LHC Phenomenology with MadGraph

Three introductory lectures

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Centre for particle physics and Phenomenology
Université de Louvain

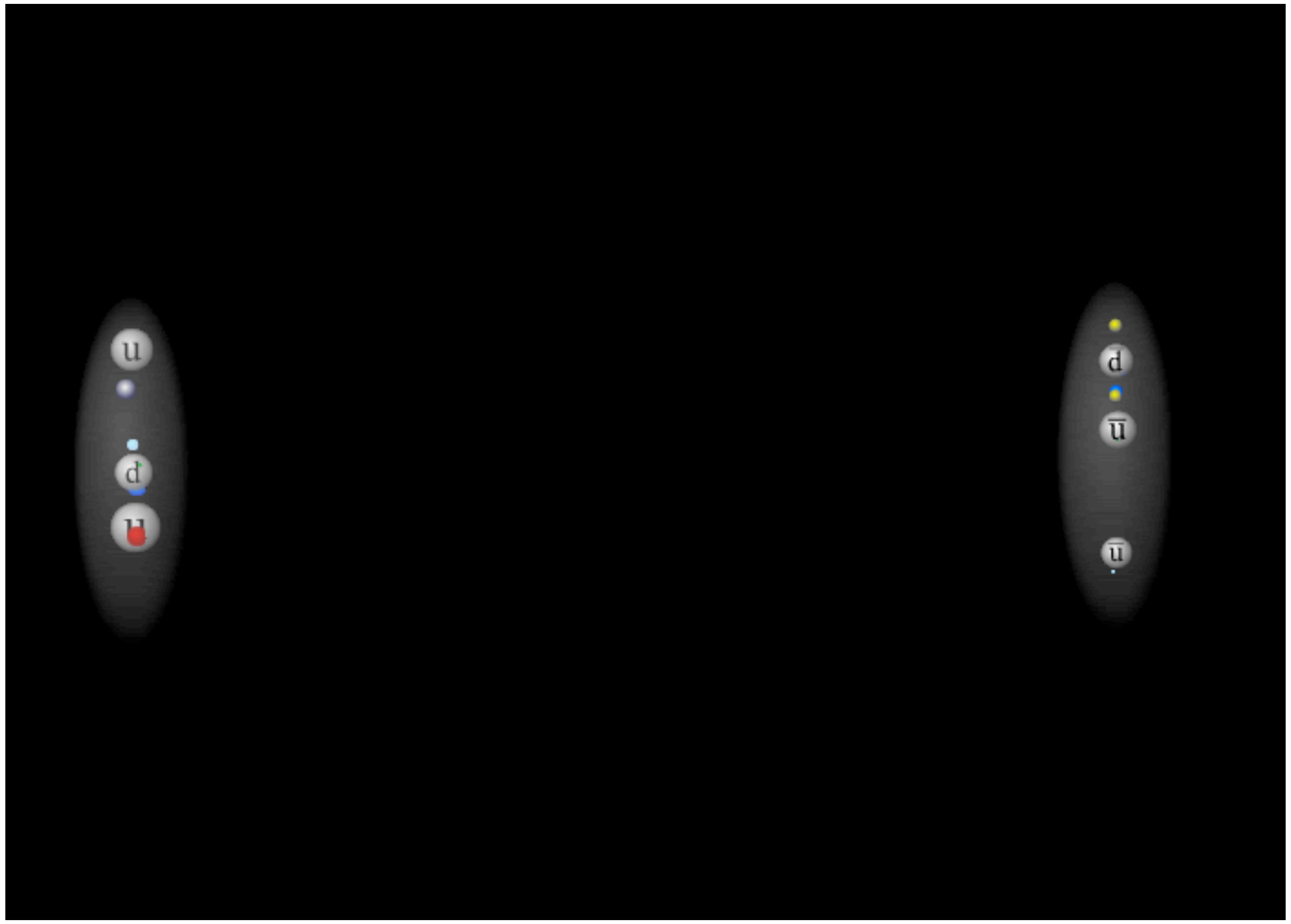
A simple plan

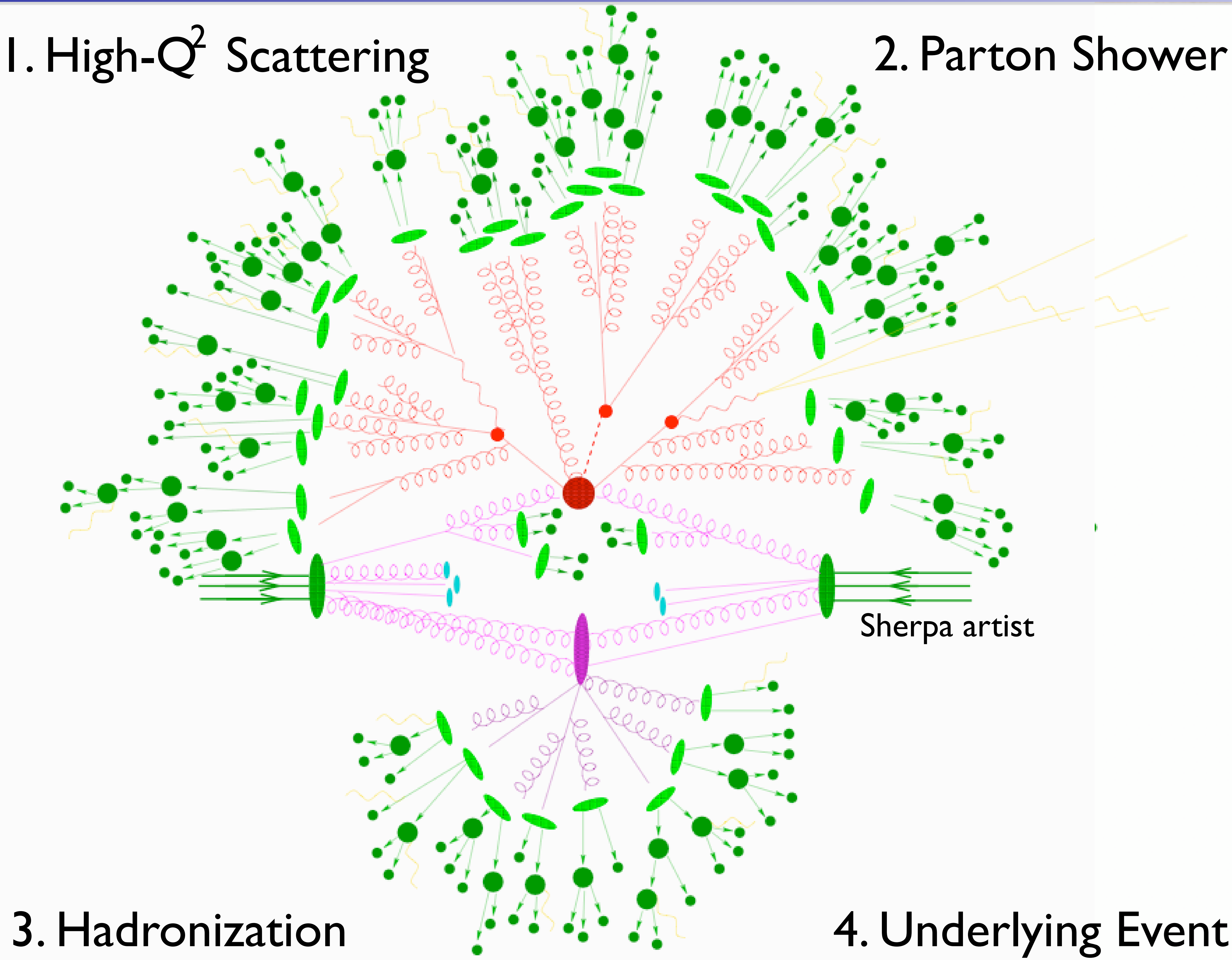
- Intro: the LHC challenge
- Tree-level matrix elements
- Parton-level cross sections and events
- Events at the LHC

A simple plan

- Intro: the LHC challenge
- Tree-level matrix elements
- Parton-level cross sections and events
- Events at the LHC now

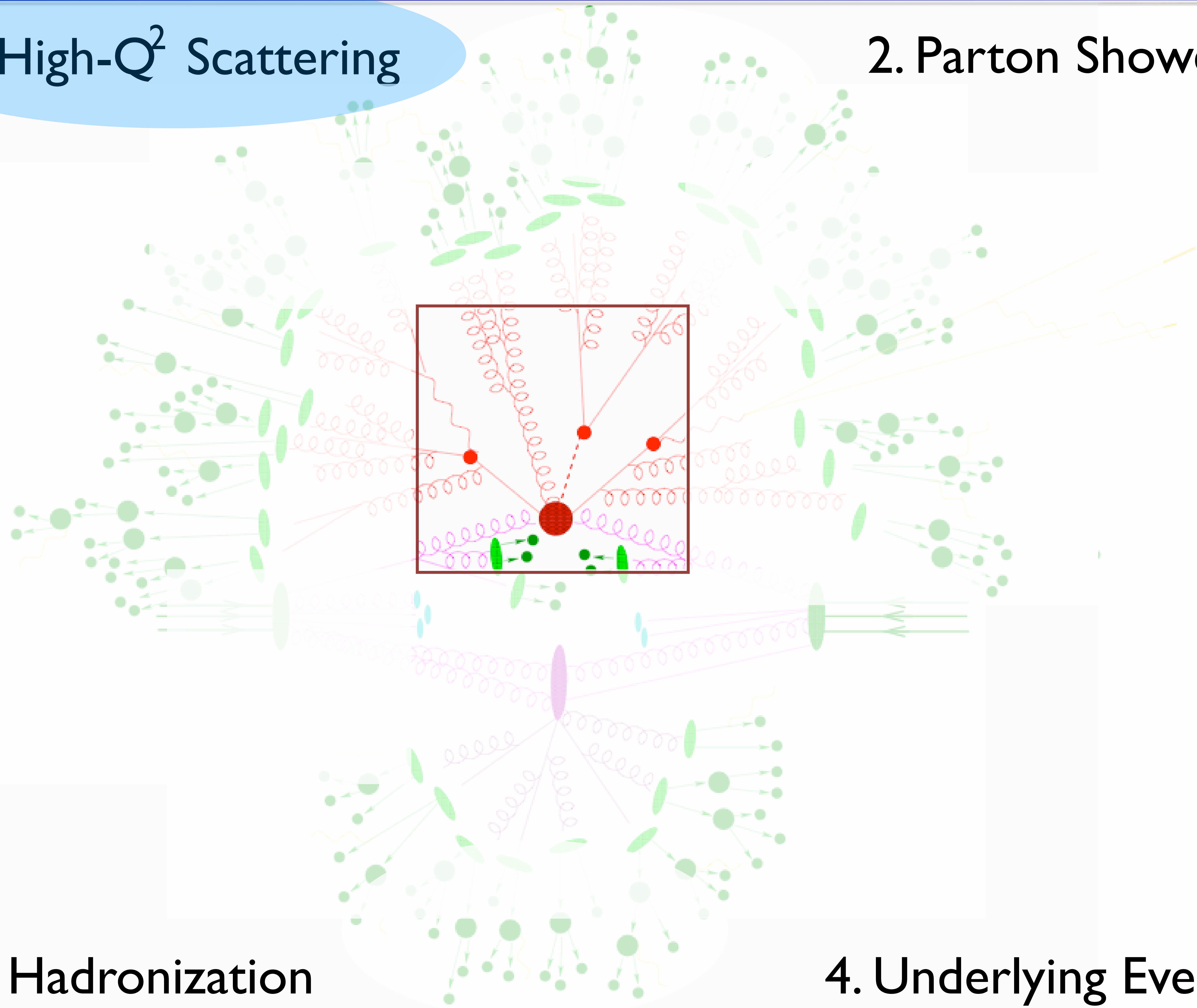
An event at hadron colliders




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

1. High-Q^2 Scattering

2. Parton Shower



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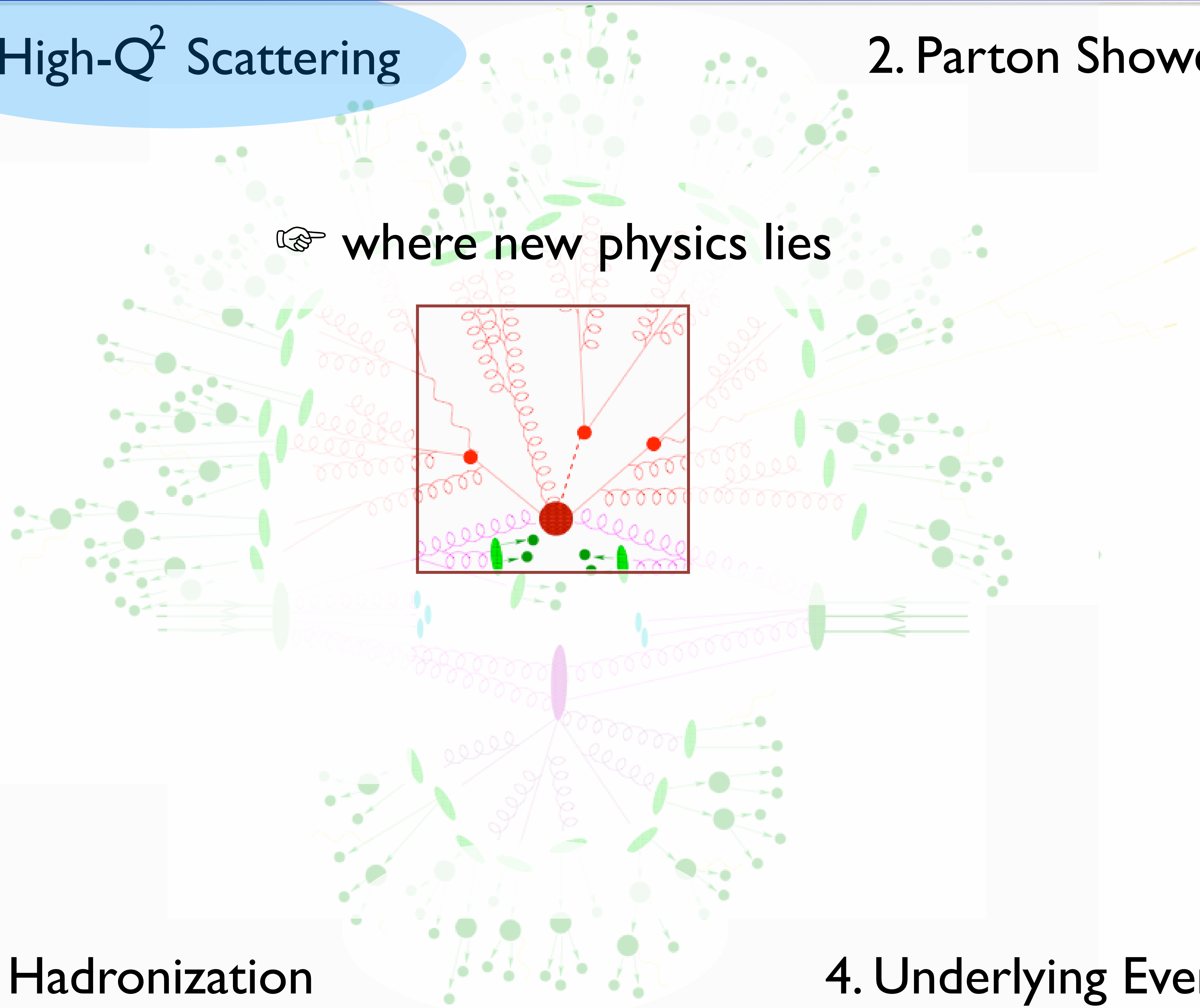
☞ where new physics lies



