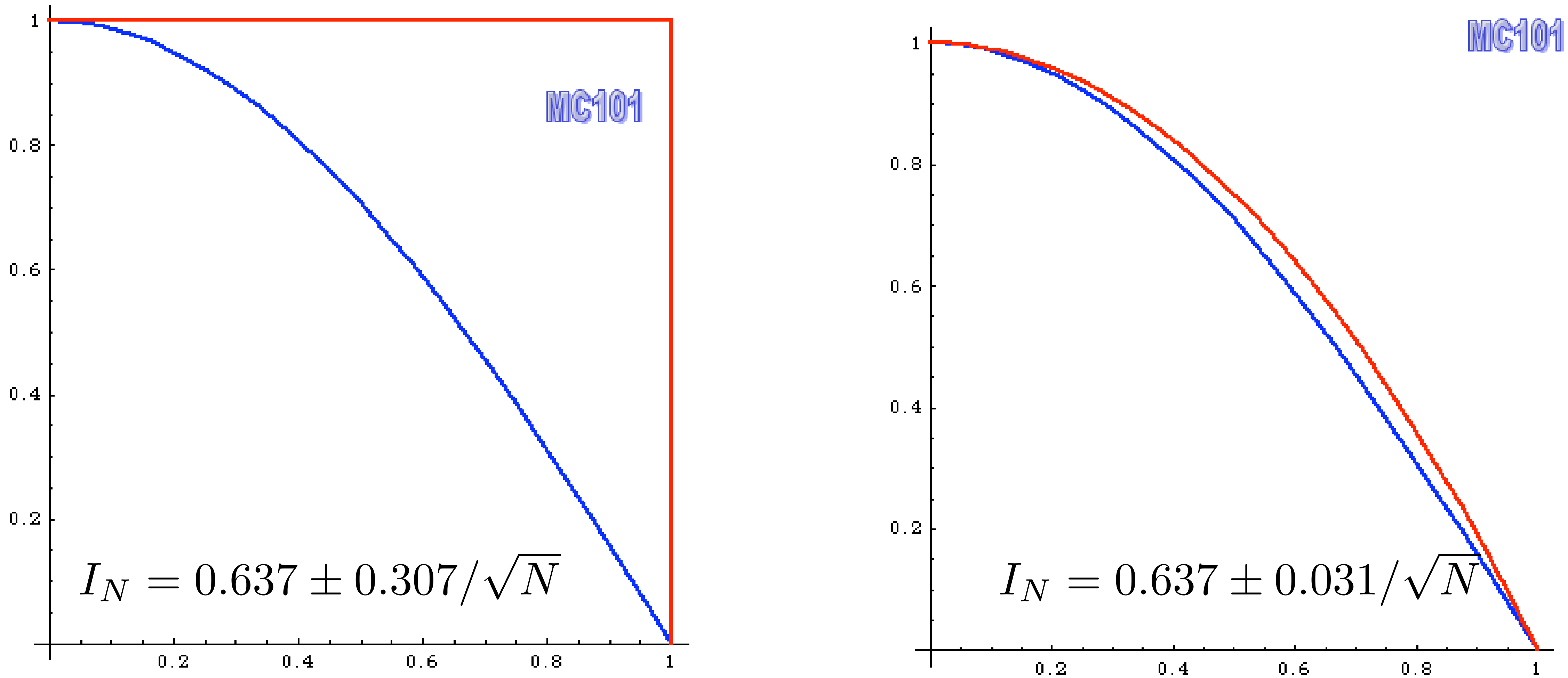


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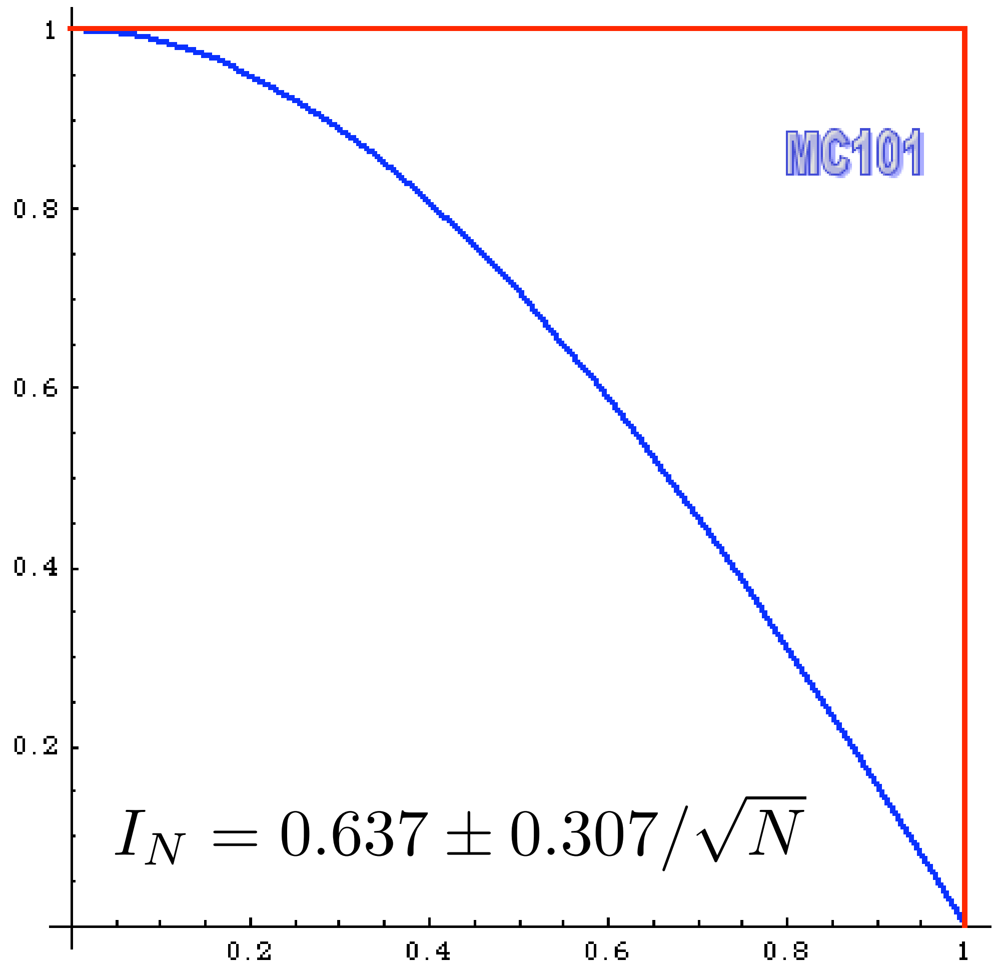


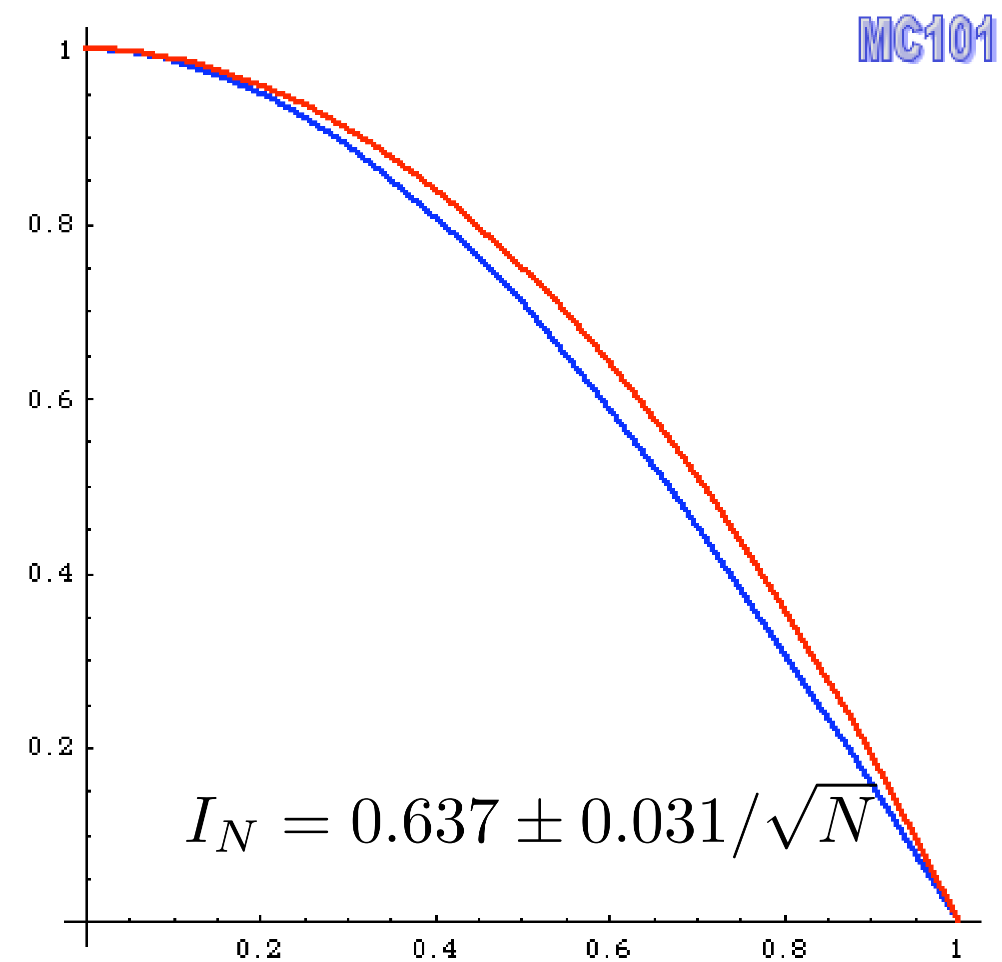


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$$= \int_{\xi_1}^{\xi_2} d\xi \frac{\cos\frac{\pi}{2}x[\xi]}{1-x[\xi]^2}$$

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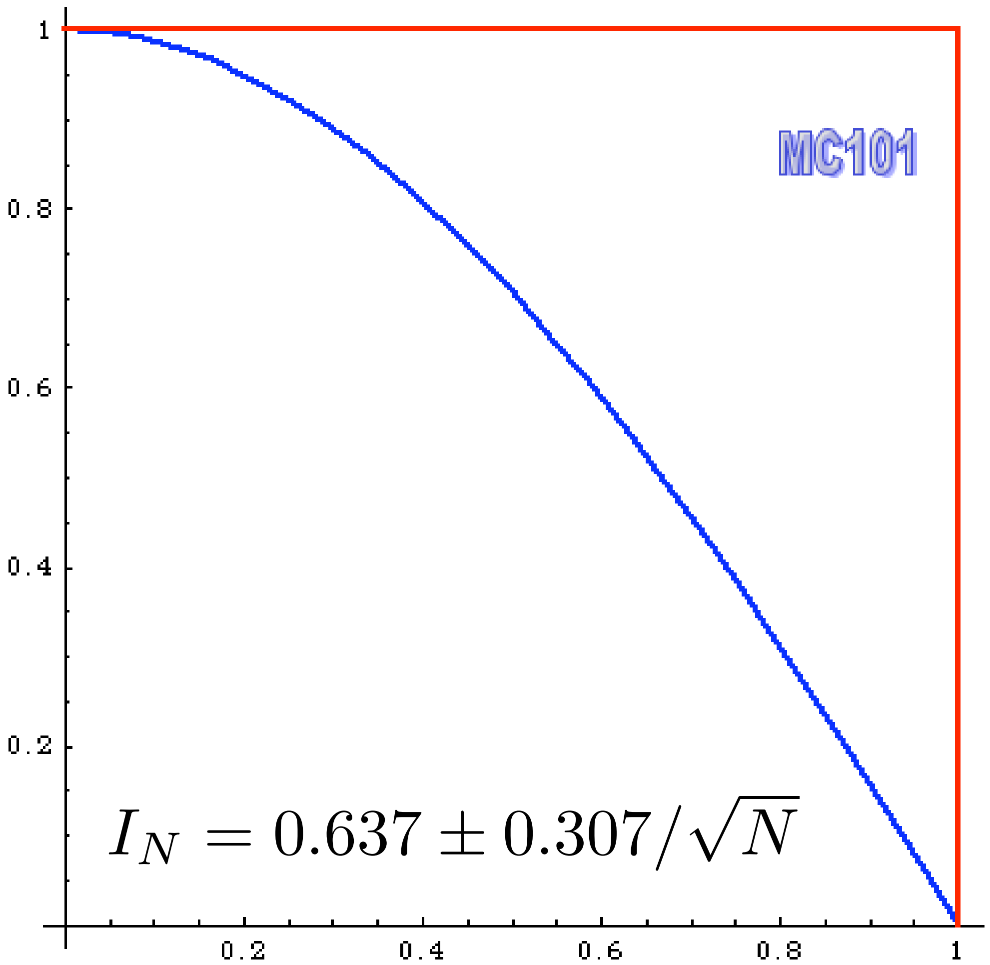


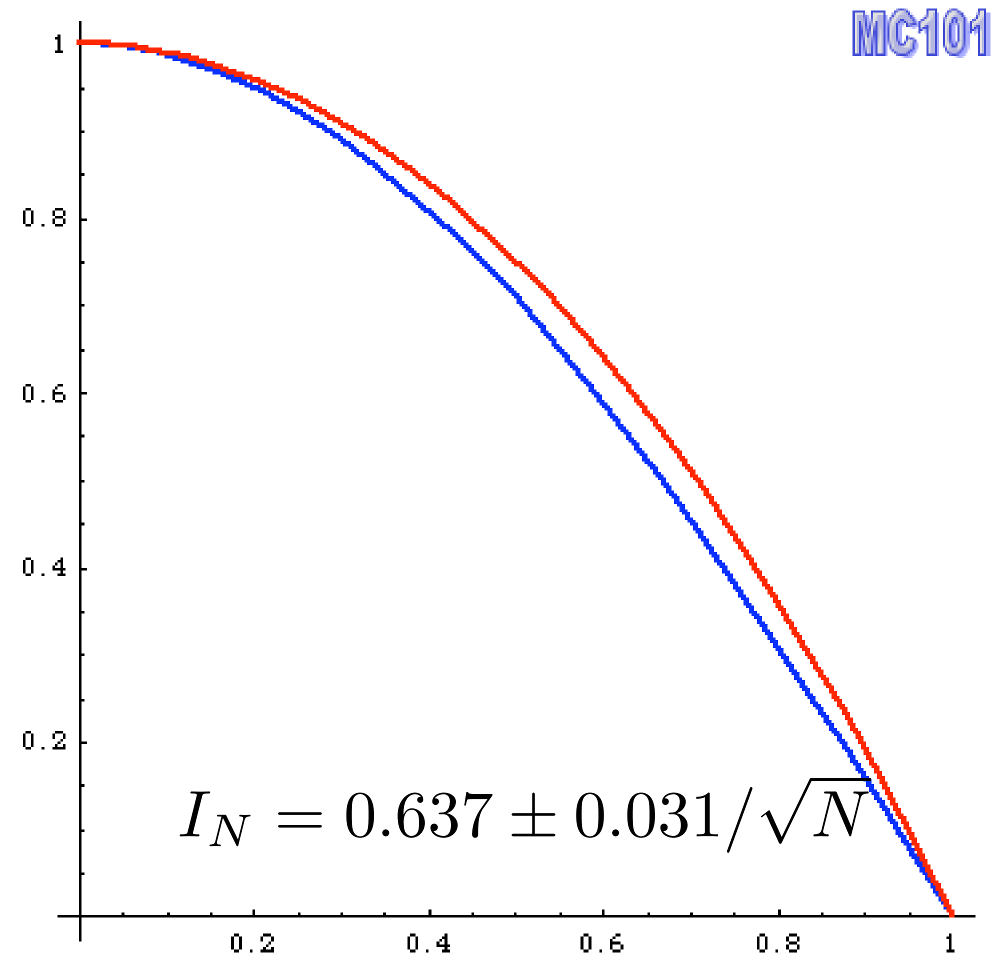


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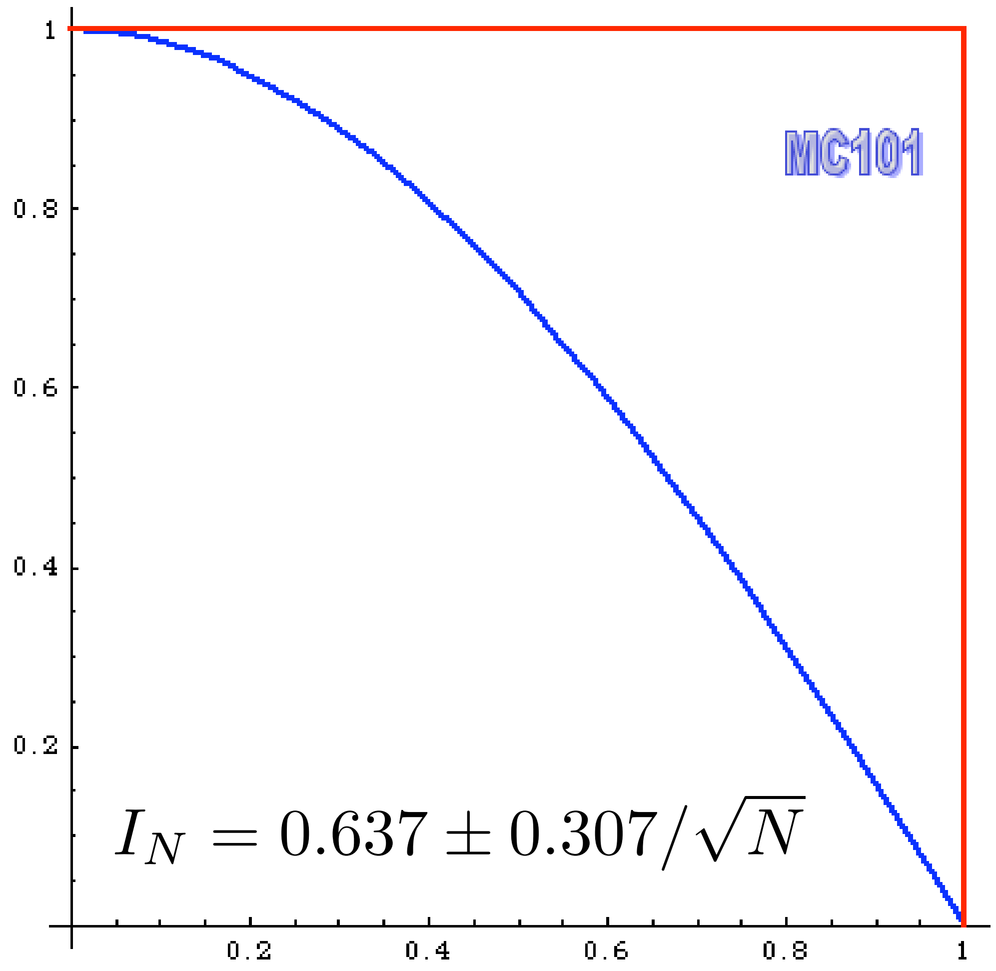
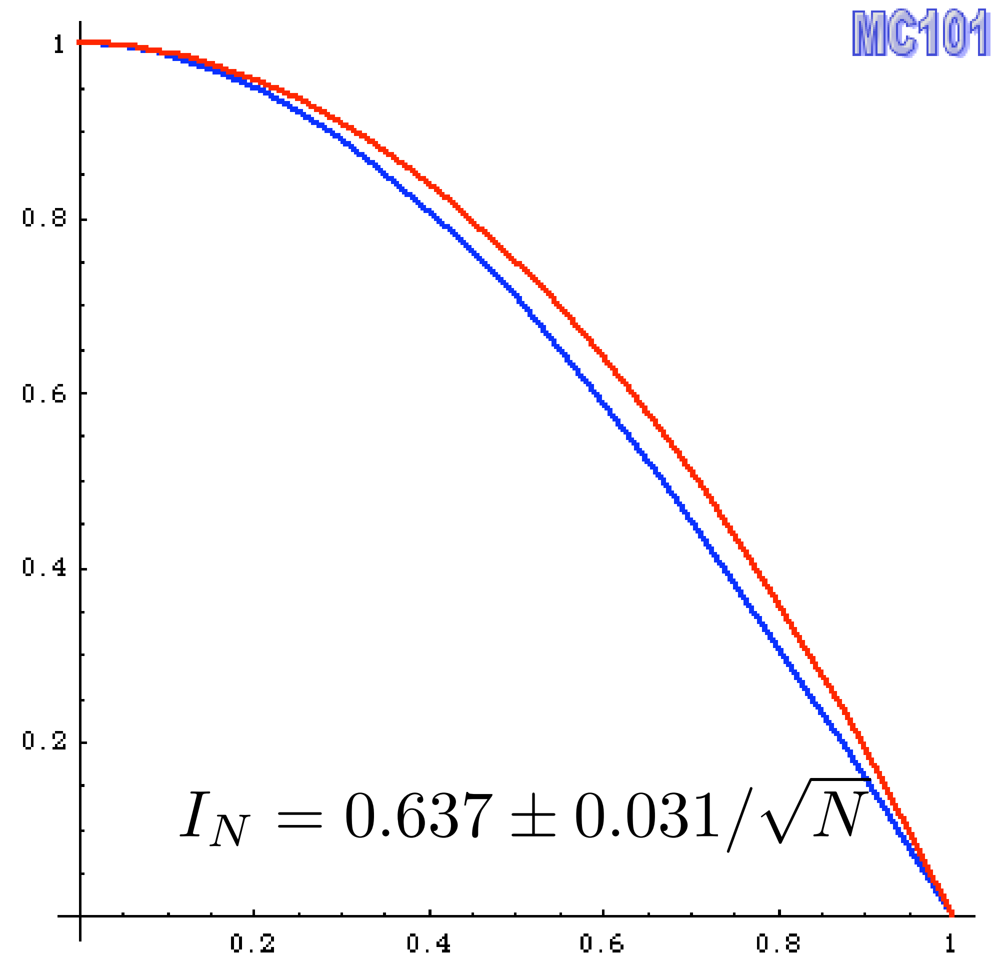
# Importance Sampling

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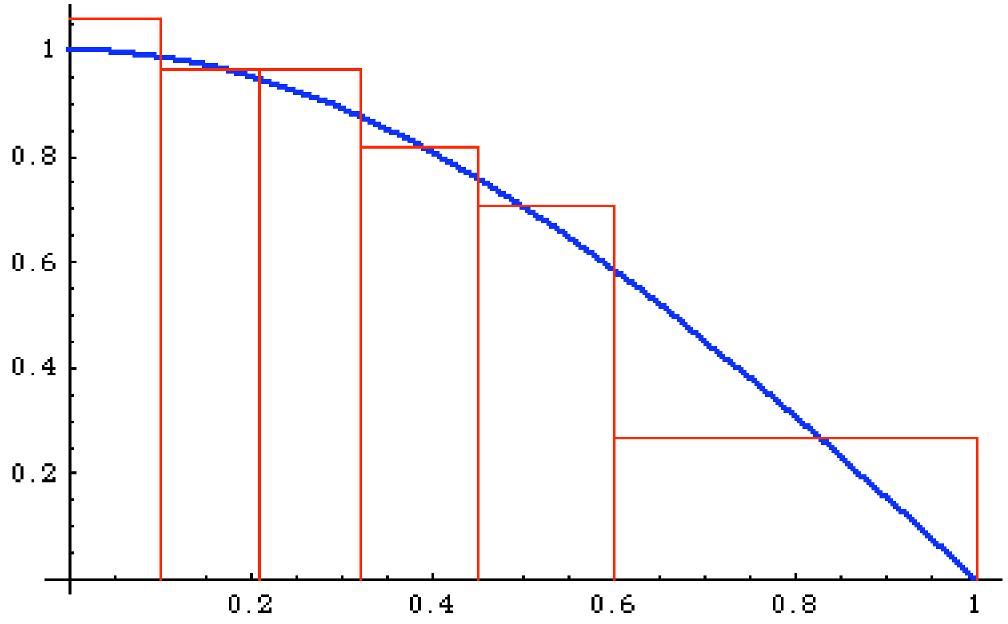
MC101



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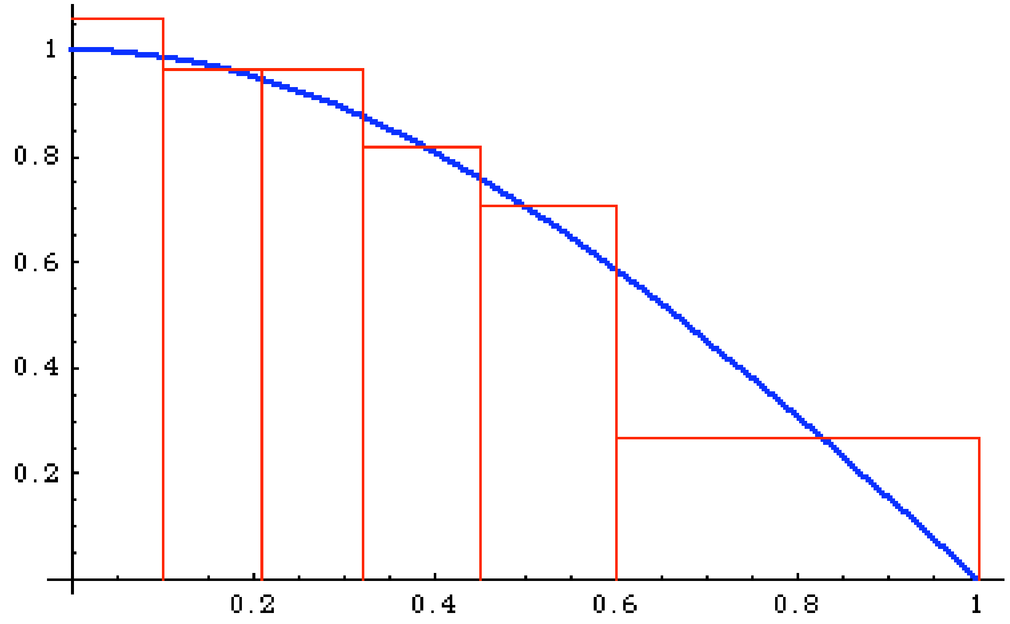


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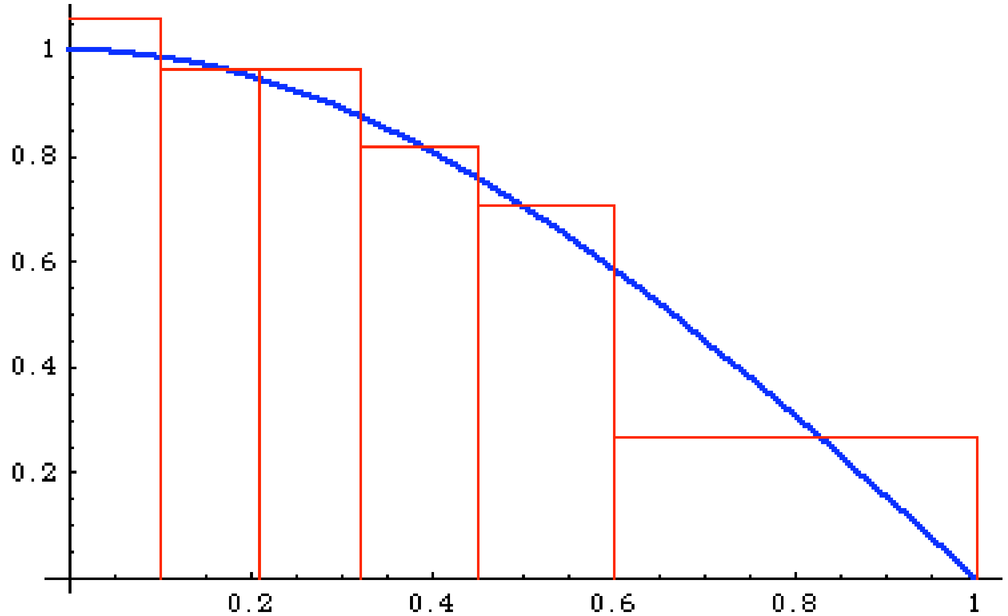


many bins where f(x) is large

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

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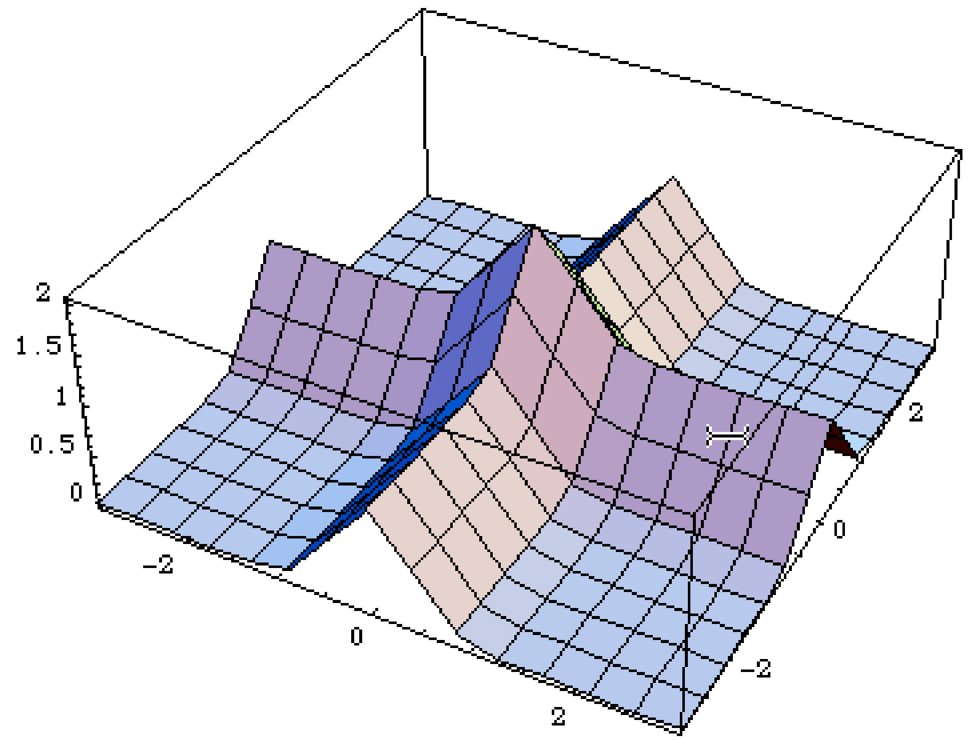


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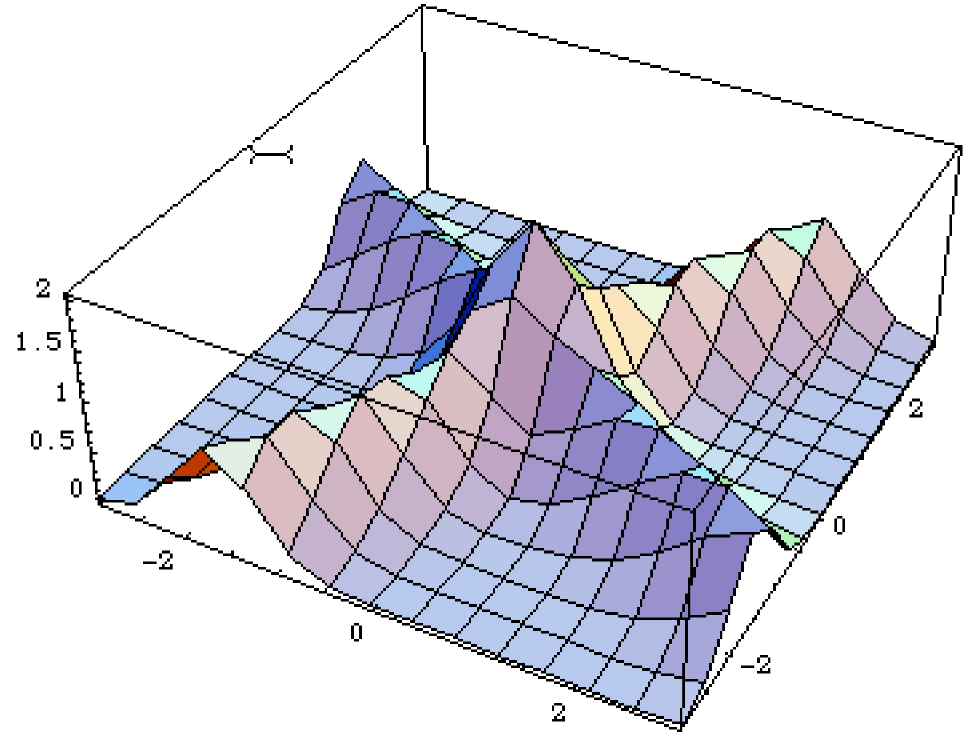


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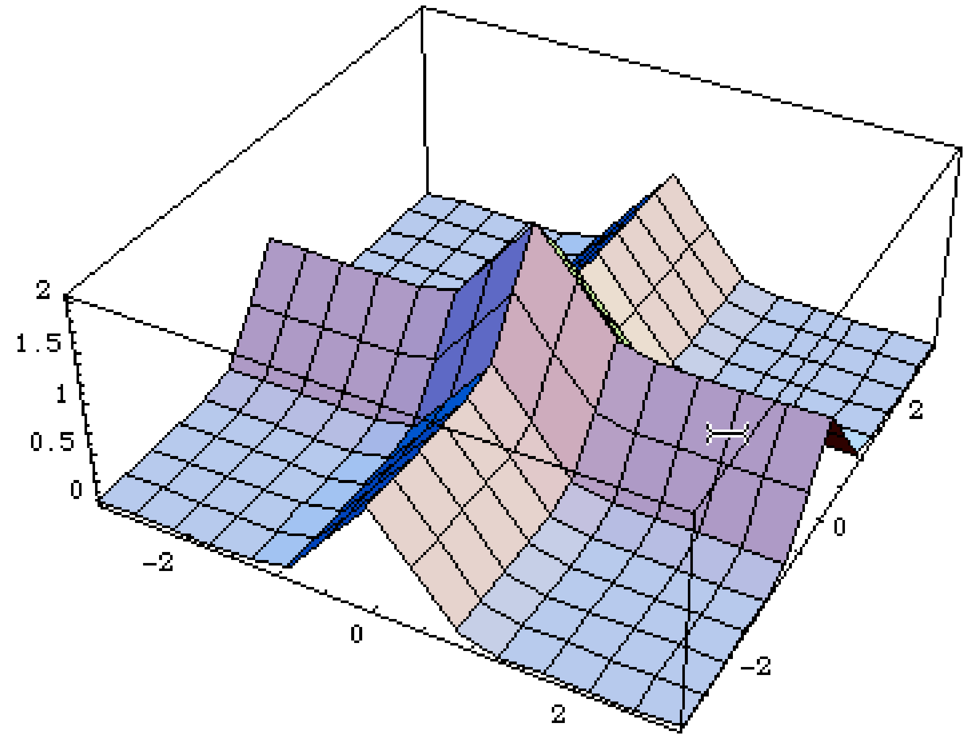


but it is sufficient to make a change of variables!

# Multi-channel

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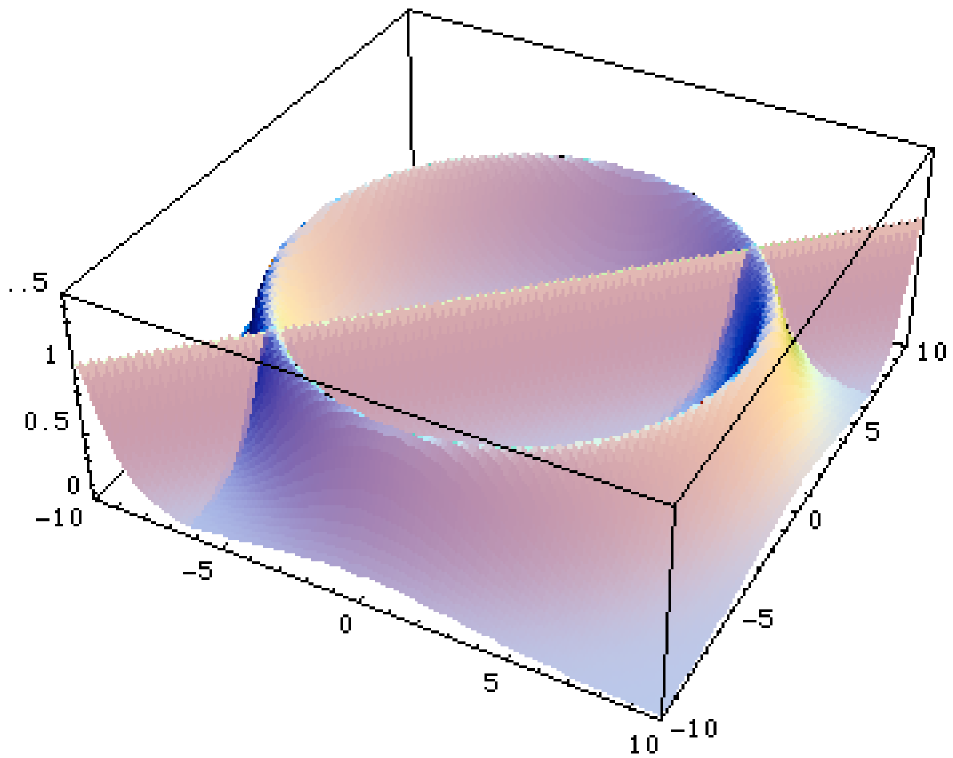

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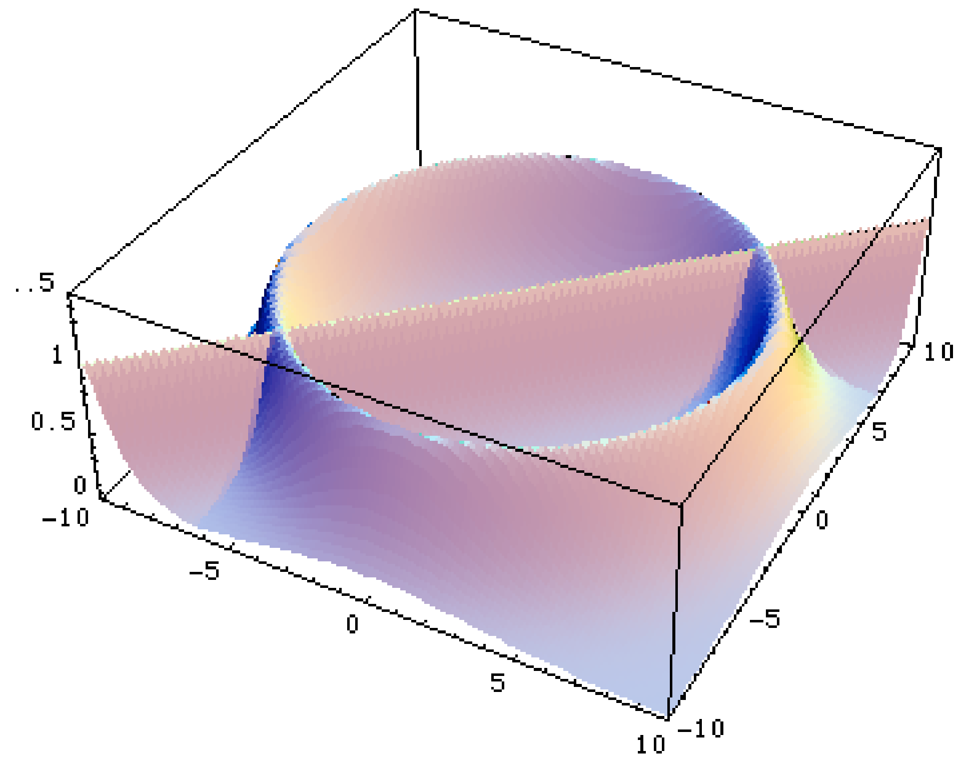


In this case there is no unique tranformation: Vegas is bound to fail!

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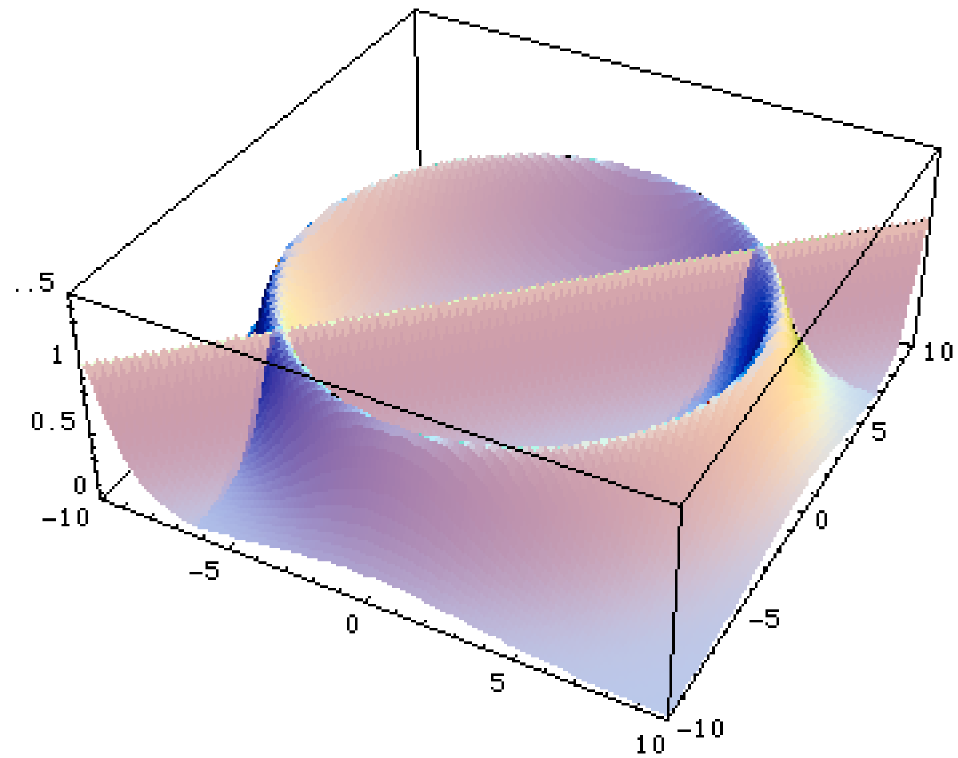


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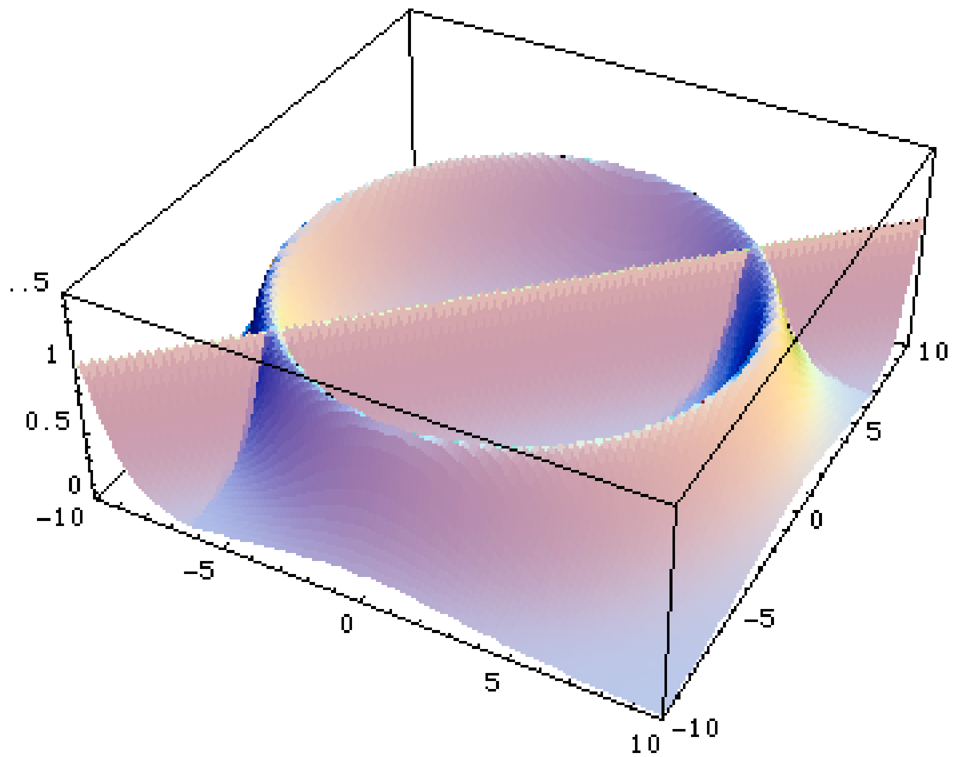
Solution: use different transformations= channels

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

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

# Multi-channel

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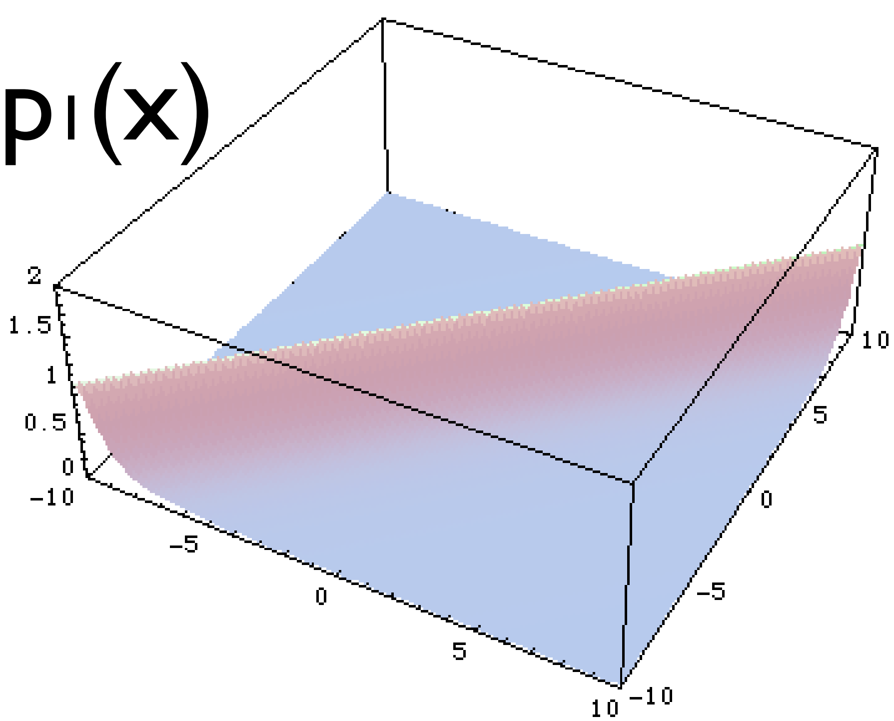
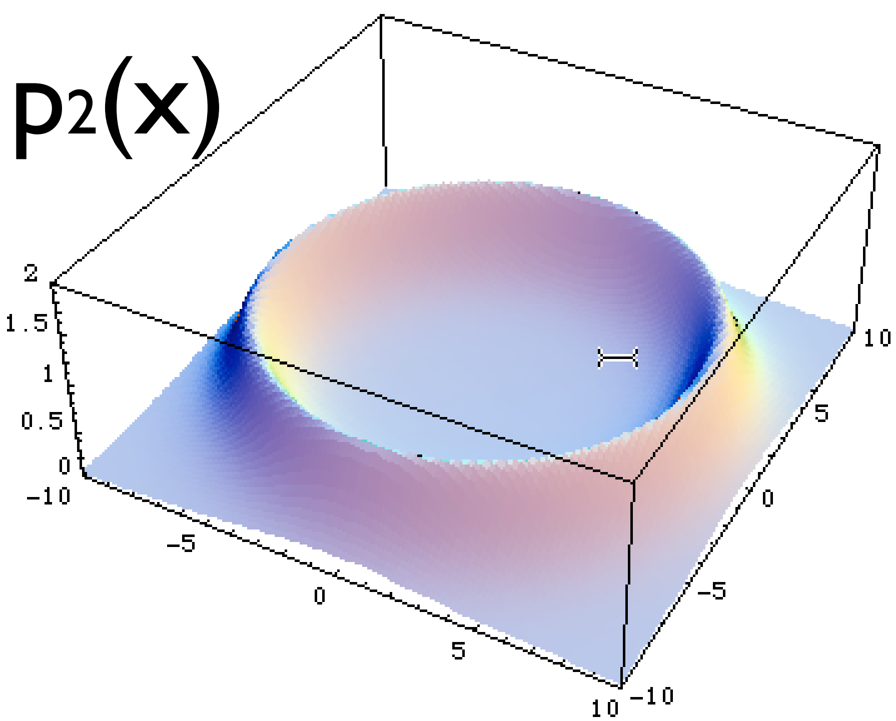
$p_1(x)$




$p_2(x)$



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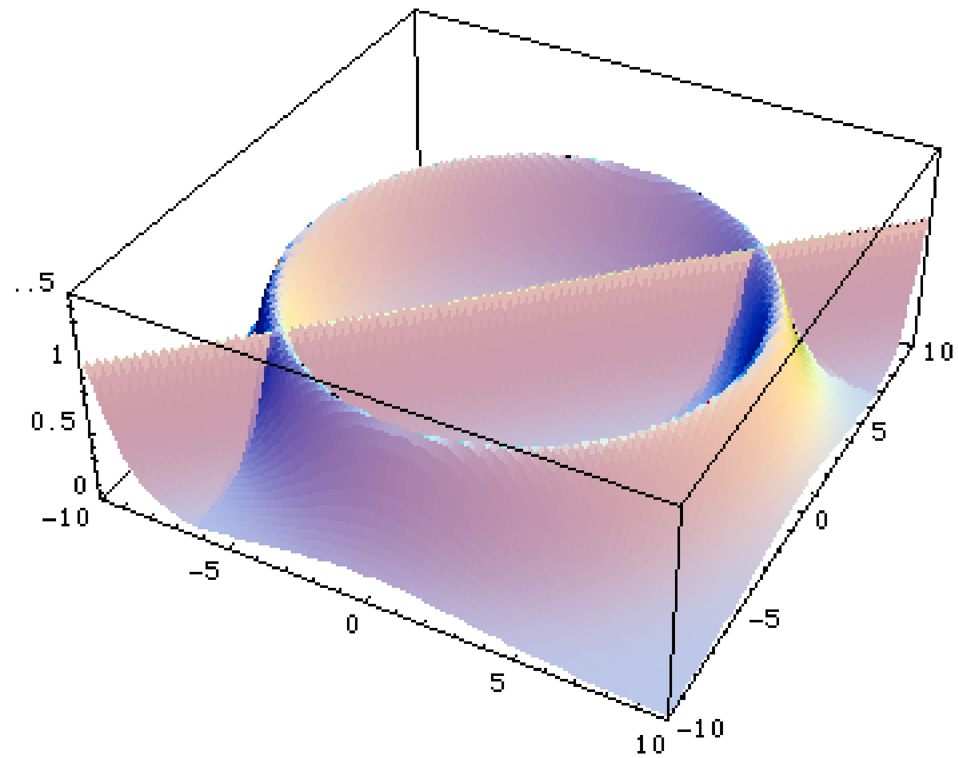


In this case there is no unique tranformation: Vegas is bound to fail!

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

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

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

# Multi-channel

- Advantages
  - The integral does not depend on the $\alpha_i$ but the variance does and can be minimised by a careful choice
- Drawbacks
  - Need to calculate all $g_i$ values for each point
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Very popular method!

# Multi-channel based on single diagrams

Consider the integration of an amplitude |M|^2 at treel level which lots of diagrams contribute to. 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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Does such a basis exist? YES!

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

# Multi-channel based on single diagrams*

- Key Idea
  - Any single diagram is "easy" to integrate
  - Divide integration into pieces, based on diagrams
- Get N independent integrals
  - Errors add in quadrature so no extra cost
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*Method used in MadGraph

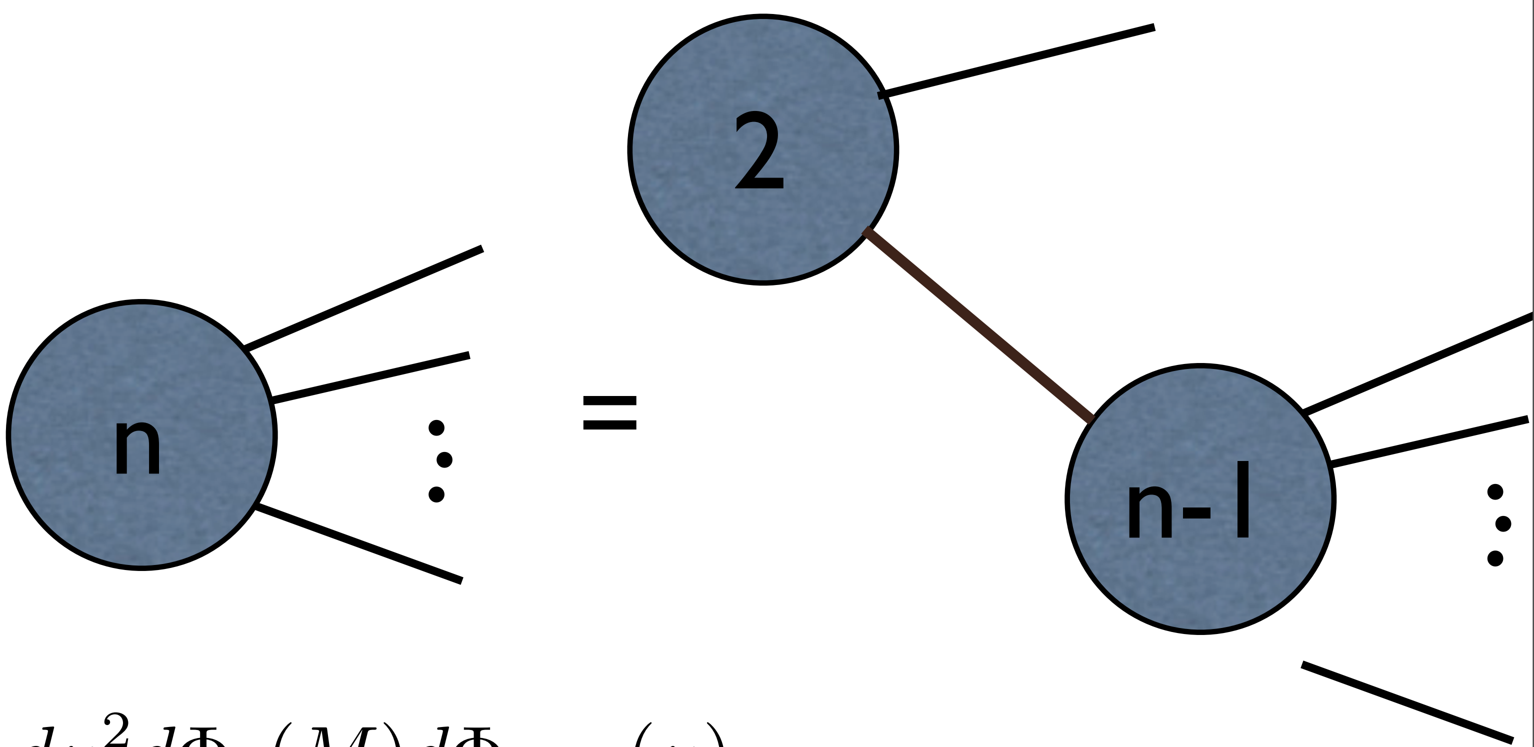
# Phase Space

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

Several methods exist to parametrize the phase space for n final state particles:

1. Basic recursive approach:

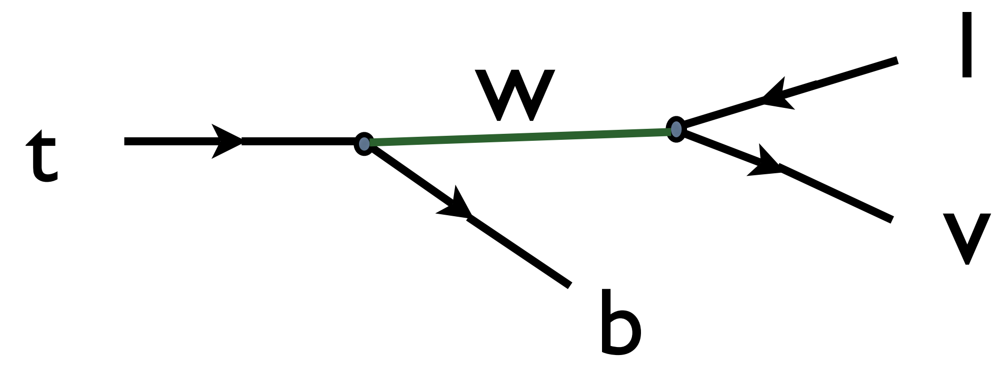
$$d\Phi_2(M) = \frac{1}{8\pi} \frac{2p}{M} \frac{d\Omega}{4\pi}$$



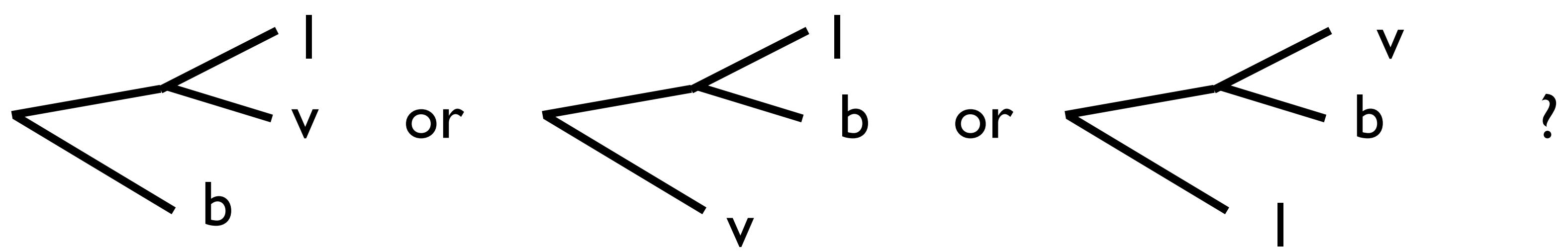

$$d\Phi_n(M) = \frac{1}{2\pi} \int_0^{(M-\mu)^2} d\mu^2 d\Phi_2(M) d\Phi_{n-1}(\mu)$$

t-channel topologies can be added. Suitable for mapping to general Feynman diagrams. Used in most of the multipurpose MC's. [Bycling and Kajante, 1973]

# Exercise: top decay




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



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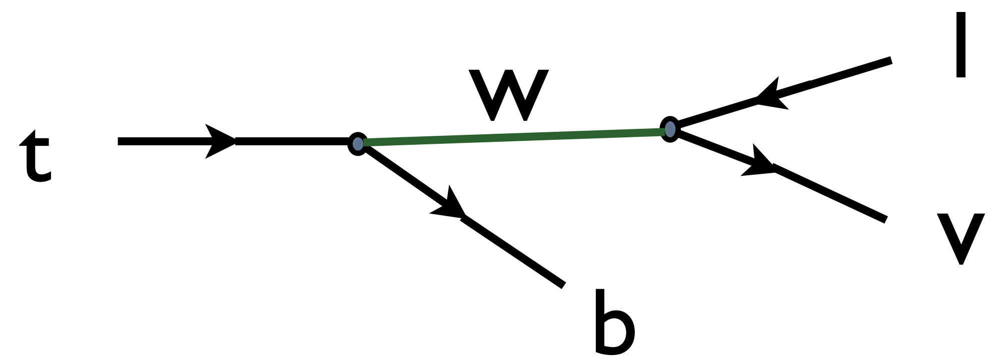
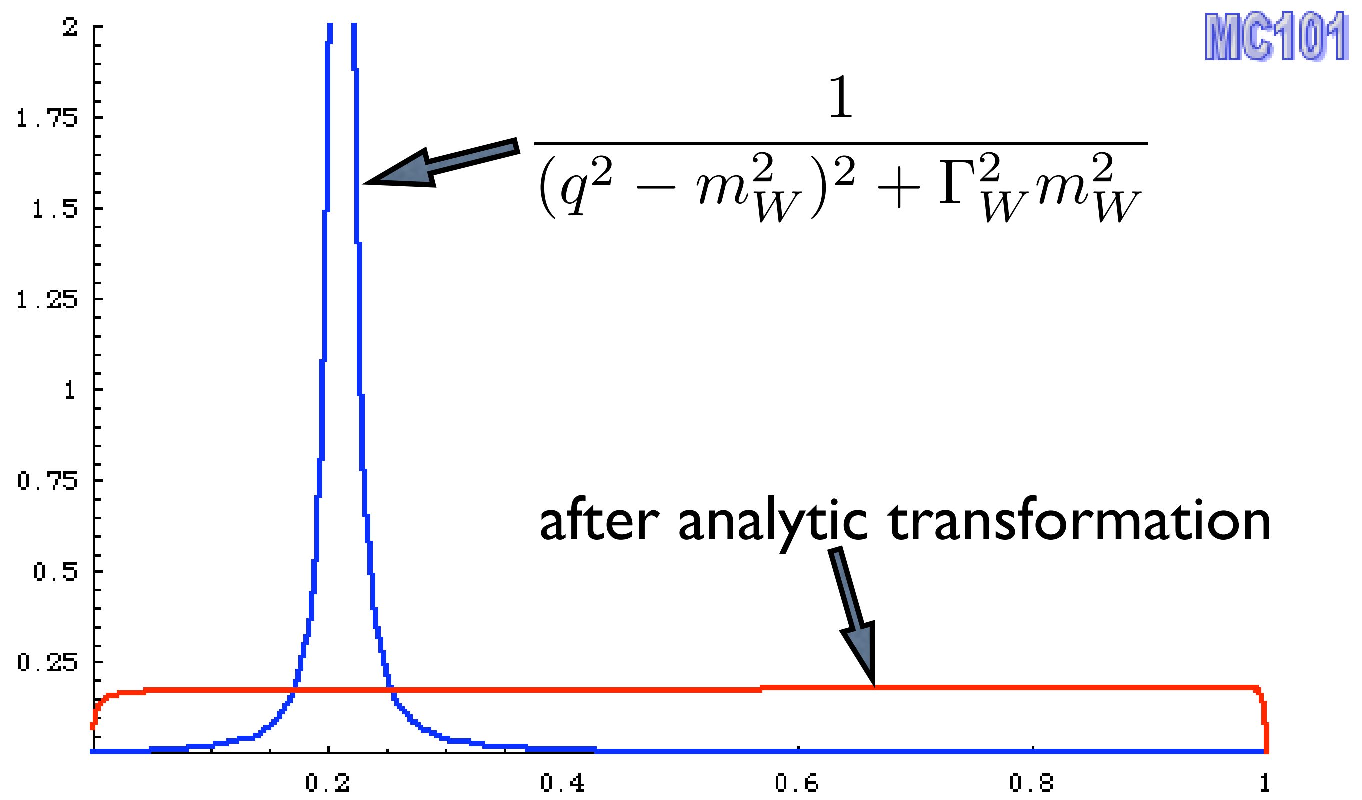
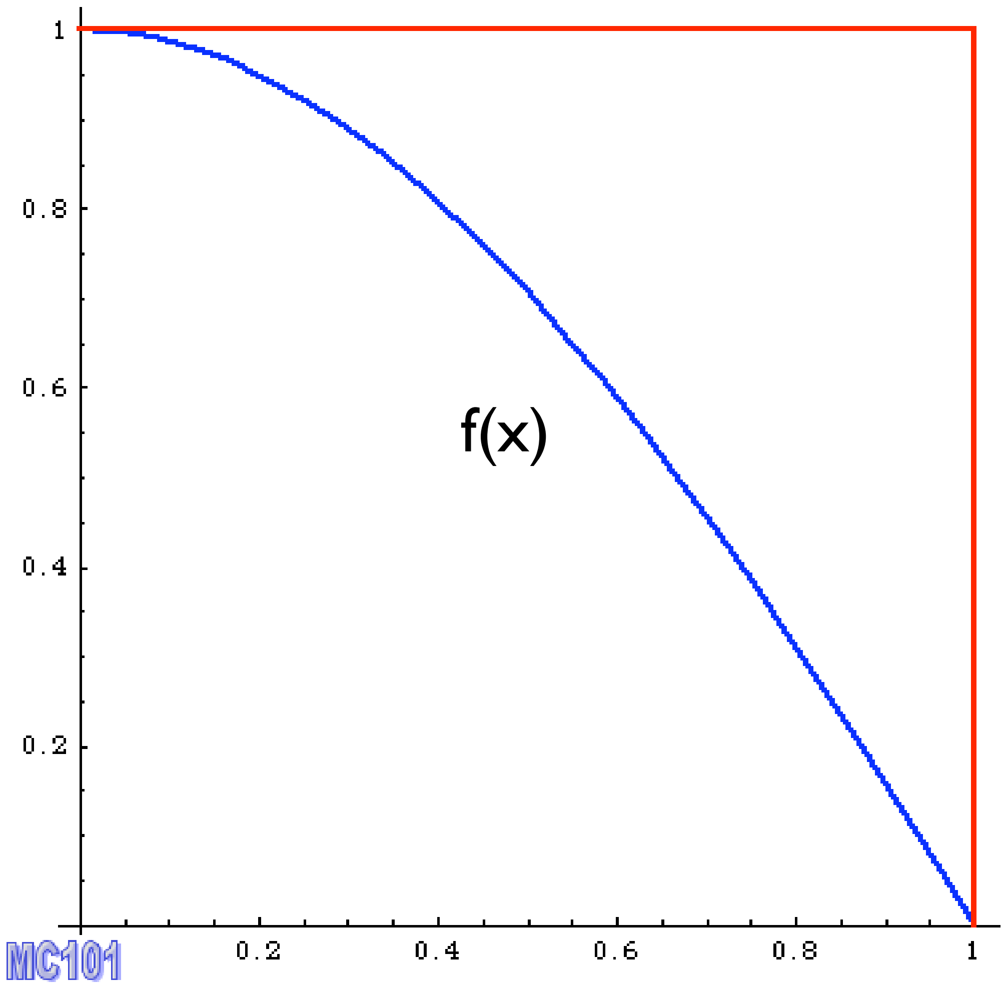


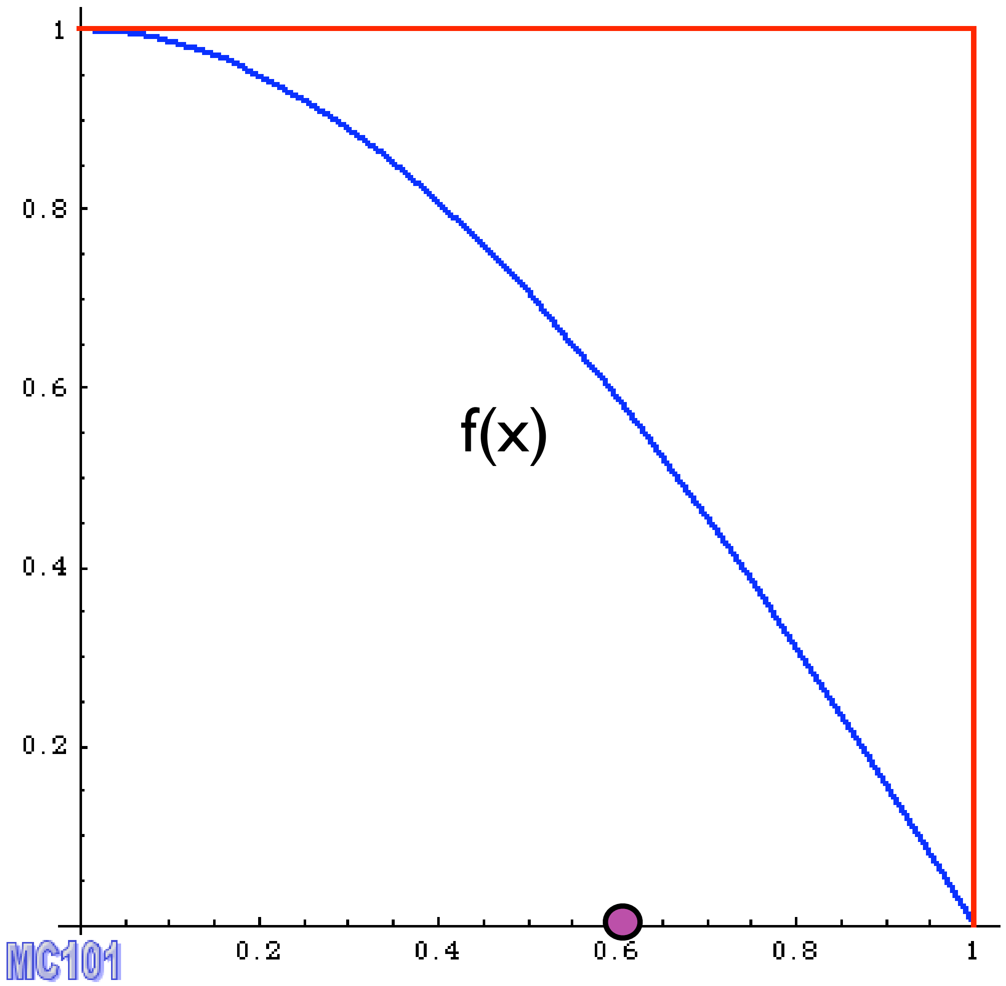



# Event generation




Alternative way

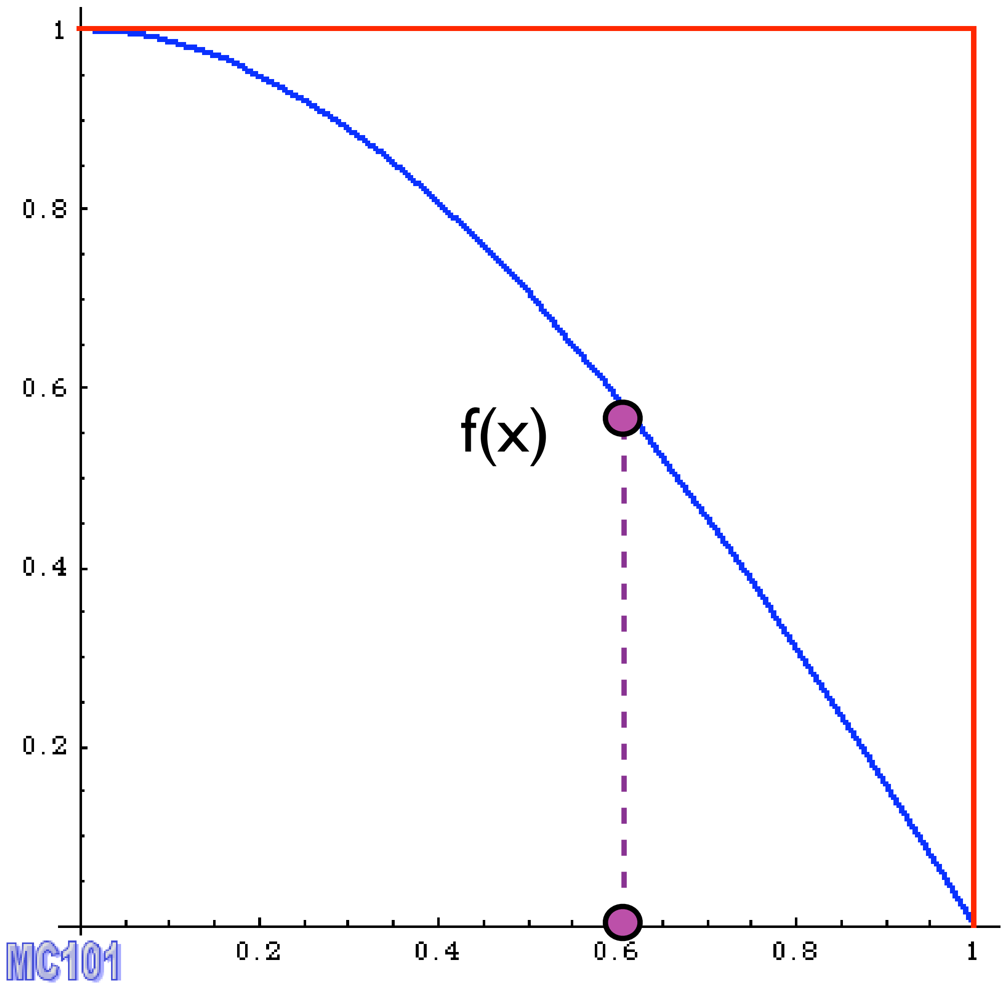
# Event generation




Alternative way

1. pick x

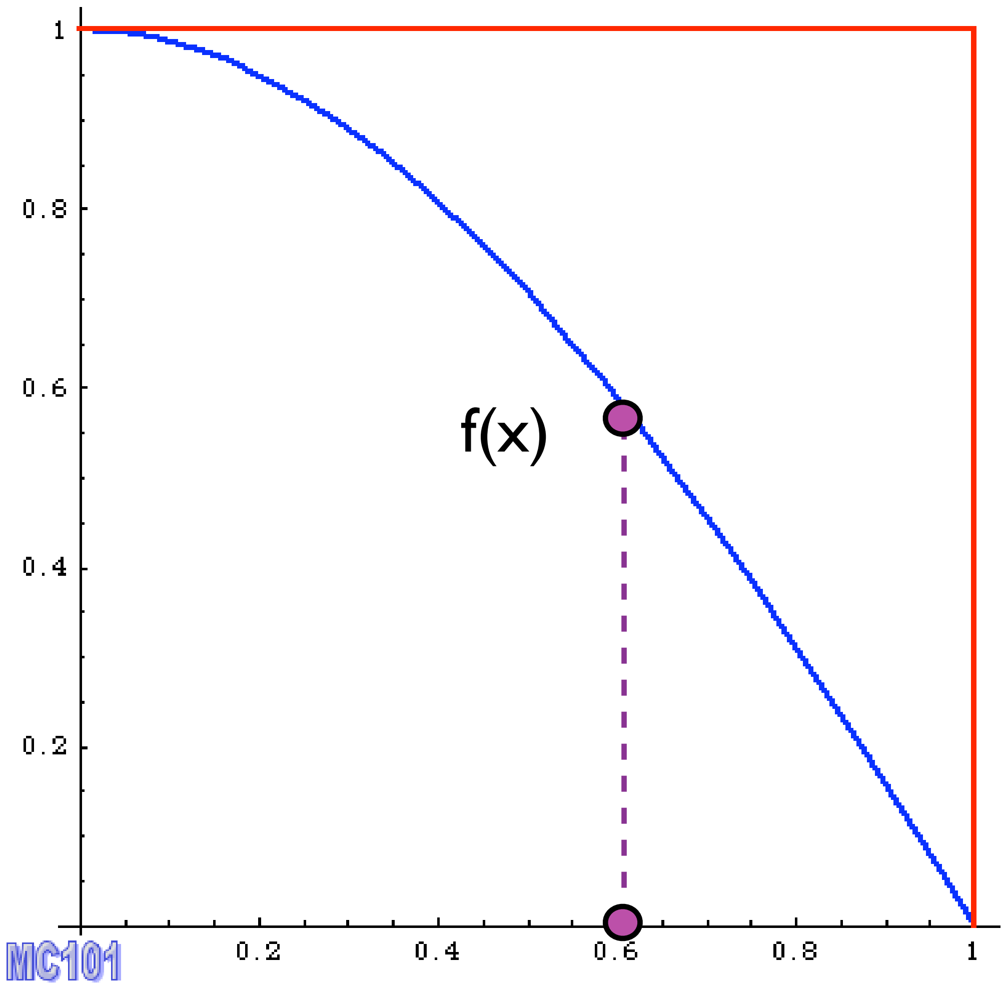
# Event generation




Alternative way

1. pick x
2. calculate f(x)

# Event generation




Alternative way

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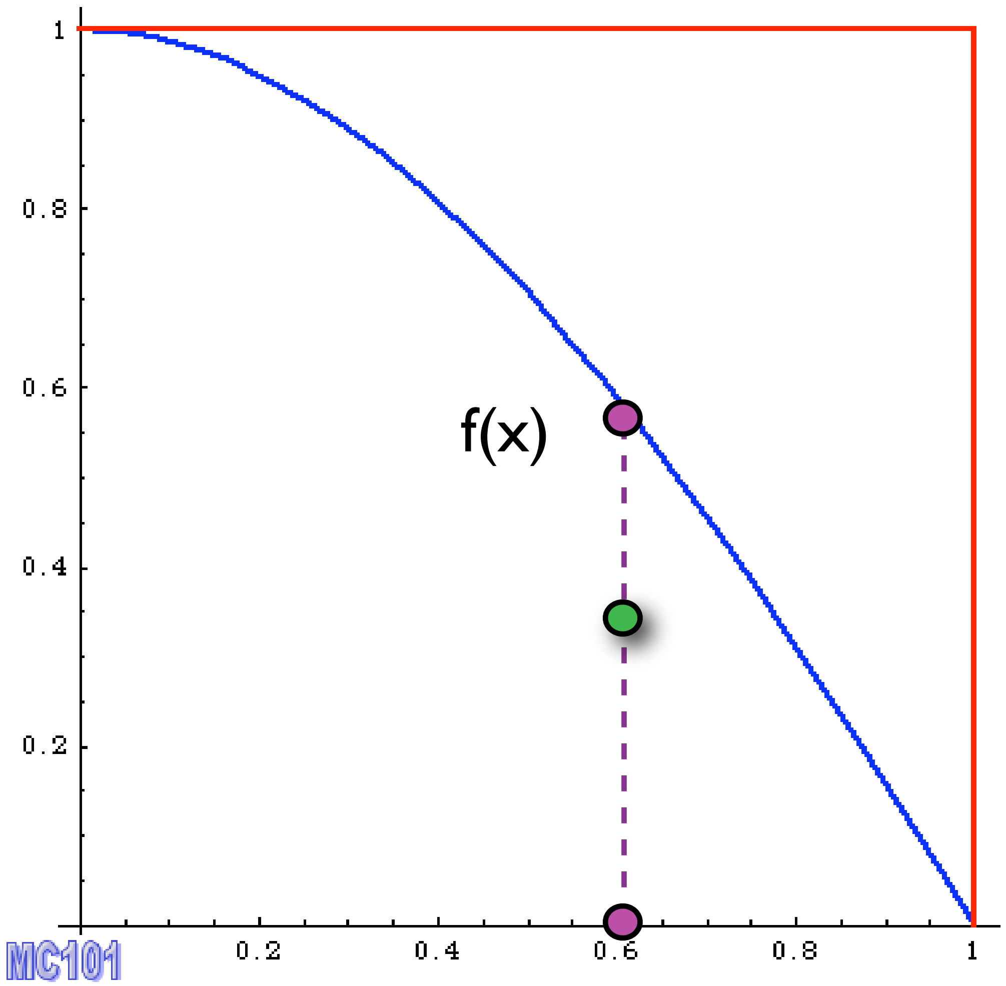


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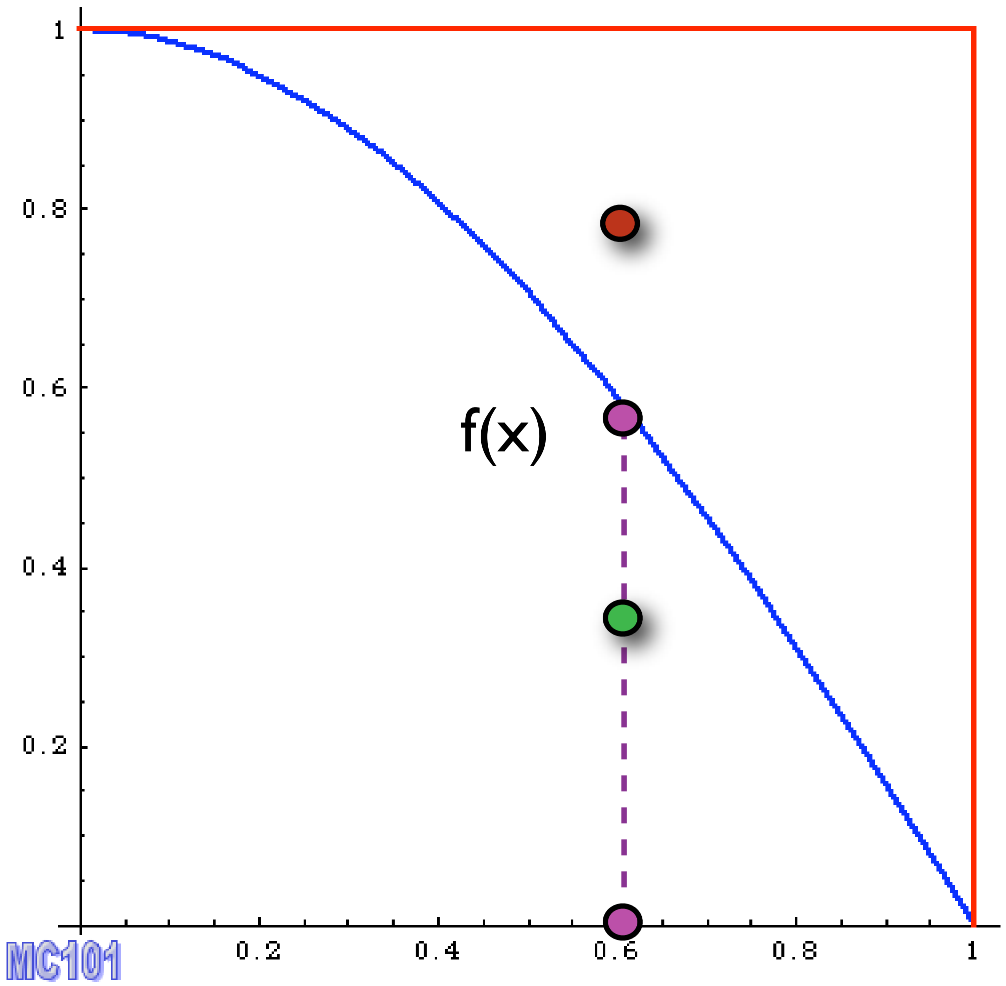


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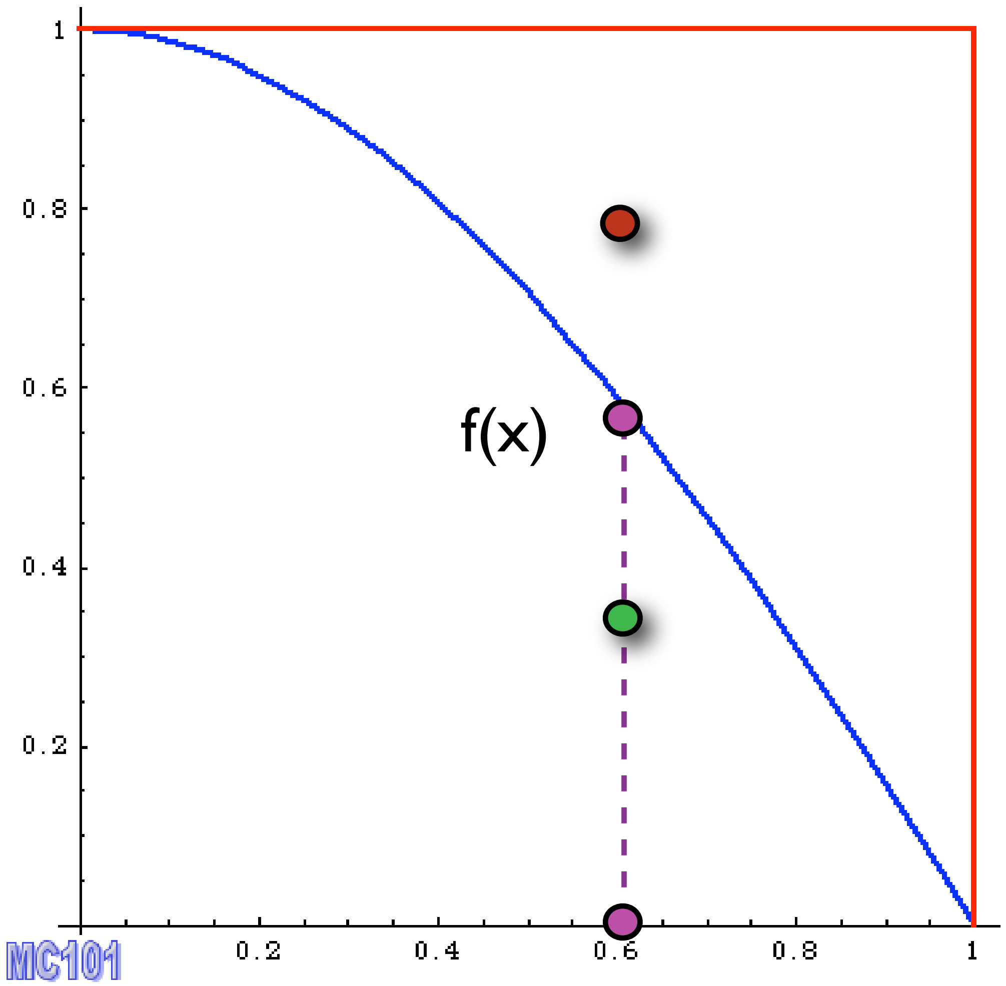


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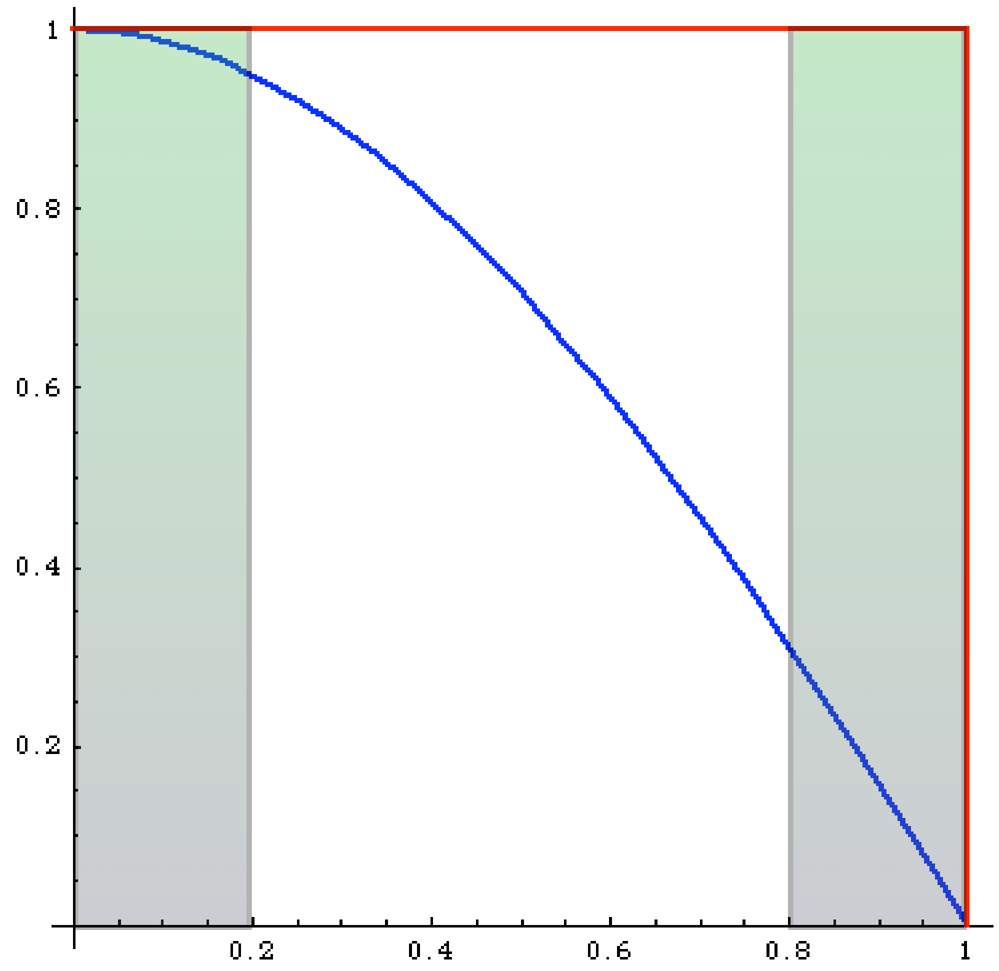
$$I = \frac{\text{accepted}}{\text{total tries}} = \text{efficiency}$$

# Event generation

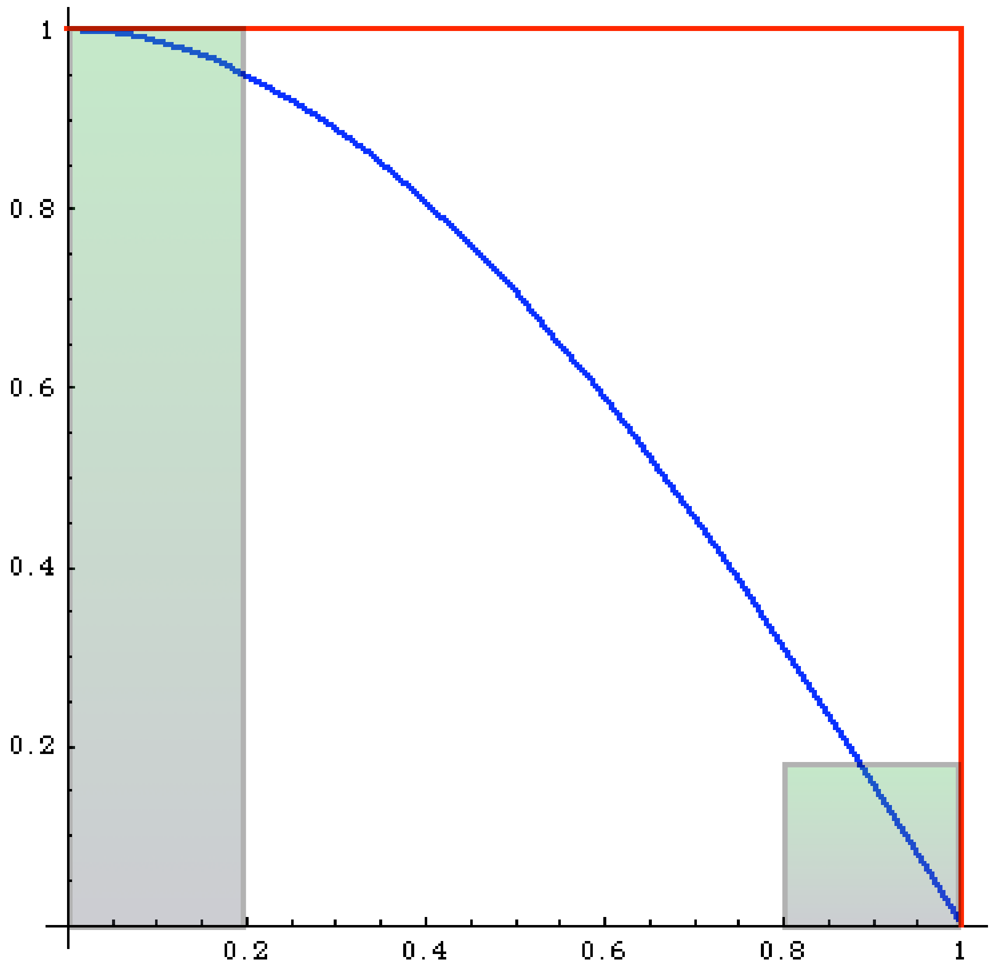



What's the difference?

before:

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

# Event generation



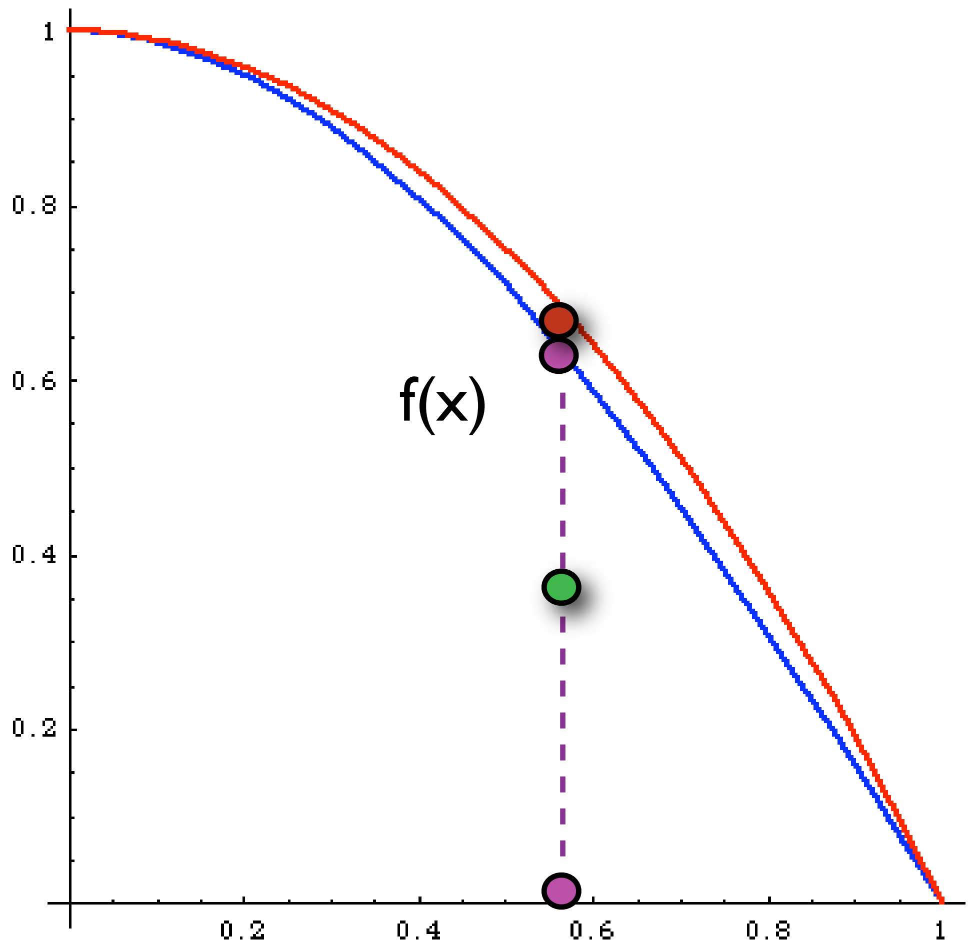

What's the difference?