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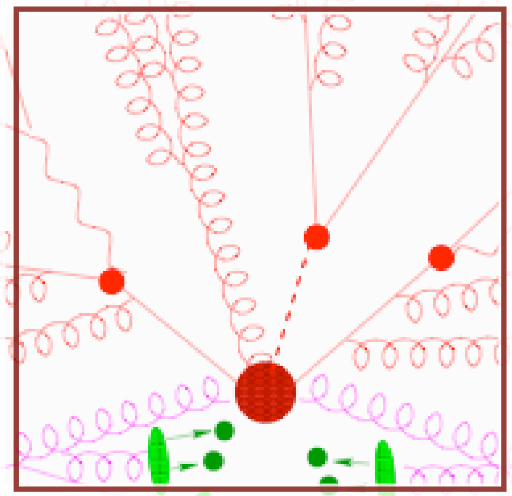

☞ process dependent

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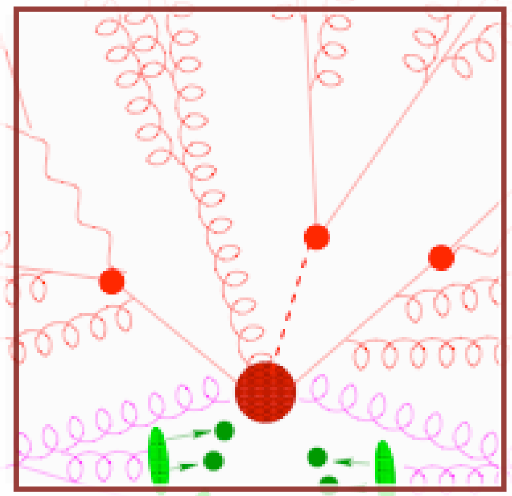

☞ process dependent

☞ first principles description

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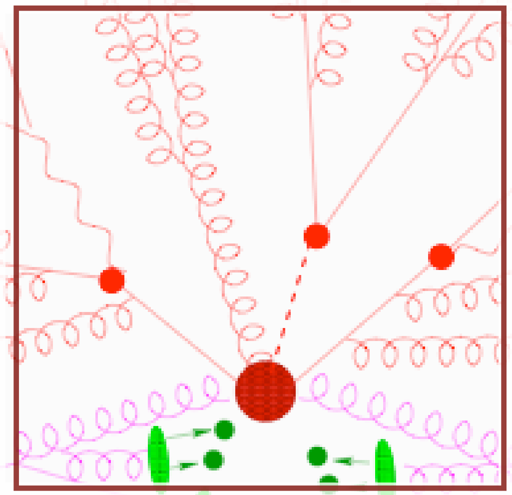

☞ process dependent

☞ first principles description

☞ it can be systematically improved

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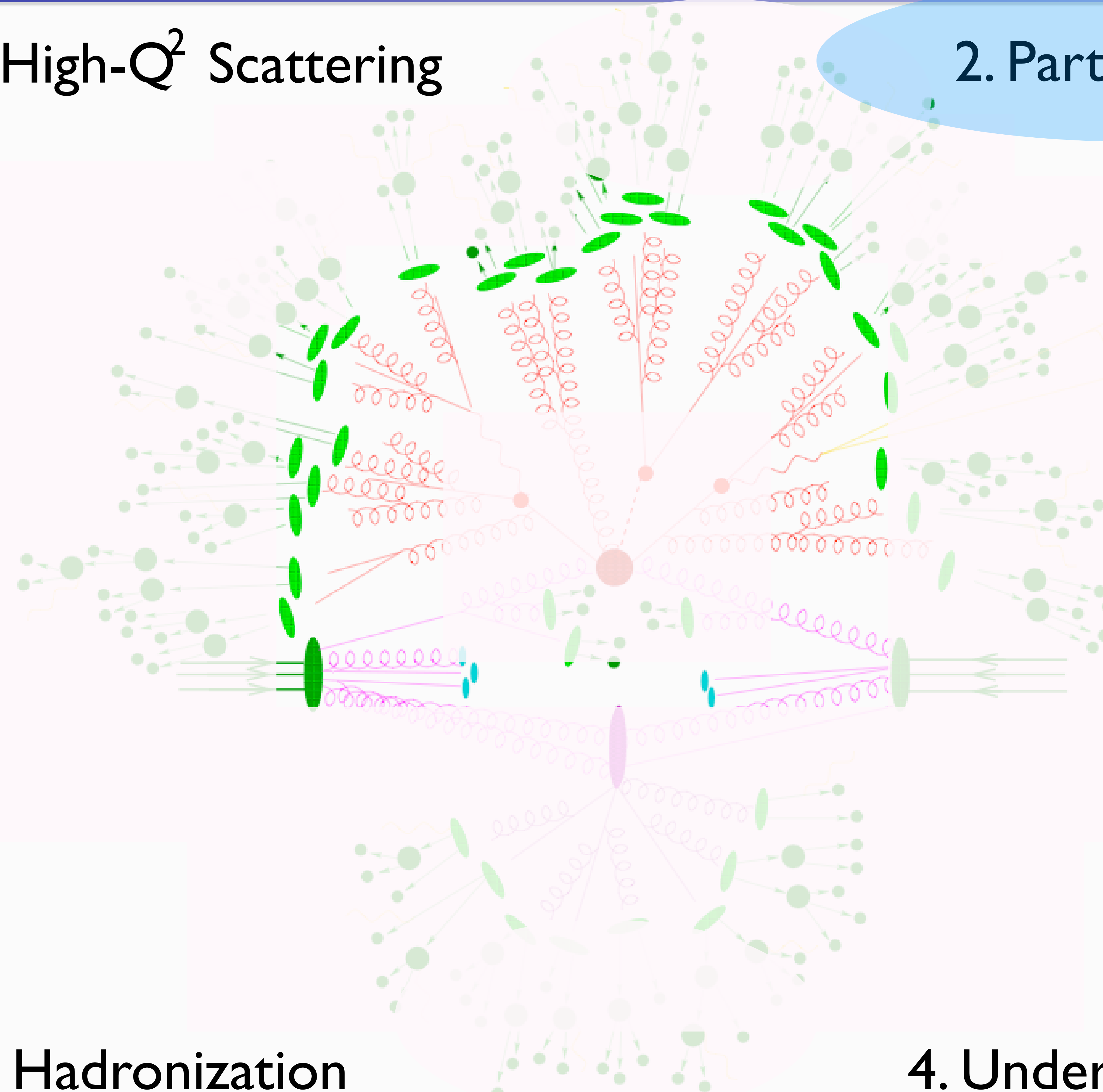

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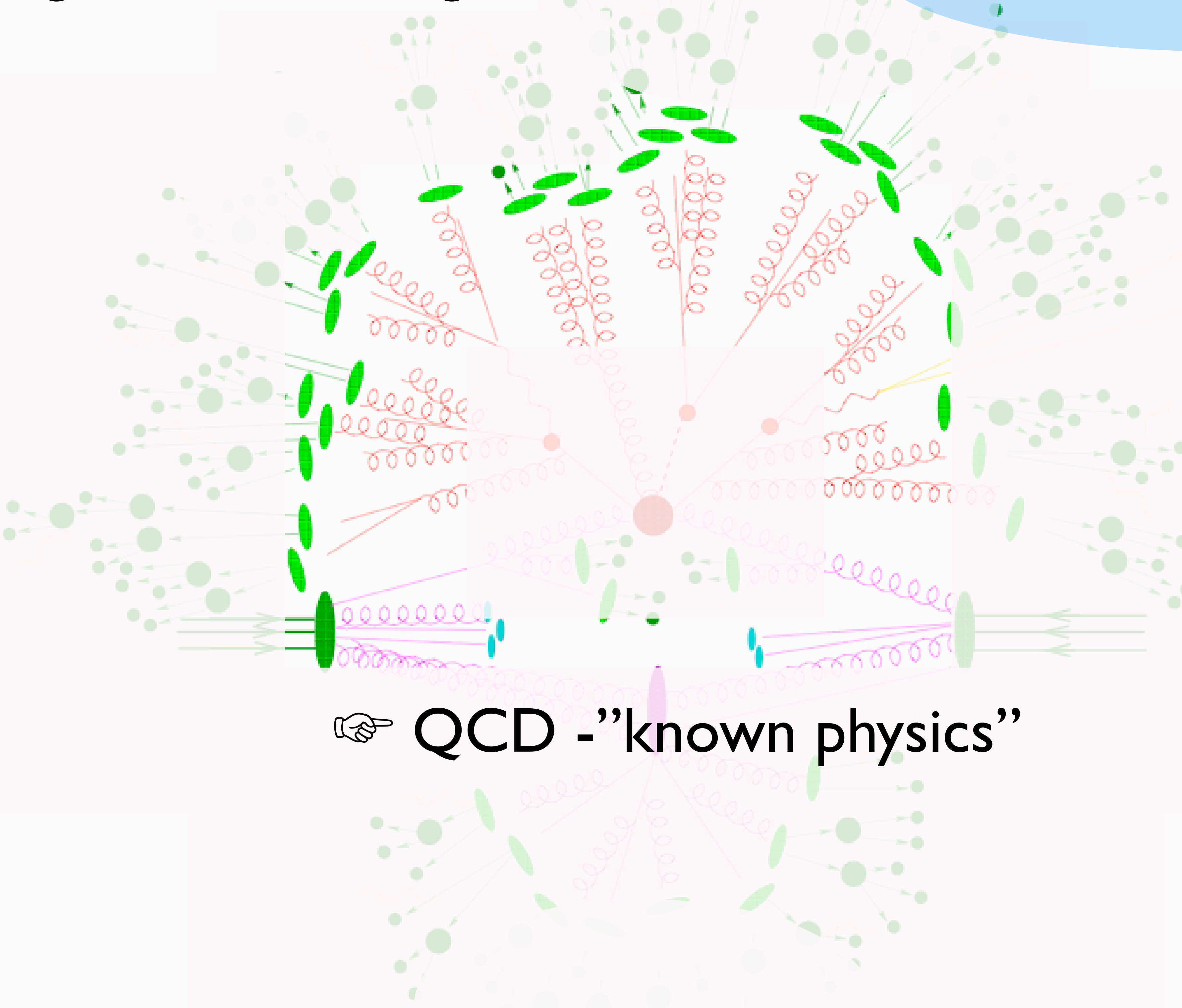

☞ QCD -”known physics”

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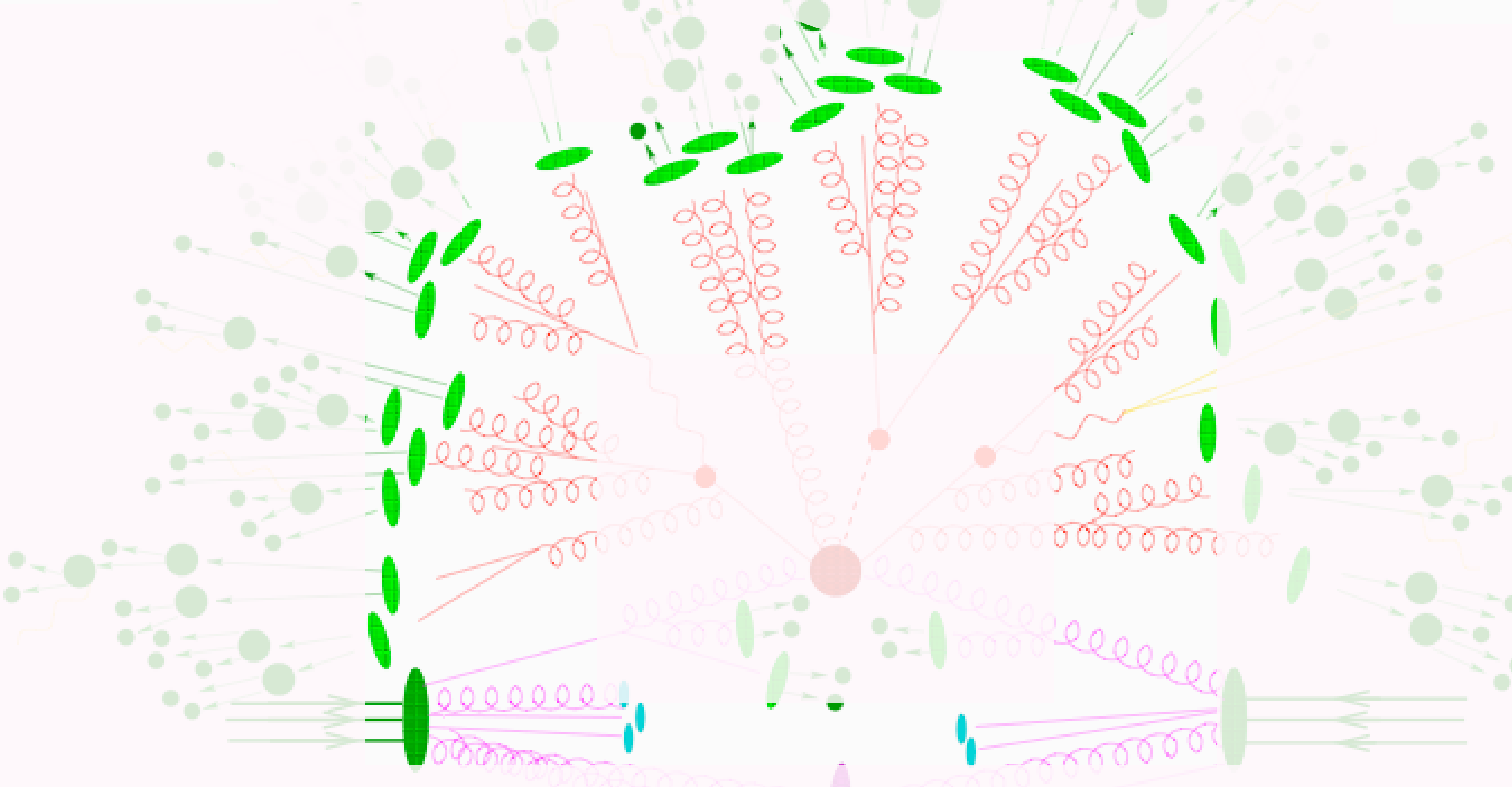