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

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

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MC integrator

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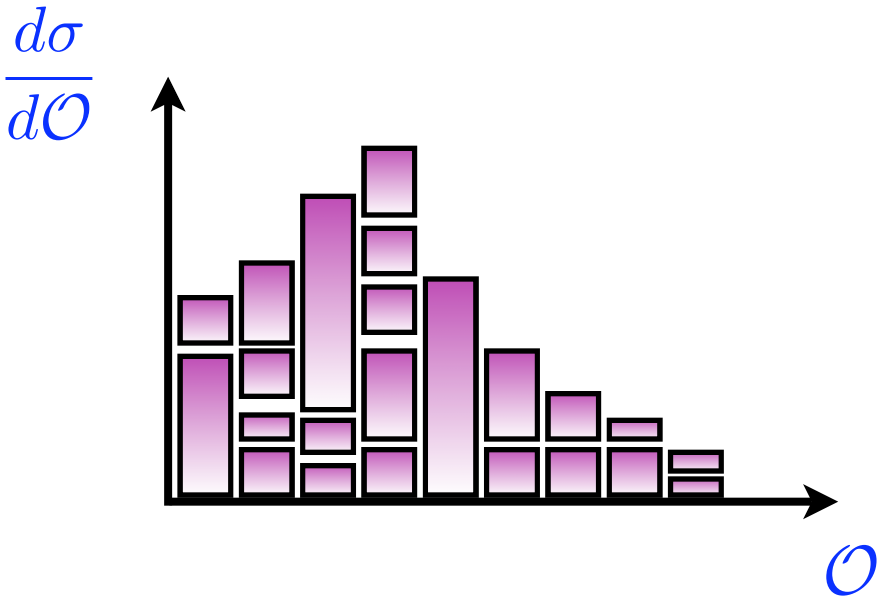

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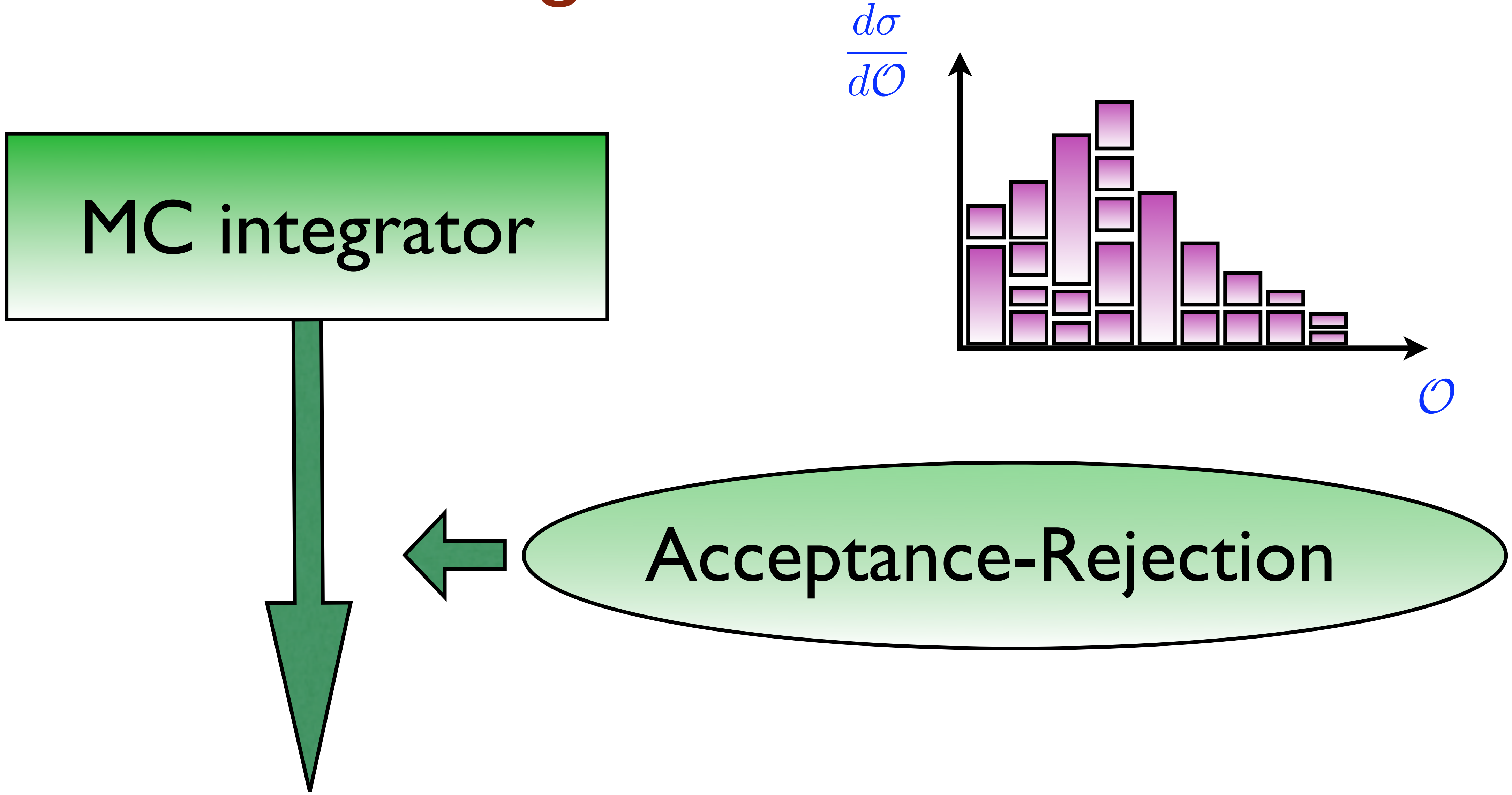

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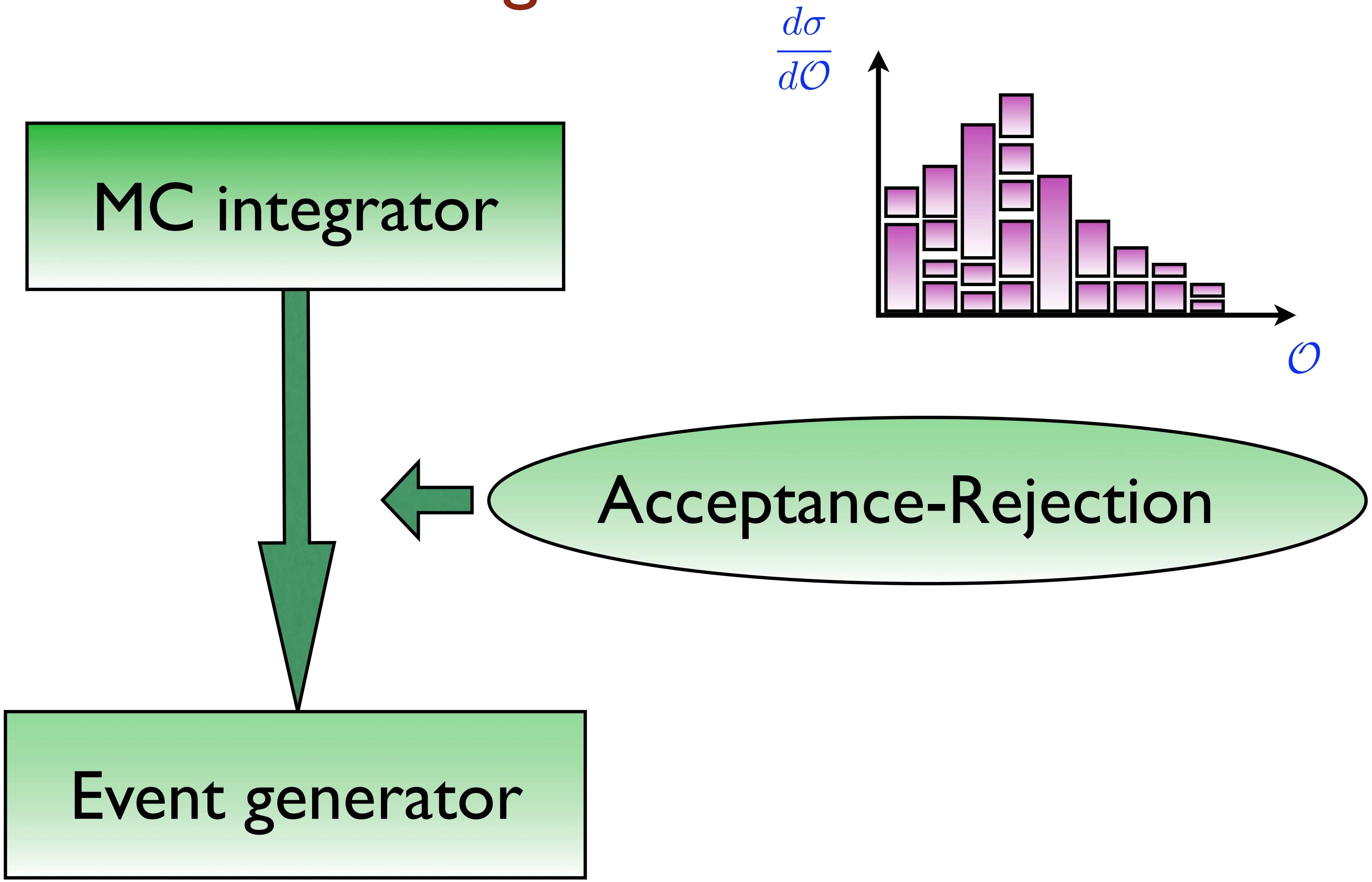

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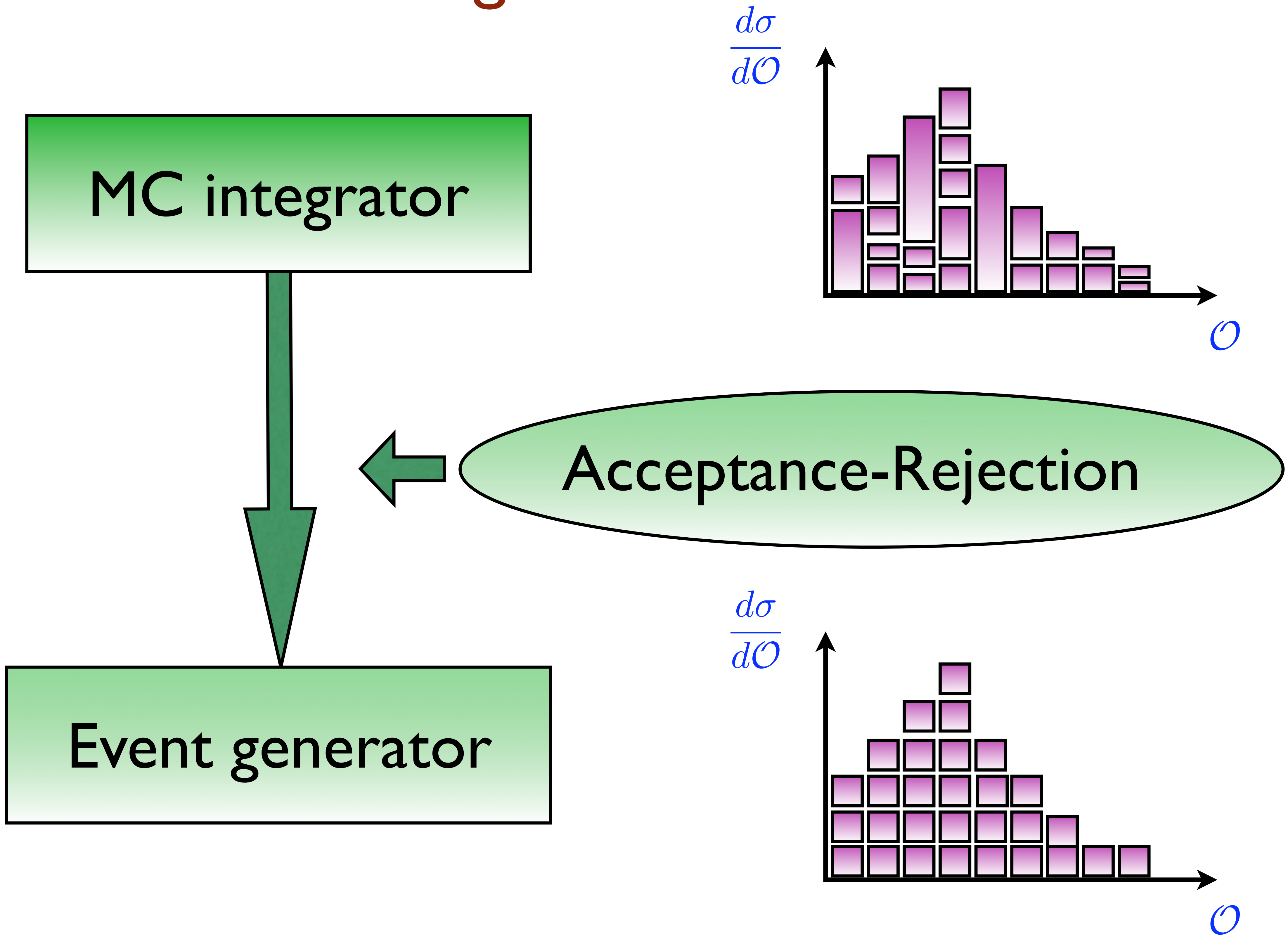

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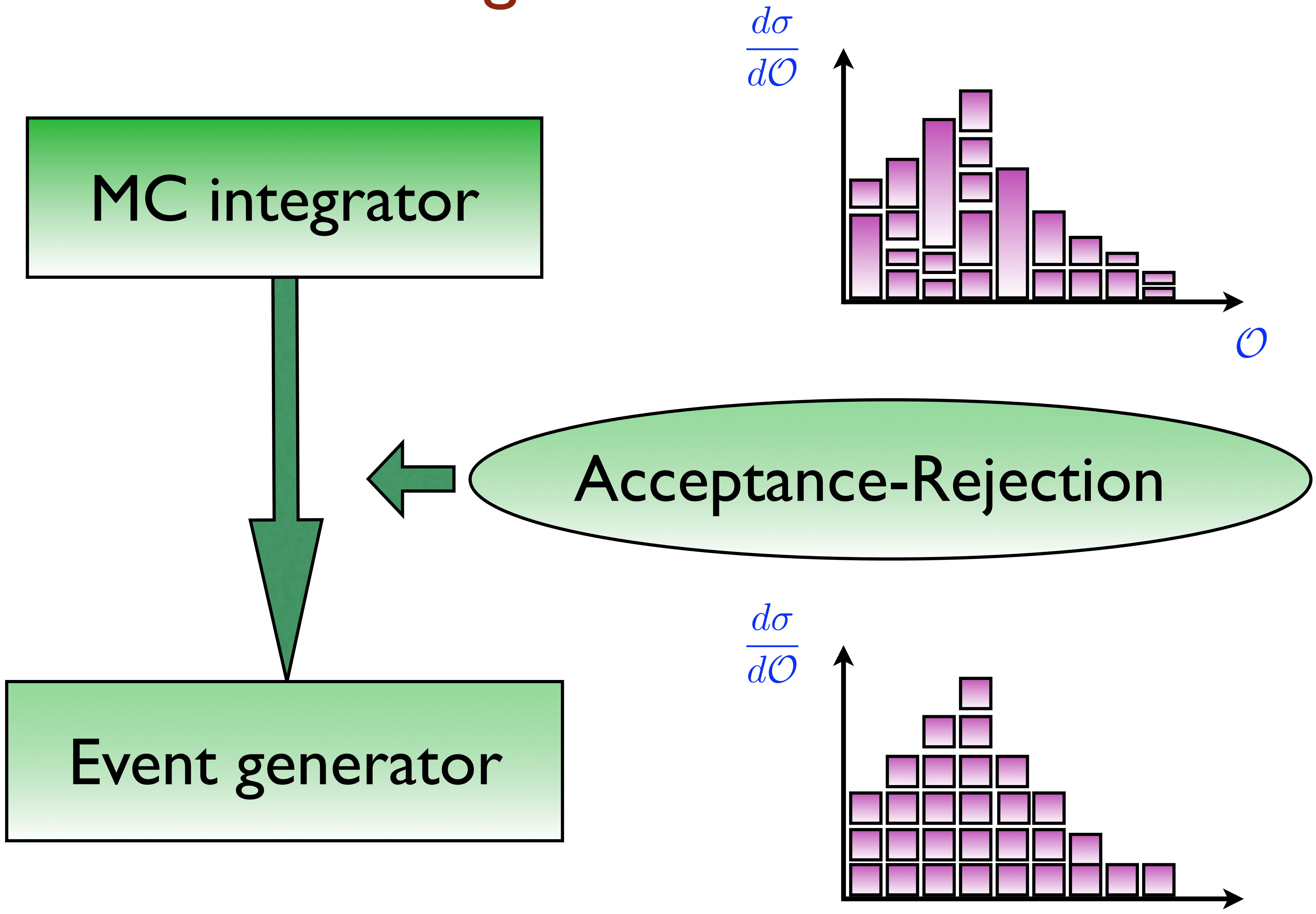


☞ This is possible only if f(x)<∞ AND has definite sign!

#1

A MC generator produces “unweighted” events , i.e., events distributed as in Nature.

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True

# 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 unweights to give the four momenta of the particles that interact with the detector (simulation).

Note that, at least among theorists, the definition of a "Monte Carlo program" also includes codes which don't provide a fully exclusive information on the final state but only cross sections or distributions at the parton level, even when no unweighting can be performed. I will refer to these kind of codes as "MC integrators".

# A simple plan

- Physics challenges at the LHC
- Basics : QCD and MC's methods
- The new generation of MC tools
- New simulations for New Physics

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# LO : the technical challenges

How do we calculate a LO cross section for 3 jets at the LHC?

I. Identify all subprocesses (gg→ggg, qg→qgg....) in

$$\sigma(pp \to 3j) = \sum_{ijk} \int f_i(x_1) f_j(x_2) \hat{\sigma}(ij \to k_1 k_2 k_3)$$

easy

II. For each one, calculate the amplitude:

$$\mathcal{A}(\{p\},\{h\},\{c\}) = \sum_i D_i$$

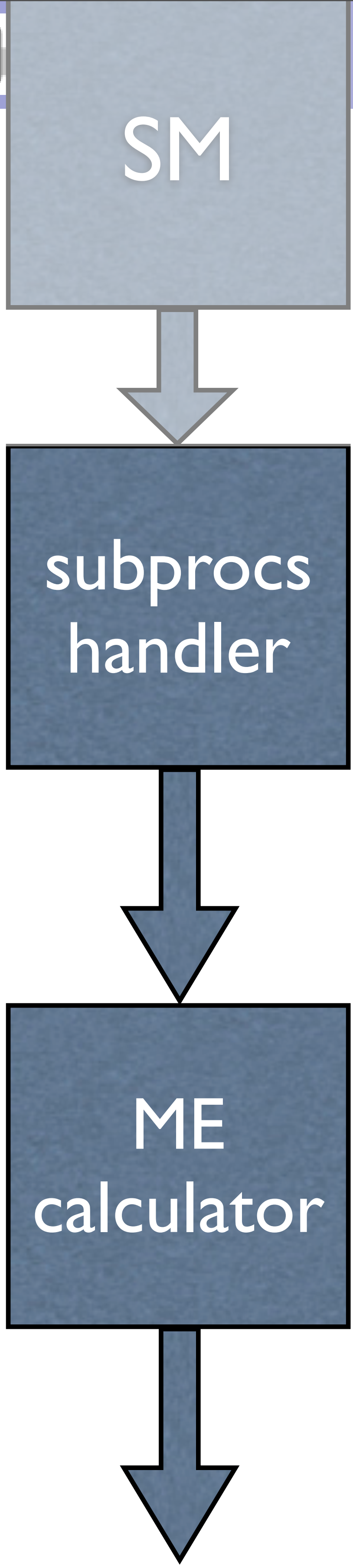
difficult

III. Square the amplitude, sum over spins & color, integrate over the phase space (D ~ 3n)

$$\hat{\sigma} = \frac{1}{2\hat{s}} \int d\Phi_p \sum_{h,c} |\mathcal{A}|^2$$

very hard

# General structure

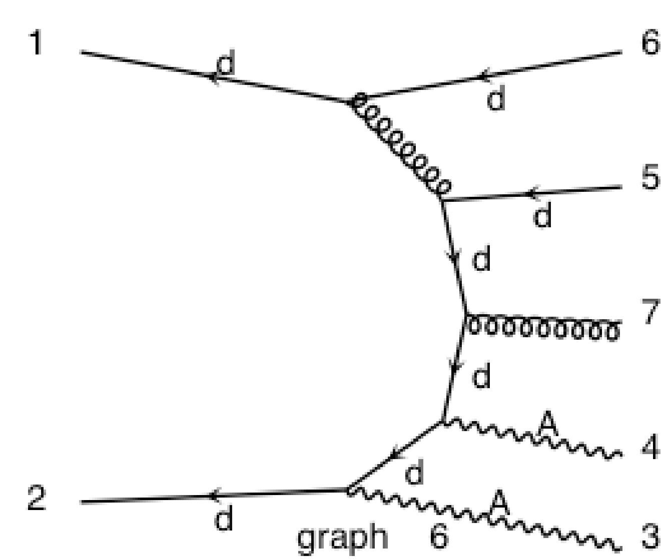



Includes all possible subprocess leading to a given multi-jet final state automatically or manually (done once for all)

d~ d -> a a u u~ g
d~ d -> a a c c~ g
s~ s -> a a u u~ g
s~ s -> a a c c~ g

<u>"Automatically"</u> generates a code to calculate |M|^2 for arbitrary processes with many partons in the final state.

Most use Feynman diagrams w/ tricks to reduce the factorial growth, others have recursive relations to reduce the complexity to exponential. ☺



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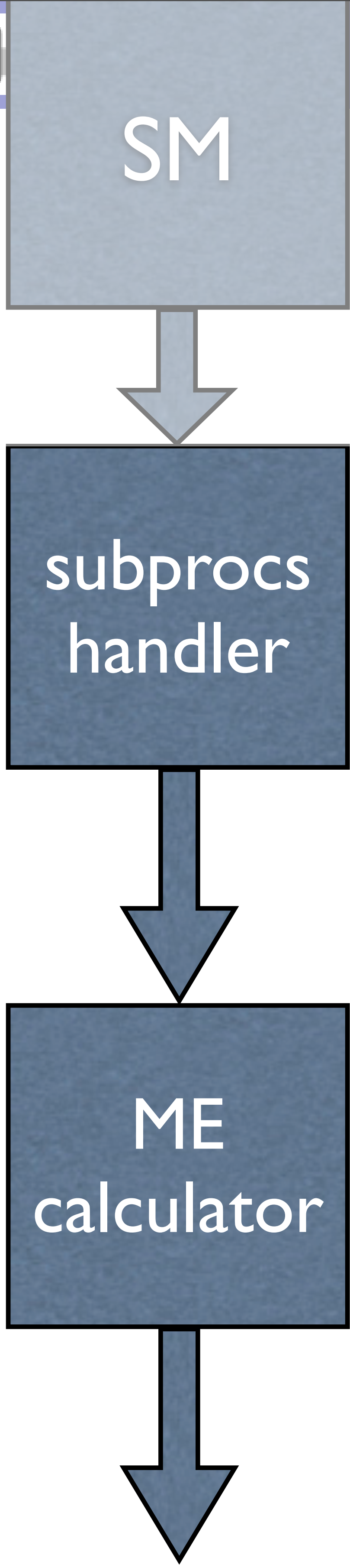


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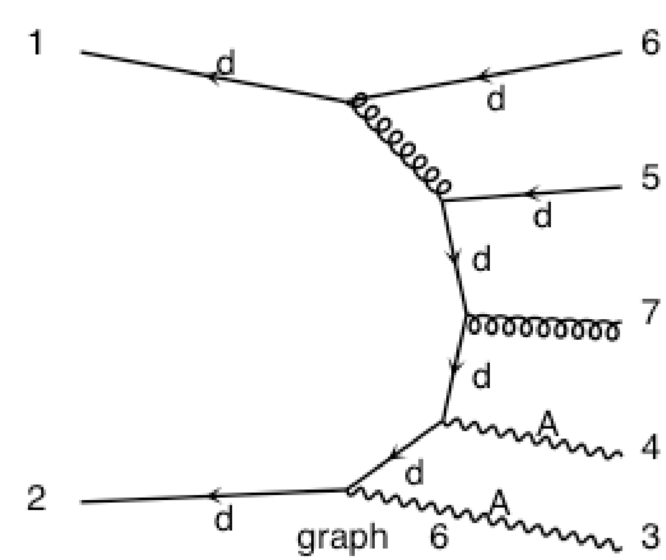

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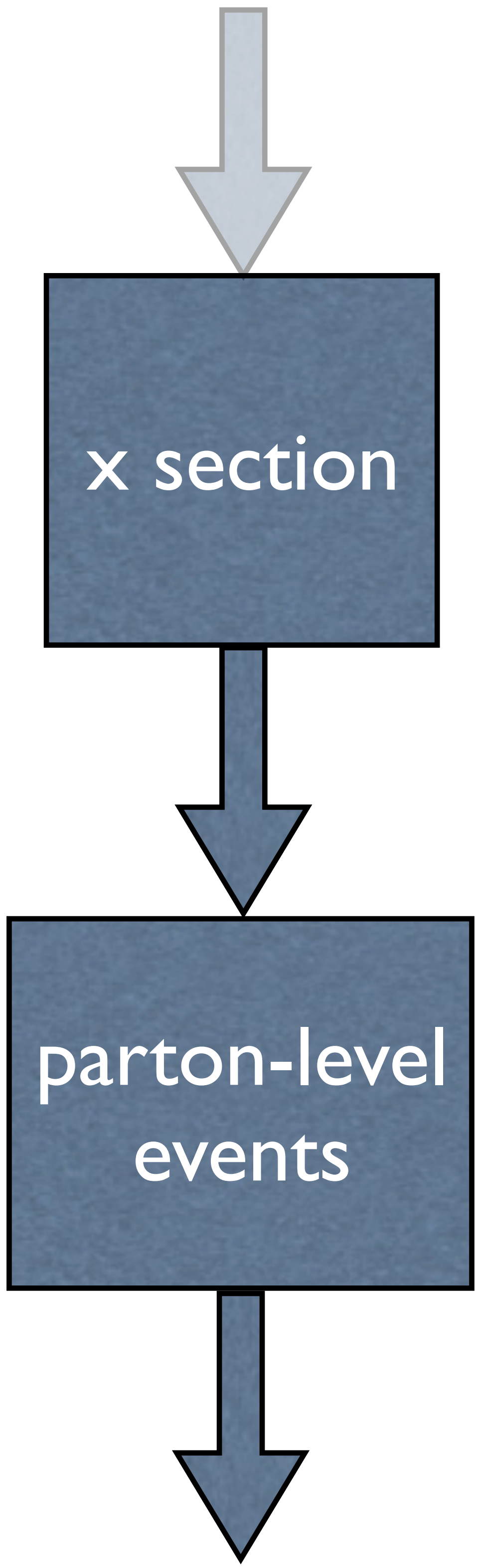
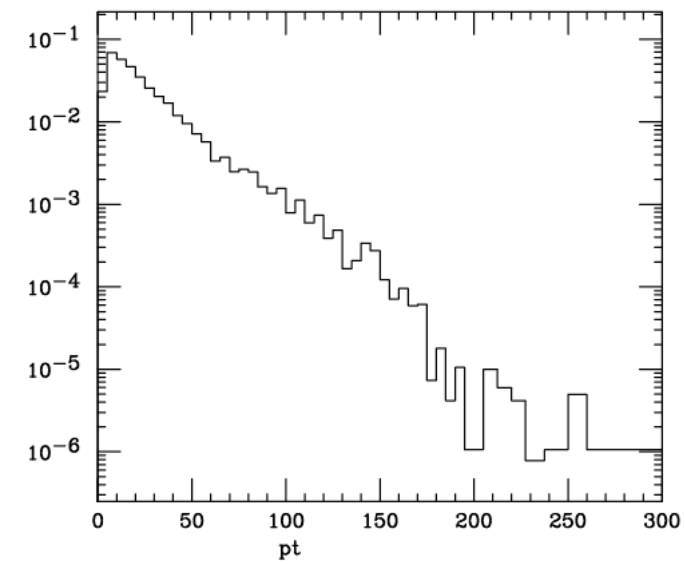
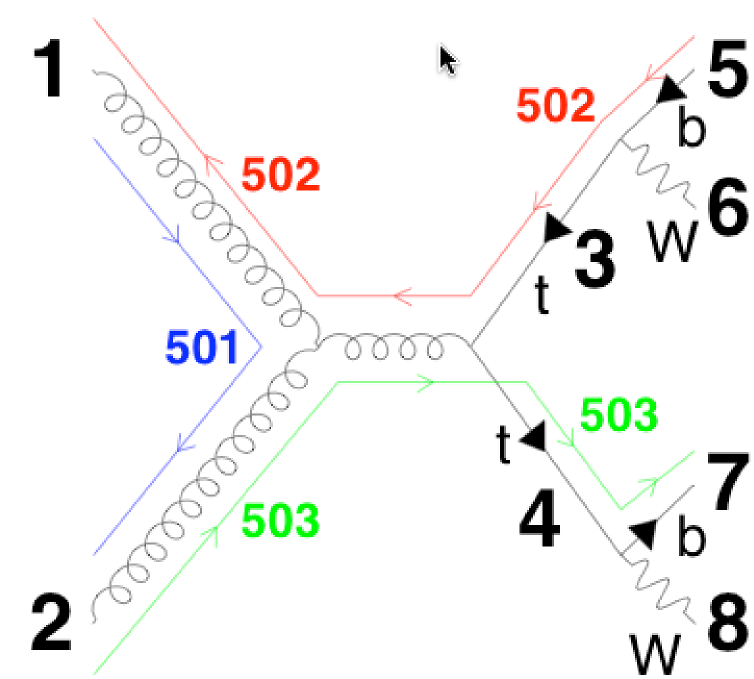



Integrate the matrix element over the phase space using a multi-channel technique and using parton-level cuts.




Events are obtained by unweighting. These are at the parton-level. Information on particle id, momenta, spin, color is given in the Les Houches format.



# Monte Carlo's and Event generators for the LHC

Fabio Maltoni
Center for Particle Physics and Phenomenology (CP3)
Université Catholique de Louvain

# Parton level computation at LO

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

- Matrix element calculators provide our first estimation of rates for inclusive final states.

- Extra radiation is included: it is described by the PDF's in the initial state and by the definition of a final state parton, which at LO represents all possible final state evolutions.

- Due to the above approximations a cross section at LO can strongly depend on the factorization and renormalization scales.

- Any tree-level calculation for a final state F can be promoted to the exclusive F + X through a shower. More on this soon...

# Master QCD formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution functions (from exp, but evolution from th).
2. Short distance coefficients as an expansion in $\alpha_S$ (from th).

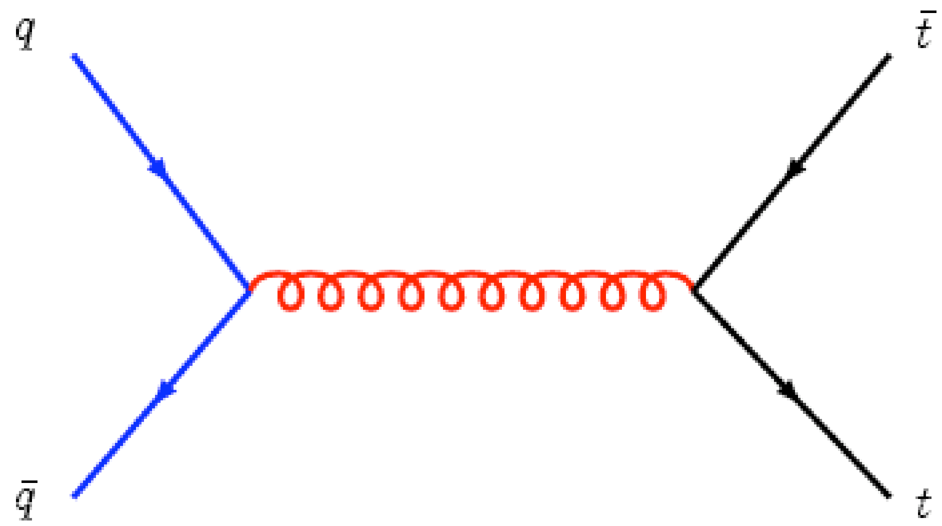
$$\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

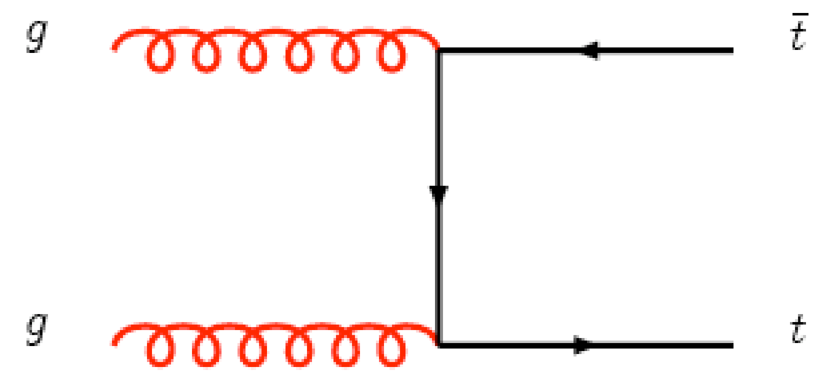
Leading order

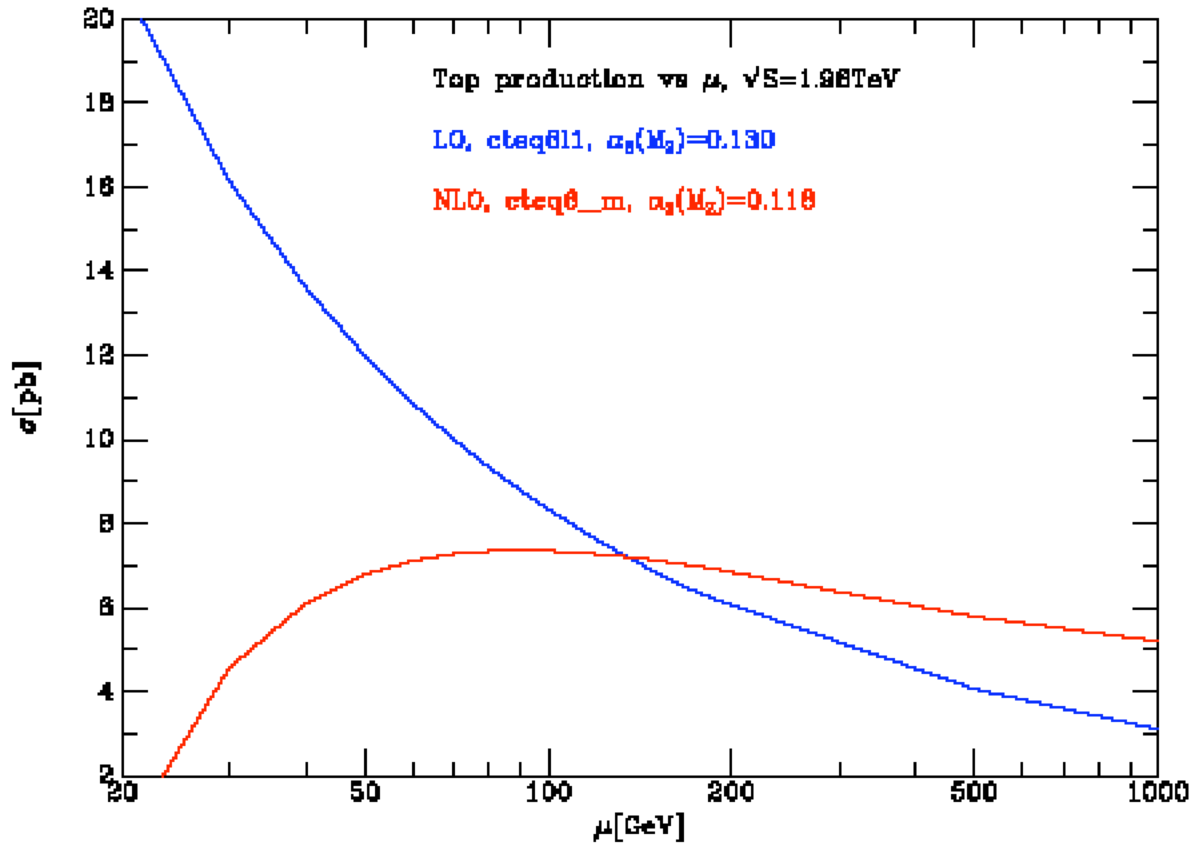
Next-to-leading order

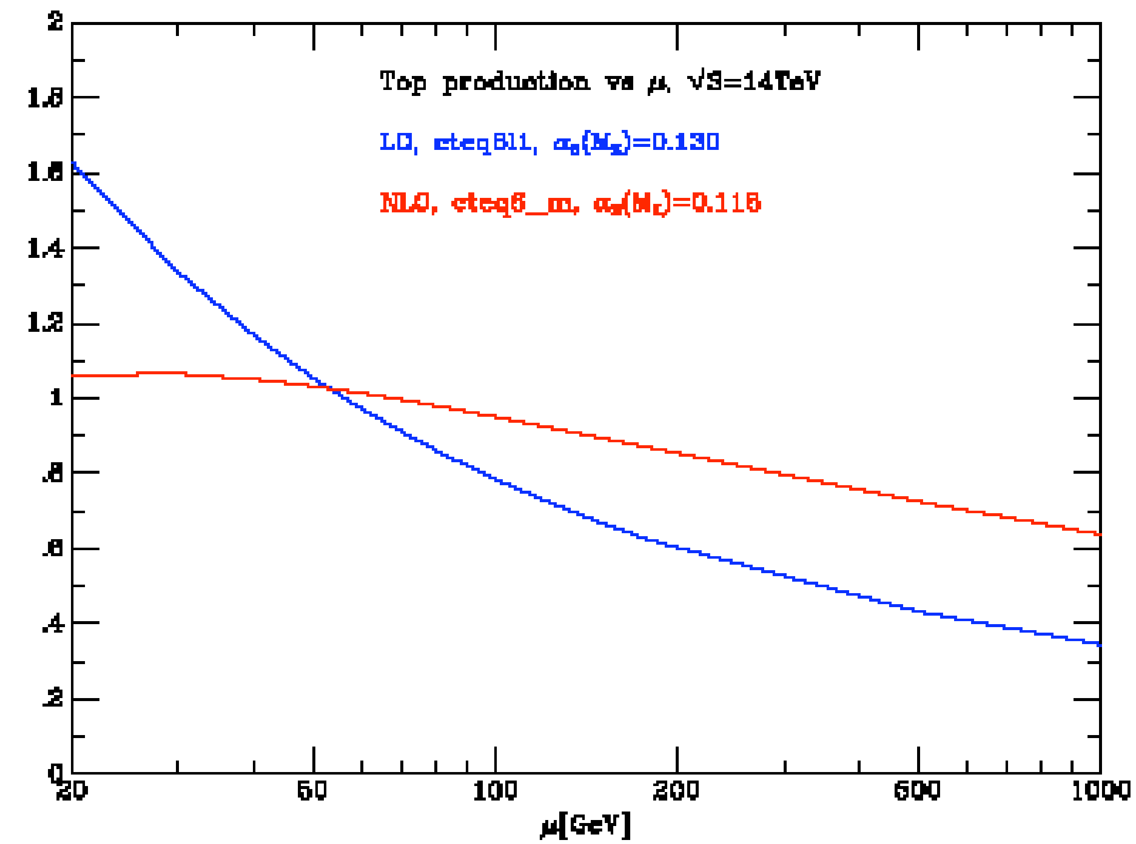
Next-to-next-to-leading order

# Top Production from LO to NLO



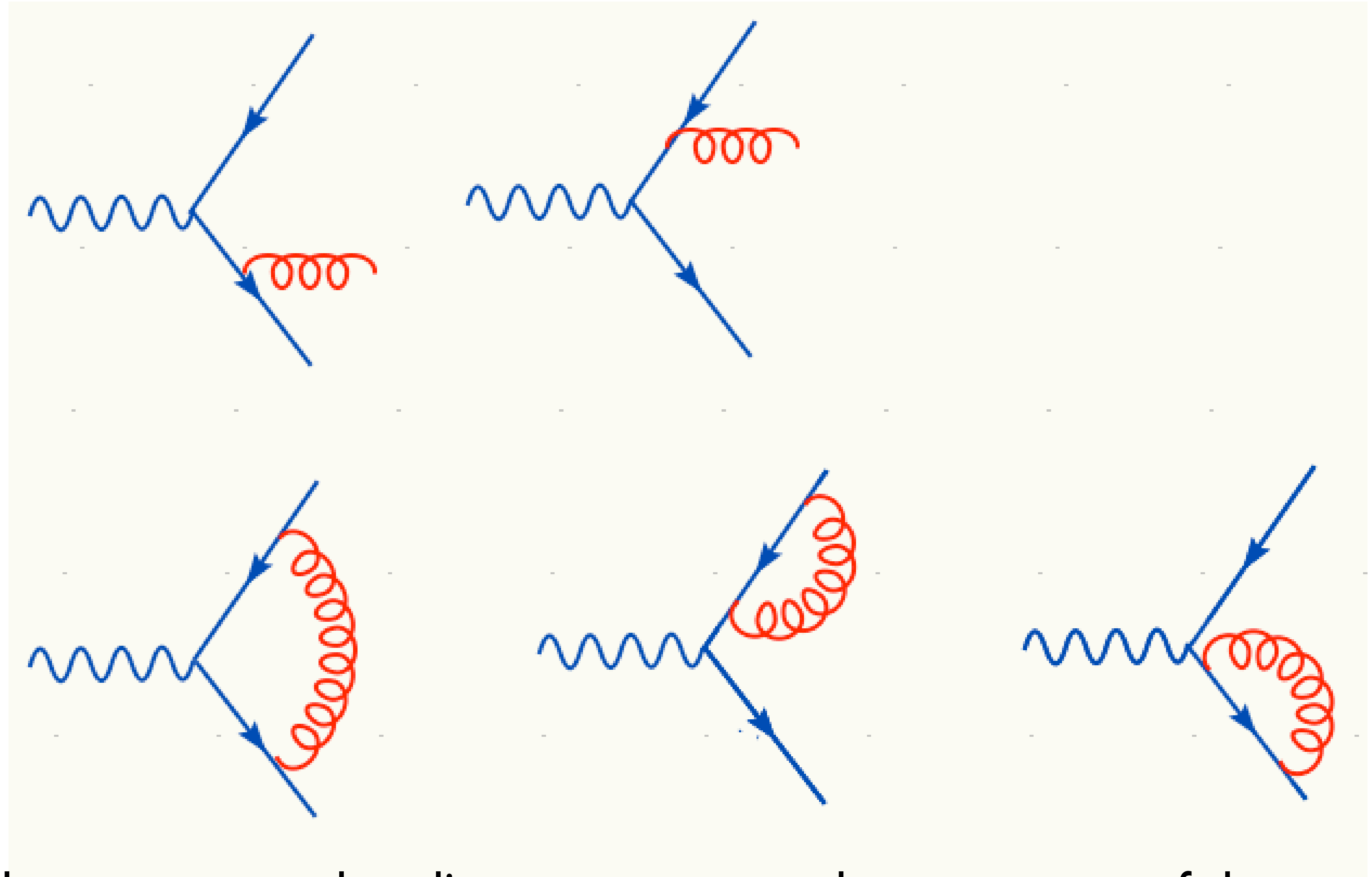




Inclusion of higher order corrections leads to a stabilization of the prediction.
At the LHC scale dependence is more difficult to estimate.

# The elements of NLO calculation



Real

Virtual

The KLN theorem states that divergences appear because some of the final state are physically degenerate but we treated them as different. A final state with a soft gluon is nearly degenerate with a final state with no gluon at all (virtual).

$$\int \frac{d^d k}{(2\pi)^d} \cdots$$

$$\sigma^{\rm NLO} = \int_R |M_{real}|^2 d\Phi_3 + \int_V 2Re\left(M_0 M^*_{virt}\right) d\Phi_2 = \text{finite!}$$

# Infrared-safe quantities

DEFINITION: quantities are that are insensitive to soft and collinear branching.

For these quantities, an extension of the general theorem (KLN) exists which proves that infrared divergences cancel betwen real and virtual or are simply removed by kinematic factors.

Such quantities are determined primarily by hard, short-distance physics. Long-distance effects give power corrections, suppressed by the inverse power of a large momentum scale (which must be present in the first place to justify the use of PT).

EXAMPLES: total rates & cross sections, jet distrubutions, shape variables...

NLO codes calculate IR safe quantities and return histograms (calculators)

# Something to remember well

Calling a code "a NLO code" is an abuse of language and can be confusing.

A NLO calculation always refers to an IR-safe observable.

An NLO code will, in general, be able to produce results for several quantities and distributions, only some of which will be at NLO accuracy.

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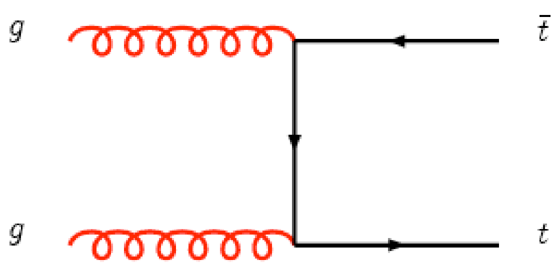
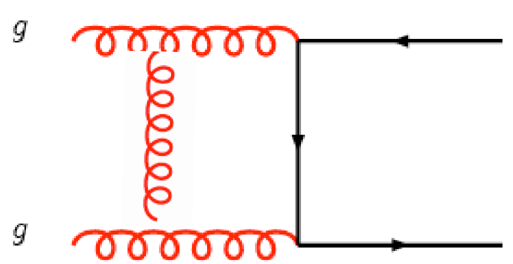
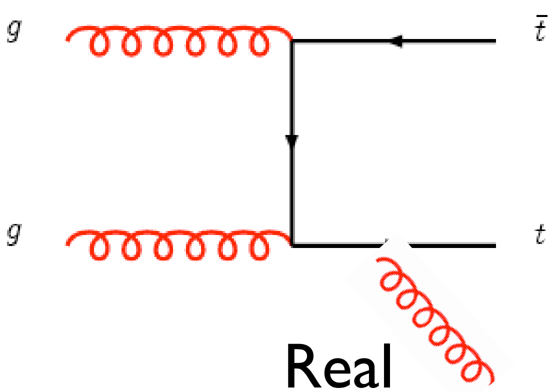



LO




Virt

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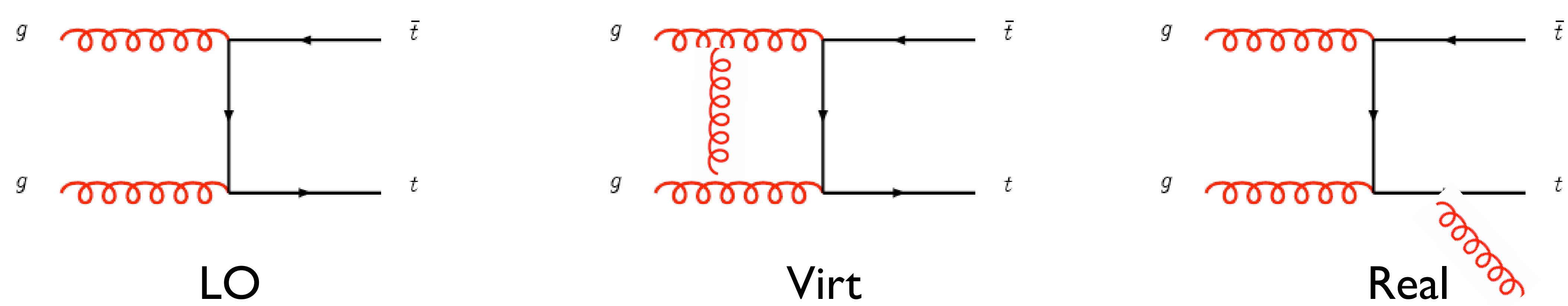


- Total cross section, σ(tt)
- $P_T$ of one top quark
- $P_T$ of the tt pair
- $P_T$ of the jet
- tt invariant mass, m(tt)
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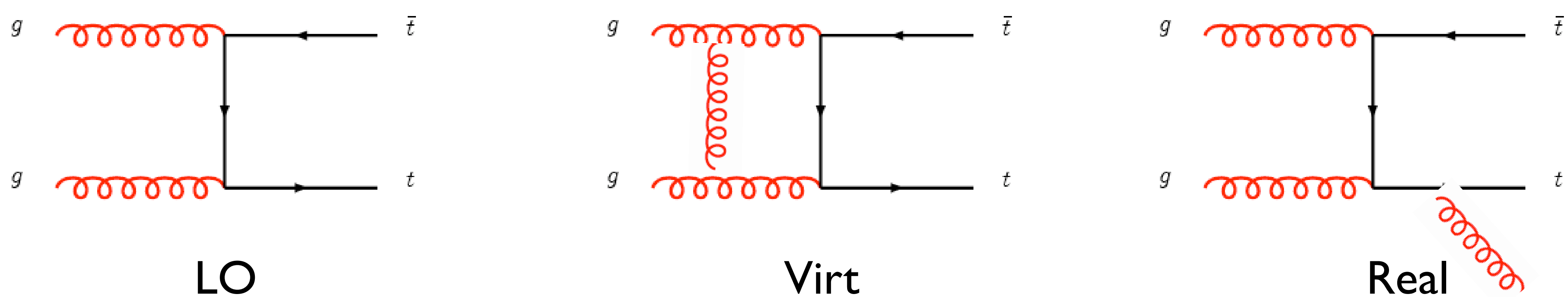


- ☞ Total cross section, σ(tt) .............. ✓
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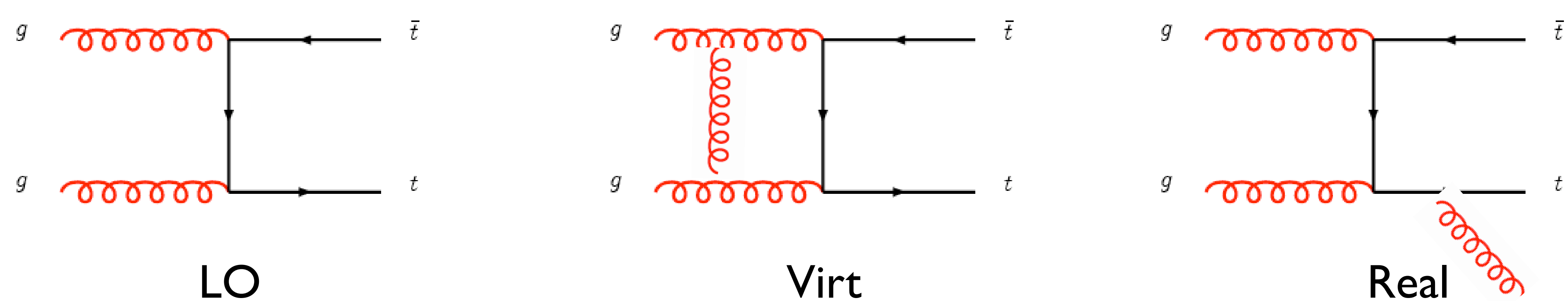


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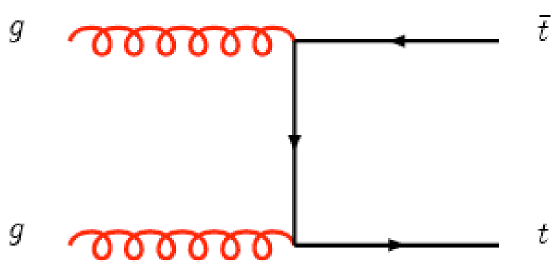


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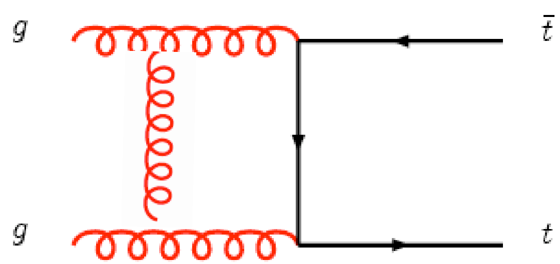


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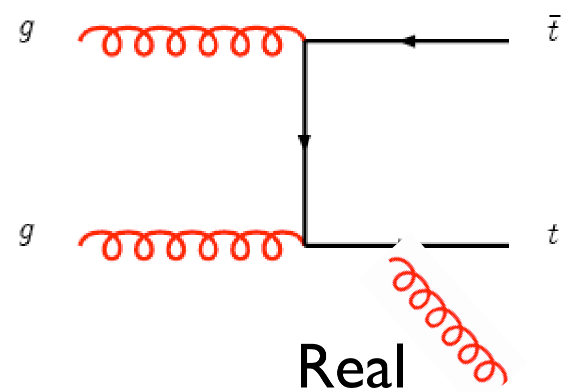


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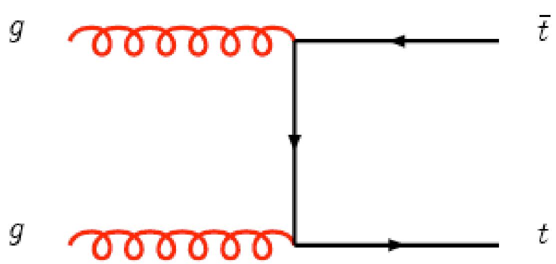


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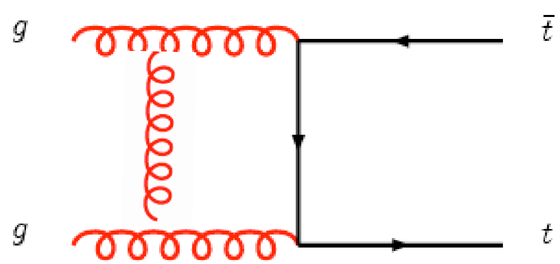


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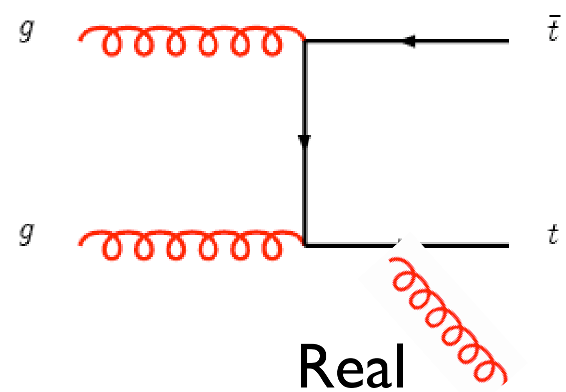


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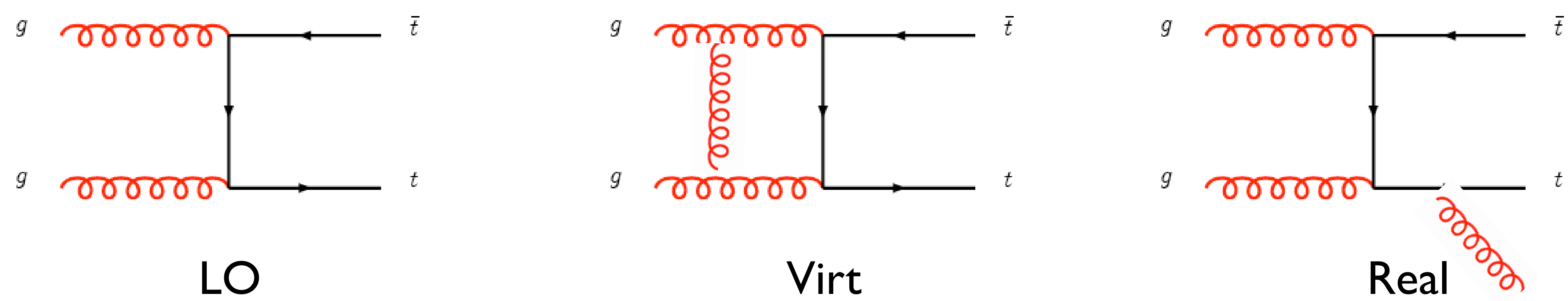


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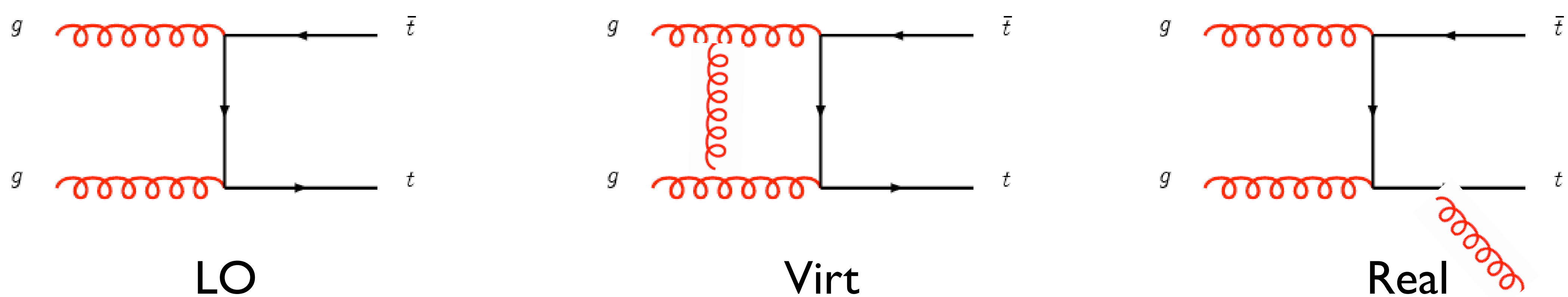


LO    Virt    Real

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- ☞ $P_T$ of one top quark ...................... ✓
- ☞ $P_T$ of the $t\bar{t}$ pair ............................... ✗
- ☞ $P_T$ of the jet ........................................ ✗
- ☞ $t\bar{t}$ invariant mass, $m(t\bar{t})$ .................... ✓
- ☞ $\Delta\Phi(t\bar{t})$ ................................................ ✗

## #4

A calculations/code at NLO for a process provides NLO predictions for any IR safe observable.

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False

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# Example:MCFM

Downloadable general purpose NLO code (Campbell & Ellis)

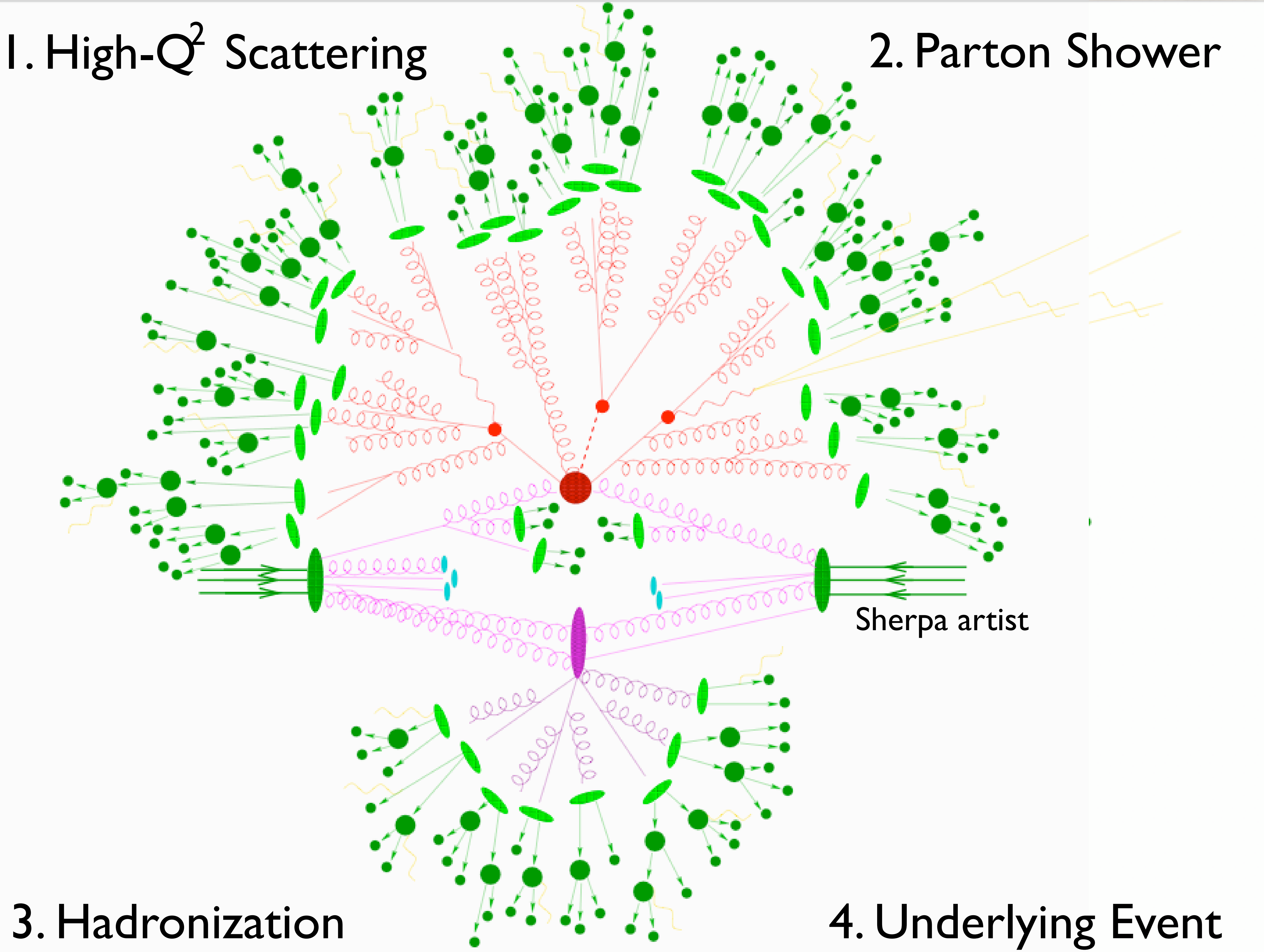
| | |
|---|---|
| $p\bar{p} \to W^\pm/Z$ | $p\bar{p} \to W^+ + W^-$ |
| $p\bar{p} \to W^\pm + Z$ | $p\bar{p} \to Z + Z$ |
| $p\bar{p} \to W^\pm + \gamma$ | $p\bar{p} \to W^\pm/Z + H$ |
| $p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$ | $p\bar{p} \to Zb\bar{b}$ |
| $p\bar{p} \to W^\pm/Z + 1$ jet | $p\bar{p} \to W^\pm/Z + 2$ jets |
| $p\bar{p}(gg) \to H$ | $p\bar{p}(gg) \to H + 1$ jet |
| $p\bar{p}(VV) \to H + 2$ jets | $p\bar{p} \to t + q$ |
| $p\bar{p} \to H + b$ | $p\bar{p} \to Z + b$ |

- ☞ Plus all single-top channels, Wc, WQJ, ZQJ,...
- ☞ Extendable/sizeable library of processes,

  relevant for signal and background studies, including spin correlations.
- ☞ Cross sections and distributions at NLO are provided
- ☞ Easy and flexible choice of parameters/cuts (input card).

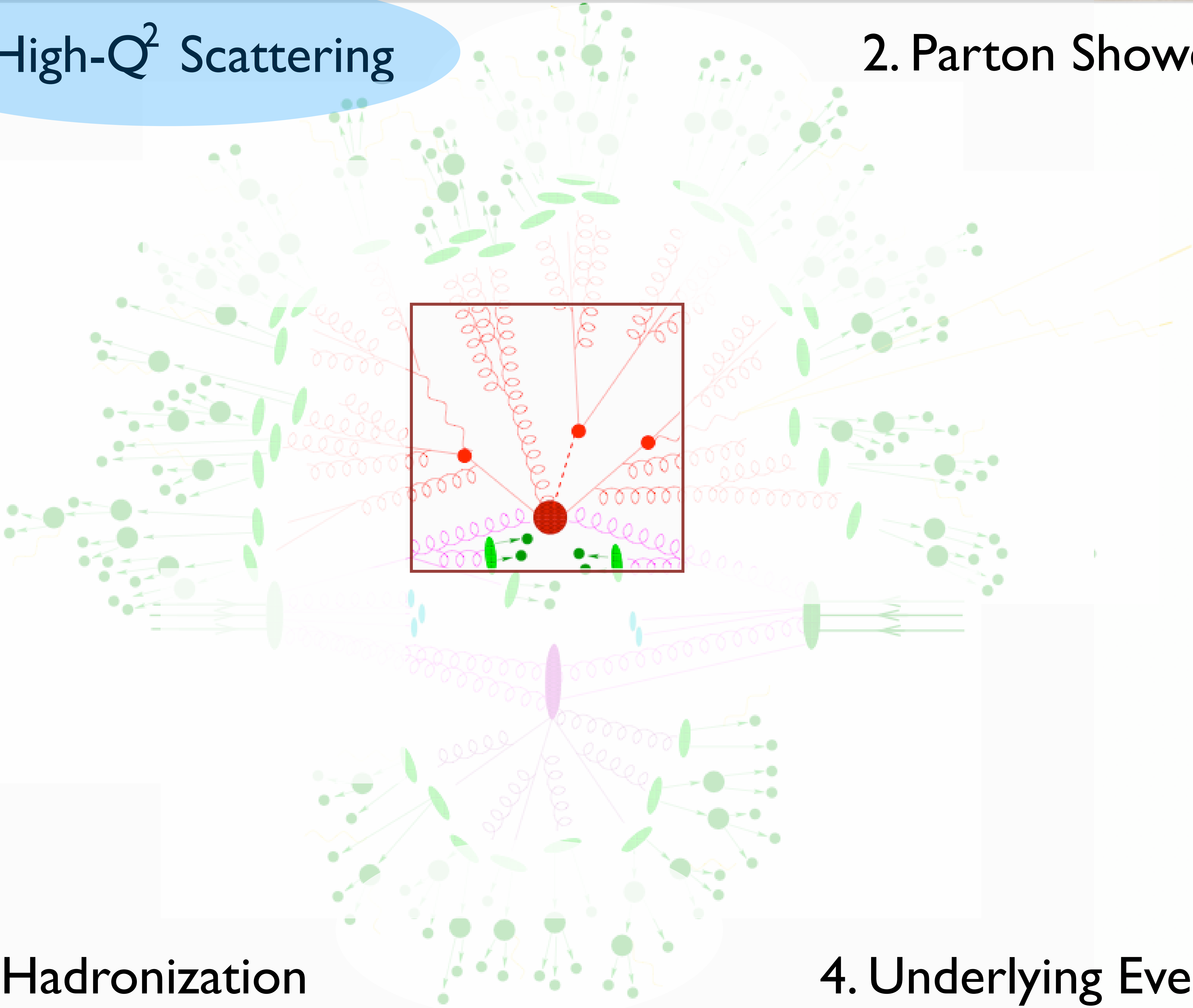
# NLO MC's integrators: summary

- Codes that compute IR-safe quantities (cross sections, jet rates, ...) at the parton level, at NLO and NNLO.
- These are NOT event generators!!
- Dedicated codes or families of codes available.
- Automatization in sight.


1. High-Q² Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event
Sherpa artist

# 1. High-$Q^2$ Scattering

# 2. Parton Shower



# 3. Hadronization

# 4. Underlying Event

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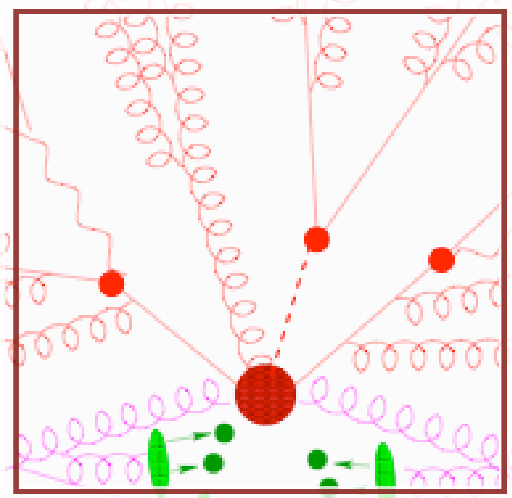
☞ where new physics lies



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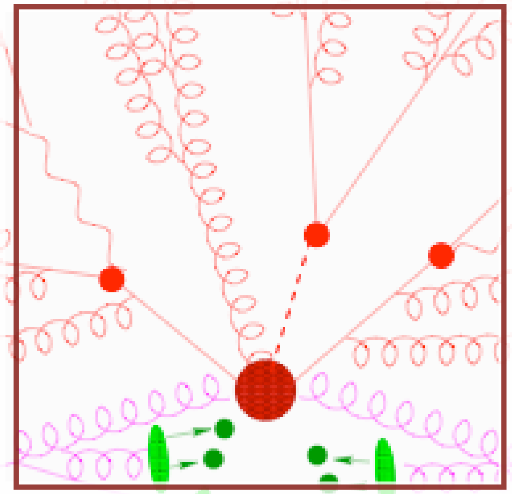

☞ process dependent

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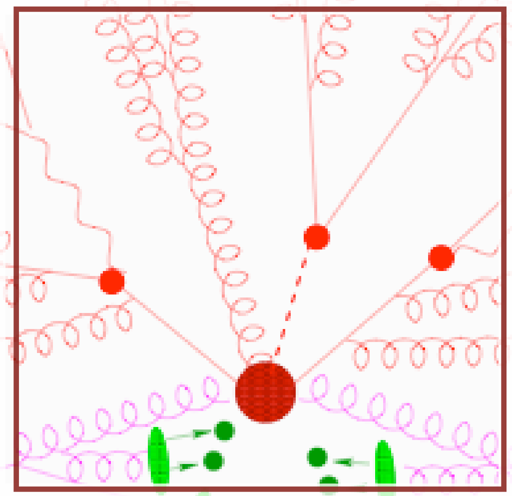

☞ process dependent

☞ first principles description

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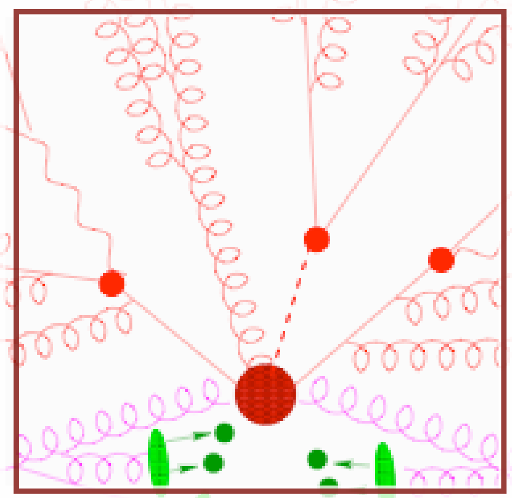
☞ where new physics lies



☞ process dependent

☞ first principles description

☞ it can be systematically improved

## 3. Hadronization

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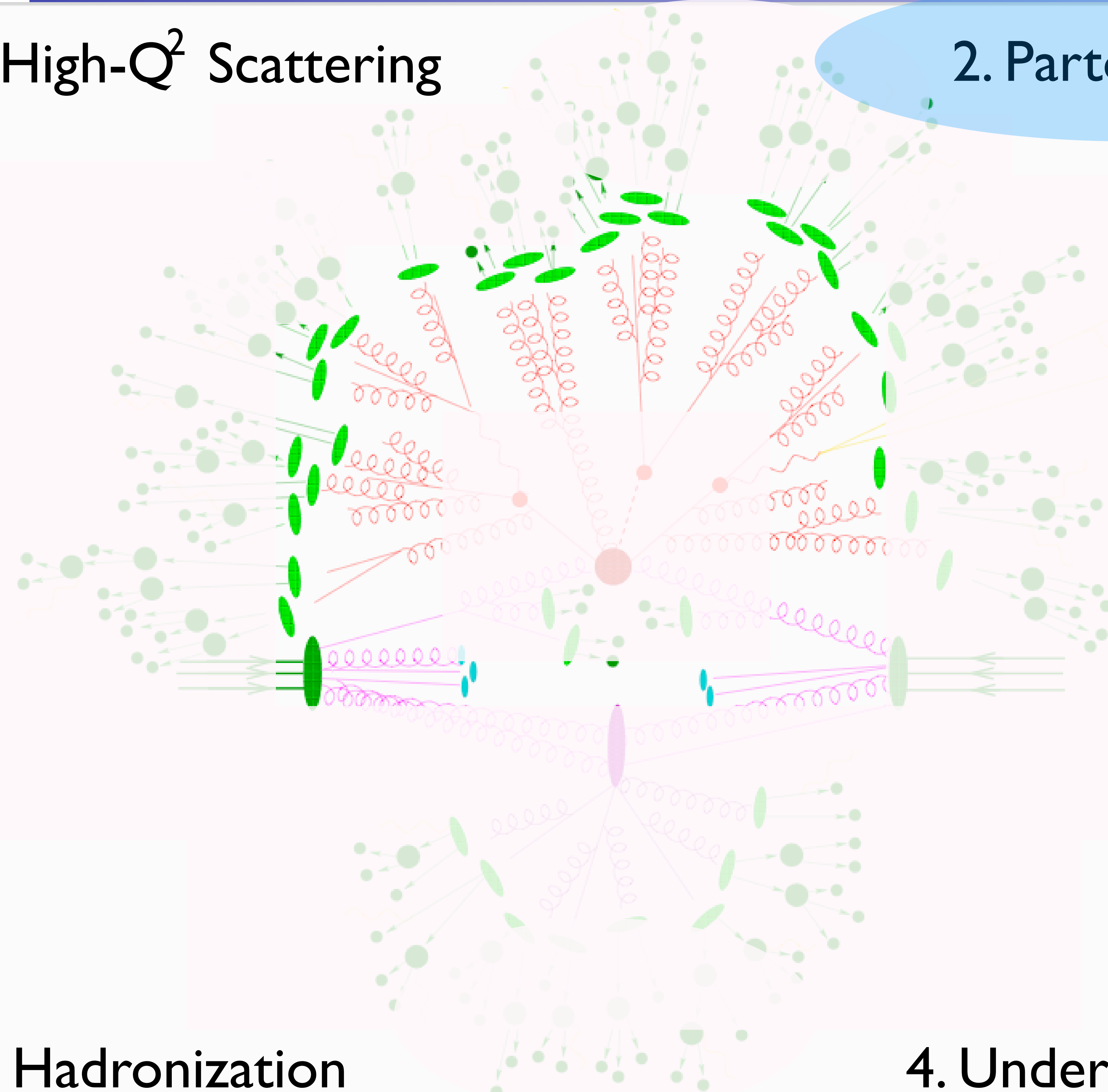

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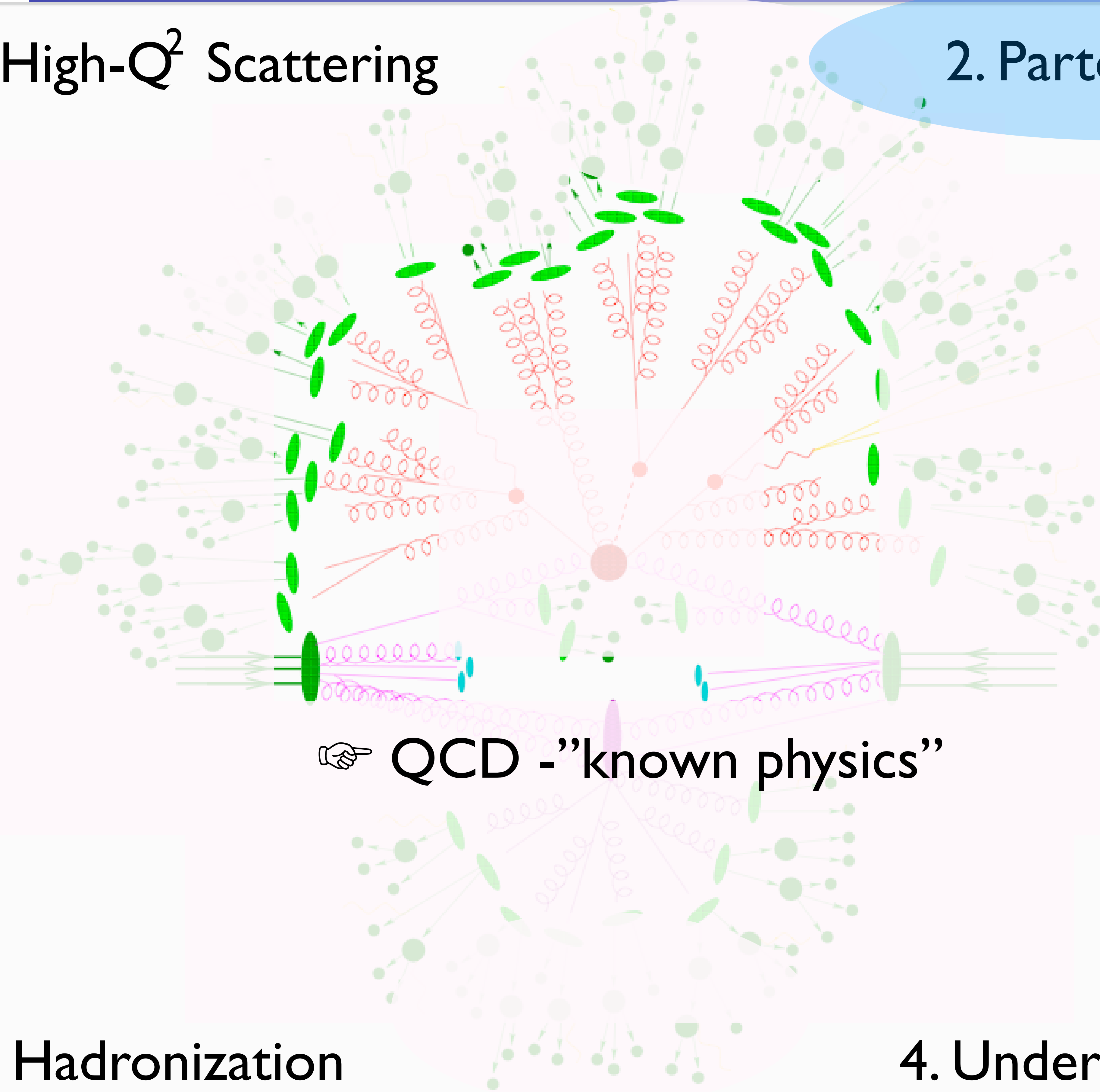

☞ QCD -"known physics"

3. Hadronization

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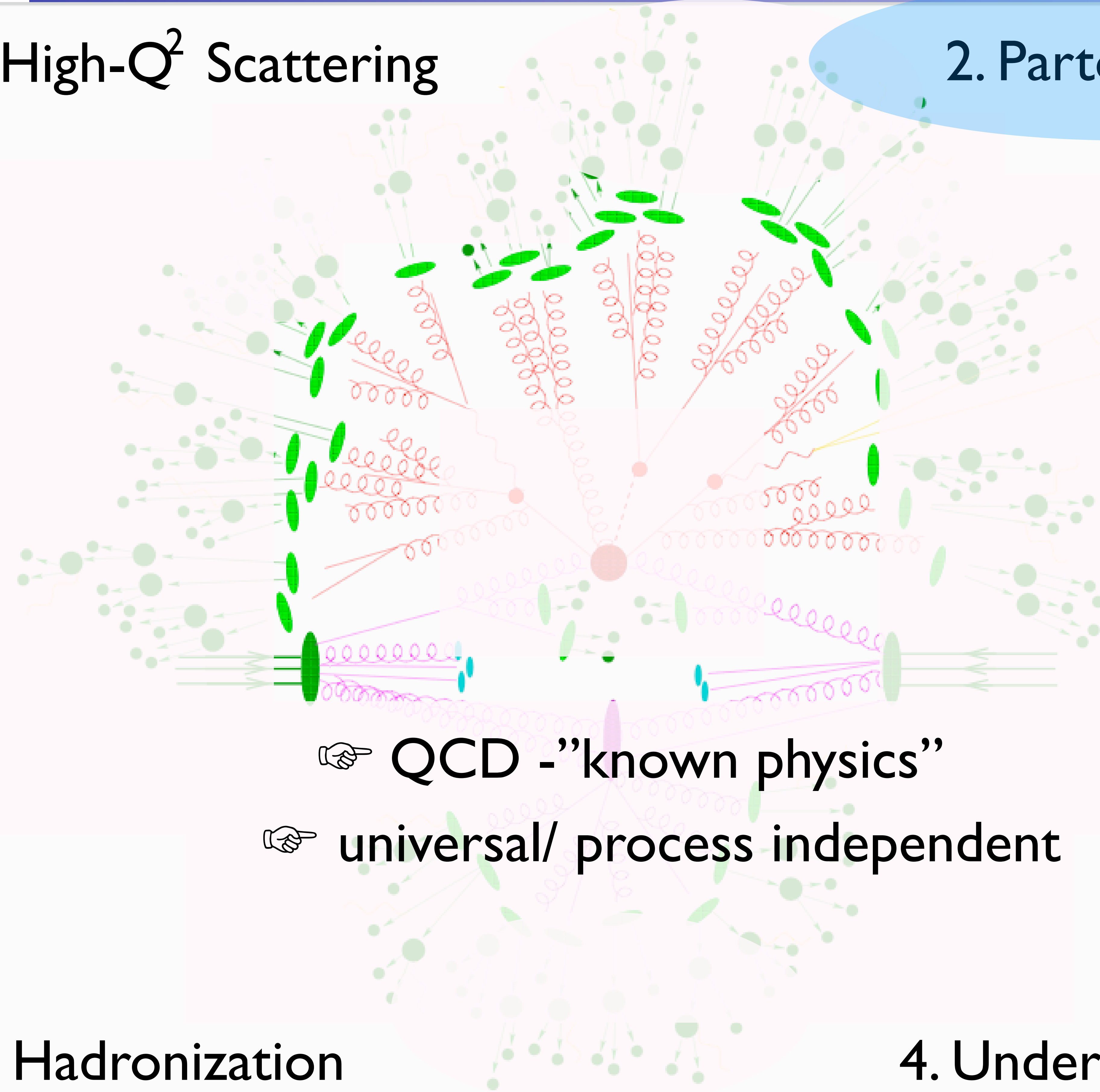

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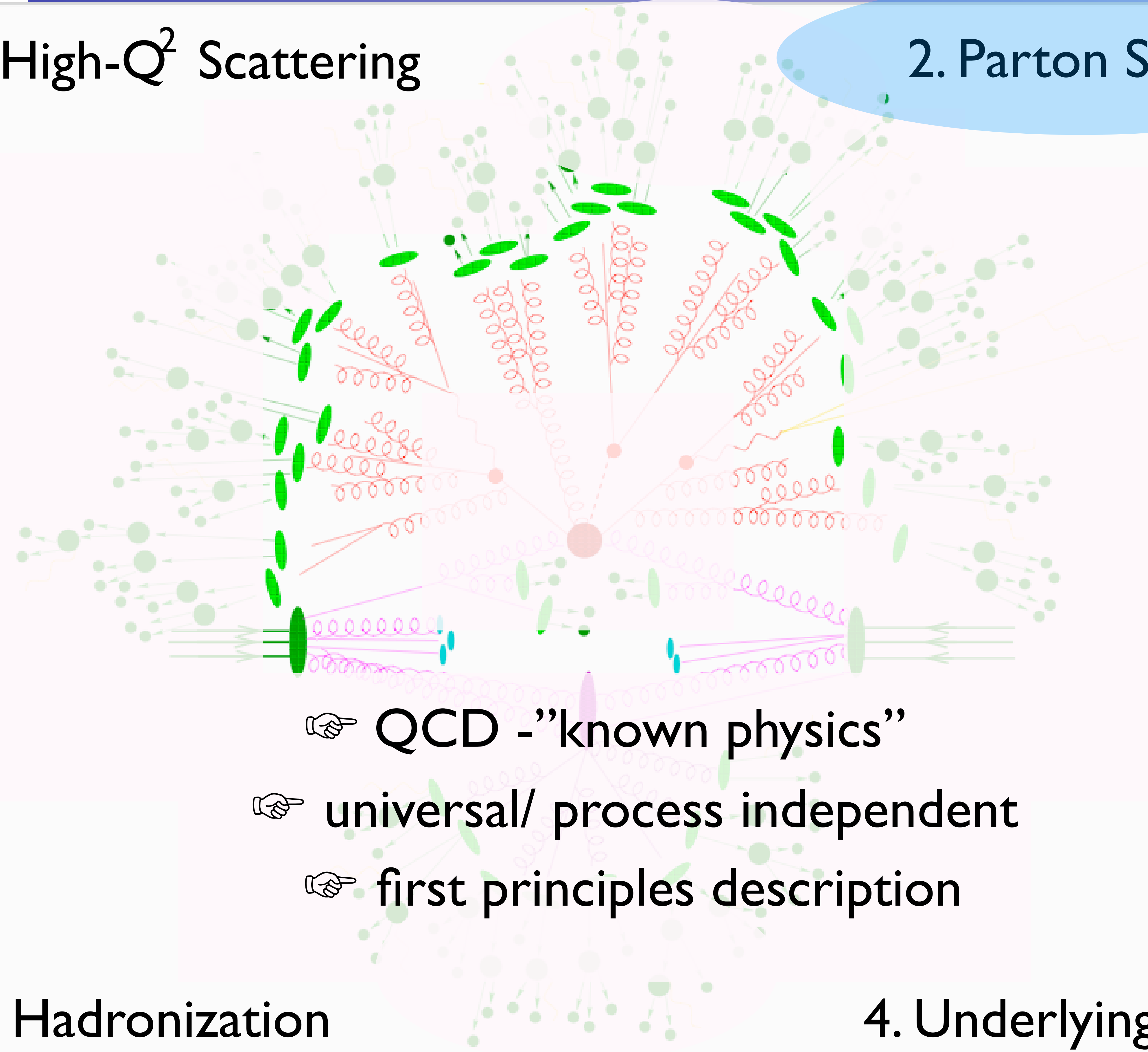

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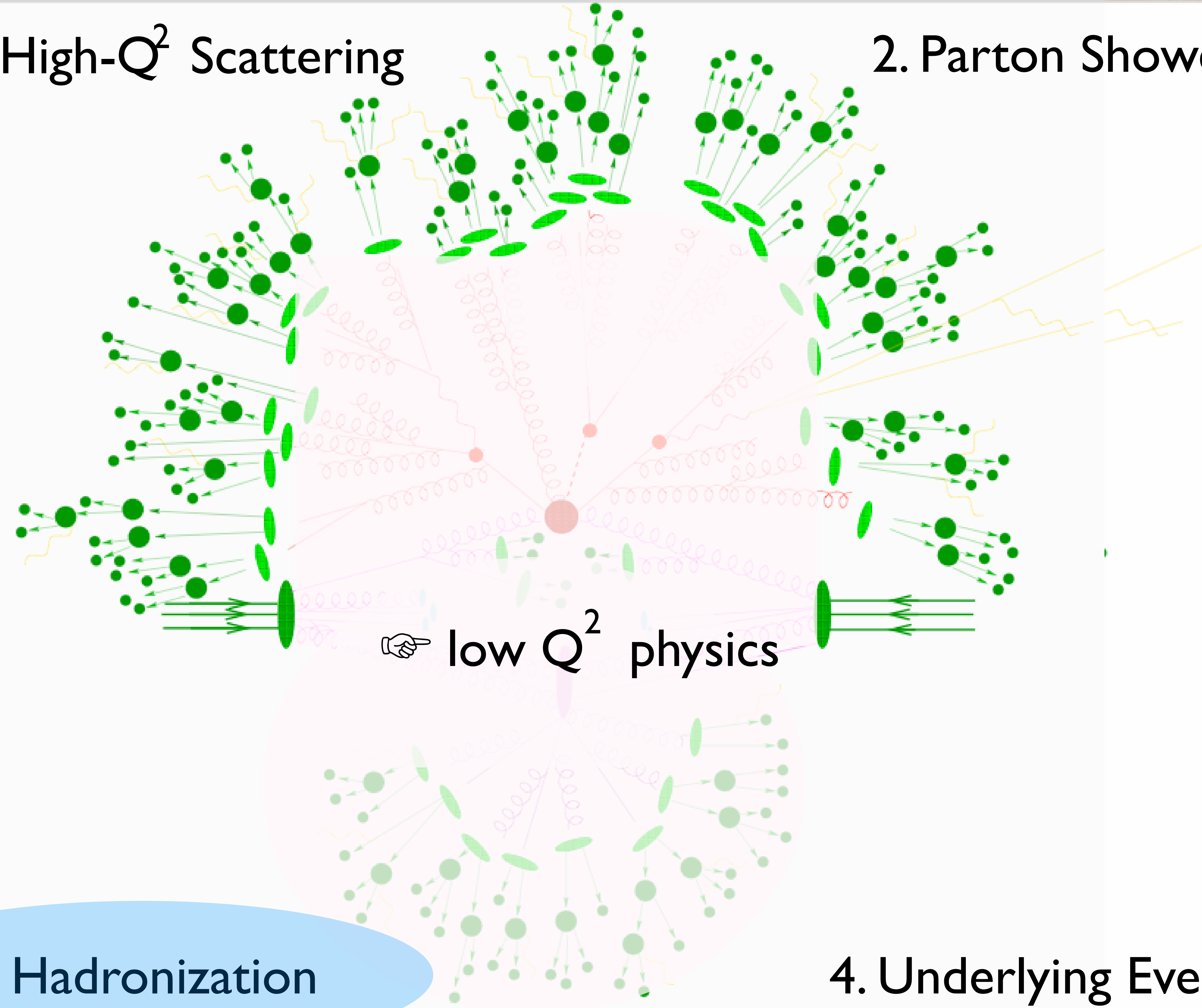