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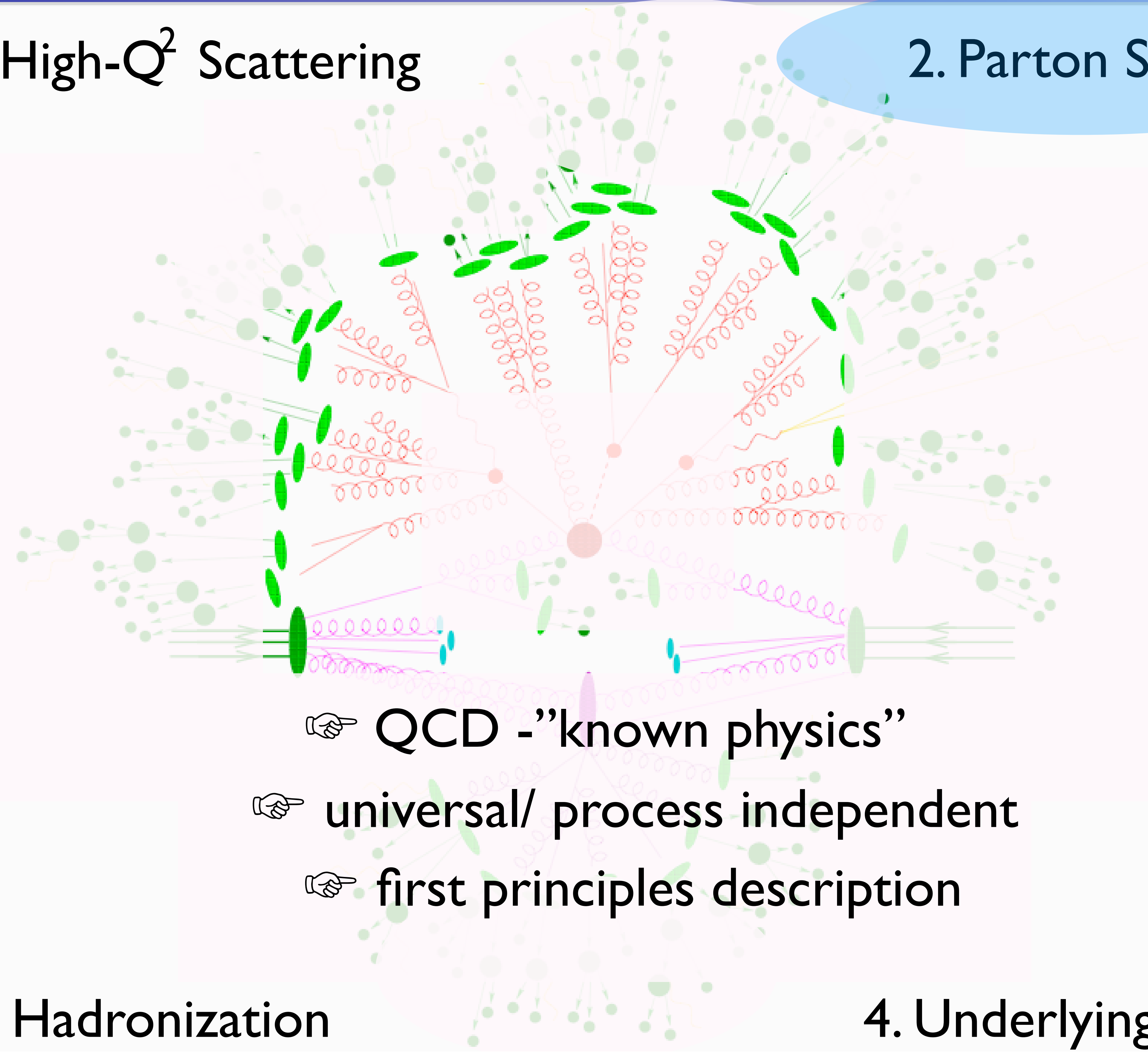

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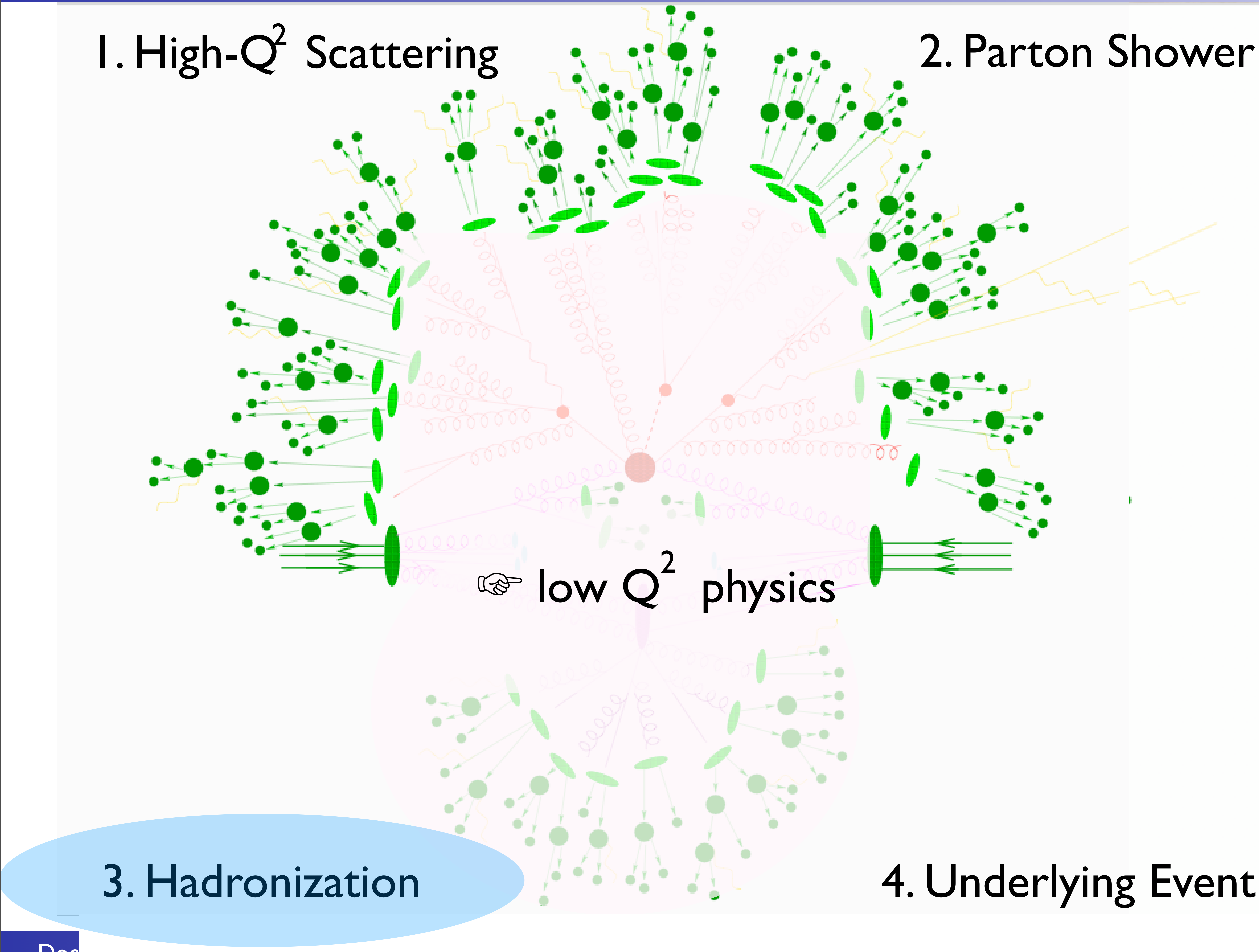
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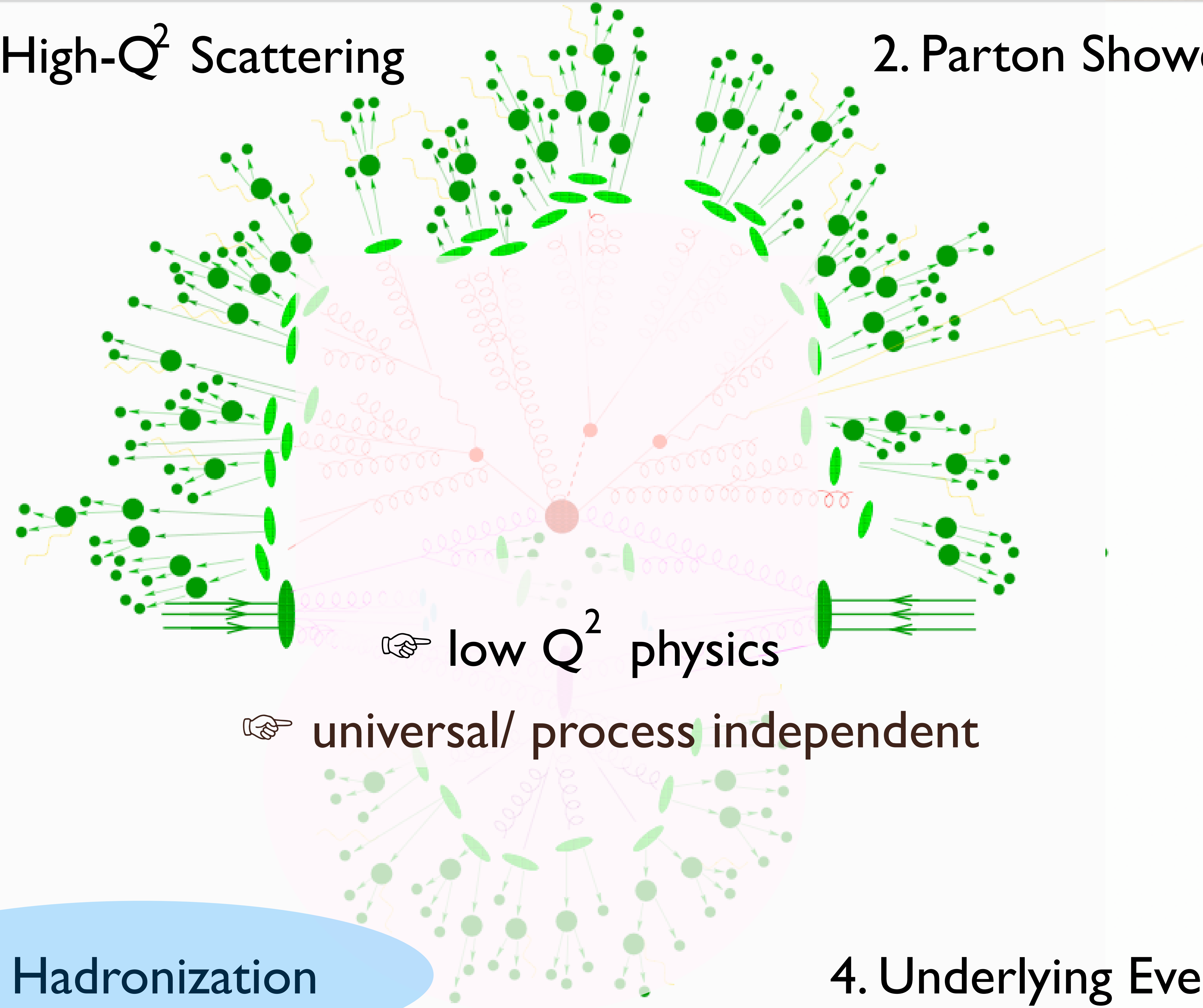

☞ low Q^2 physics

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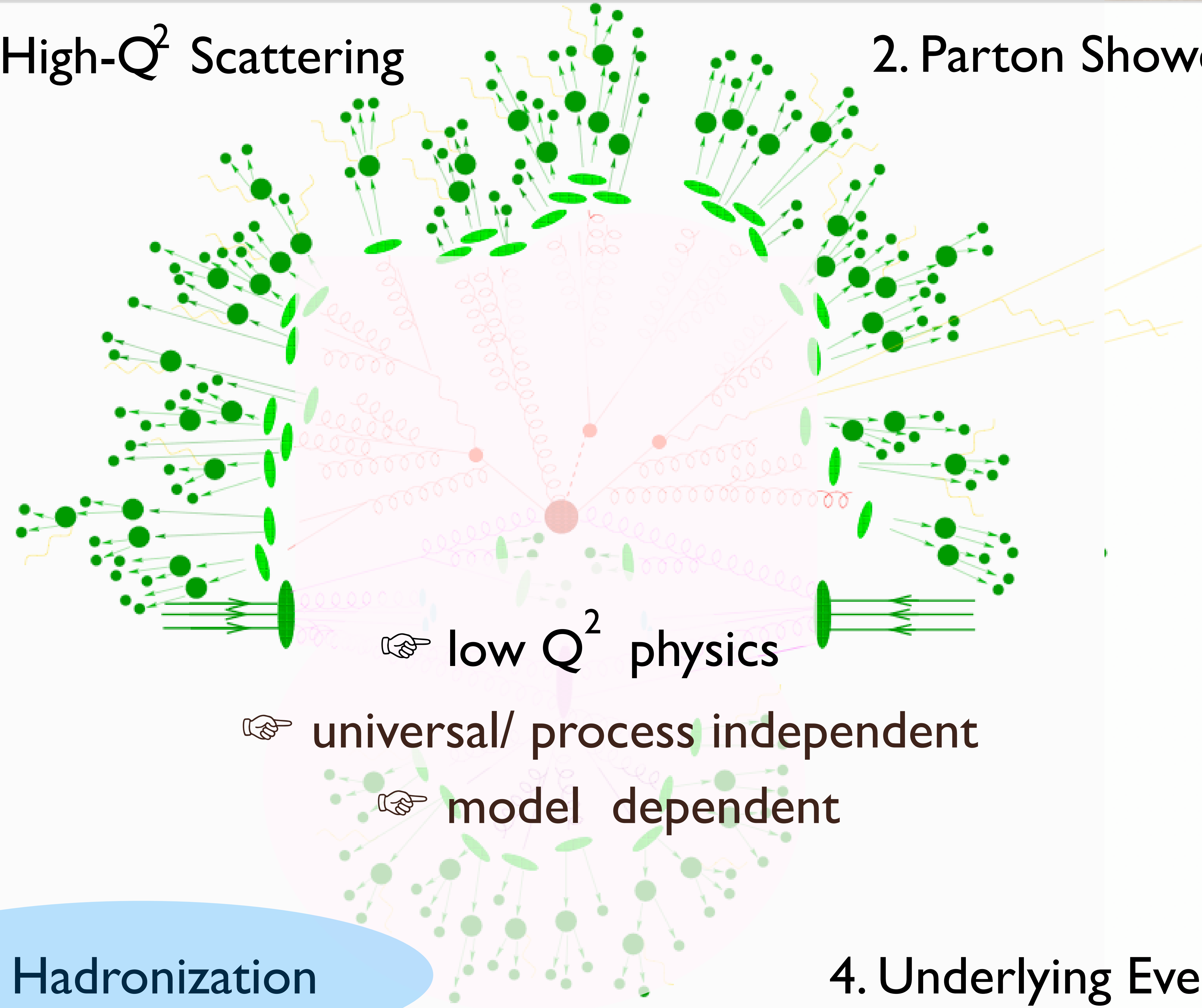

☞ low Q^2 physics

☞ universal/ process independent

☞ model dependent

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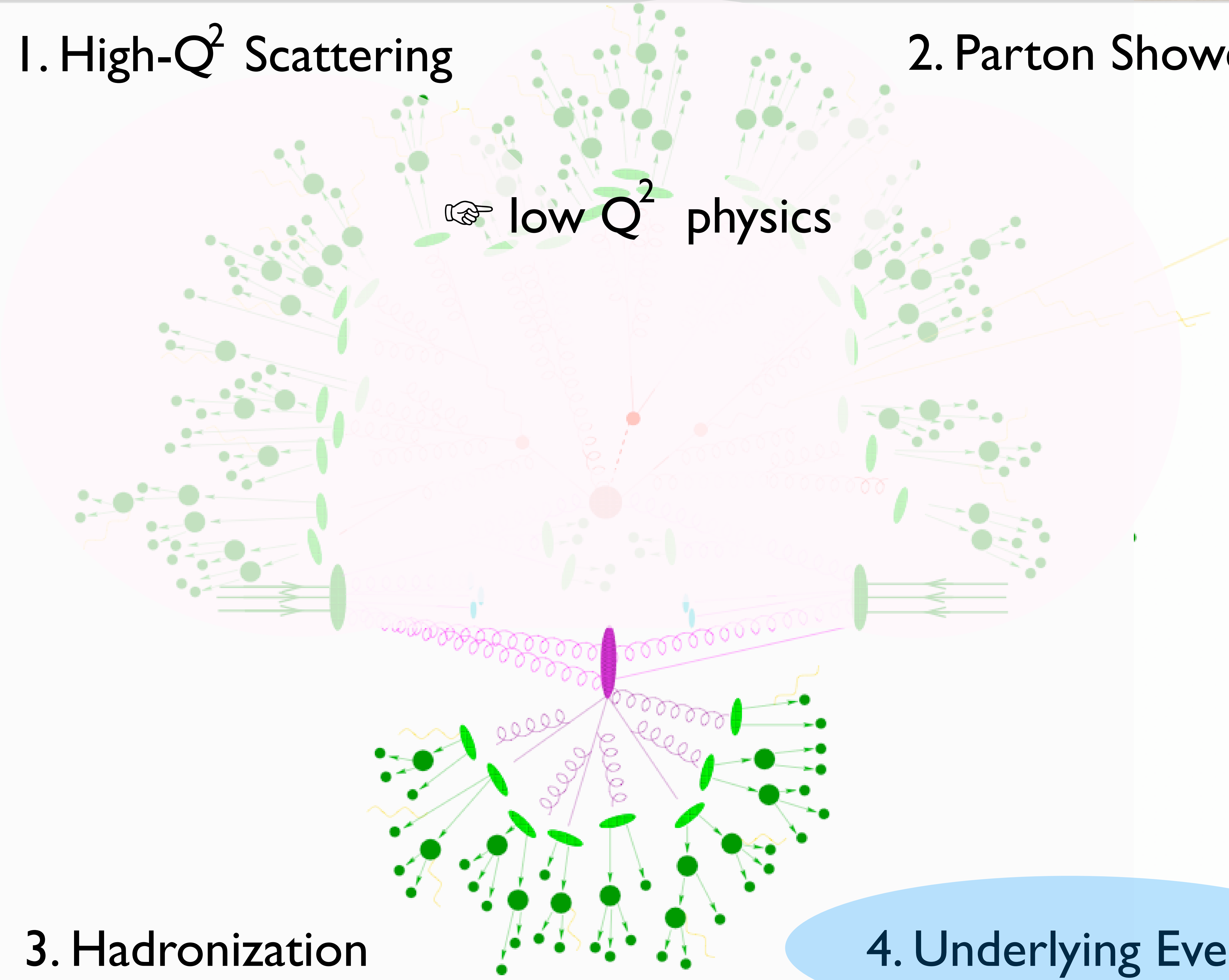
☞ low Q^2 physics



3. Hadronization

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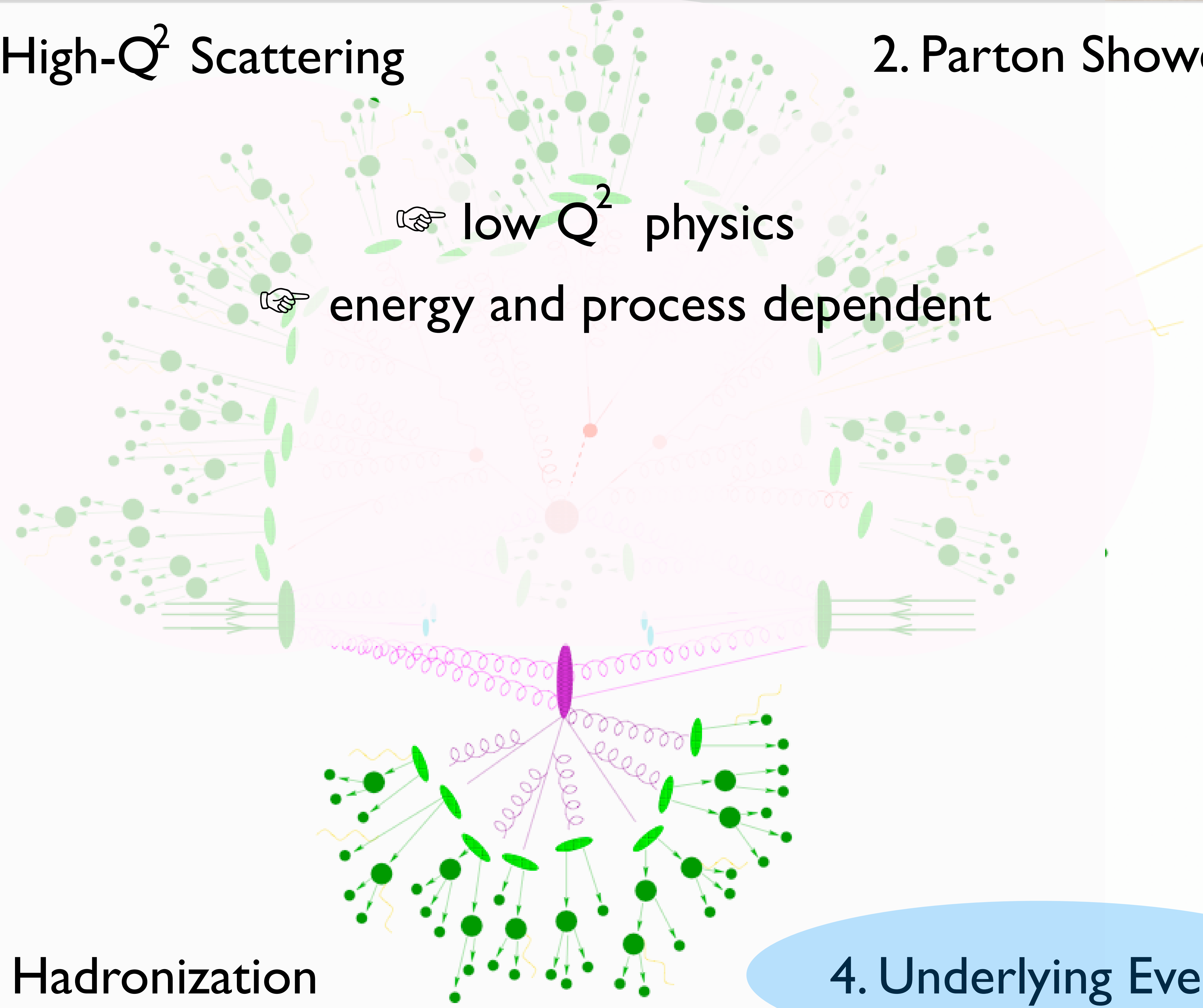
☞ low Q^2 physics

☞ energy and process dependent



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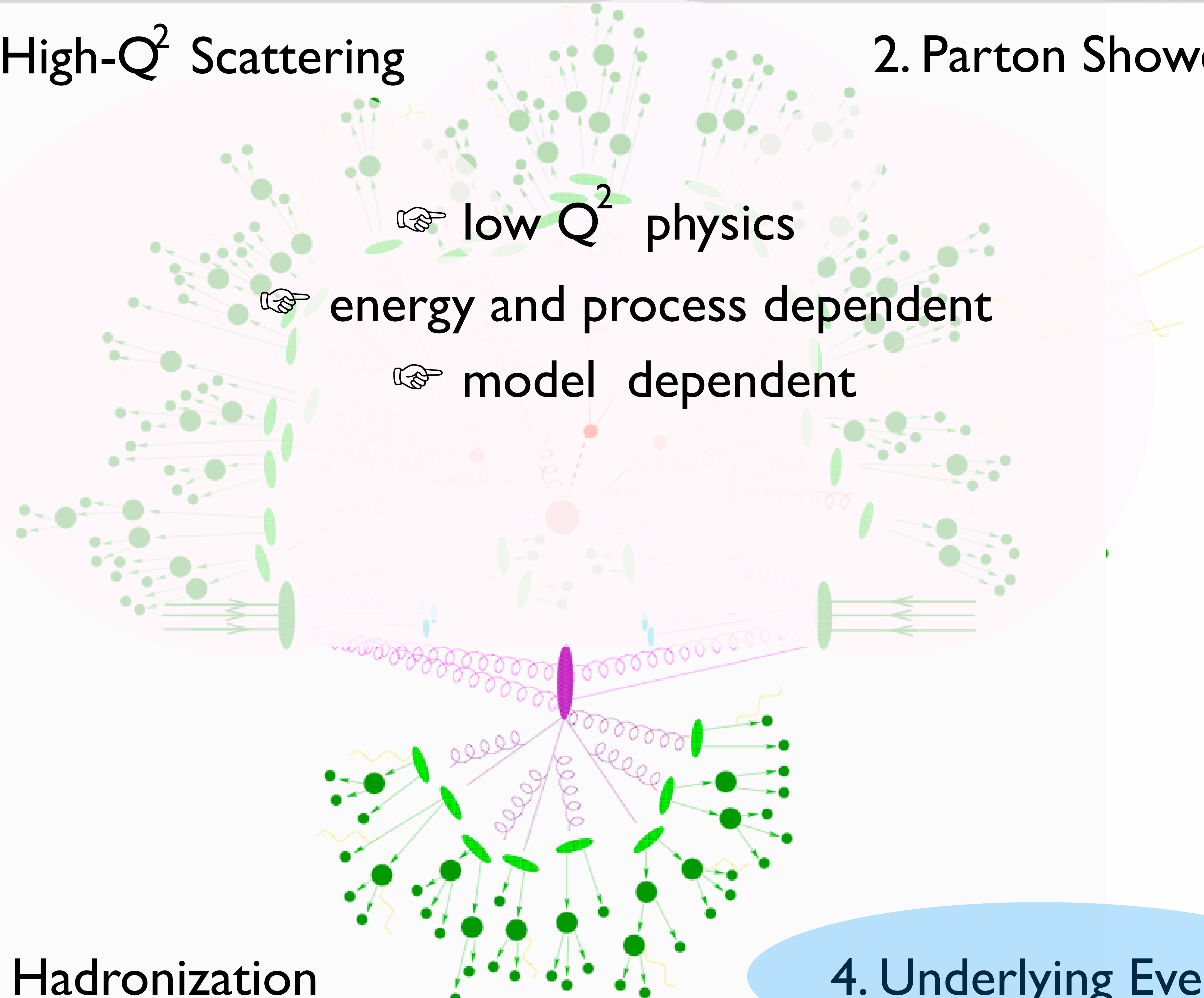


- low Q^2 physics
- energy and process dependent
- model dependent

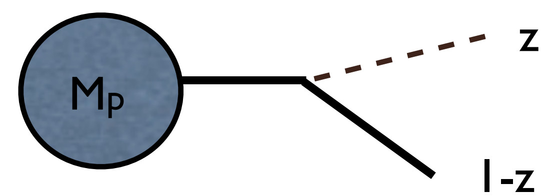
3. Hadronization

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:

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



Both soft and collinear divergences: very different nature!