☞ low $Q^2$ physics

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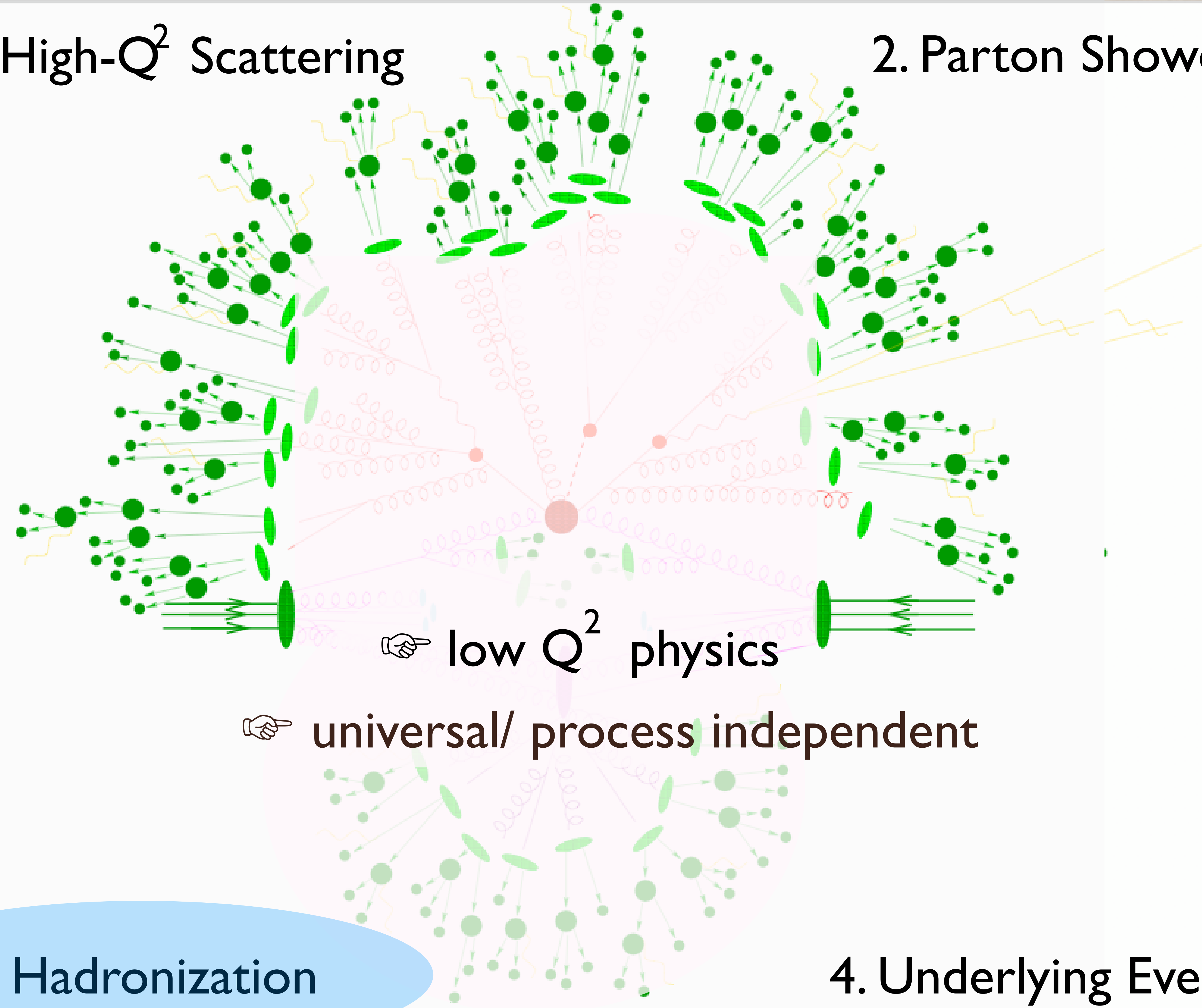

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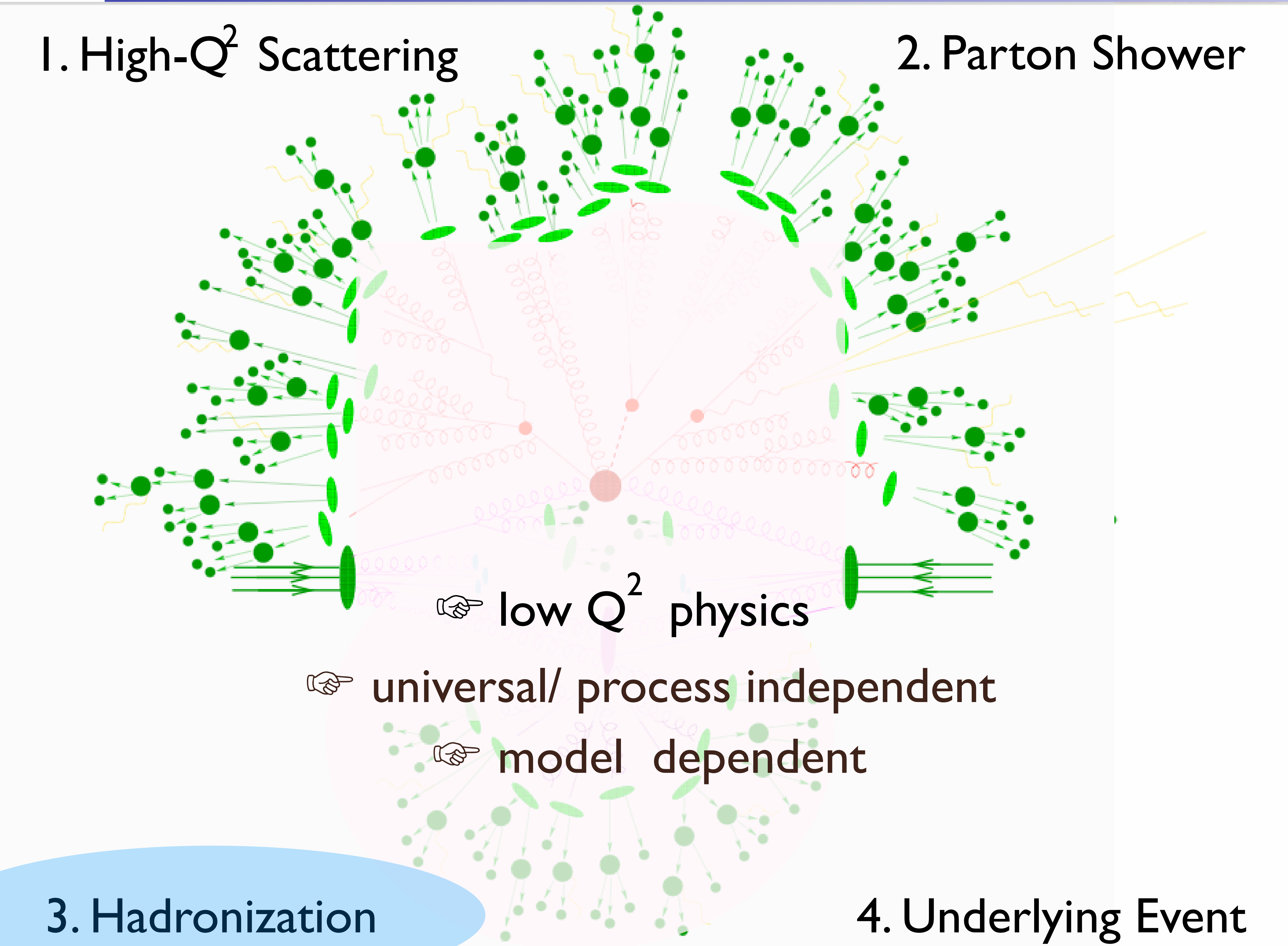
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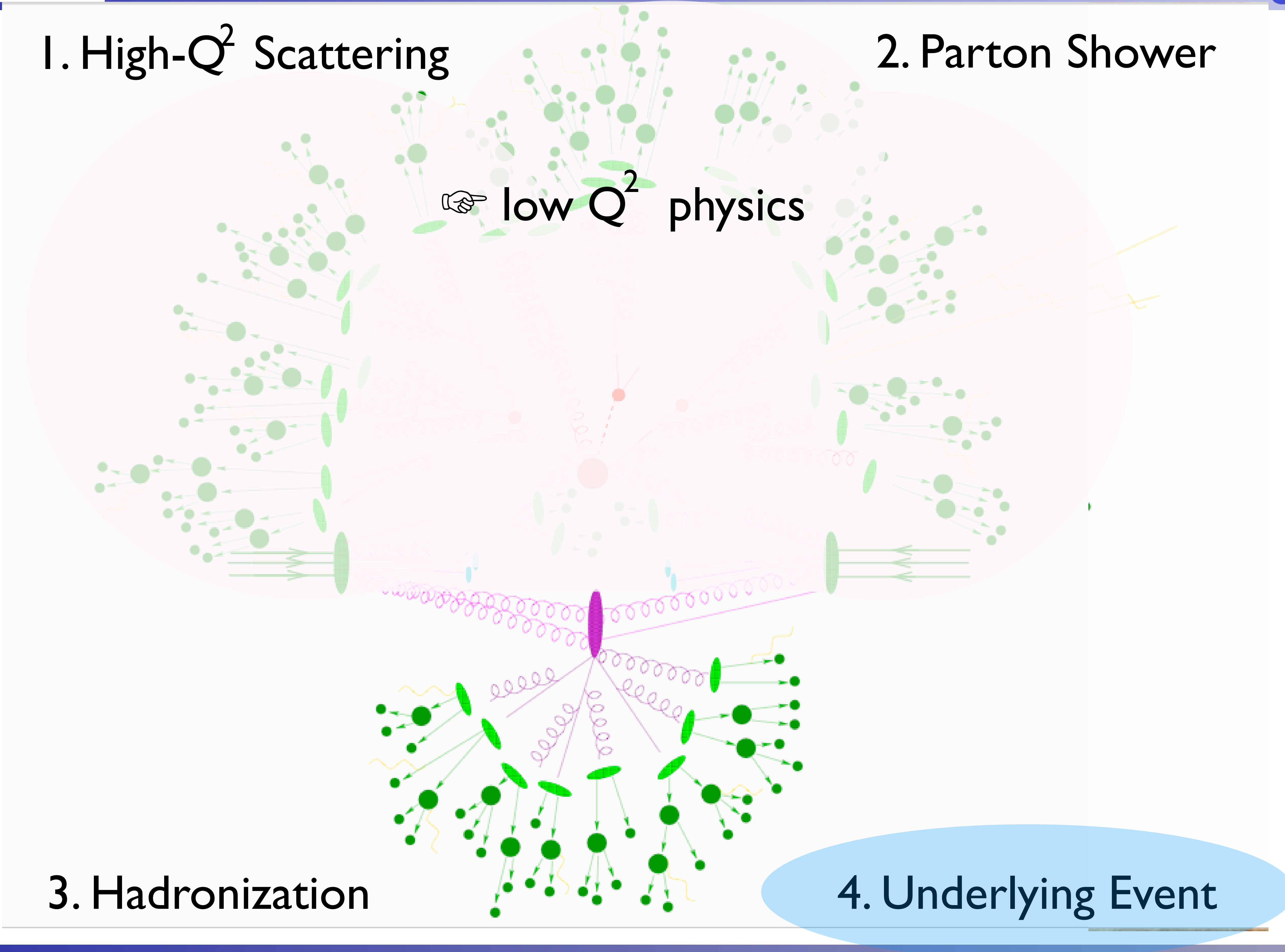
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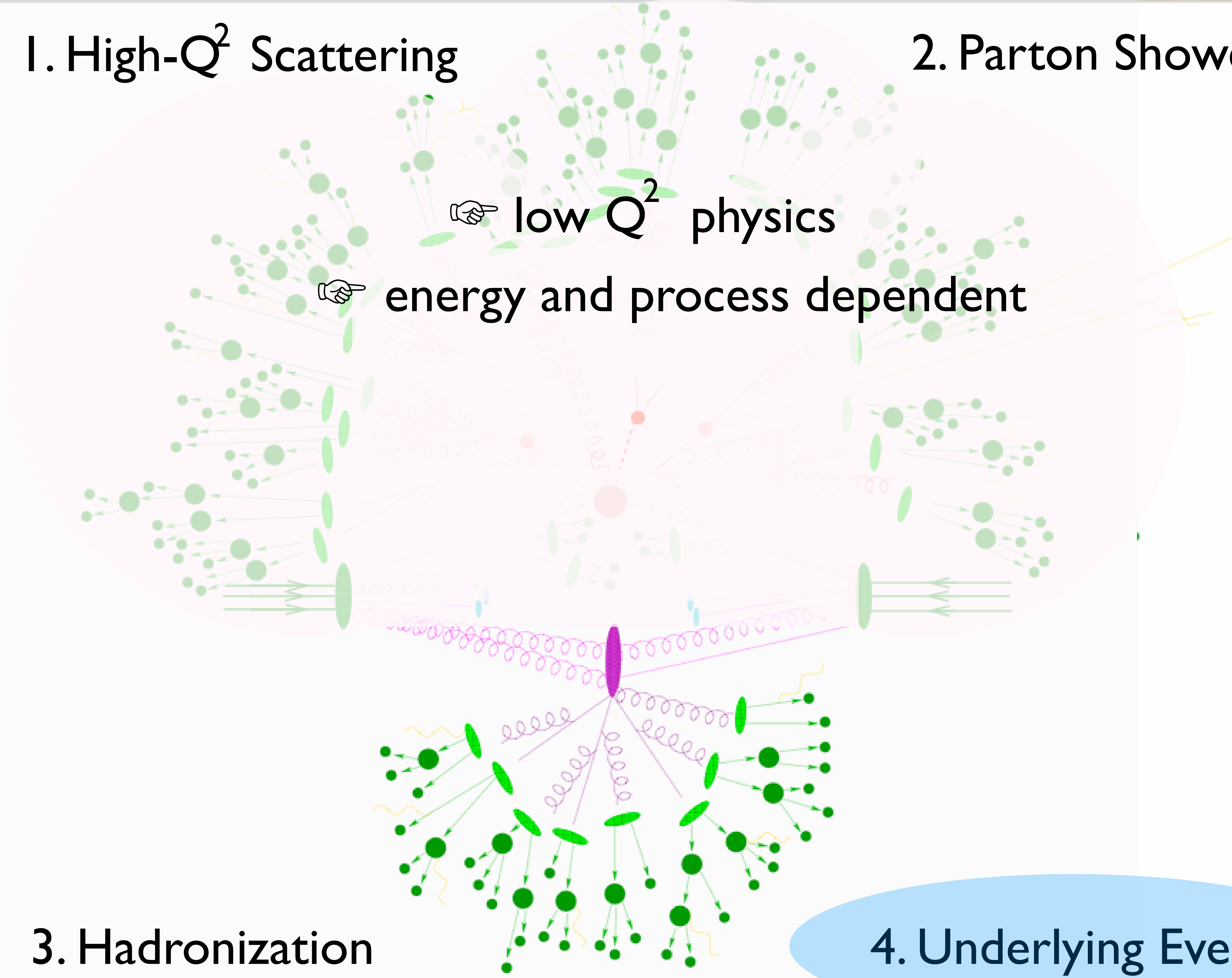

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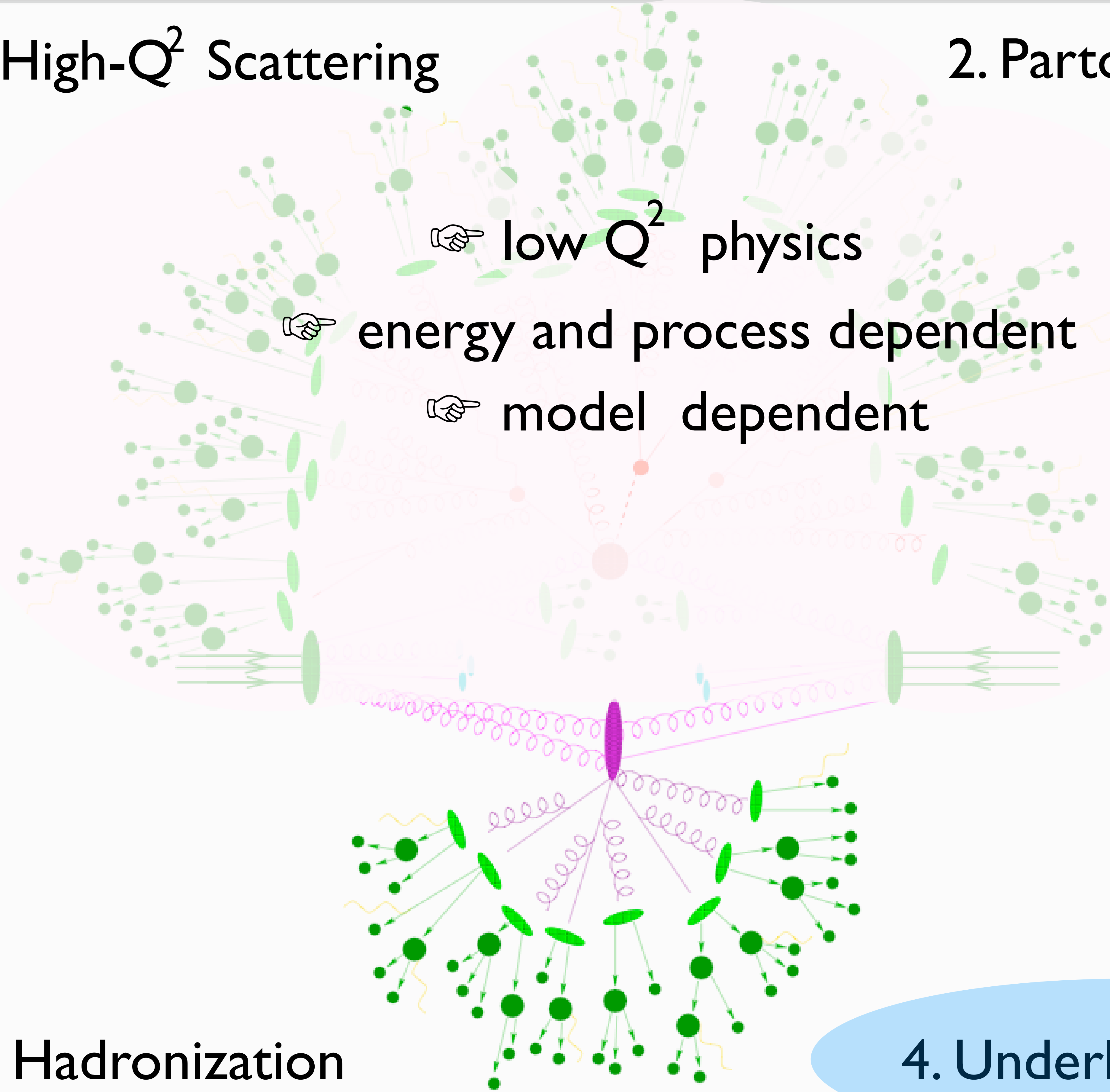

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- ☞ energy and process dependent
- ☞ model dependent

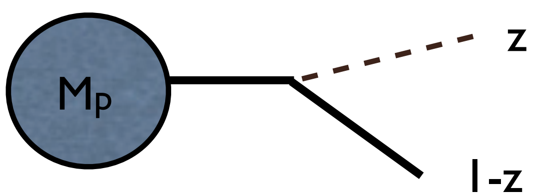
3. Hadronization

4. Underlying Event

# Parton Shower MC event generators

ME involving q →q g ( or g → gg) are strongly enhanced when they are close in the phase space:

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




Collinear factorization:

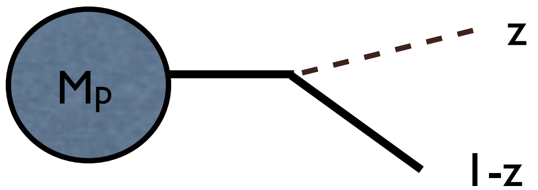
$$|M_{p+1}|^2 d\Phi_{p+1} \simeq |M_p|^2 d\Phi_p \frac{dt}{t} \frac{\alpha_S}{2\pi} P(z) dz d\phi$$

1. Allows for a parton shower (Markov process) evolution
2. The evolution resums the dominant leading-log contributions
3. By adding angular ordering the main quantum (interference) effects are also included

# Parton Shower MC event generators

ME involving q →q g ( or g → gg) are strongly enhanced when they are close in the phase space:

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




Both soft

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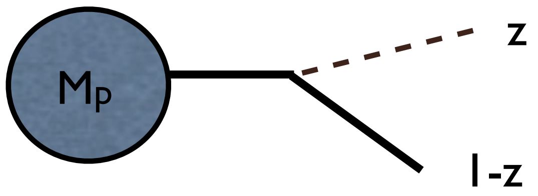


Both soft and collinear divergences: very different nature!

Collinear factorization:

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# Parton branching

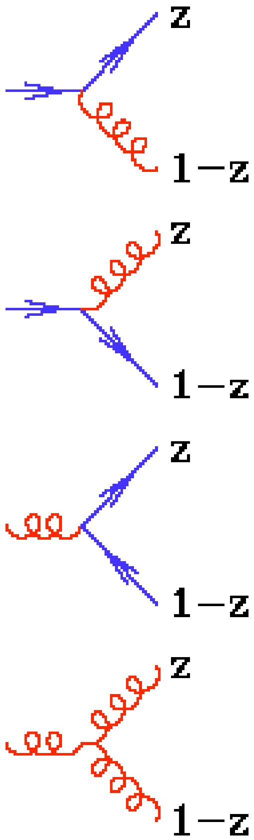
The spin averaged (unregulated) splitting functions for the various types of branching are:

$$\hat{P}_{qq}(z) = C_F \left[\frac{1+z^2}{(1-z)}\right],$$

$$\hat{P}_{gq}(z) = C_F \left[\frac{1+(1-z)^2}{z}\right],$$

$$\hat{P}_{qg}(z) = T_R \left[z^2+(1-z)^2\right],$$

$$\hat{P}_{gg}(z) = C_A \left[\frac{z}{(1-z)} + \frac{1-z}{z} + z(1-z)\right].$$




$C_F = \frac{4}{3}, C_A = 3, T_R = \frac{1}{2}.$

Comments:

* Gluons radiate the most
* There soft divergences in z=1 and z=0.
* $P_{qg}$ has no soft divergences.

# Parton branching

Following a given line in a branching tree, it is clear that contributions coming from the strongly-ordered region will be leading

$$Q^2 \gg t_1 \gg t_2 \gg \dots t_N \gg Q_0^2$$

$$\sigma_N \propto \sigma_0 \alpha_S^N \int_{Q_0^2}^{Q^2} \frac{dt_1}{t_1} \int_{Q_0^2}^{t_1} \frac{dt_2}{t_2} \dots \int_{Q_0^2}^{t_{N-1}} \frac{dt_N}{t_N} = \sigma_0 \frac{\alpha_S^N}{N!} \left( \log \frac{Q^2}{Q_0^2} \right)^N$$

Denote by

$$\Phi_a[E, Q^2]$$

the ensemble of parton cascades initiated by a parton a of energy E and emerging from a hard process with scale $Q^2$ (Generating functional). Also, define

$$\Delta(Q_1^2, Q_2^2)$$

as the probability that a does not branch for virtualities $Q_1^2 > t > Q_2^2$

# Evolution equation and Sudakov

With this, it easy to write a formula that takes into account all the branches associated to a parton a:

$$\Phi_a[E,Q^2] = \Delta_a(Q^2,Q_0^2)\Phi_a[E,Q_0^2] + \int_{Q_0^2}^{Q^2} \frac{dt}{t}\Delta_a(Q^2,t)\sum_b \int dz \frac{\alpha_S}{2\pi} P_{ba}(z)\Phi_b[zE,t]\Phi_c[(1-z)E,t]$$

Simple interpretation. First term describes the evolution to $Q_0$, where no branching has occurred. The second term is the contribution coming from evolving with no branching up to a given t and then branching there.

Now conservation of probability imposes that:

$$1 = \Delta_a(Q^2,Q_0^2) + \int_{Q_0^2}^{Q^2} \frac{dt}{t}\Delta_a(Q^2,t)\sum_b \int dz \frac{\alpha_S}{2\pi} P_{ba}(z)$$

Which can be solved to give an explicit expression for Δ.

# Evolution equation and Sudakov

$$\Delta_a(Q^2, Q_0^2) = \exp\left( - \int_{Q_0^2}^{Q^2} \frac{dt}{t} \sum_b \int dz \frac{\alpha_S}{2\pi} P_{ba}(z) \right)$$

Proof:

derive the conservation of probability equation

$$0 = \frac{d\Delta_a}{dQ_0^2}(Q^2, Q_0^2) - \frac{\mathcal{P}_a}{Q_0^2} \Delta_a(Q^2, Q_0^2)\,, \qquad \mathcal{P}_a = \sum_b \int dz \frac{\alpha_S}{2\pi} P_{ba}(z)$$

and impose the initial condition

$$\Delta_a(Q^2, Q^2) = 1$$

Note that $\Delta_a(Q^2, t) = \dfrac{\Delta_a(Q^2, Q_0^2)}{\Delta_a(t, Q_0^2)}$ and therefore sometimes the second argument is not used.

#3

The “Sudakov form factor” directly quantifies how likely is for a parton to undergo branching.

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False

# Evolution equation and Sudakov

Note that we can define the following quantities with mass squared dimensions

$$
\begin{aligned}
Q^2 &= z(1-z)\theta^2 E^2 \\
p_T^2 &= z^2(1-z)^2\theta^2 E^2 \\
\tilde{t} &= \theta^2 E^2
\end{aligned}
$$

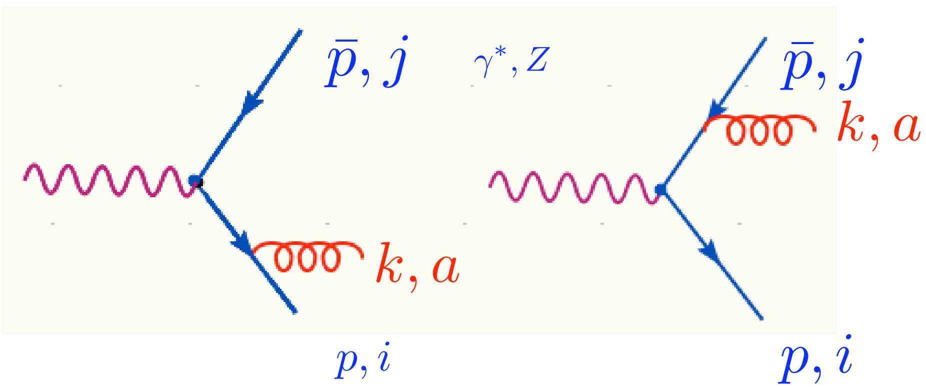
and obtain

$$
\frac{d\theta^2}{\theta^2} = \frac{dQ^2}{Q^2} = \frac{dp_T^2}{p_T^2} = \frac{d\tilde{t}}{\tilde{t}}
$$

This fact has an important consequence: the evolution parameter of the shower is not uniquely defined. This is because the scales chosen above have all the same angular behaviour, provided that z is not too close to 0 or 1.

Differences stem from the SOFT region.

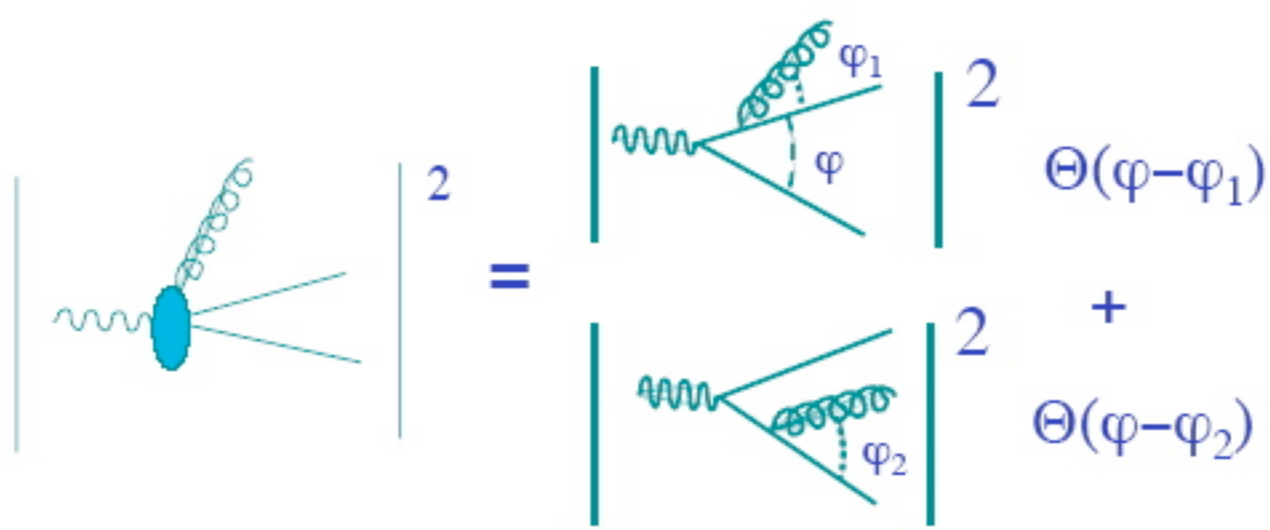
# Angular ordering




$$d\sigma_g = \sum |A_{soft}|^2 \frac{d^3k}{(2\pi)^3 2k^0} \sum |A_0|^2 \frac{-2p^\mu \bar{p}^\nu}{(pk)(\bar{p}k)} g^2 \sum \varepsilon_\mu \varepsilon_\nu^* \frac{d^3k}{(2\pi)^3 2k^0}$$

$$= d\sigma_0 \frac{\alpha_s C_F}{\pi} \frac{dk^0}{k^0} \frac{d\phi}{2\pi} \frac{1-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} d\cos\theta$$

You can easily prove that:




Radiation happens only for angles smaller than the color connected (antenna) opening angle!

#2

MC's are based on a classical approximation (Markov Chain), QM effects are not properly described.

Quantum effects are included:

1. Exactly in the hard scattering matrix element.
2. Approximately by the angular-ordering of the shower

# #2

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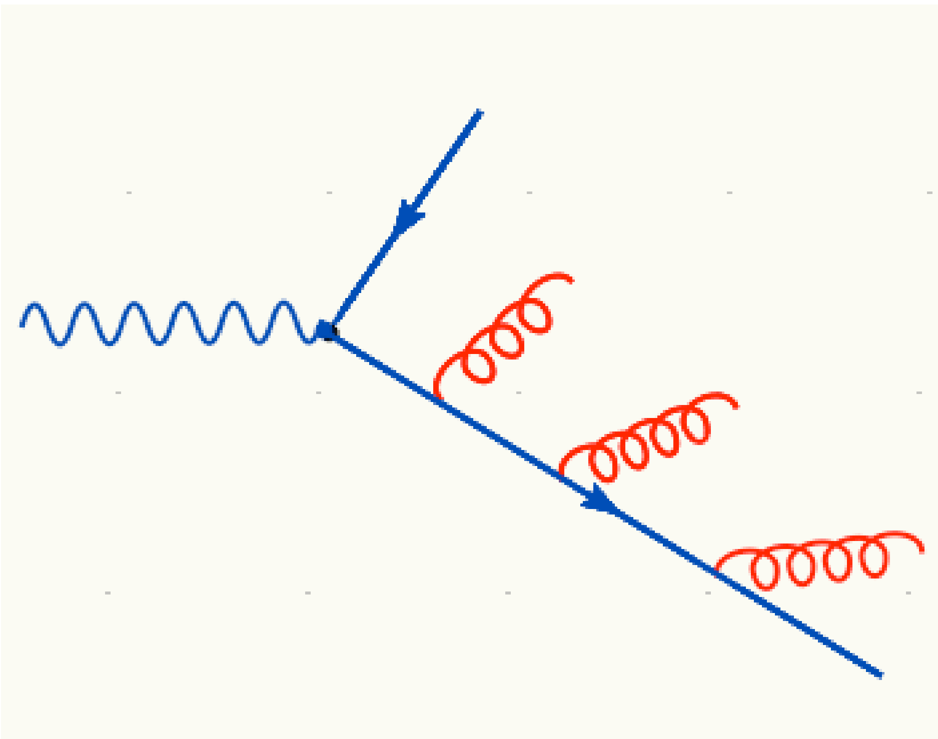
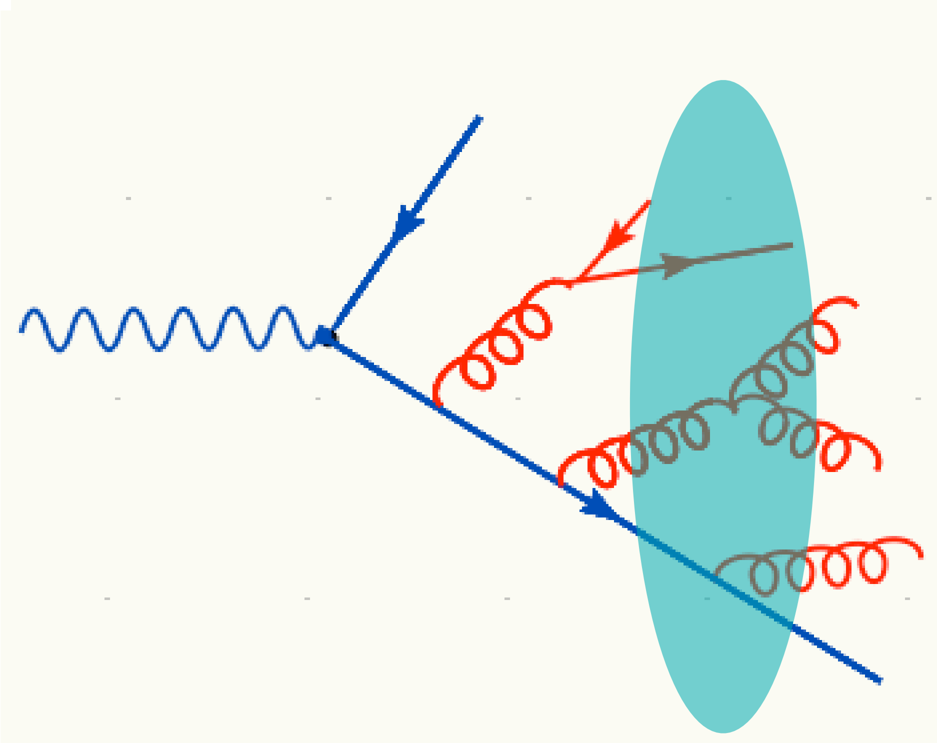
# Angular ordering





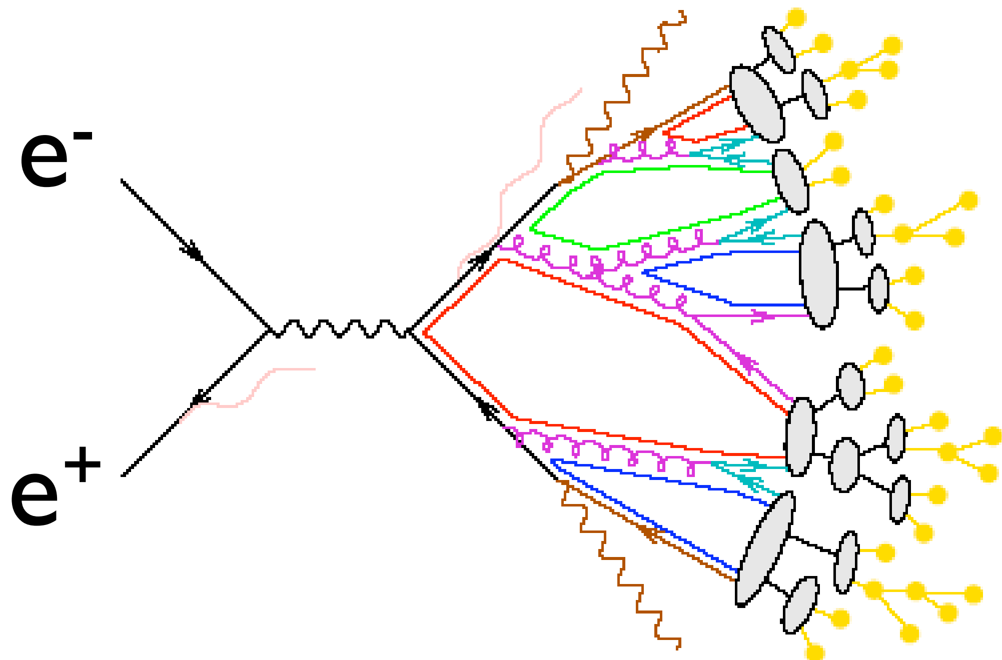
The construction can be iterated to the next emission, with the result that the emission angles keep getting smaller and smaller.

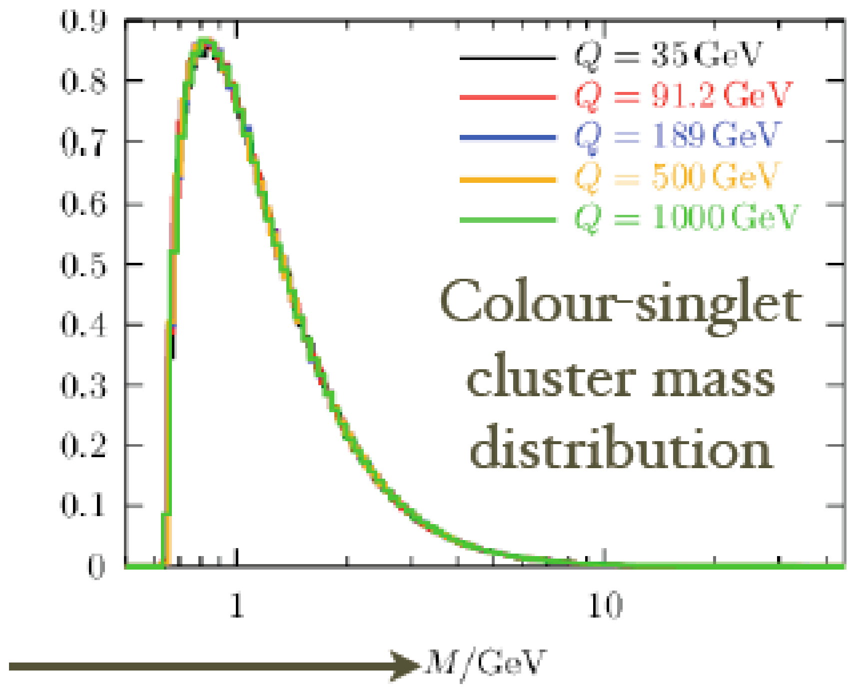
In fact one can generalize the treatment before to a generic parton of color charge $Q_k$ splitting into two partons i and j , $Q_k=Q_i+Q_j$. The result is that inside the cones i and j emit as independent charges, and outside their angular-order cones the emission is coherent and can be treated as if it was directly from color charge $Q_k$.

This has an effect on the multiplicity of hadrons in jets (INTRAjet radiation), since the radiation is more suppressed with respect to the total phase space available, which one would get from an incoherent radiation. Color ordering enforces coherence and leads to the proper evolution with energy of particle multiplicities.

# Monte Carlo approach to PS

The structure of the perturbative evolution, including angular ordering, leads naturally to the clustering in phase-space of color-singlet parton pairs (preconfinement). Long-range correlations are strongly suppressed. Hadronization will only act locally, on low-mass color singlet clusters.



# Parton Shower MC event generators

- General-purpose tools
- Always the first exp choice
- Complete exclusive description of the events: hard scattering, showering & hadronization, underlying event
- Reliable and well tuned tools.

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]

# A simple plan

- Physics challenges at the LHC
- Basics : QCD and MC's methods
- The new generation of MC tools
- New simulations for New Physics

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# How we (used to) make predictions?

## First way:

- For low multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)

  $\Rightarrow \quad \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$

TH

- For high multeplicity use the tree-level results

## Comments:

1. The theoretical errors systematically decrease.
2. Pure theoretical point of view.
3. A lot of new techniques and universal algorithms are developed.
4. Final description only in terms of partons and calculation of IR safe observables ⇒ not directly useful for simulations

# How we (used to) make predictions?

## Second way:

- Describe final states with high multiplicities starting from 2 → 1 or 2 → 2 procs, using parton showers, and then an hadronization model.

EXP

## Comments:

1. Fully exclusive final state description for detector simulations
2. Normalization is very uncertain
3. Very crude kinematic distributions for multi-parton final states
4. Improvements are only at the model level.

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

# ME vs PS

| ME | Shower MC |
| --- | --- |
| 1. parton-level description | 1. hadron-level description |
| 2. fixed order calculation | 2. resums large logs |
| 3. quantum interference exact | 3. quantum interference through angular ordering |
| 4. valid when partons are hard and well separated | 4. valid when partons are collinear and/or soft |
| 5. needed for multi-jet description | 5. nedeed for realistic studies |

Difficulty: avoid double counting

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**Approaches are complementary: merge them!**

**Difficulty: avoid double counting**

# How to improve our predictions?

New trend: TH & EXP

Match fixed-order calculations and parton showers to obtain the most accurate predictions in a detector simulation friendly way!