Collinear factorization:

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

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

Sudakov Form factor

From: 2006 lectures on MC by T. Sjostrand

Conservation of total probability:

$\mathcal{P}(\text{nothing happens}) = 1 - \mathcal{P}(\text{something happens})$

"multiplicativeness" in "time" evolution:

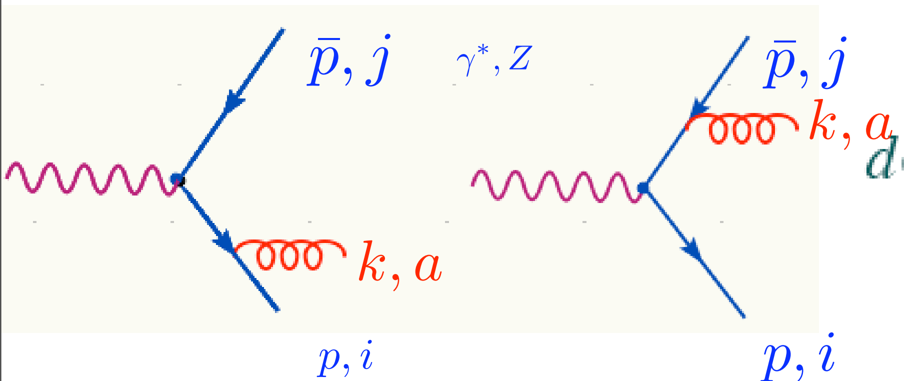
$\mathcal{P}_{\text{nothing}}(0 < t \leq T) = \mathcal{P}_{\text{nothing}}(0 < t \leq T_1)\, \mathcal{P}_{\text{nothing}}(T_1 < t \leq T)$

Subdivide further, with $T_i = (i/n)T$, $0 \leq i \leq n$:

$$
\begin{aligned}
\mathcal{P}_{\text{nothing}}(0 < t \leq T) &= \lim_{n\to\infty} \prod_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \leq T_{i+1}) \\
&= \lim_{n\to\infty} \prod_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \leq T_{i+1})\right) \\
&= \exp\left(- \lim_{n\to\infty} \sum_{i=0}^{n-1} \mathcal{P}_{\text{something}}(T_i < t \leq T_{i+1})\right) \\
&= \exp\left(- \int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t}\mathrm{d}t\right) \quad = \Delta(T)
\end{aligned}
$$

$$
\Longrightarrow \quad \mathrm{d}\mathcal{P}_{\text{first}}(T) = \mathrm{d}\mathcal{P}_{\text{something}}(T) \exp\left(- \int_0^T \frac{\mathrm{d}\mathcal{P}_{\text{something}}(t)}{\mathrm{d}t}\mathrm{d}t\right)
$$

Angular ordering



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

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

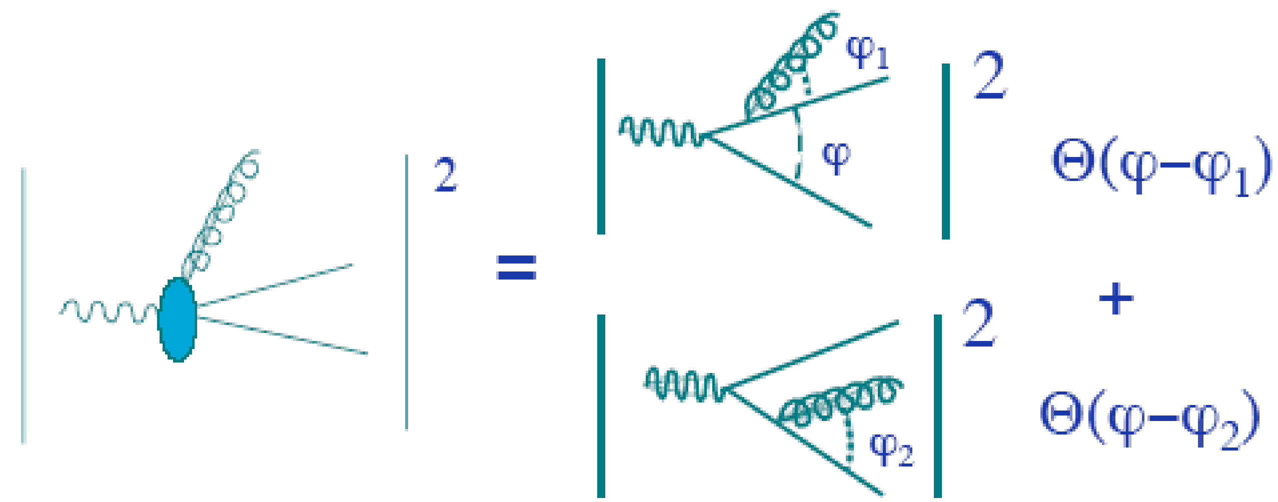
You can easily prove that:

$$\frac{1-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} = \frac{1}{2}\left[\frac{\cos\theta_{jk}-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} + \frac{1}{1-\cos\theta_{ik}}\right] + \frac{1}{2}[i \leftrightarrow j] \equiv W_{(i)} + W_{(j)}$$

where

$$W_{(i)} \rightarrow finite\ if\ k \parallel j\ (\cos\theta_{jk} \rightarrow 1)$$
$$W_{(j)} \rightarrow finite\ if\ k \parallel i\ (\cos\theta_{ik} \rightarrow 1)$$

The probabilistic interpretation of $W_{(i)}$ and $W_{(j)}$ is a priori spoiled by their non-positivity. However, you can prove [EXERCISE] that after azimuthal averaging:

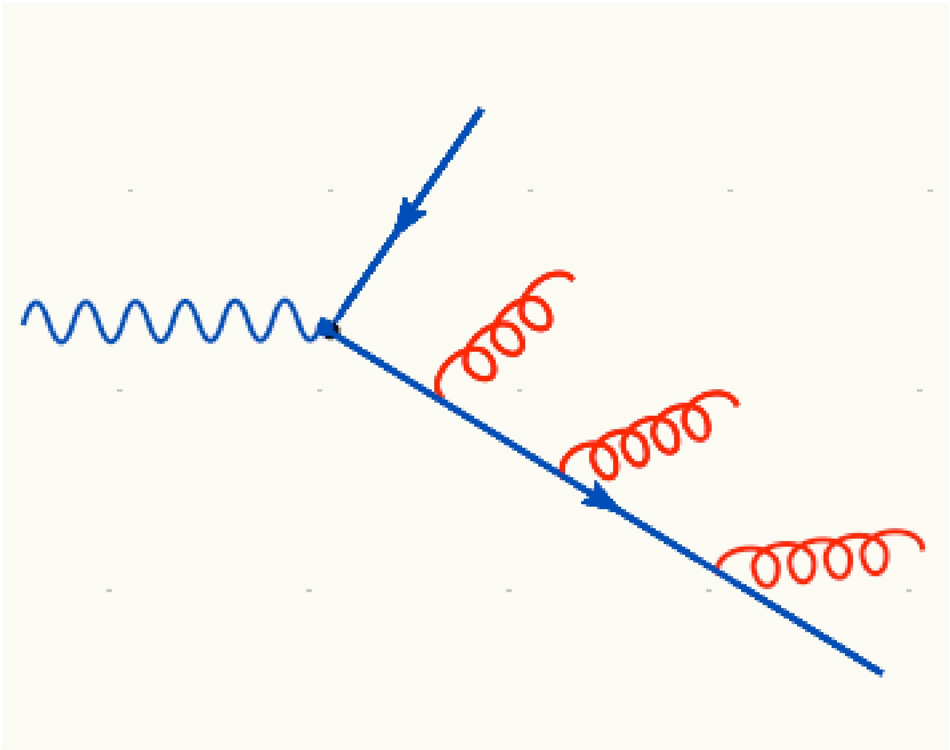


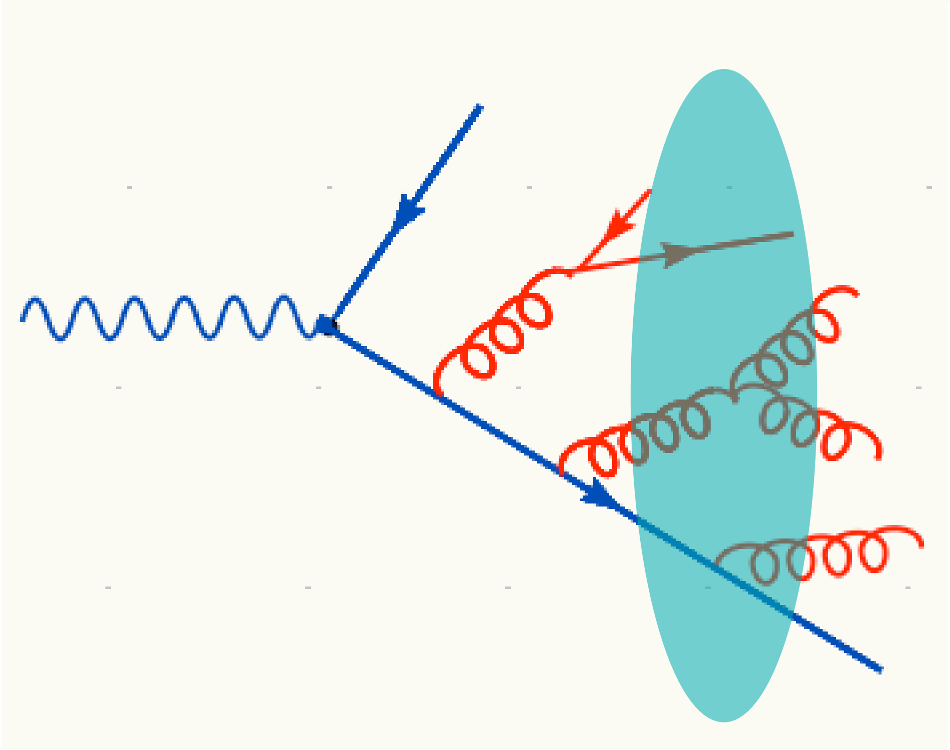
$$\int \frac{d\phi}{2\pi} W_{(i)} = \frac{1}{1-\cos\theta_{ik}} \text{ if } \theta_{ik} < \theta_{ij}\ , \quad 0 \text{ otherwise}$$

$$\int \frac{d\phi}{2\pi} W_{(j)} = \frac{1}{1-\cos\theta_{jk}} \text{ if } \theta_{jk} < \theta_{ij}\ , \quad 0 \text{ otherwise}$$

Further branchings will obey angular ordering relative to the new angles. As a result emission angles get smaller and smaller, squeezing the jet.

Angular ordering





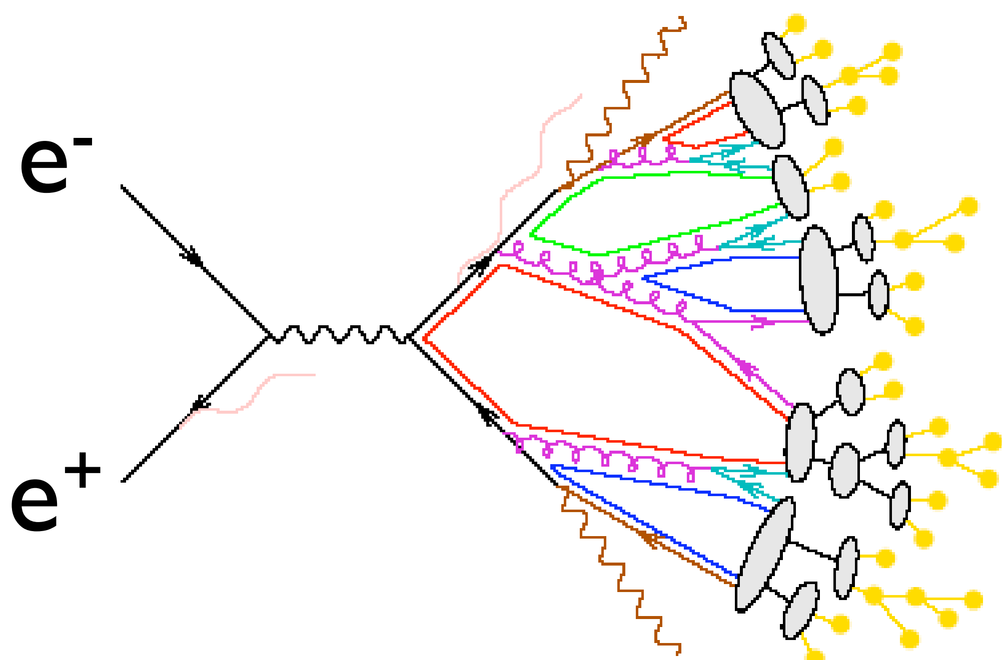
The construction can be iterated to the next emision, with the result that the emisssion angles keep getting smaller and smaller.

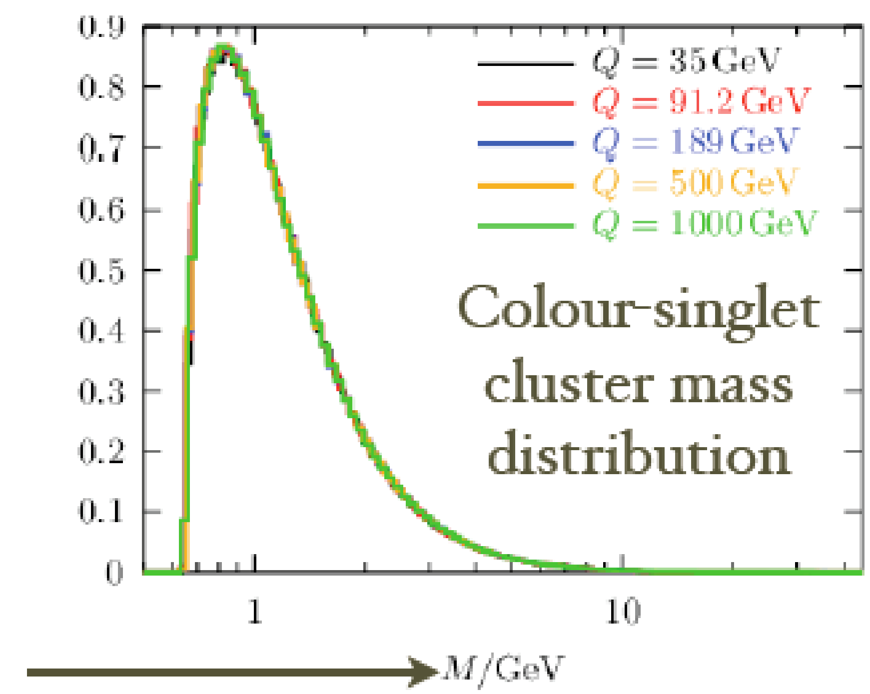
In fact one can generalize the treament before to a generic parton of color charge Q_k splitting into two partons i and j , $Q_{k}=Q_i+Q_j$. The result is that inside the cones i and j emit as independent charges, and outside their angular-order cones the emission is coherent and can be treated as if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