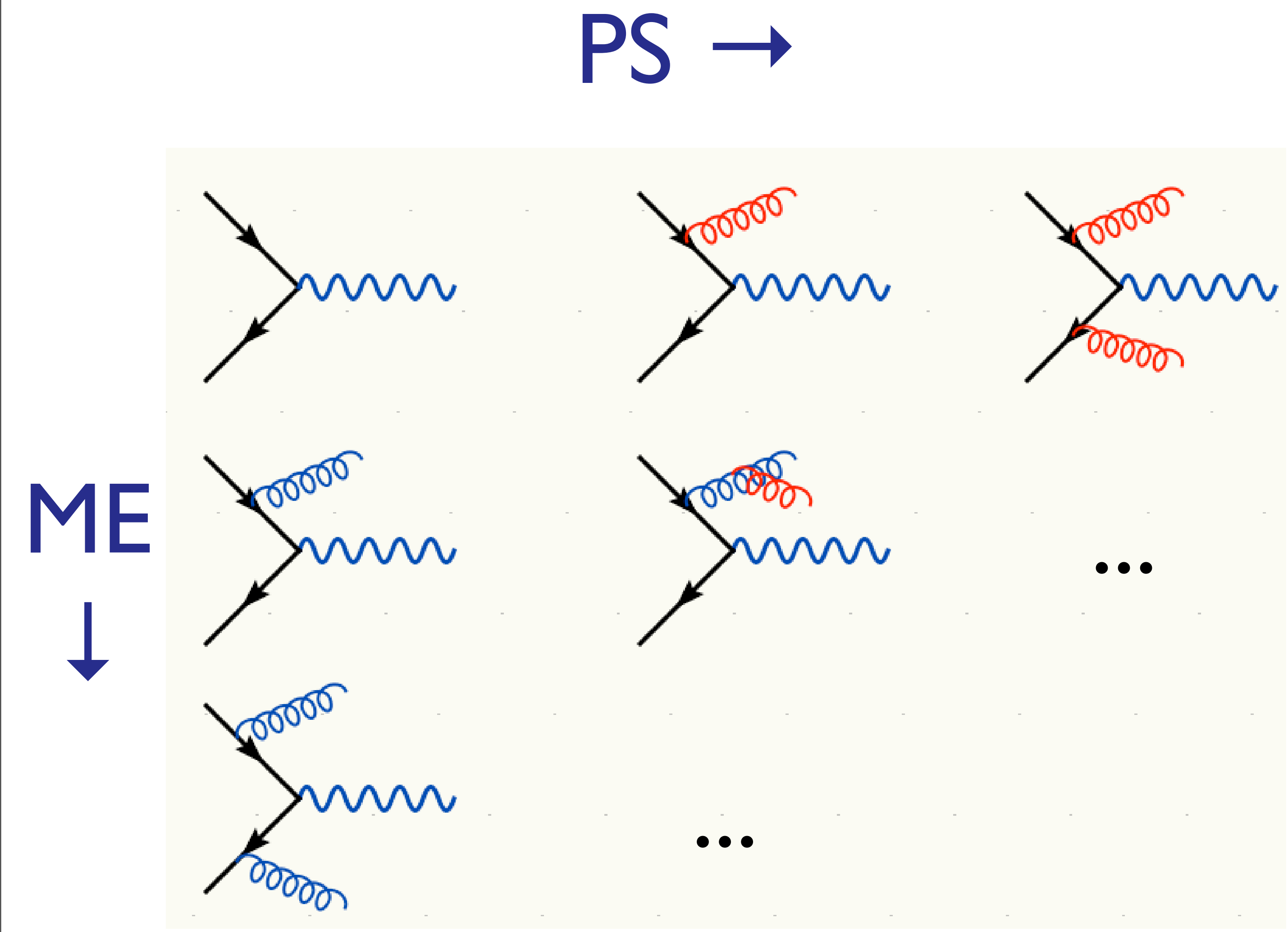
Two directions:

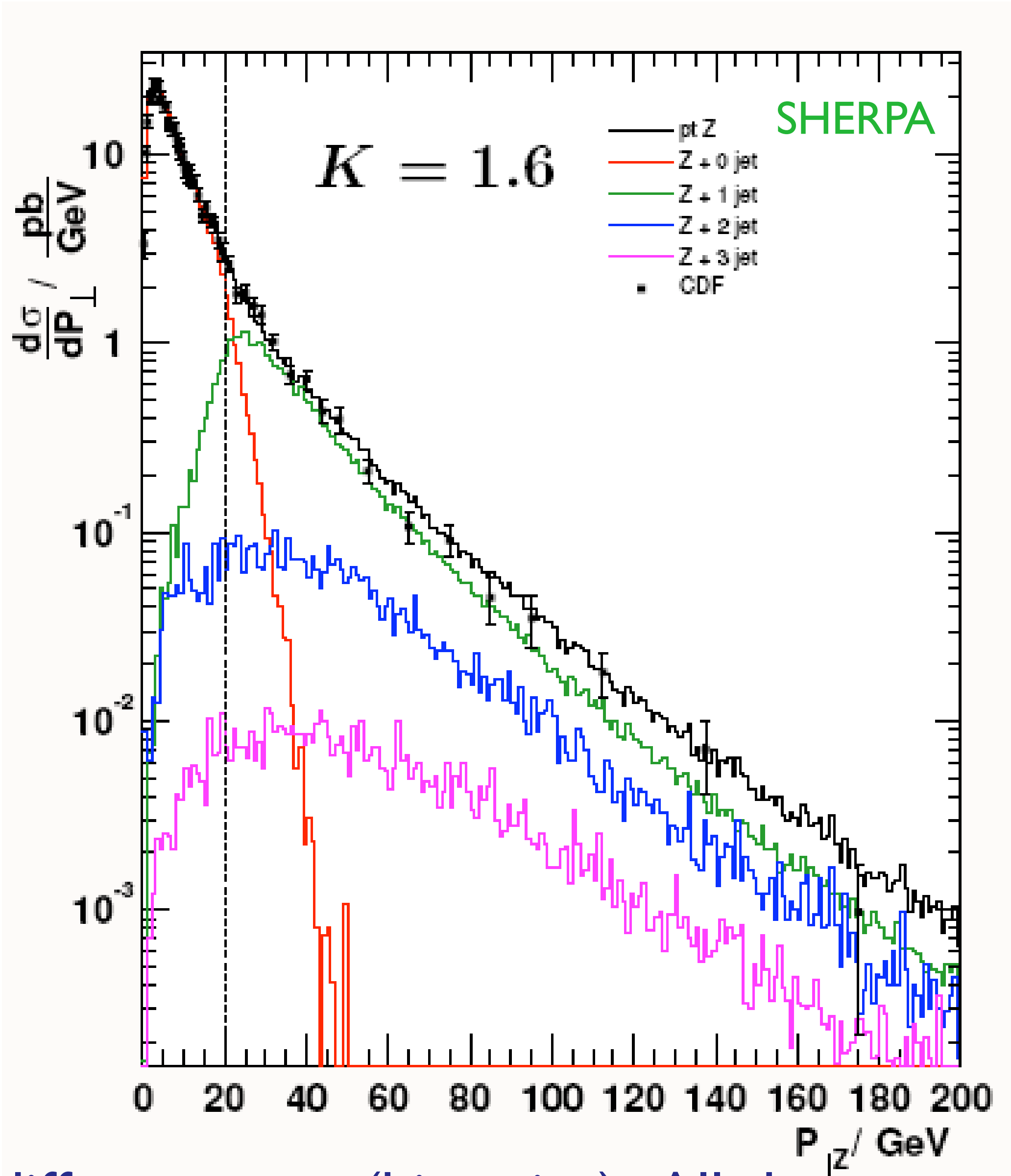
1. Get fully exclusive description of many parton events correct at LO (LL) in all the phase space. ME+PS

2. Get fully exclusive description of events correct at NLO in the normalization and distributions. NLOwPS

# Merging fixed order with PS

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



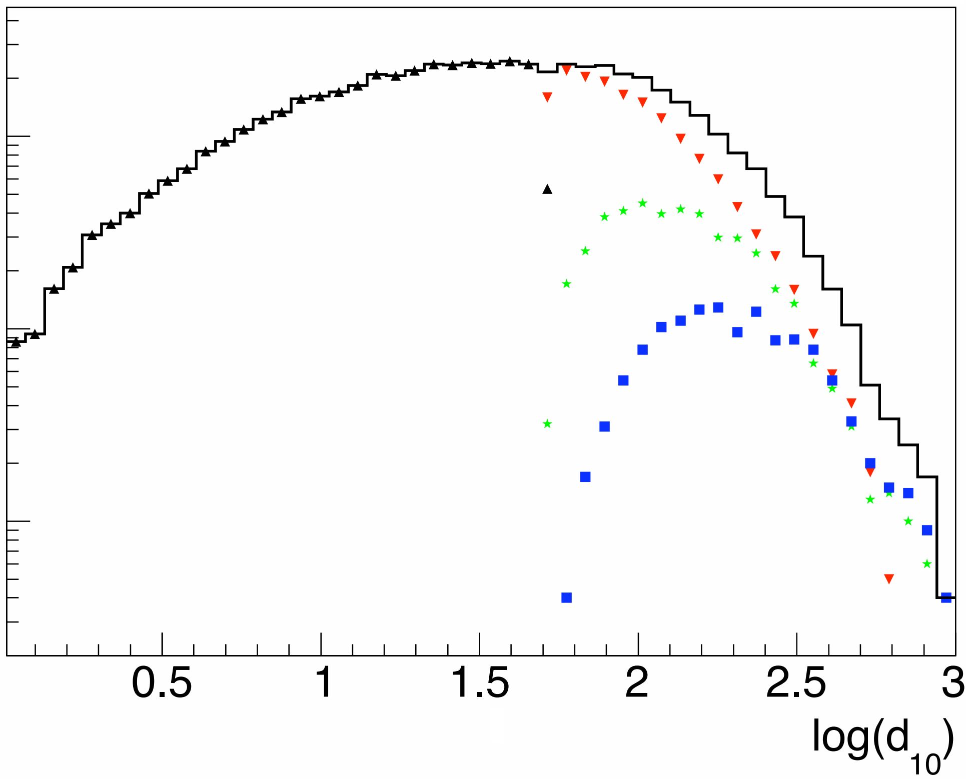



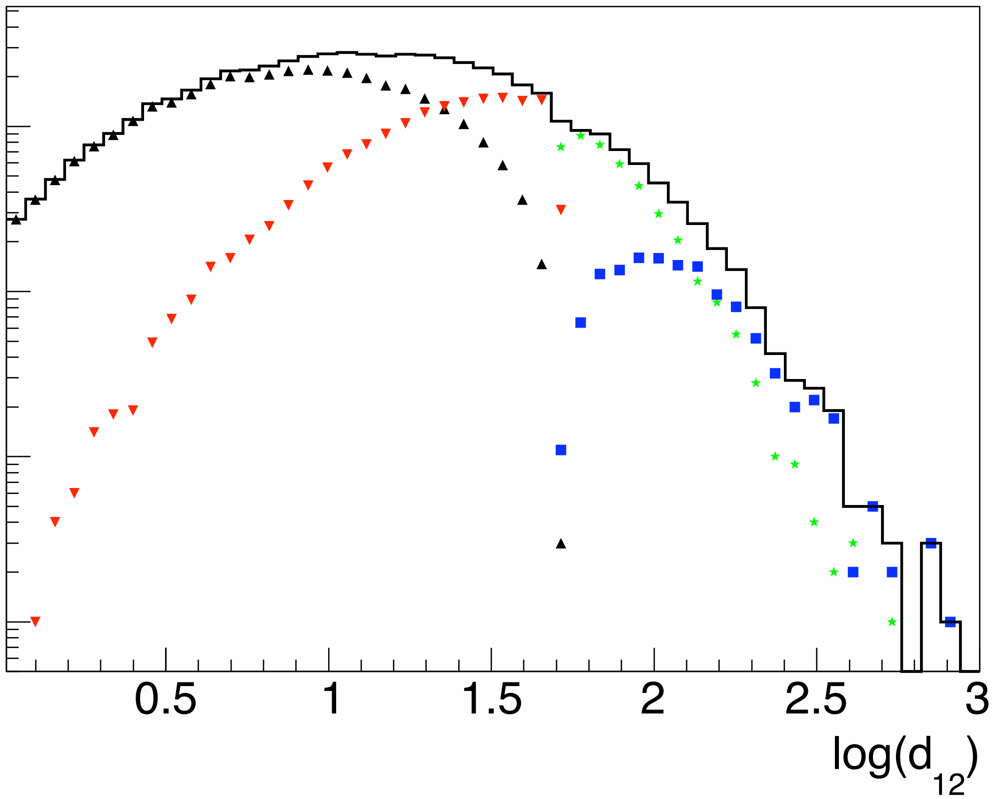

Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample. Distributions are accurate but overall normalization still "arbitrary".

# The MLM matching algorithm

- Generate events with the ME, using hard partonic cut, e.g., $p_T > p_{Tmin}$, $\Delta R_{jj} > \Delta R_{MIN}$, (Alpgen) or with a $k_T$ algorithm (MadEvent).
- Reweight the event to optimize scale choices.
- Shower the event and jet-cluster it (with the same algorithm).
- Require the original partons to be one-to-one associated to the jets.

# Sanity checks: differential jet rates




Jet rates are smooth at the cutoff scale

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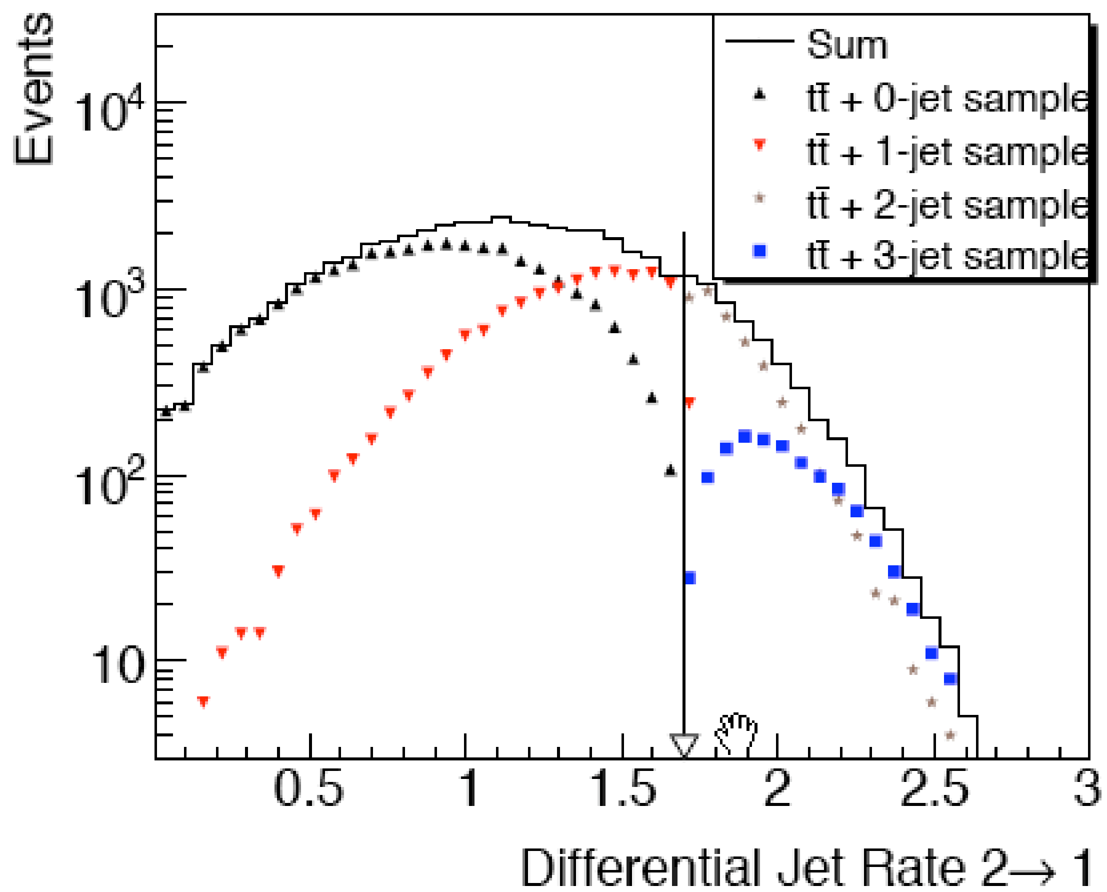
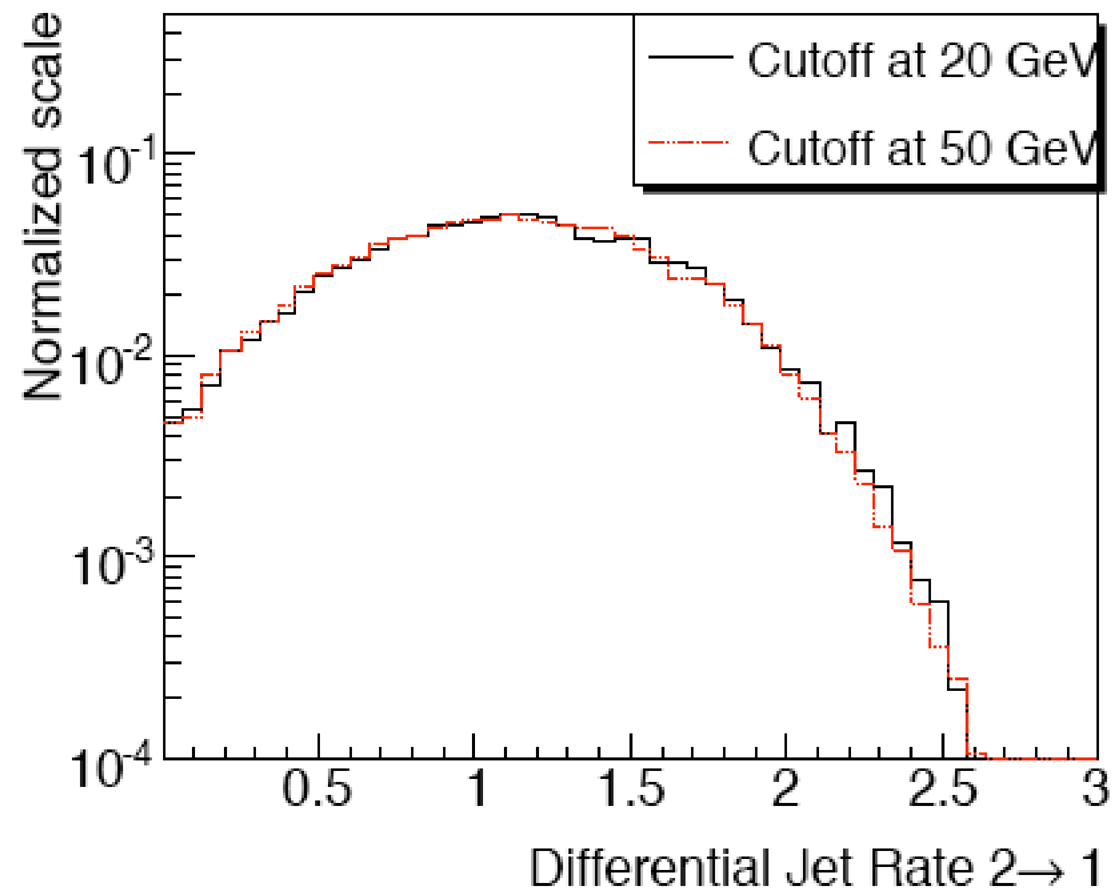
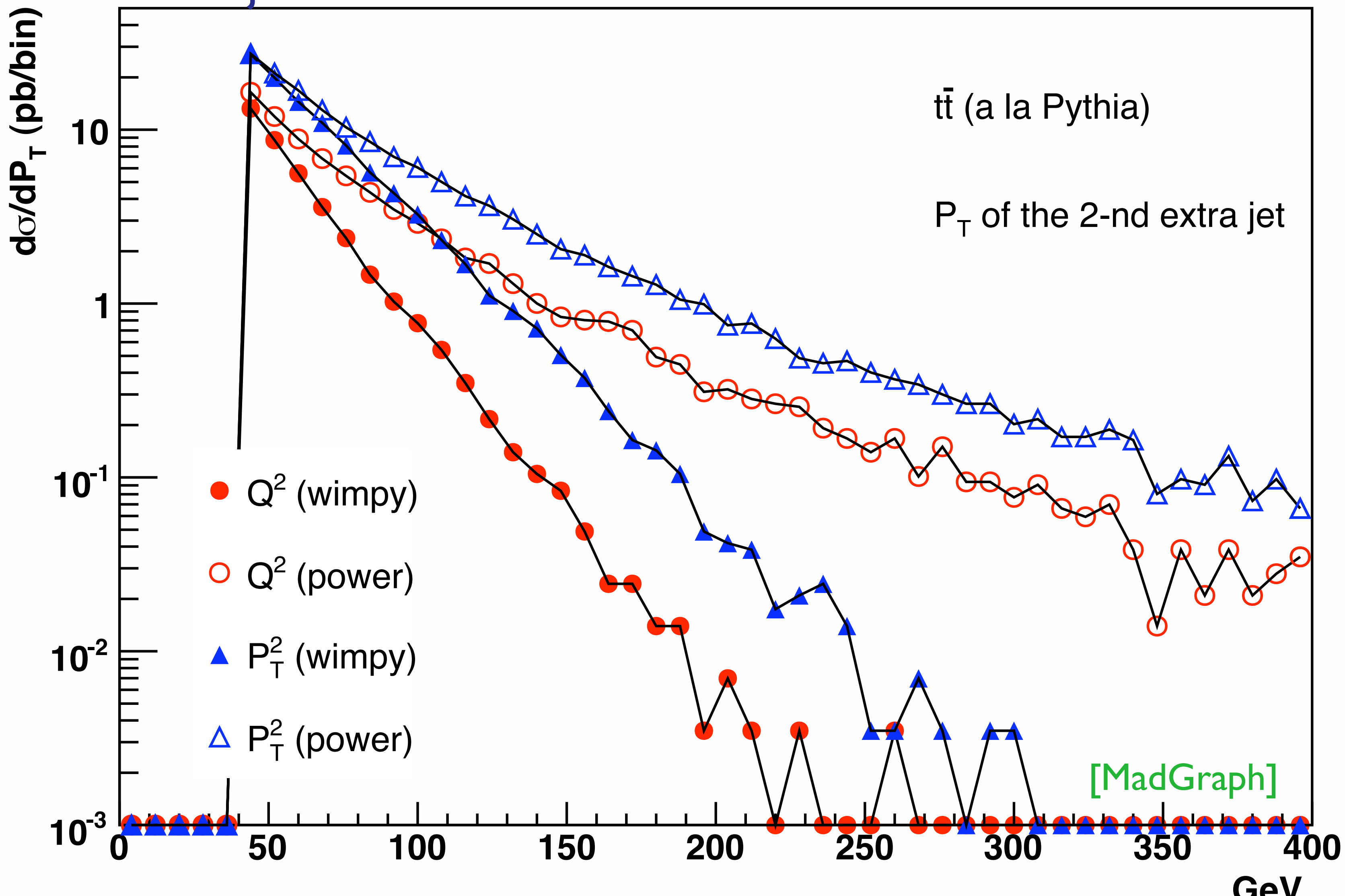



Jet rates are independent of the cutoff scale

# PS alone vs matched samples

A MC Shower like Pythia produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution of the second jet in ttbar events:




Changing some choices/parameters leads to huge differences ⇒ self diagnosis. Trying to tune the log terms to make up for it is not a good idea ⇒ mess up other regions/shapes, process dependence.

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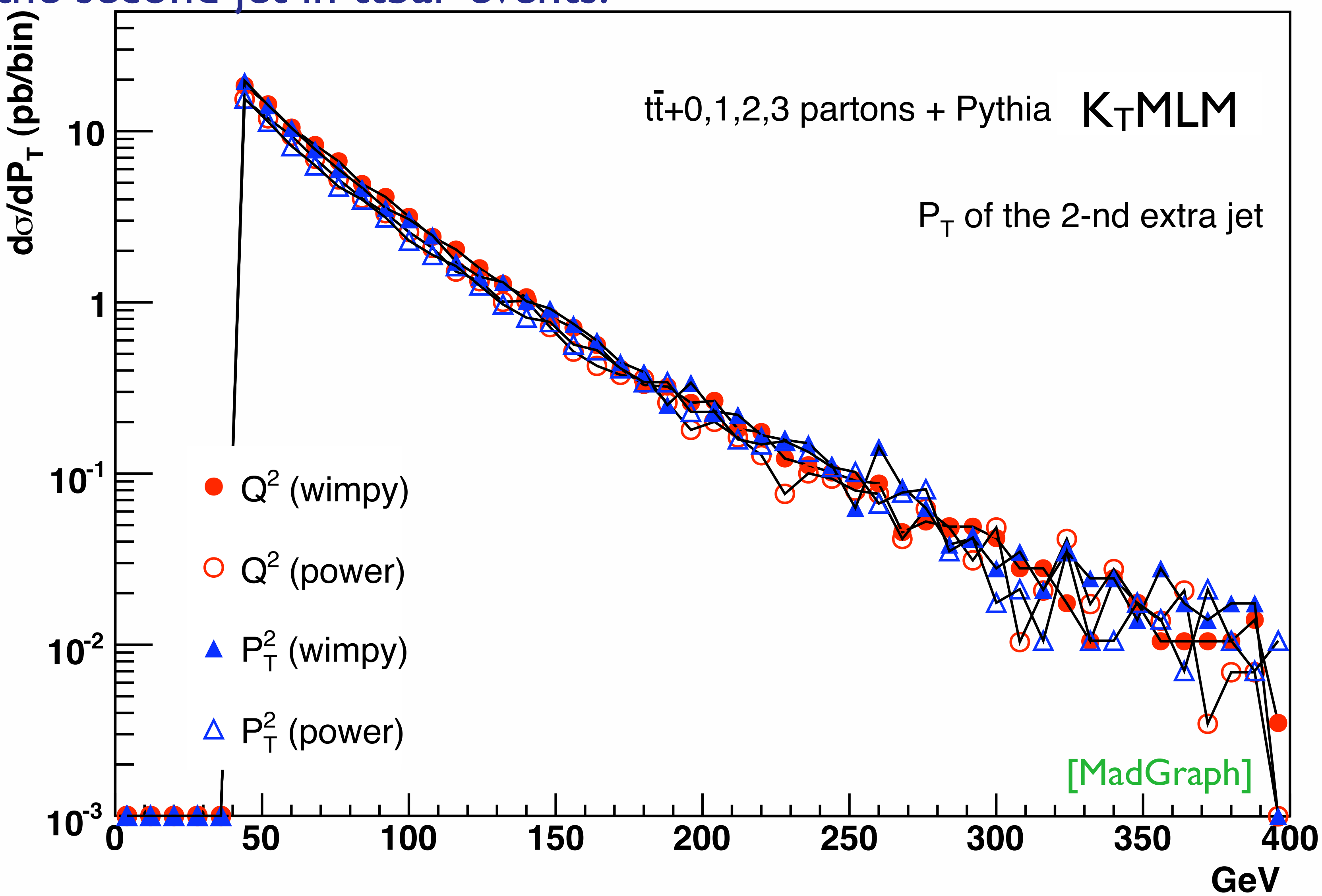
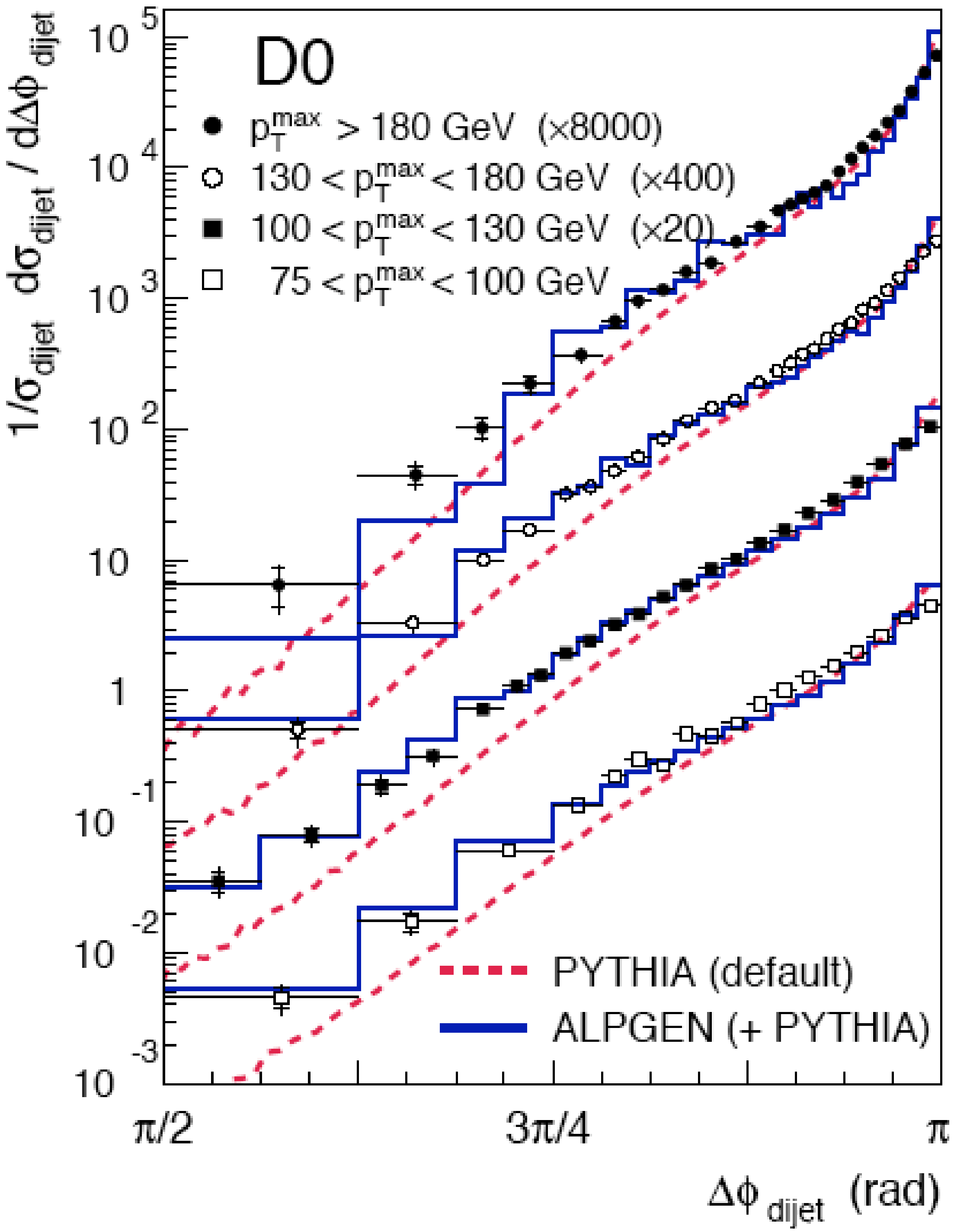
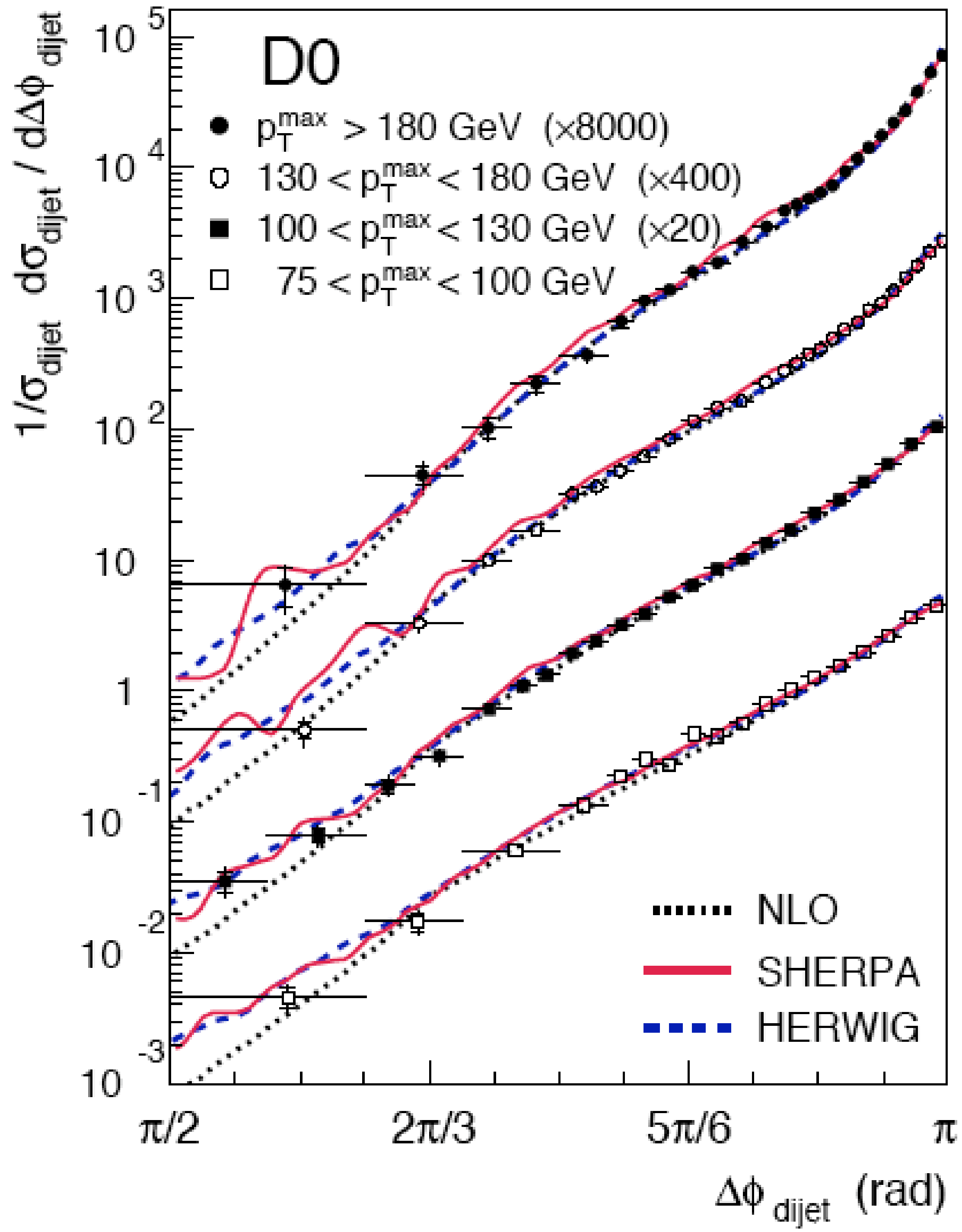
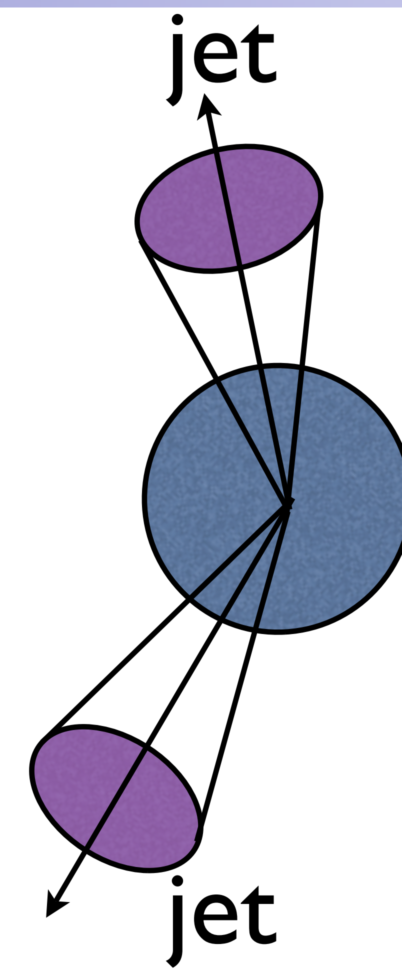



In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

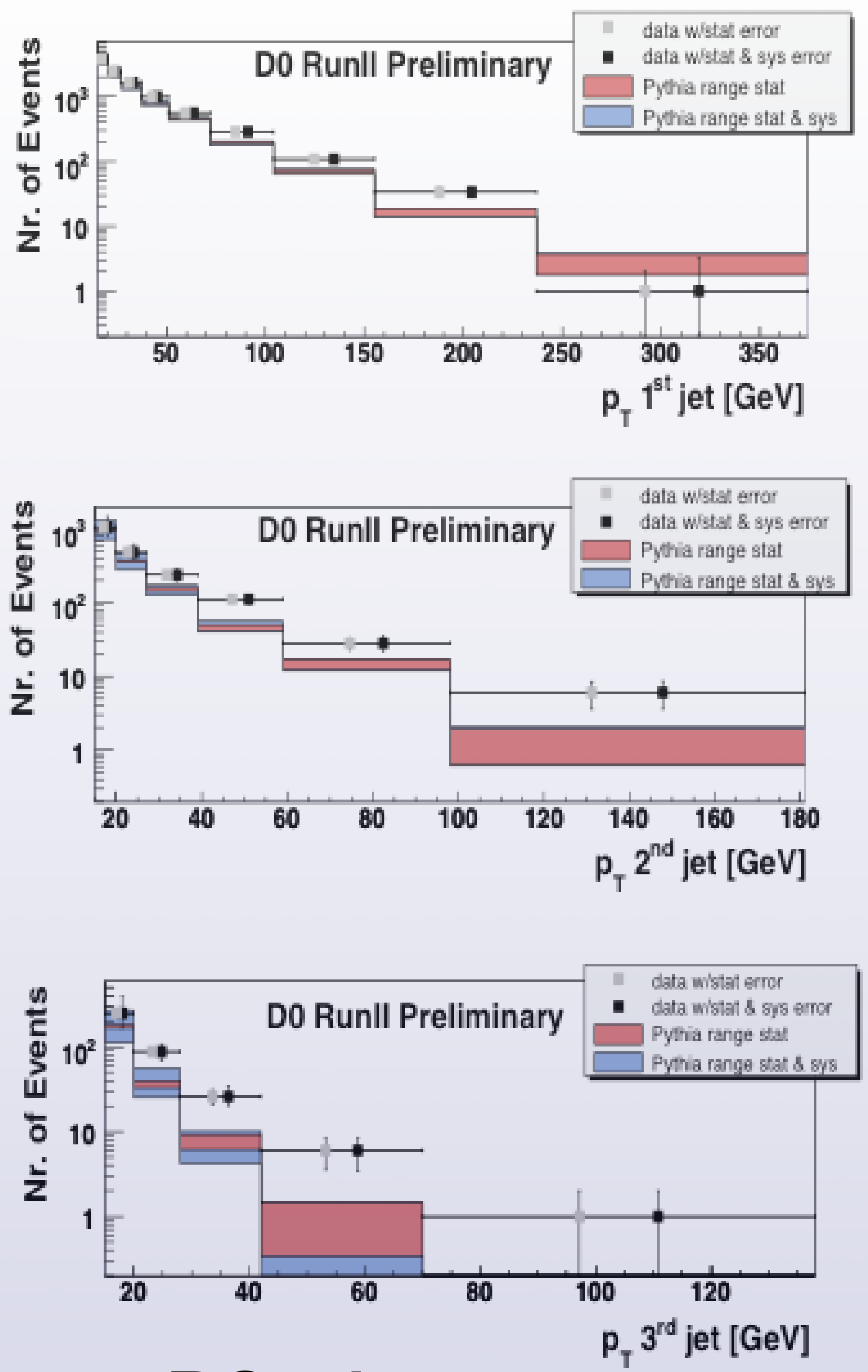
# Angular decorrelations pp→2j events



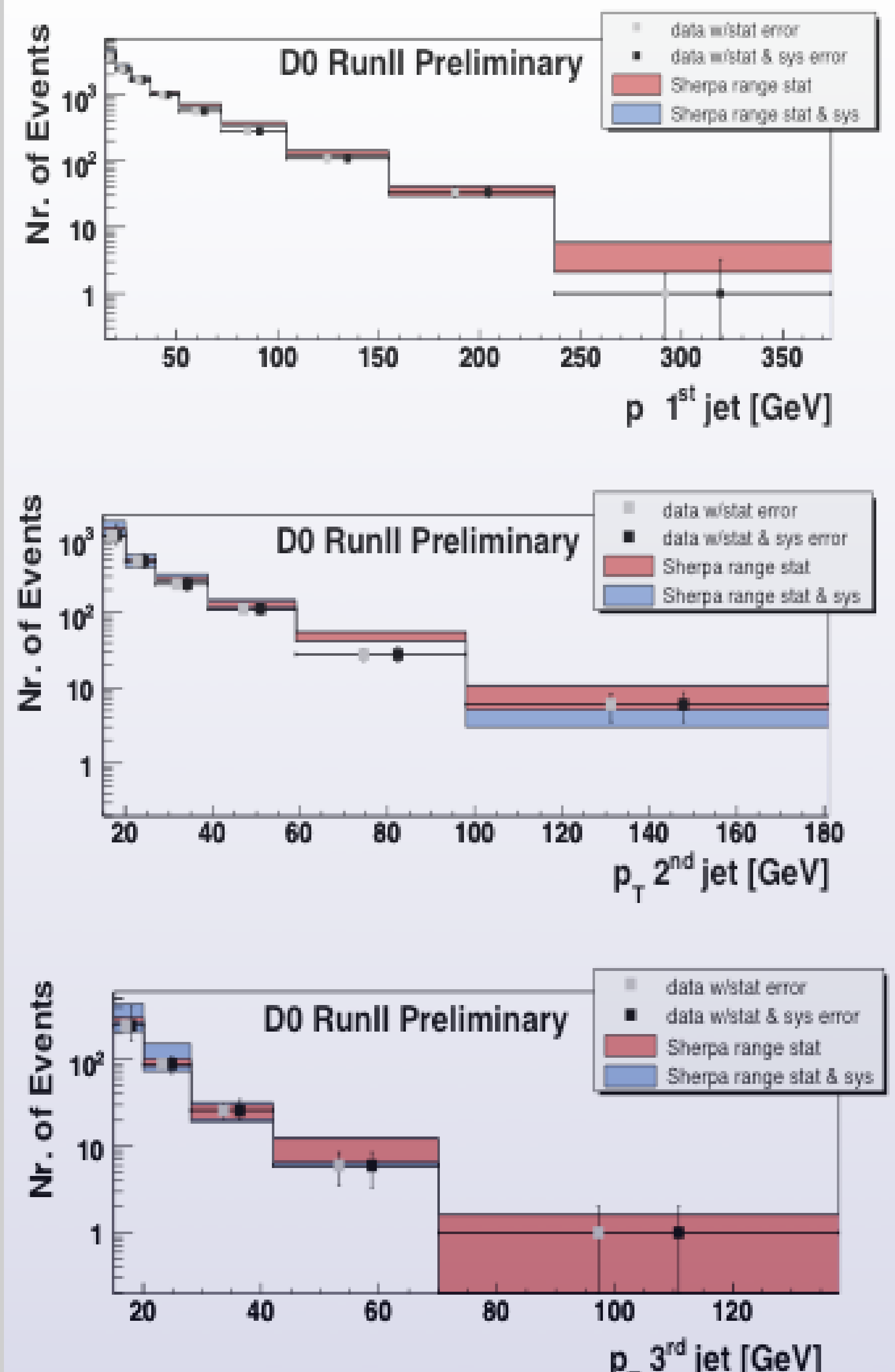



# PS alone vs matched samples : Z+jets at D0

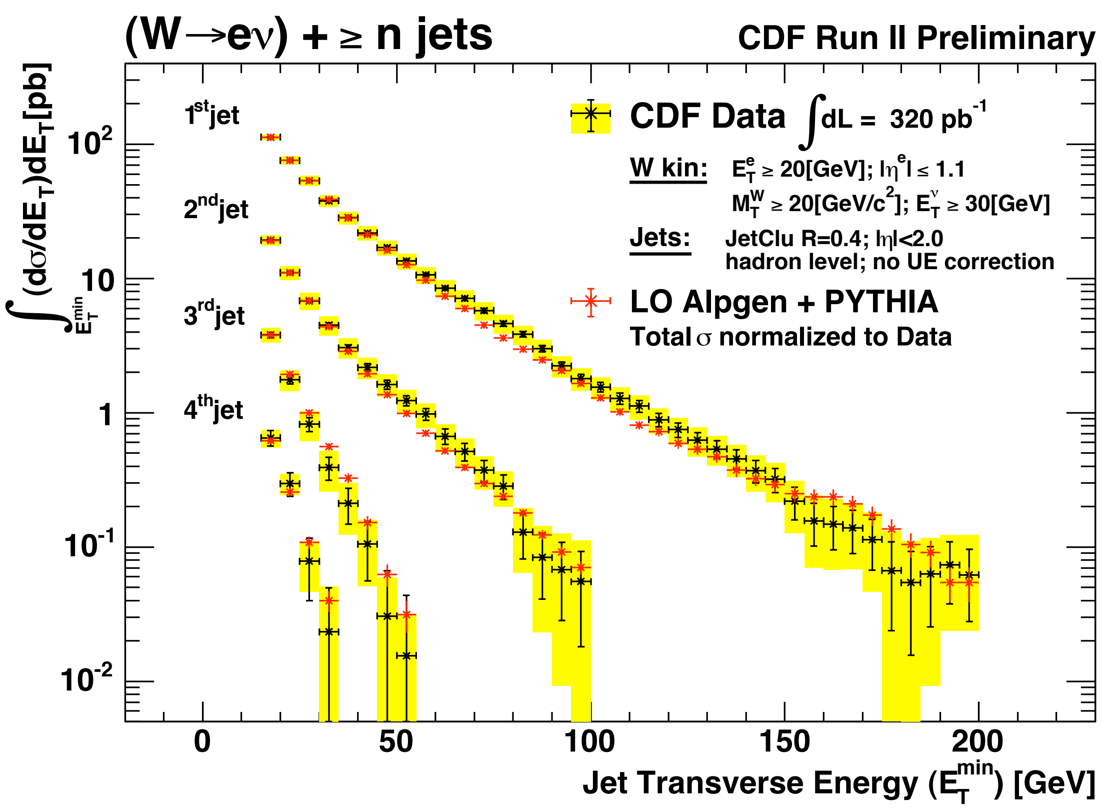


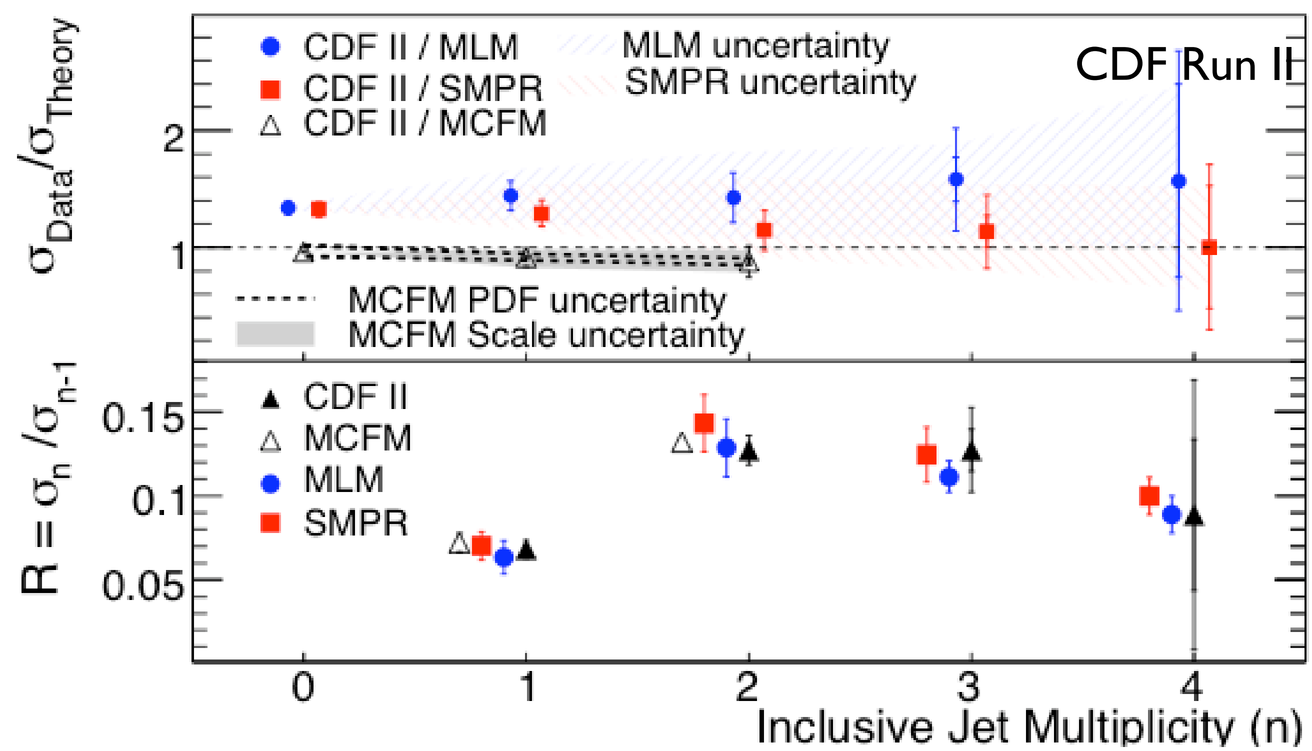

PS alone (Pythia)




ME+PS (SHERPA)

# W+jets at CDF




* Very good agreement in shapes (left) and in relative normalization (right).

* NLO rates in outstanding agreement with data.

* Matched samples obtained via different matching schemes (MLM and CKKW) consistent within the expected uncertaintes. Differences might arise in more exclusive quantities.

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- The matching (à la CKKW) has been rigorously proved in e+e- collisions and it is believed to be true also in pp collisions. The MLM matching is problematic in e+e- and just a prescription in pp, where, however, seem to work really well.

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- Since no exact virtual contribution is included the normalization of the cross section is uncertain and it has to be obtained from a NLO calculation.
- On the other hand, shapes (and often even normalizations) are (so far) in very good agreement with NLO.

# NLOwPS

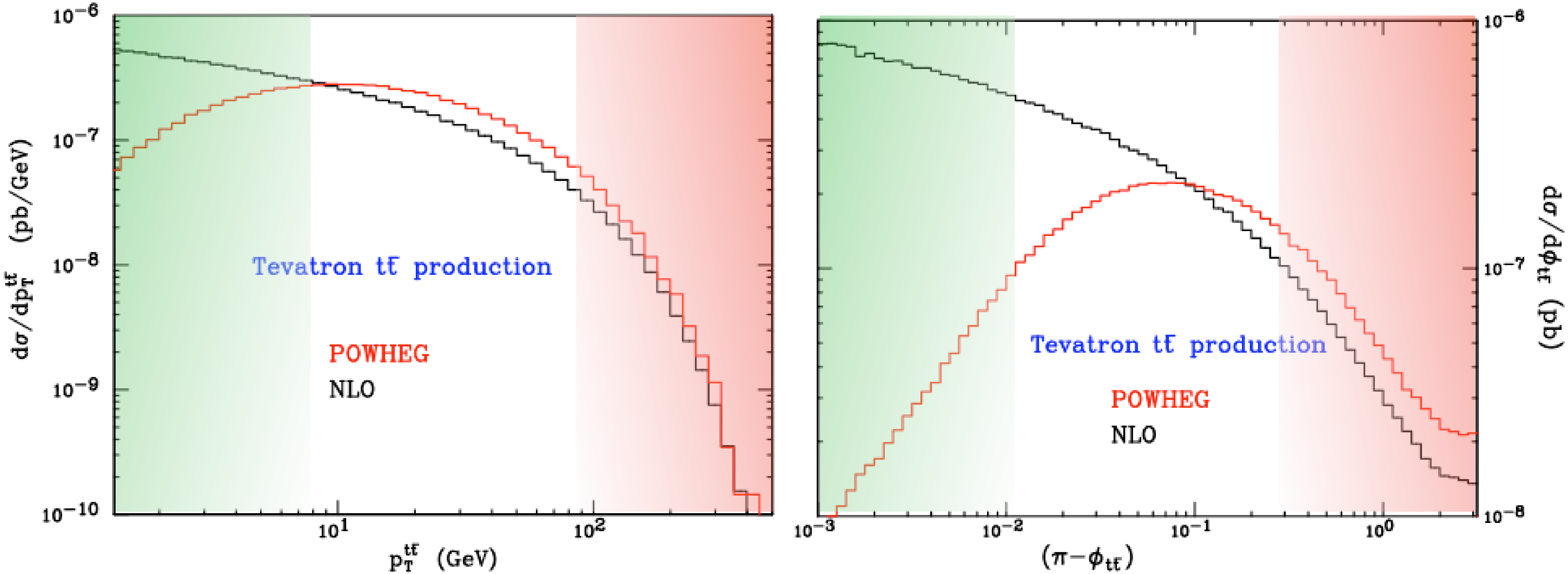
Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

Current available (and working) solutions:

MC@NLO [Frixione, Webber, 2003; Frixione, Nason, Webber, 2003]
- Matches NLO to HERWIG angular-ordered PS.
- "Some" work to interface an NLO calculation to HERWIG. Uses only FKS subtraction scheme.
- Some events have negative weights.
- Sizable library of procs now.

POWHEG [Nason 2004; Frixione, Nason, Oleari, 2007]
- Is independent from the PS. It can be interfaced to PYTHIA or HERWIG.
- Can use existing NLO results.
- Generates only positive unit weights.
- For top only ttbar (with spin correlations) is available so far.

# ttbar : NLOwPS vs NLO




* Soft/Collinear resummation of the $p_T(tt) \to 0$ region.
* At high $p_T(tt)$ it approaches the tt+parton (tree-level) result.
* When $\Phi(tt) \to 0$ ($\Phi(tt) \to \pi$) the emitted radiation is hard (soft).
* Normalization is FIXED and non trivial!!

# NLOwPS

"Best" tools when NLO calculation is available (i.e. low jet multiplicity).

* Main points:

  * NLOwPS provide a  consistent to include K-factors into MC's
  * Scale dependence is meaningful
  * Allows a correct estimates of the PDF errors.
  * Non-trivial dynamics beyond LO included for the first time.

N.B. : The above is true for observables which are at NLO to start with!!!

* Current limitations:

  * Considerable manual work for the implementation of a new process.
  * Only SM.
  * Only available for low multiplicity.

# A look into the future

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Leading Order :

* fully automatized + matching algorithms
* Continuously improved : new ideas for showers, better hadronization/ underlying events), better matrix element generators, new matching schemes.
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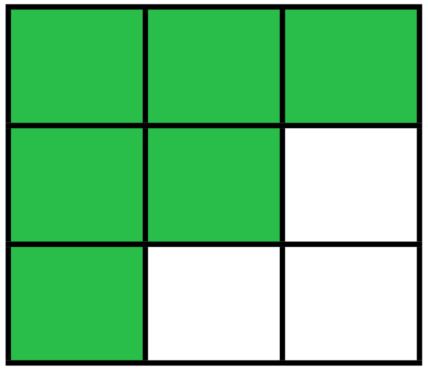
Basics covered, room for improvement

## Next-to-leading Order :

* Automatic generation of reals + counterterms available
* General framework for interfacing to the shower (POWHEG)
* Impressive results in automatic 1-loop computations [BlackHat, Rocket, Cuttools]



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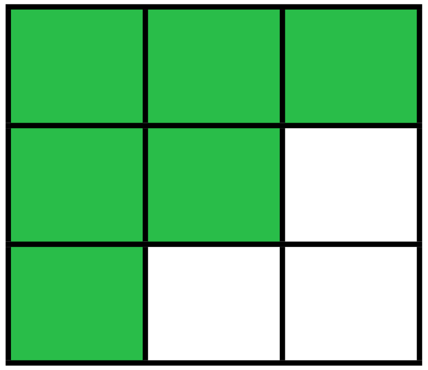
Leading Order :

* fully automatized + matching algorithms
* Continuously improved : new ideas for showers, better hadronization/ underlying events), better matrix element generators, new matching schemes.
* Several fully working frameworks available.

Basics covered, room for improvement

Next-to-leading Order :

* Automatic generation of reals + counterterms available
* General framework for interfacing to the shower (POWHEG)
* Impressive results in automatic 1-loop computations [BlackHat, Rocket, Cuttools]



Fully automatized NLOwPS in sight

# Tools

New generation of integrated/interfaced tools:

- Example I:
  SHERPA, Matrix Element generator + PS with CKKW

- Example II:
  AlpGen + Pythia or Herwig, ME + PS with MLM
  MadGraph + Pythia or Herwig, ME + PS with MLM (or CKKW)
  ...

- Example III :
  MC@NLO, NLO + HERWIG with Frixione-Webber method.
  POWHEG tools, NLO + PS with Nason et al. method (POWHEG).
  HERWIG++, NLO + new HERWIG with POWHEG method.

More tools/techniques for merging under continuous development:
VINCIA, GENEVA, Dipole Showers,CKKW-NLO,....

# #5

Tree-level based MC's are less accurate than those at NLO.

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It depends

Again, it depends on the observable. A NLO code can only provide some observable at NLO, and in particular not those with extra-jets.

Example : t tbar in NLOwPS vs t tbar + jets matched.

Overall normalization : better t tbar at NLO
pt of the first jet : the same accuracy
pt of the 2nd jet : better the t tbar matched sample

So, if I am considering ttbar as a signal, most probably NLOwPS is the best tool.

While if I am considering ttbar as a background to SUSY or to tt h with h->b bbar, the matched sample is a better approximation.

# Status : SM

pp→ n particles

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pp→ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

# Status : SM

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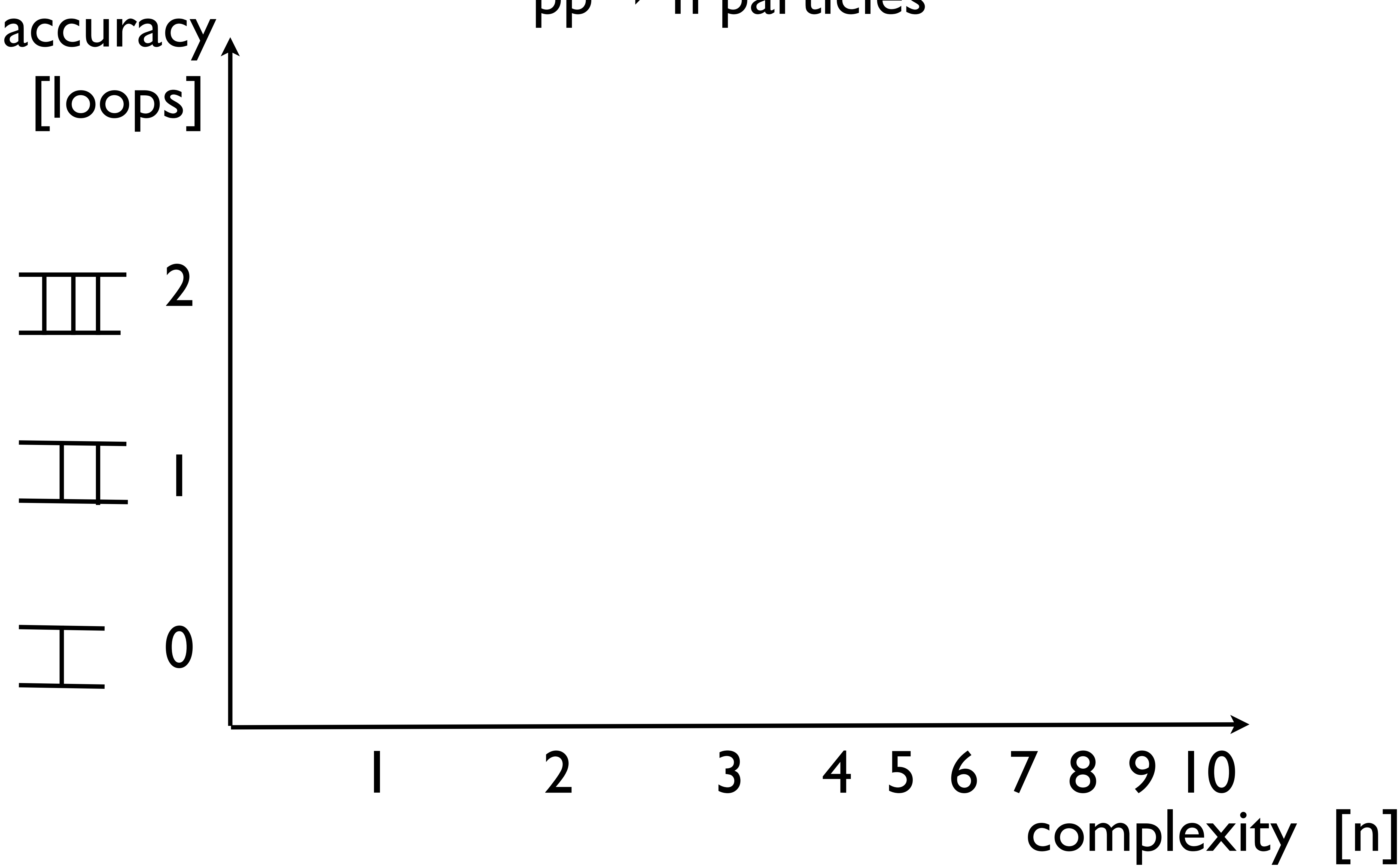

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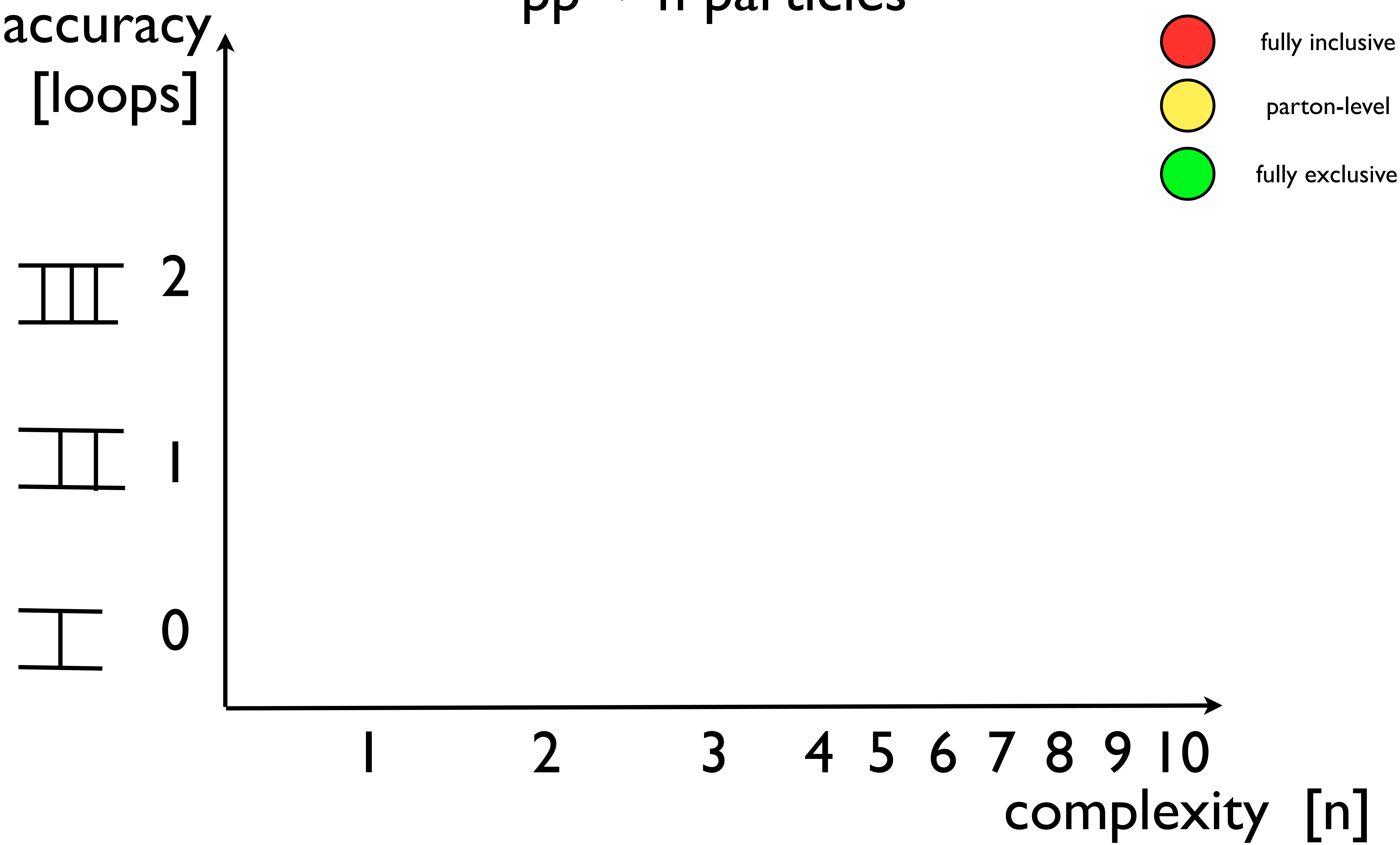

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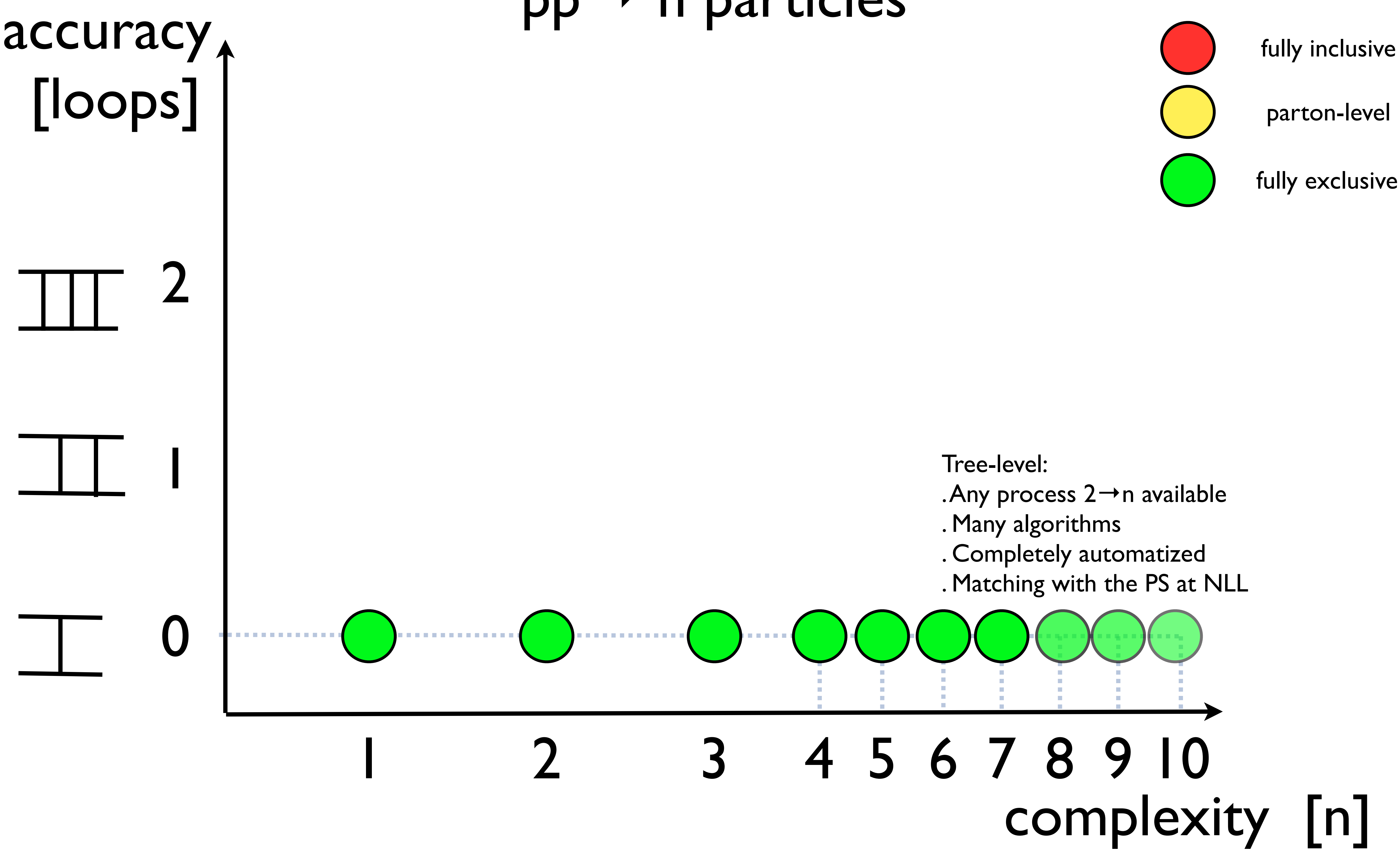

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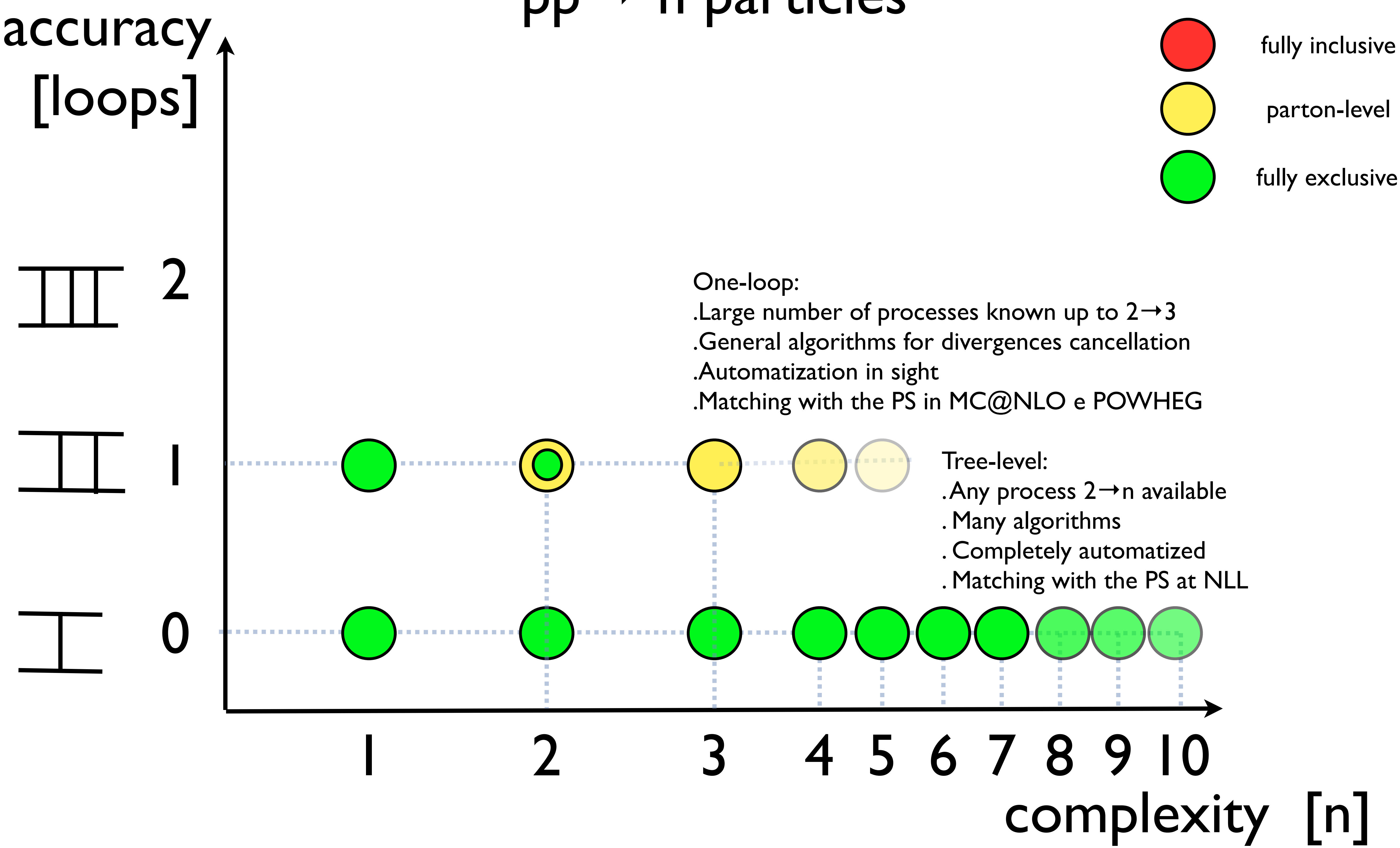

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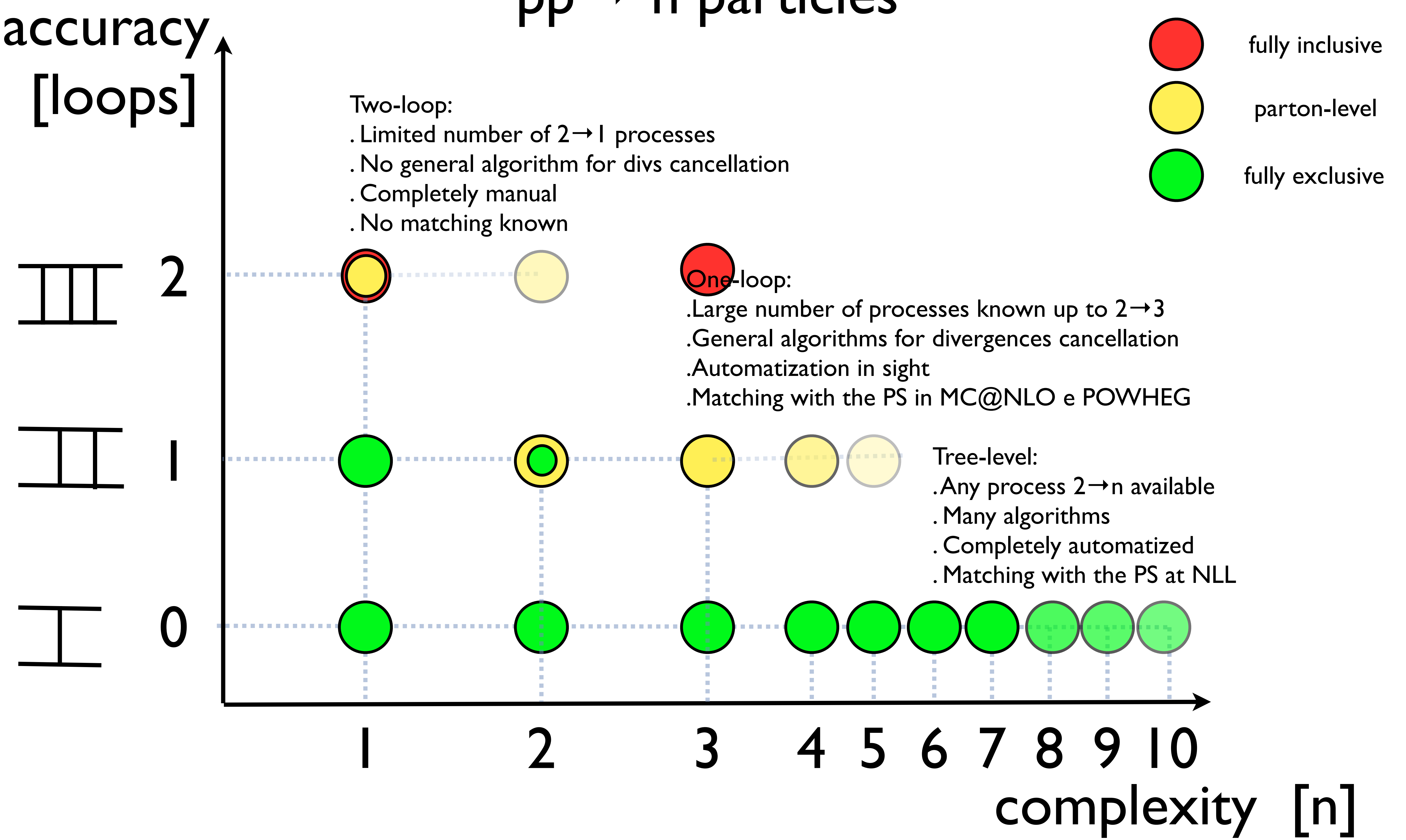

# A simple plan

- Physics challenges at the LHC
- Basics : QCD and MC's methods
- The new generation of MC tools
- New simulations for New Physics

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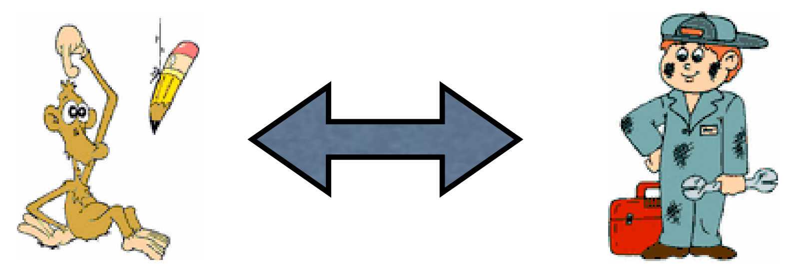
# What about BSM?

Two main (related) issues:

1. A plethora of BSM proposals exist to be compared with data. It will be essential to have an efficient, validated MC framework for theorists to communicate with experimentalits their idea (and viceversa).



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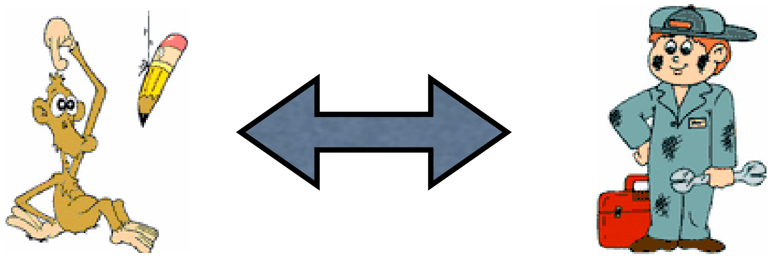

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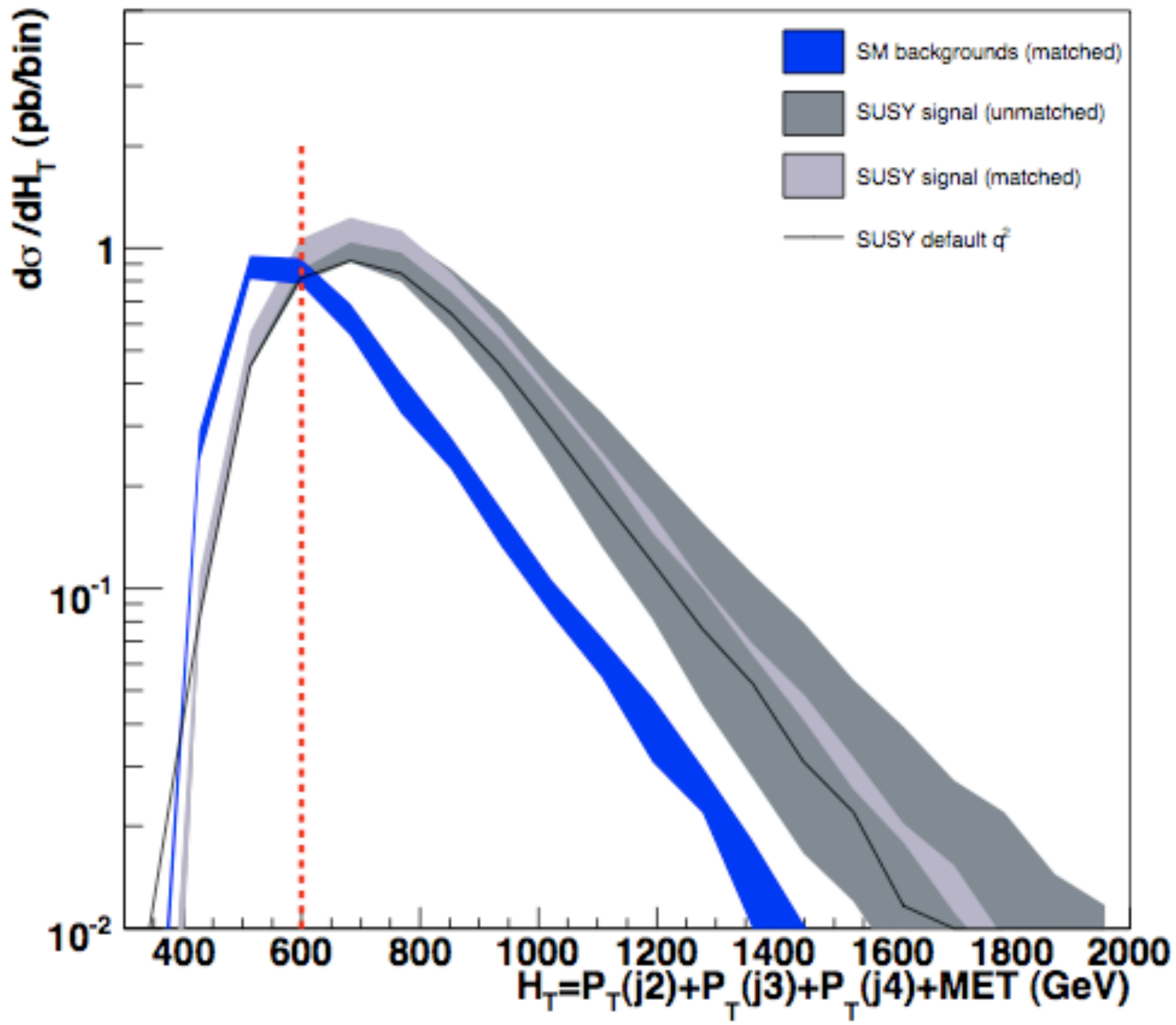
# BSM @ LHC : present

[Alwall, de Visscher, FM, 2009]



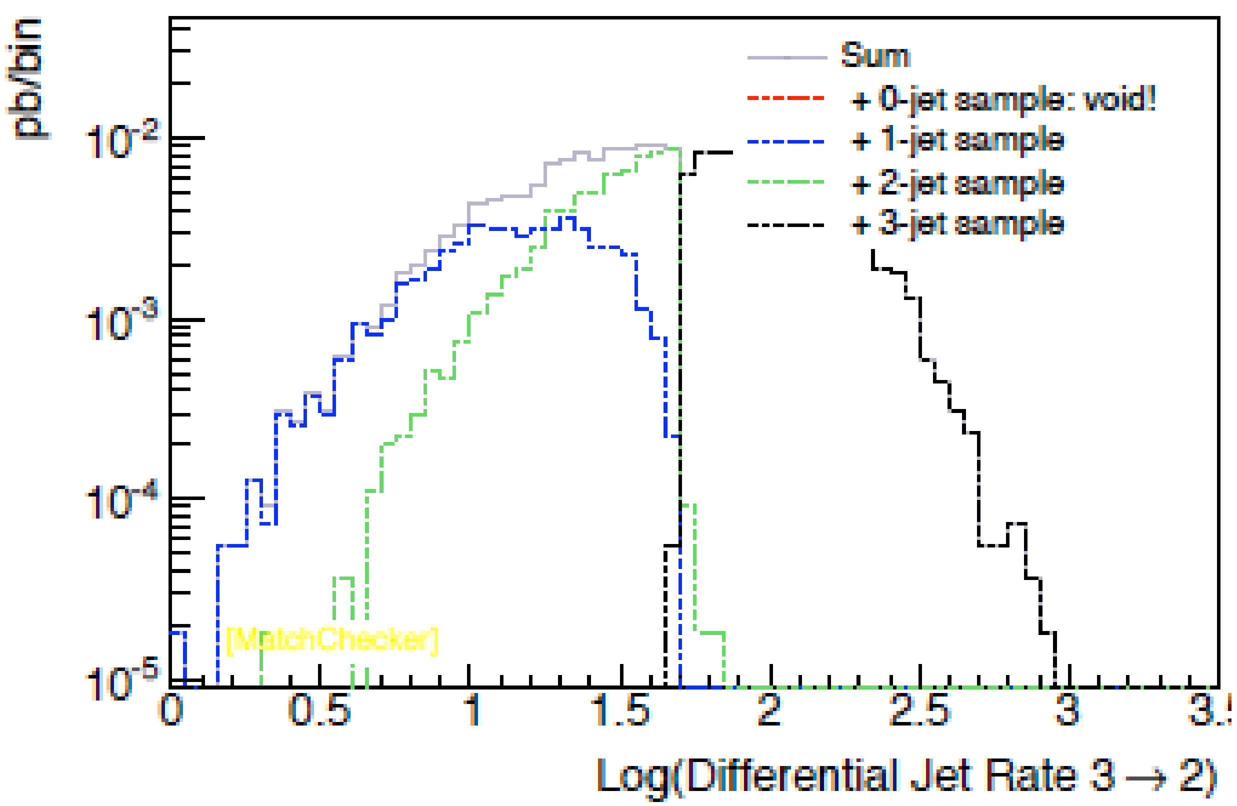

Both signal and background matched!

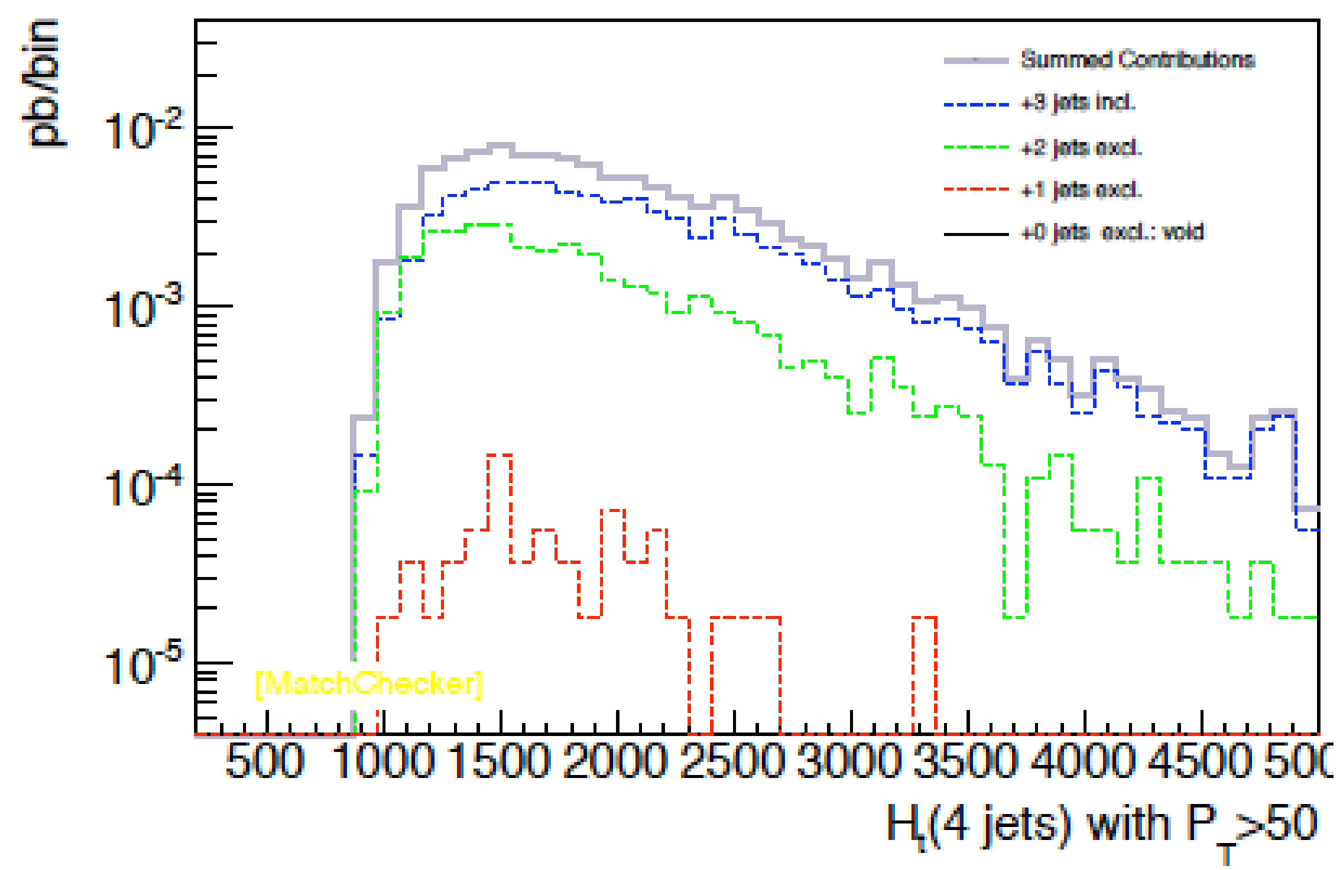
Sizable reduction of the uncertainties. Overall picture unchanged for SPS1a.

# Gravitons

[K. Hagiwara, J. Kanzaki, Q. Li and K. Mawatari, 2009]
[P. de Aquino, K. Hagiwara, Q. Li, F. M. ]

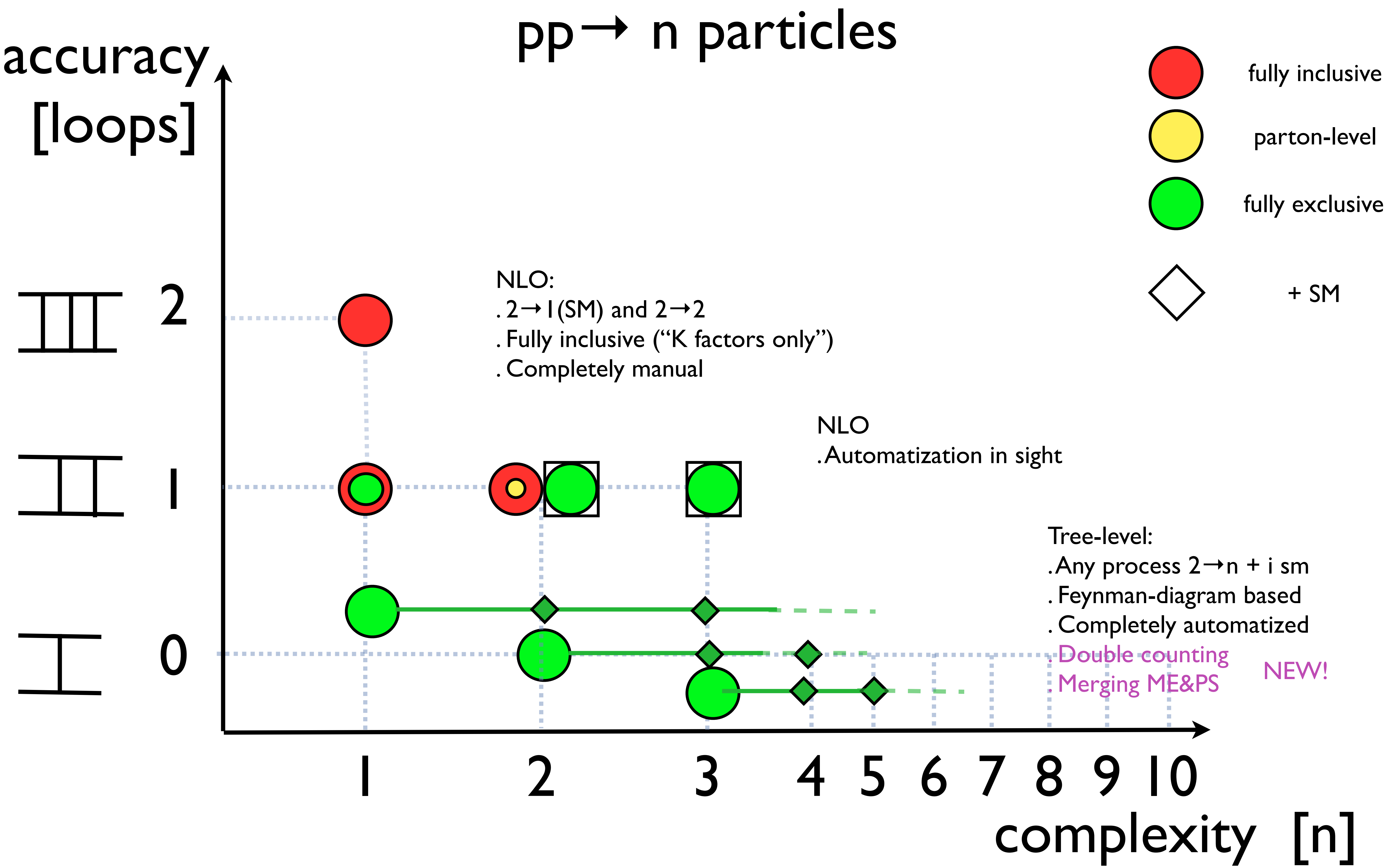
- Fixed mass gravitons (RS and also mG=0)
- ADD gravitons also available : challenging due peculiar "propagator" : this is automatically handled in MG now.




Works out of the box..