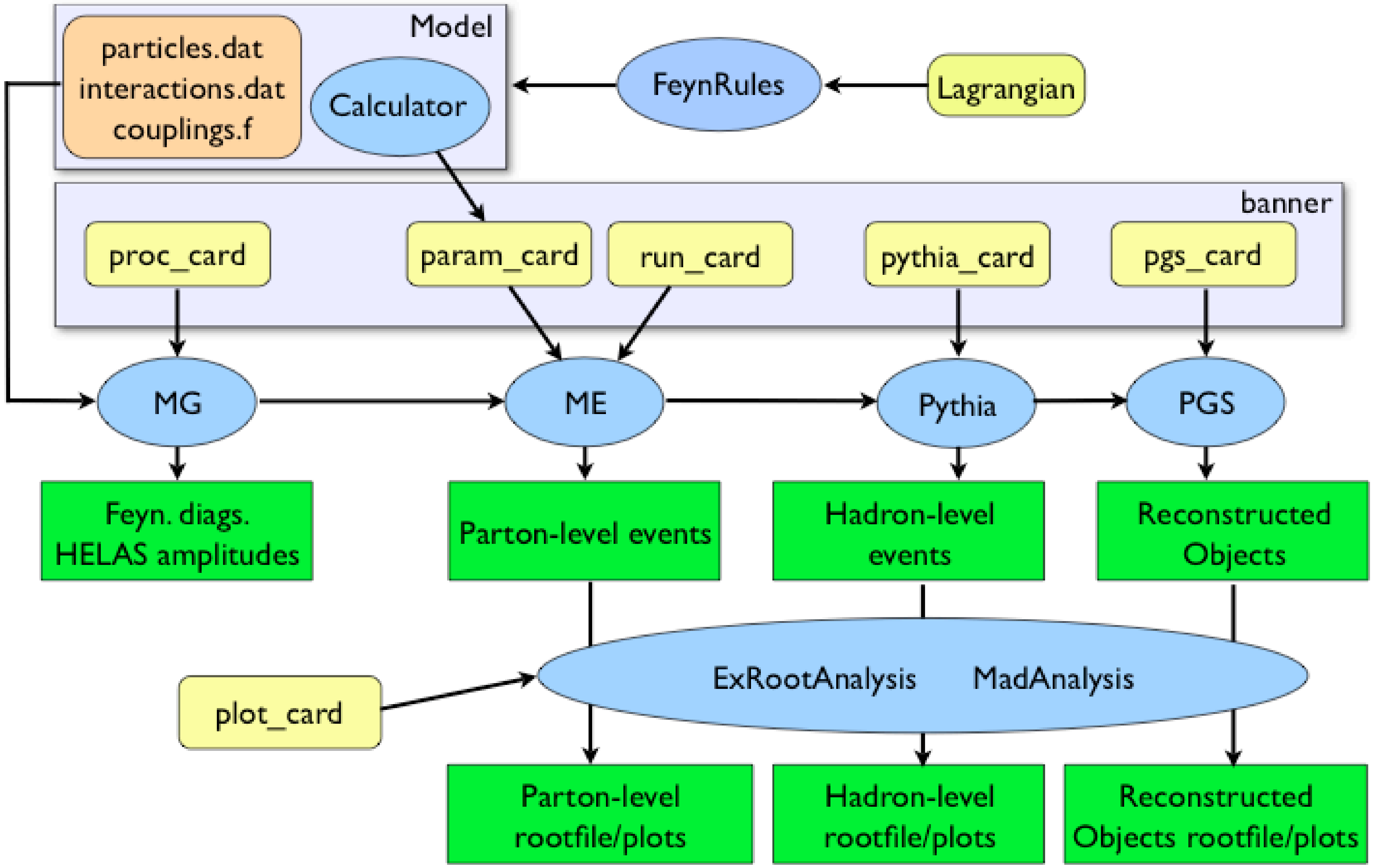
Monte Carlo approach to PS

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.





FlowChart


Model
particles.dat
interactions.dat
couplings.f
Calculator
FeynRules
Lagrangian
banner
proc_card
param_card
run_card
pythia_card
pgs_card
MG
ME
Pythia
PGS
Feyn. diags.
HELAS amplitudes
Parton-level events
Hadron-level events
Reconstructed Objects
ExRootAnalysis
MadAnalysis
plot_card
Parton-level rootfile/plots
Hadron-level rootfile/plots
Reconstructed Objects rootfile/plots

MadGraph advanced features

- Latest information available at the Wiki page
- Examples : decay rates, multiprocesses, decay chains,..
- Tools and Calculators
- Full expert/developer's package downloadable
- Standalone
- MadWeight
- New physics models : FeynRules and USERMOD

Let's play advanced!

Multi-processes

http://madgraph.phys.ucl.ac.be/EXAMPLES/Cards/proc_card_2.dat

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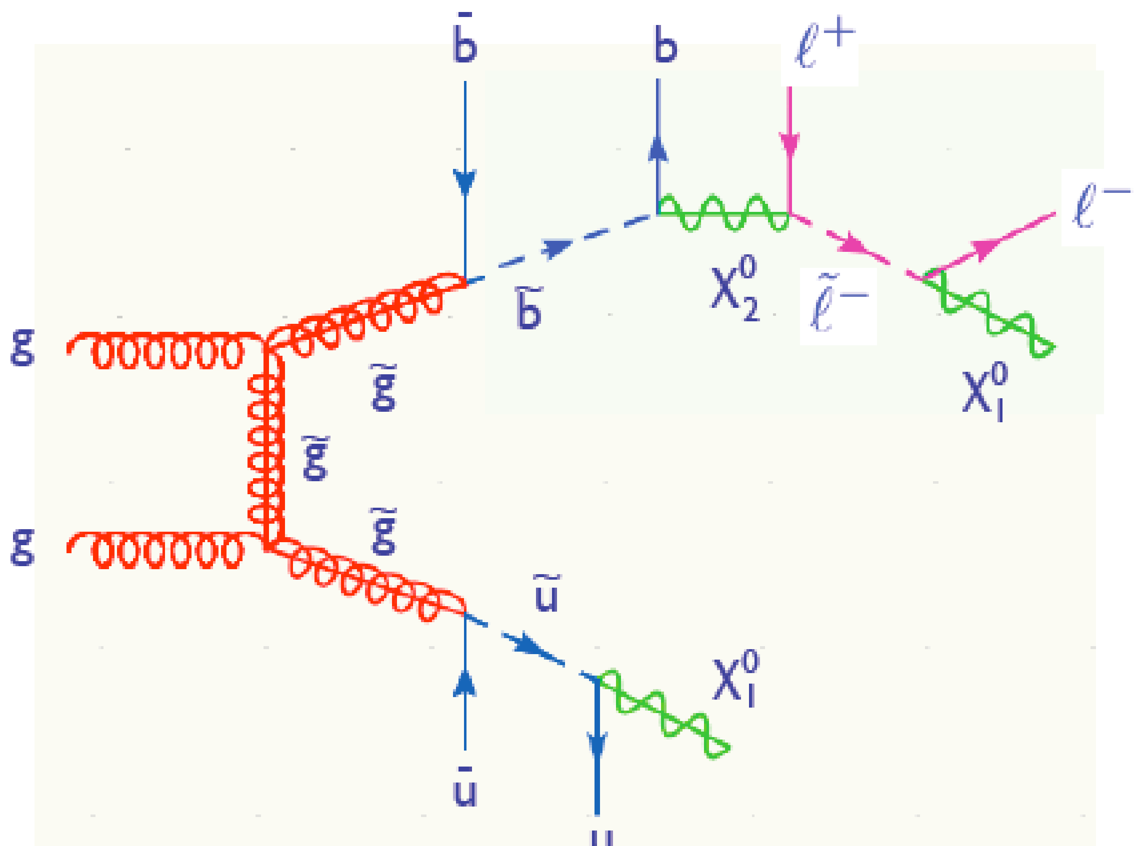
```
#----------------------------------------------------------------------*
# Process(es) requested : mg2 input                                    *
#----------------------------------------------------------------------*
# Begin PROCESS # This is TAG. Do not modify this line

pp>h>tt~bb~ @1     # First Process: signal for tt~h
QCD=2              # Max QCD couplings
QED=2              # Max QED couplings
end_coup           # no more couplings for this proc

pp>tt~bb~   @2     # Second Process: QCD background tt~bb~
QCD=99             # Max QCD couplings
QED=0              # Max QED couplings
end_coup           # no more couplings for this proc

pp>tt~bb~/h @3     # First Process: EW background  tt~bb~
QCD=2              # Max QCD couplings
QED=2              # Max QED couplings
end_coup           # no more couplings for this proc

done               # Write 'done' to tell MG to stop

# End PROCESS  # This is TAG. Do not modify this line
#----------------------------------------------------------------------*
# Model information                                                    *
```

Decay chains

[Alwall and Stelzer,2007]

```
gg >(go>u~(ul > u n1 ))(go>b~(b1>(b(n2>mu+(mul- >mu- n1)))))
```



In this case:

1. Full matrix element is obtained which includes correlations between production and decays.
2. Spin of the intermediate states is kept.
3. One can go beyond 1→2 decays.
4. Resonances have BW.
5. Non-resonant contributions can be systematically included only where relevant.

Example simplification: the process can exactly factorized in

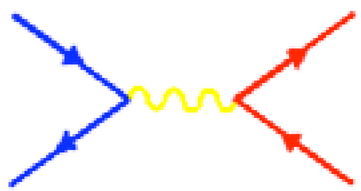
```
gg >(go>u~ul)(go>b~b1)
```

where the squarks can be decayed at the event level, for example by BRIDGE

[Maede and Reece,2007]

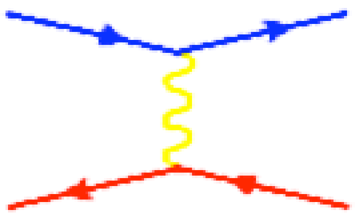
```
ul > u n1
b1 > b(n2>mu+(mul- >mu- n1))
```

Web tools



MadGraph Version 4

UCL UIUC Fermi
by the MG/ME Development team



Generate Process | Register | Tools | My Database | Cluster Status | Downloads (needs registration) | Wiki/Docs | Admin

Online MadGraph/MadEvent related tools

Calculators

Plotting Interface (ExRootAnalysis)

Plotting Interface (MadAnalysis)

Decay Interface

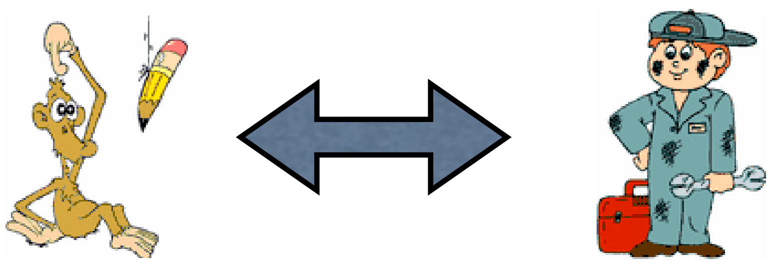
A Z' model How-To

- Copy the usrmod to zprime
- Edit particles.dat, interactions.dat and VariableName.dat to add a Z' coupling to uu~,dd~ and mu+mu- like the usual Z
- Run the ConversionScript
- Edit couplings.f and param_card.dat (eg mZ'=500GeV, WZ'=WZ)
- Use testprog and SA version of MG to debug your implementation
- Generate pp>mu+mu- events with an without Z
- Create invariant mass plots for the mu+mu- pair in both cases with SA, what do you observe ?

What about BSM?

What about BSM?

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).



A Roadmap (with roadblocks) for BSM @ the LHC

TH

EXP

Idea

Data

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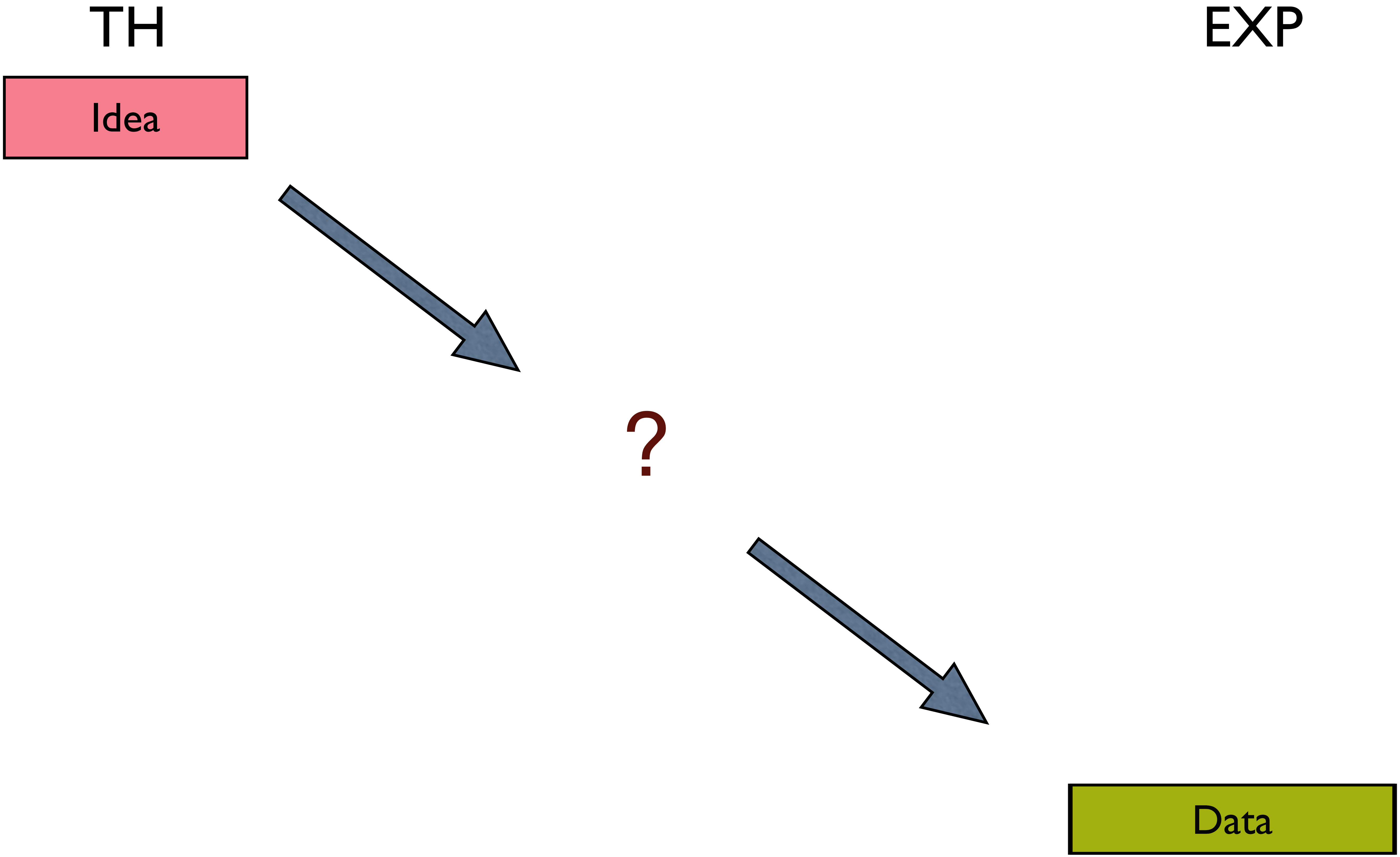

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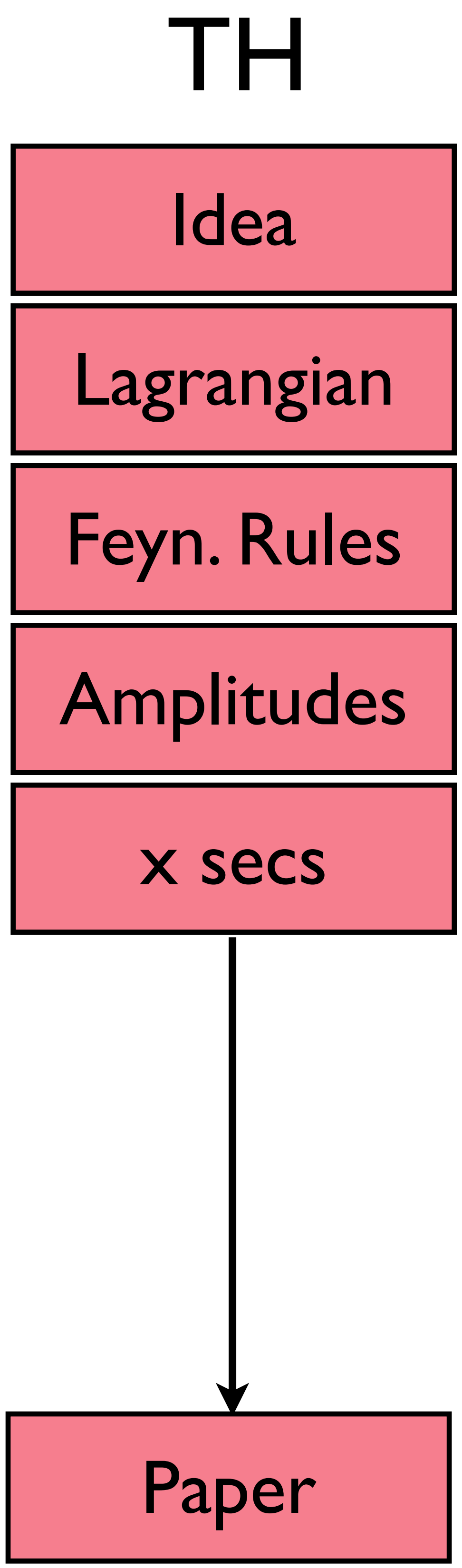

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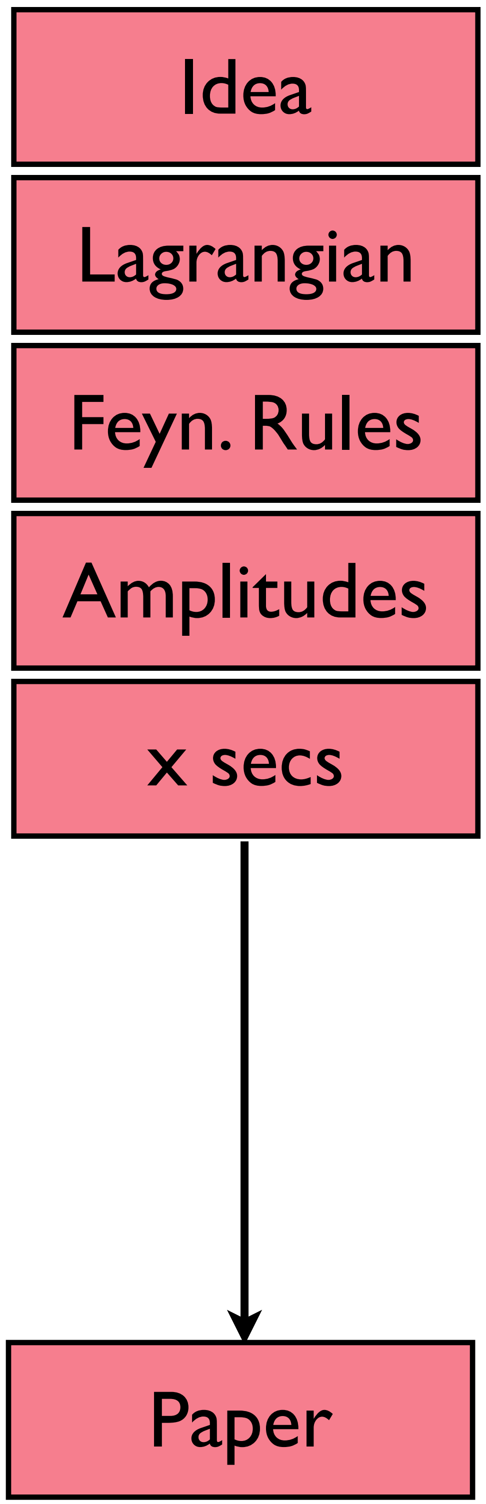
TH PHENO



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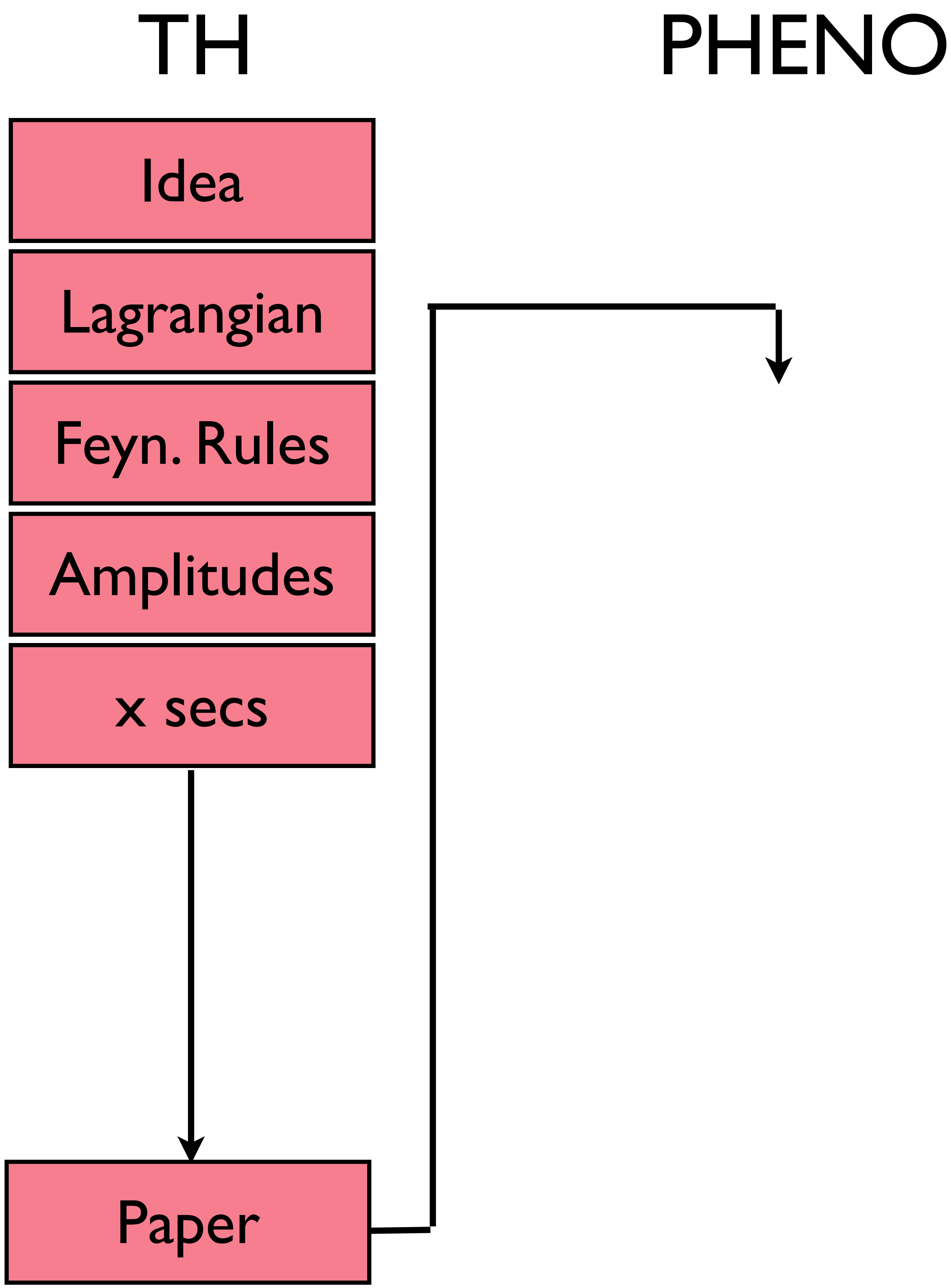

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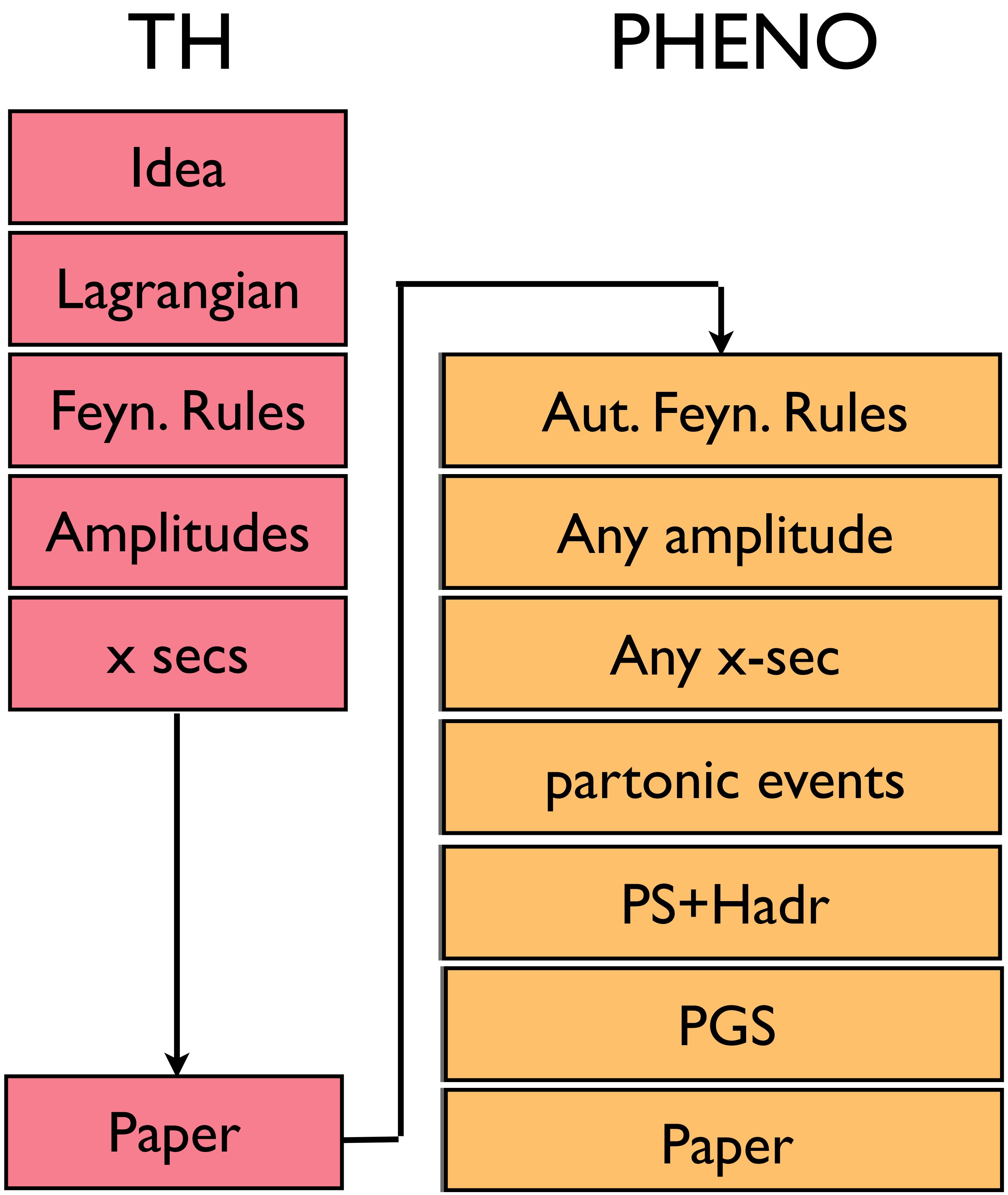