# BSM : status and outlook



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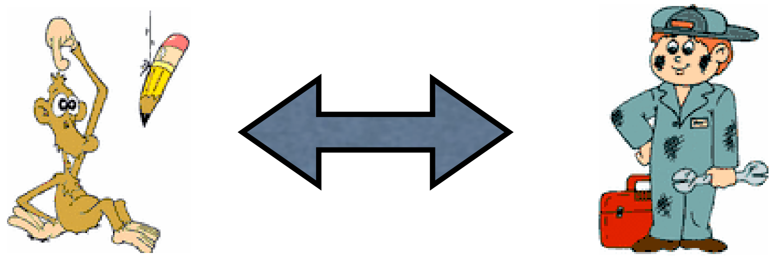

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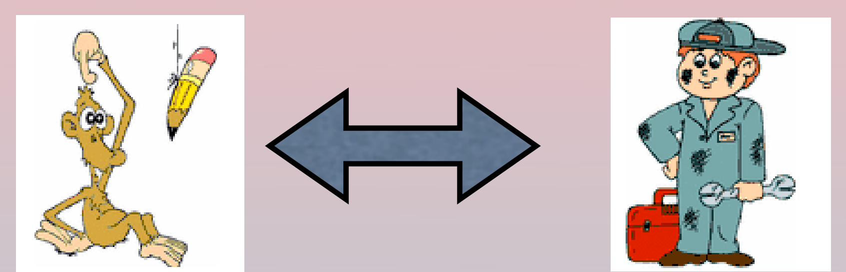

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# A Roadmap (with roadblocks) for BSM @ the LHC

TH

EXP

Idea

Data

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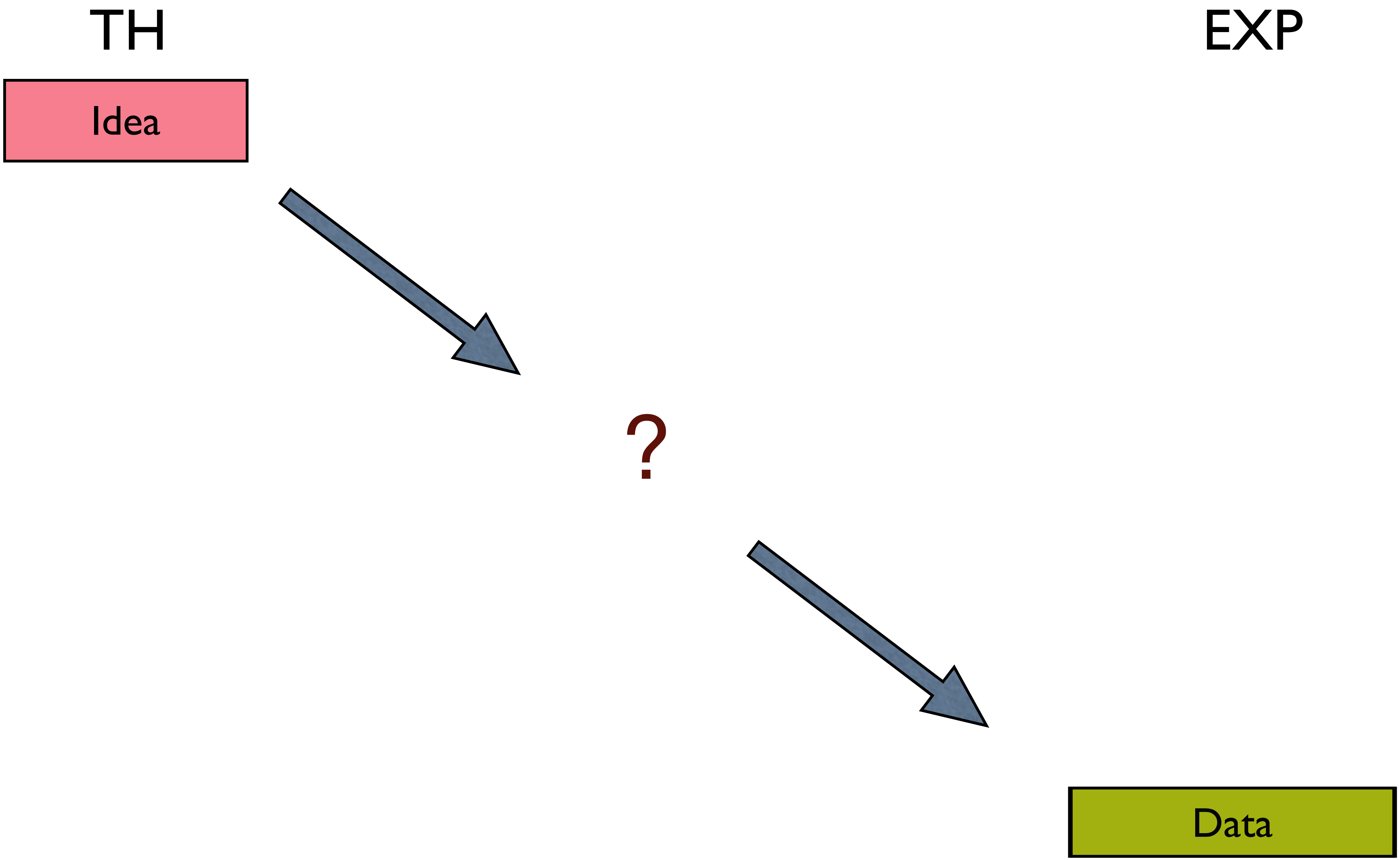

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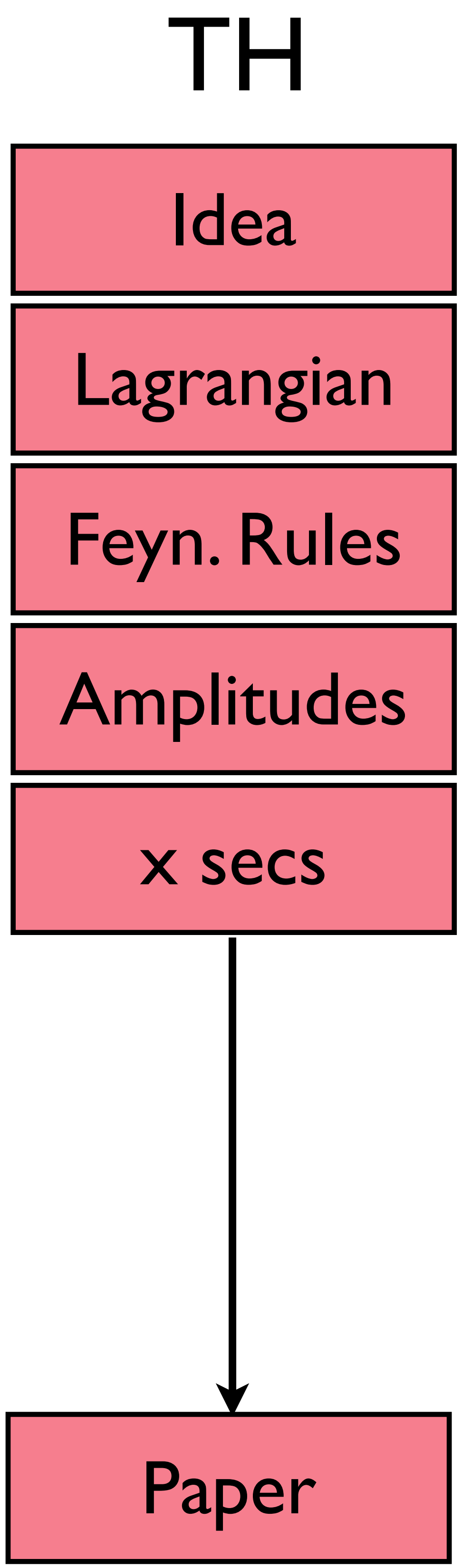

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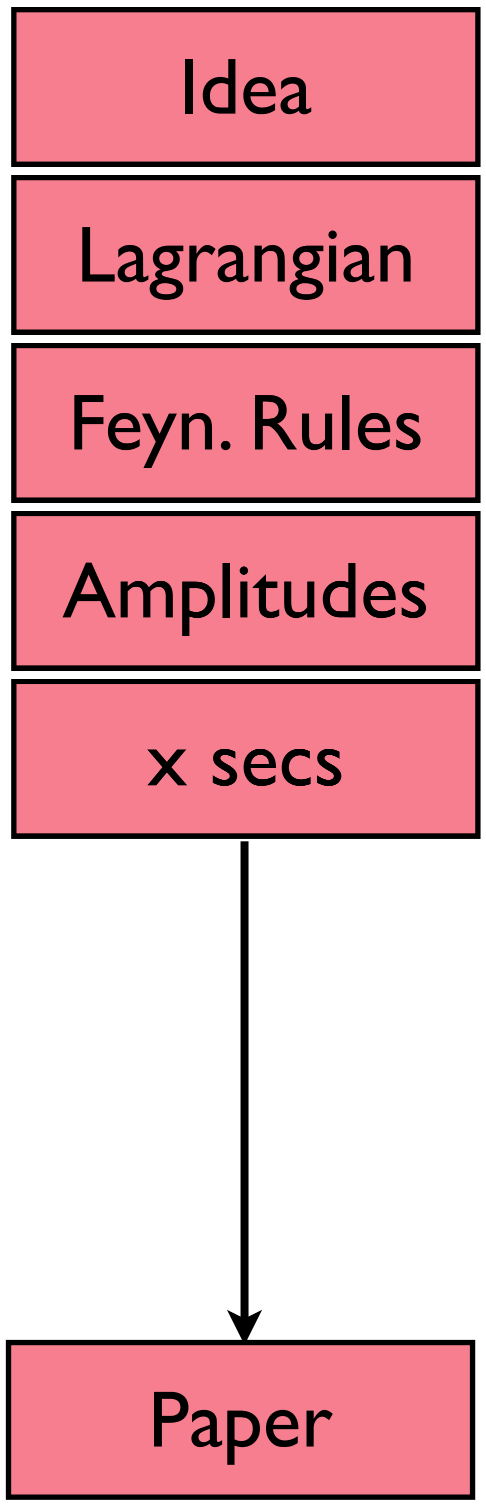

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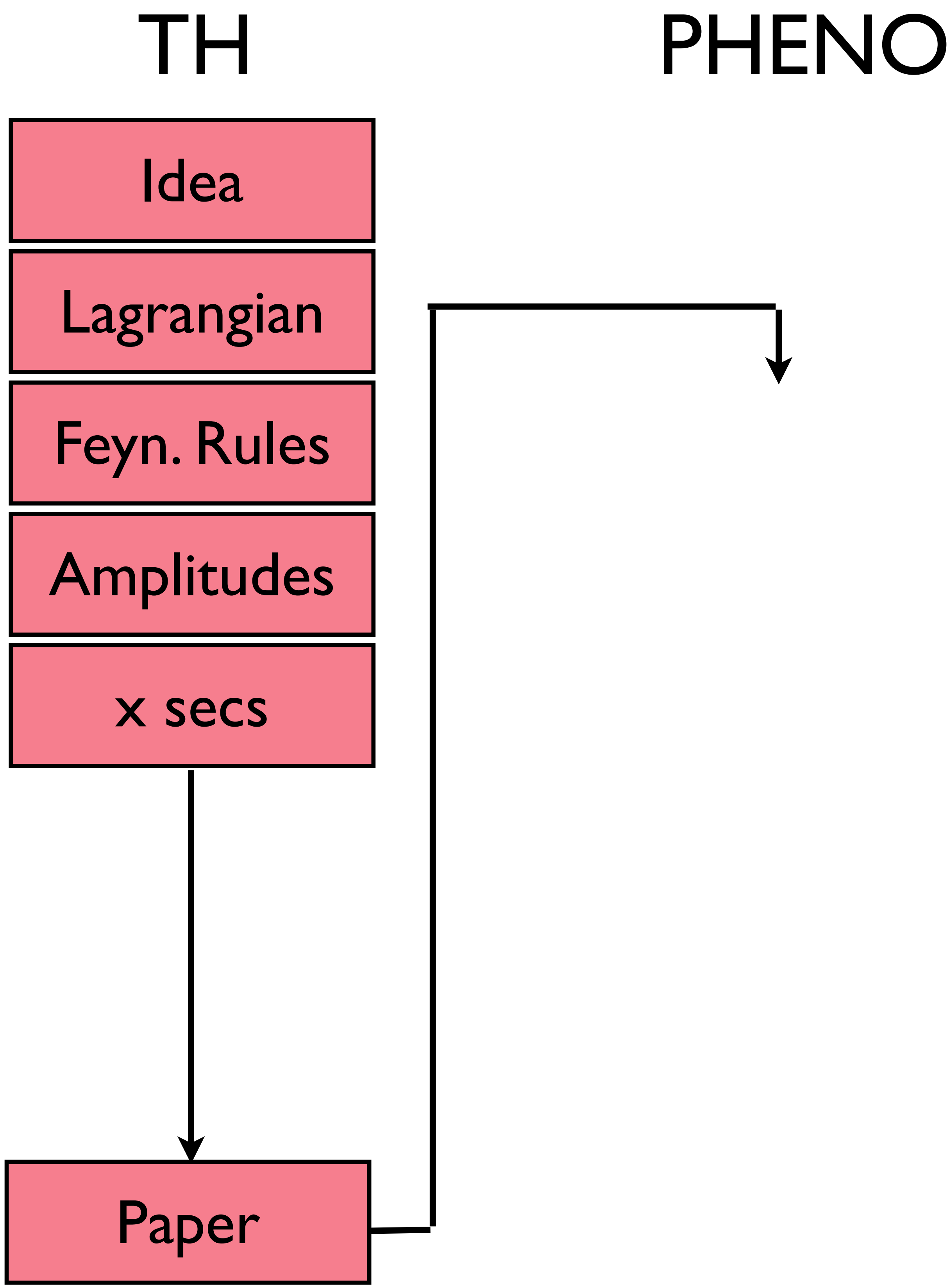

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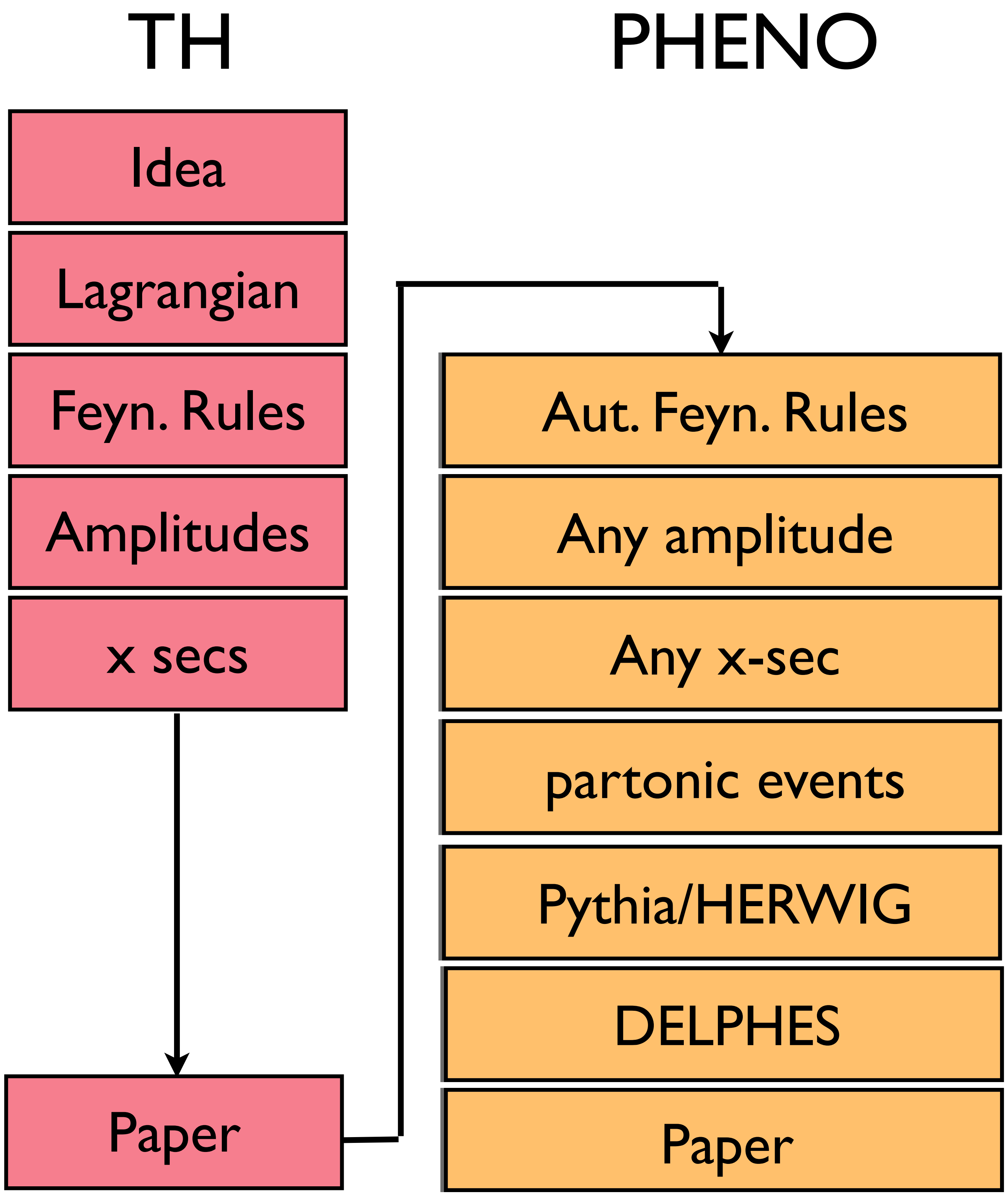

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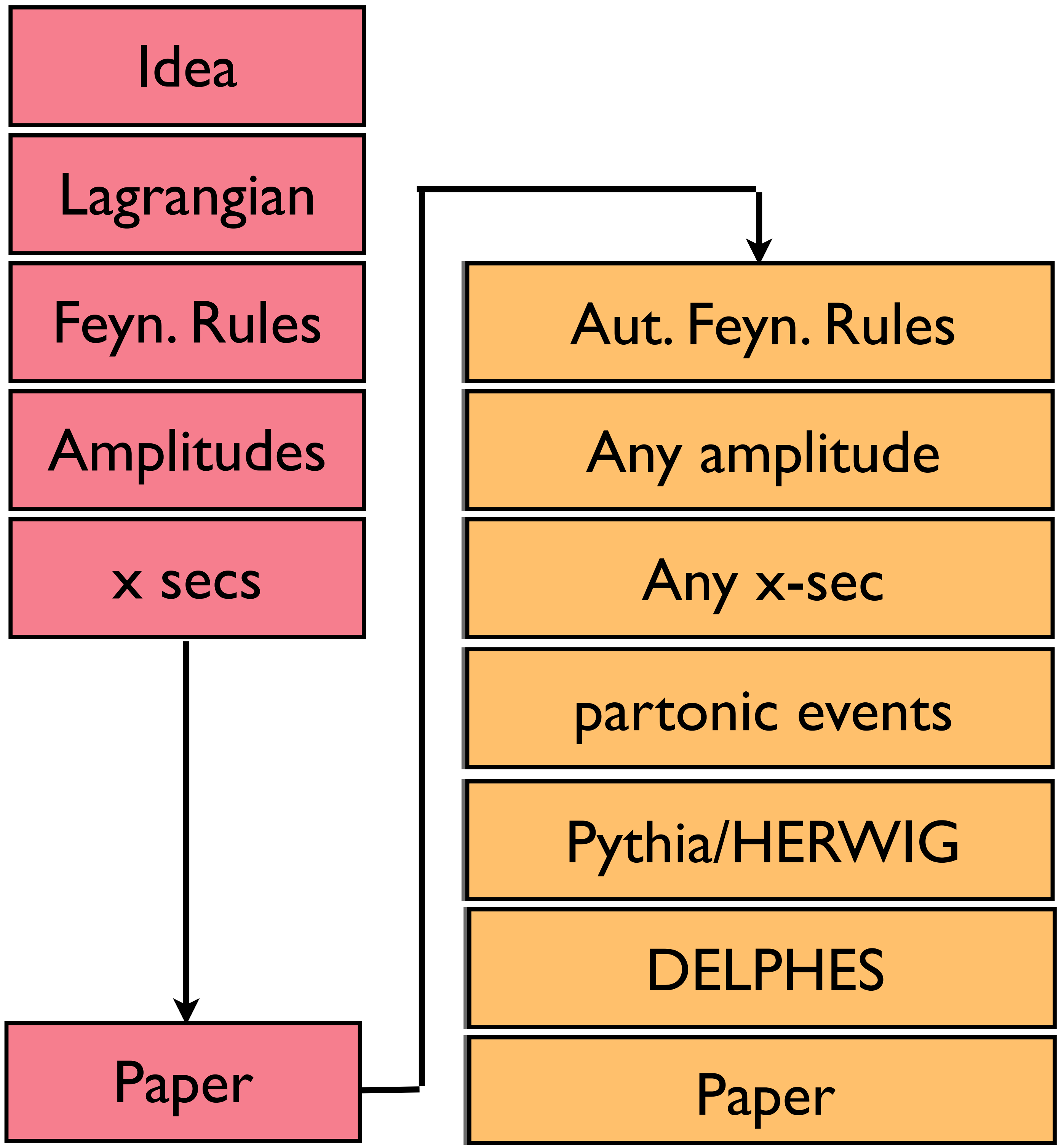

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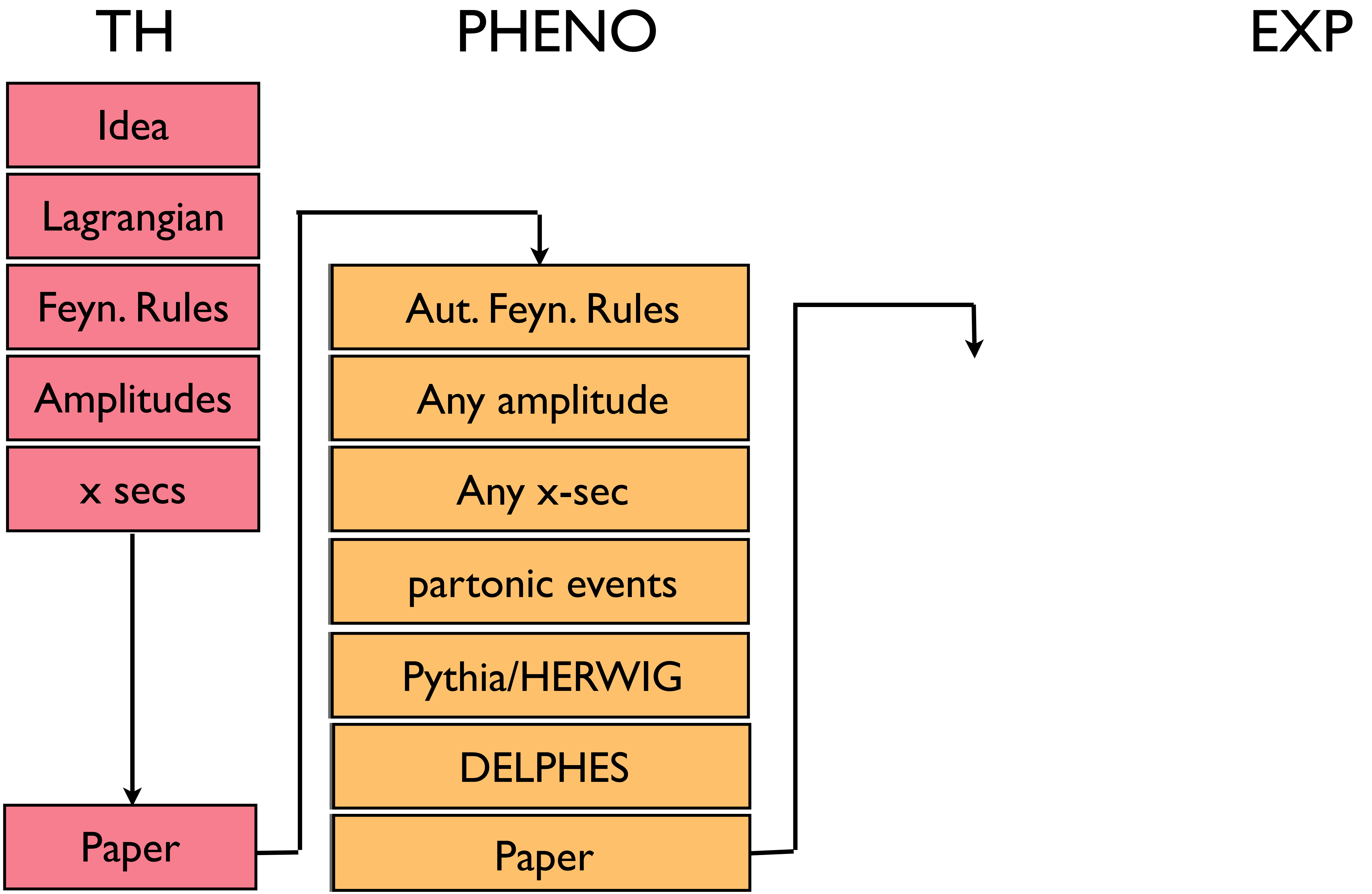

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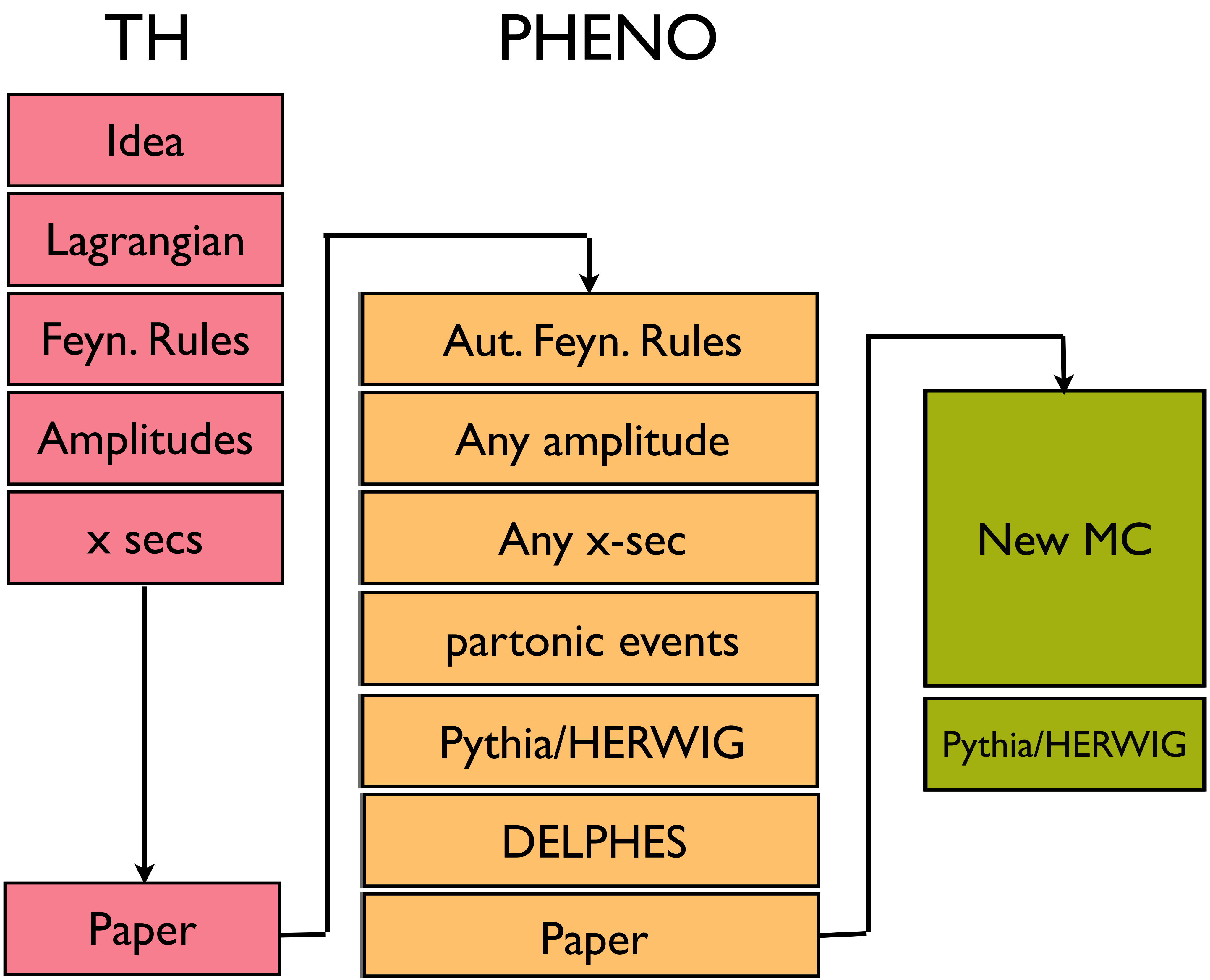

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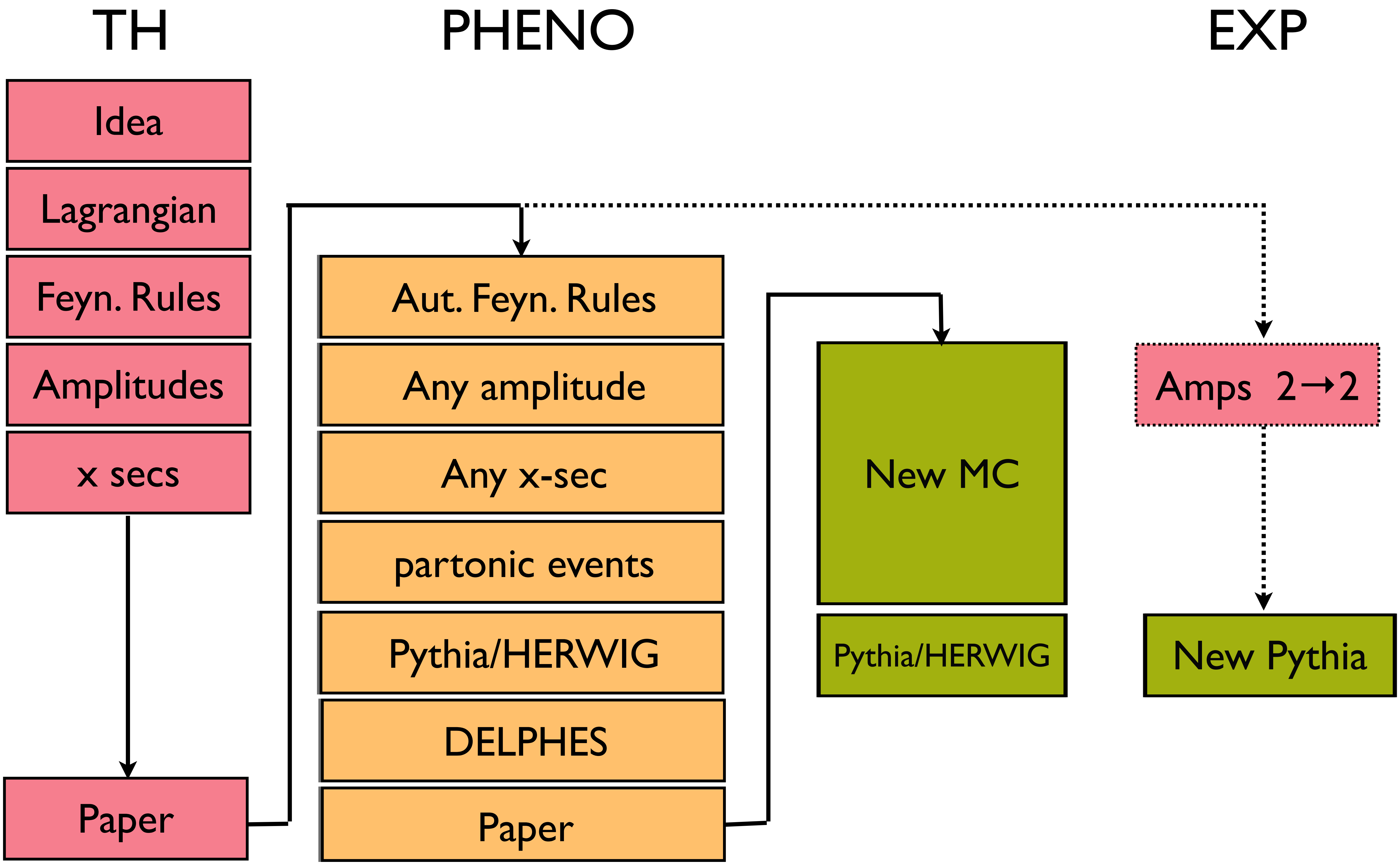

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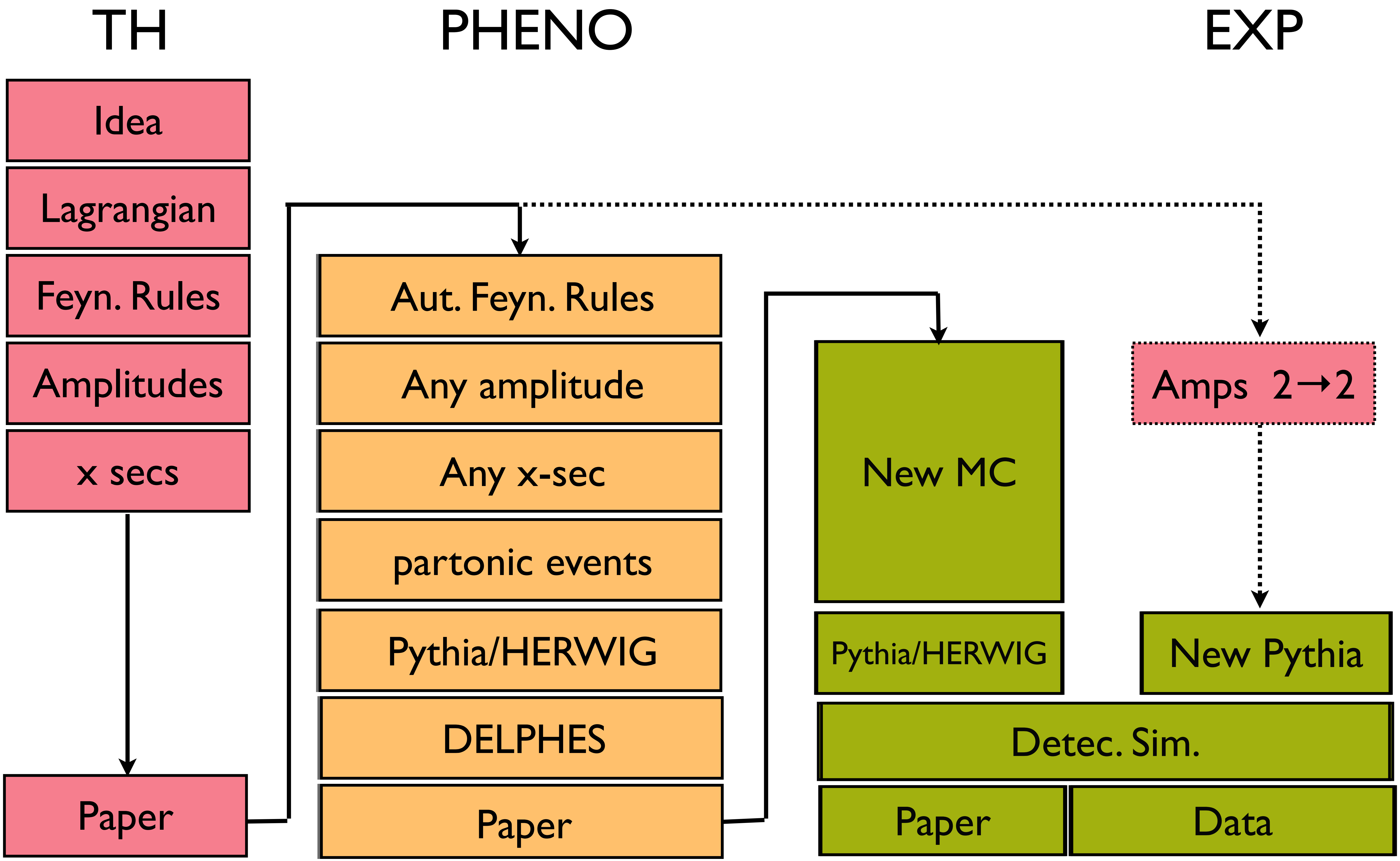
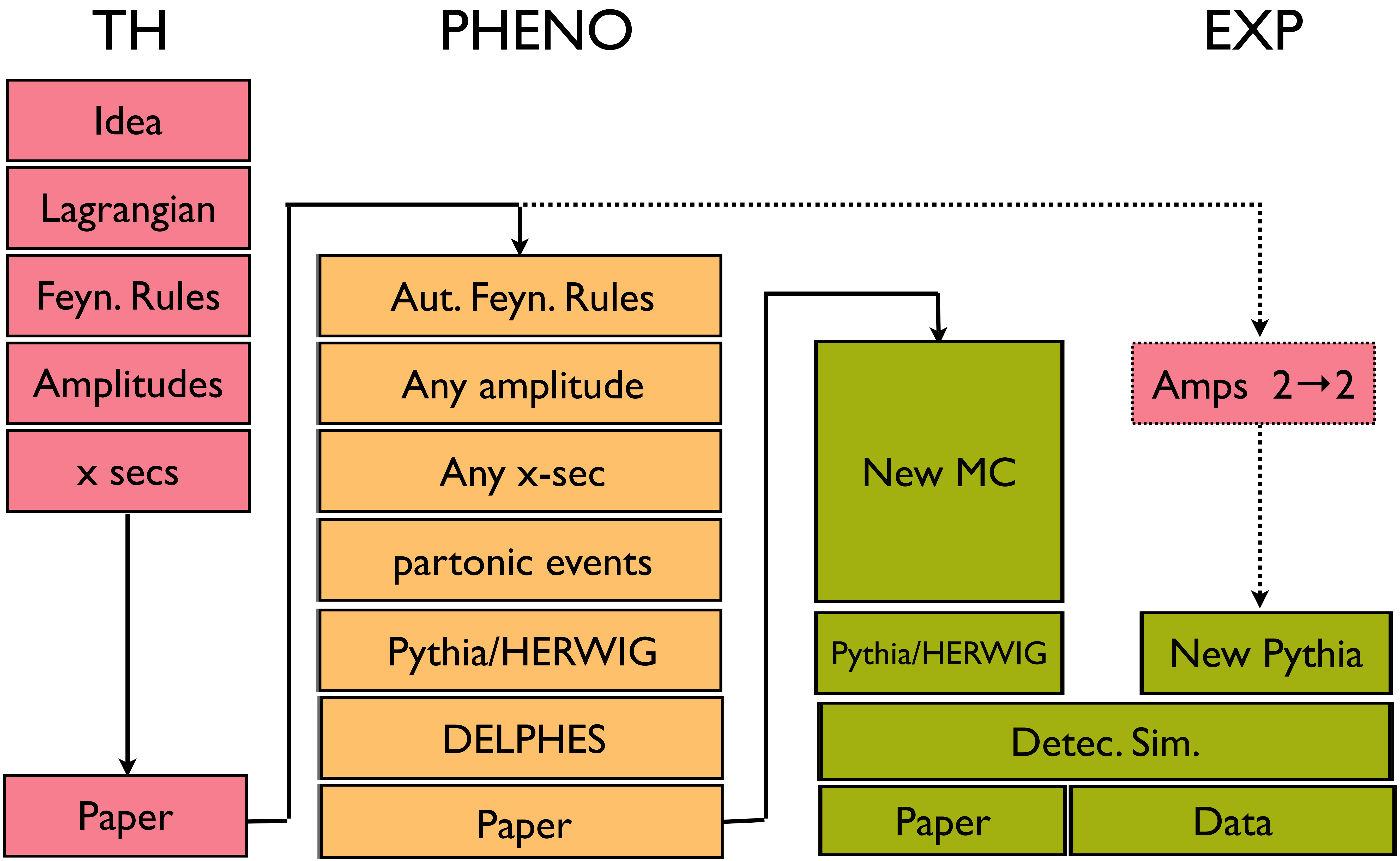


## A Roadmap (with roadblocks) for BSM @ the LHC

- Workload is tripled!
- Long delays due to localized expertises and error prone. Painful validations are necessary at each step.
- It leads to a proliferation of private MC tools/ sample productions impossible to maintain, document and reproduce on the mid- and long-term.
- Just publications is a very inefficient way of communicating between TH/PHENO/EXP.

# A Roadmap (with roadblocks) for BSM @ the LHC



# A Roadmap (with roadblocks) for BSM @ the LHC

TH | PHENO | EXP

Idea

Lagrangian

Aut. Feyn. Rules

Any amplitude

Any x-sec

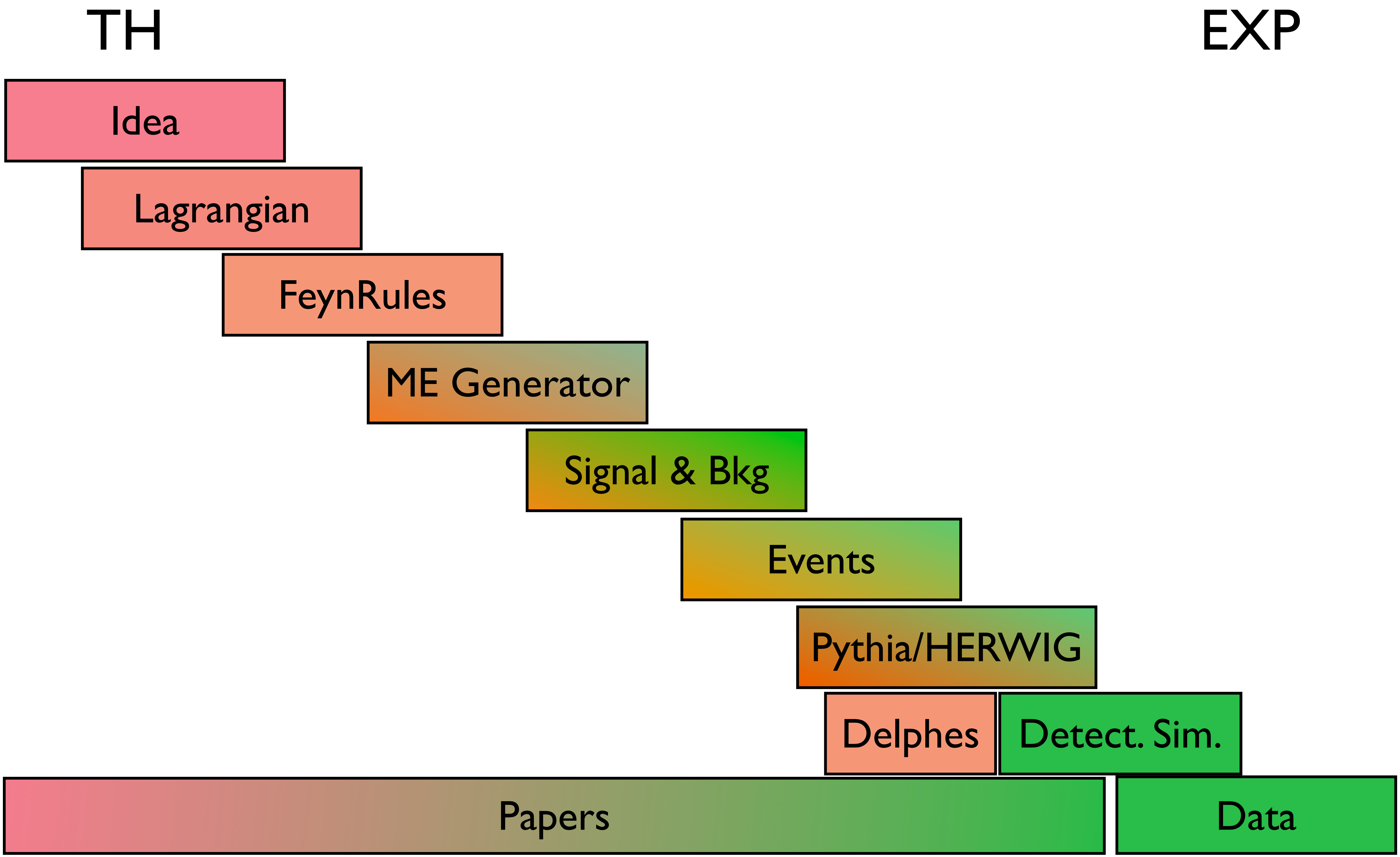
partonic events

Pythia/HERWIG

Detec. Sim.

Data

# A Roadmap for BSM @ the LHC



# A Roadmap for BSM @ the LHC

**TH** | **EXP**

- Idea
- Lagrangian
- FeynRules
- ME Generator
- Signal & Bkg
- Events
- Pythia/HERWIG
- Delphes | Detect. Sim.
- Papers | Data

- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

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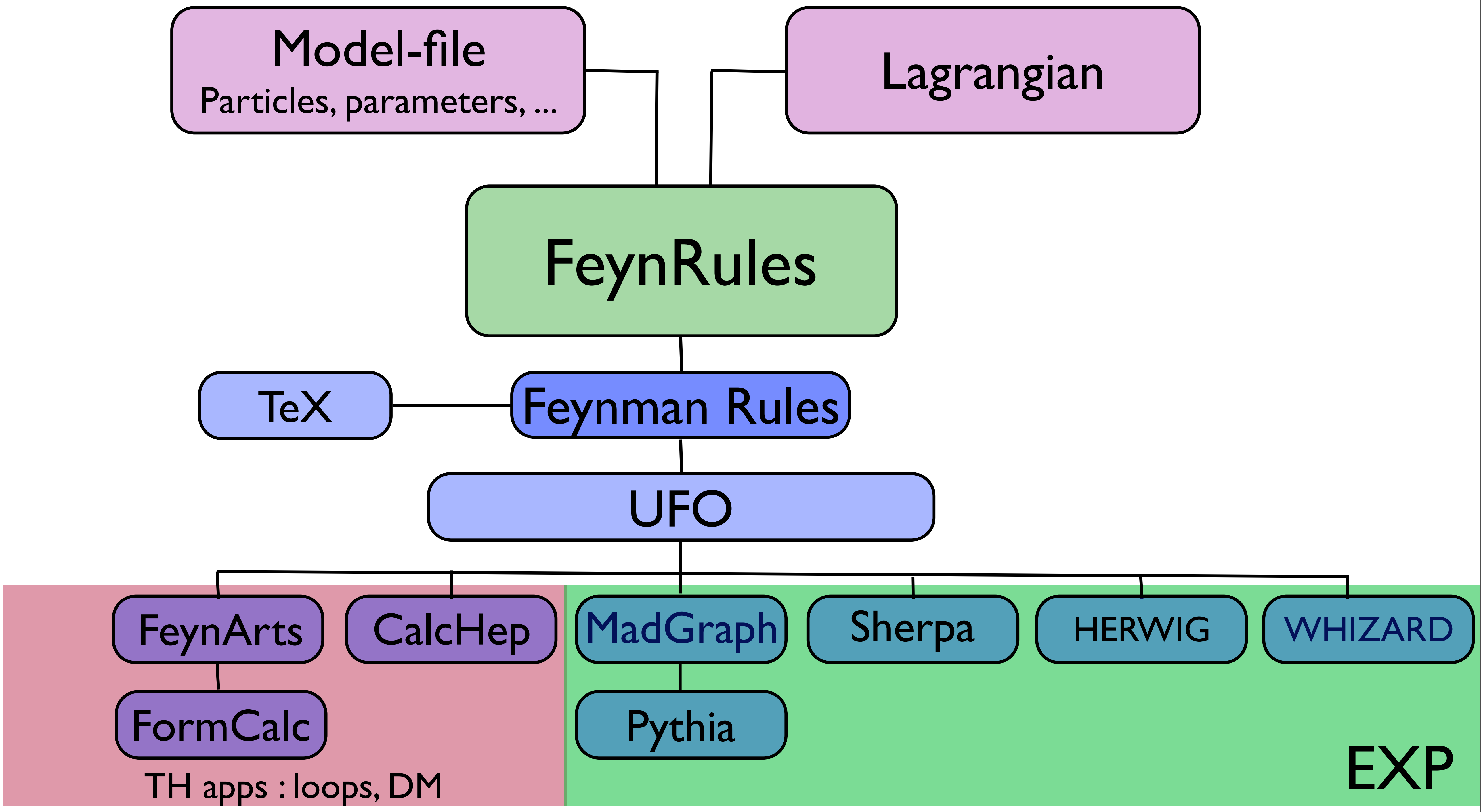
Complete automatization for tree-level based calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics. Automatization of NLO is very promising now...

# A working implementation

[Christensen, et al.2009]



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- Automation of NLO and MC@NLO/POWHEG in sight.
- Shift in paradigm: useful TH predictions in the form of tools that can be used by EXP's. Communication and collaboration between THs & EXPs easier $\Rightarrow$ emergence of an integrated LHC community.