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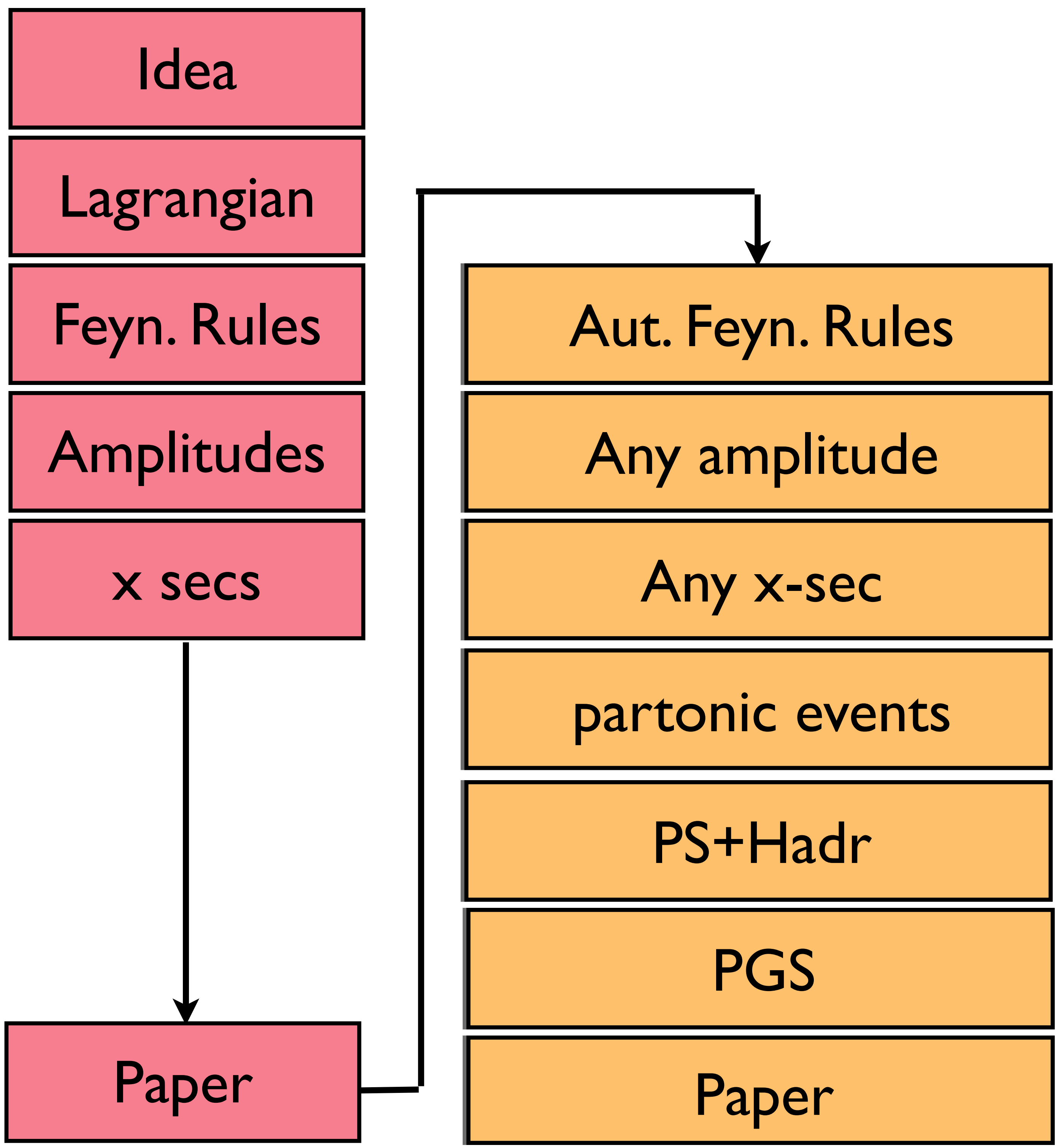

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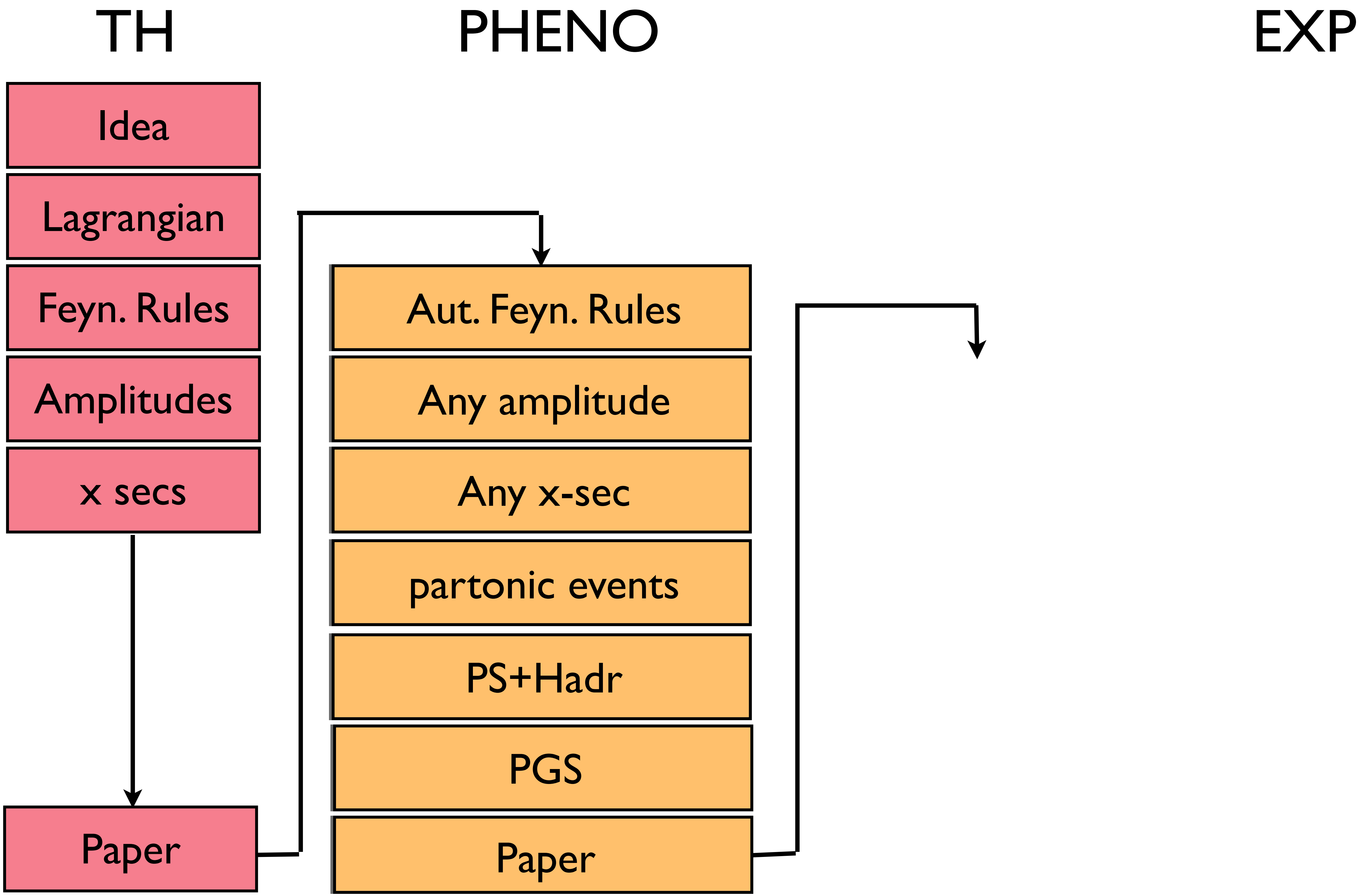

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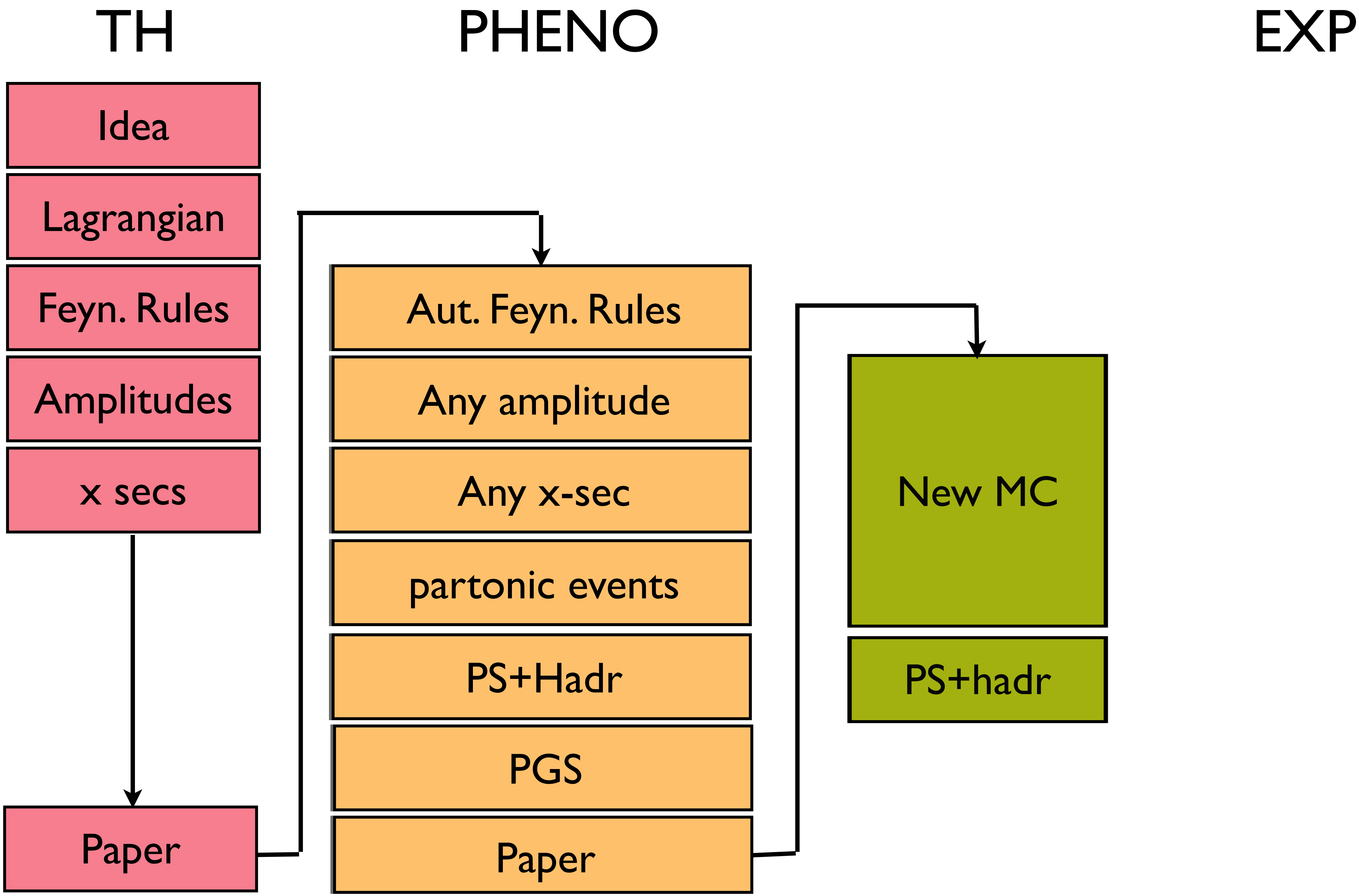

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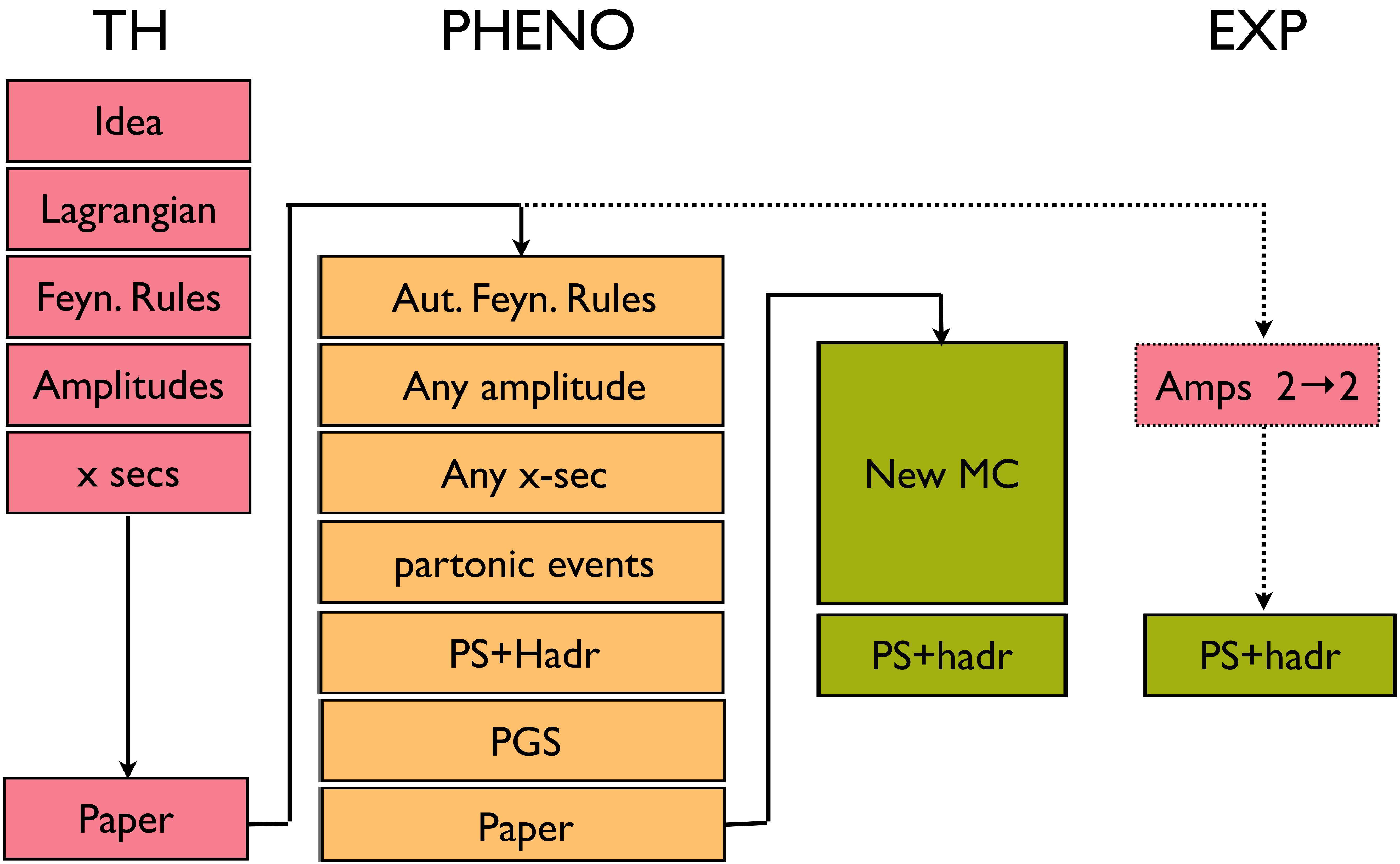

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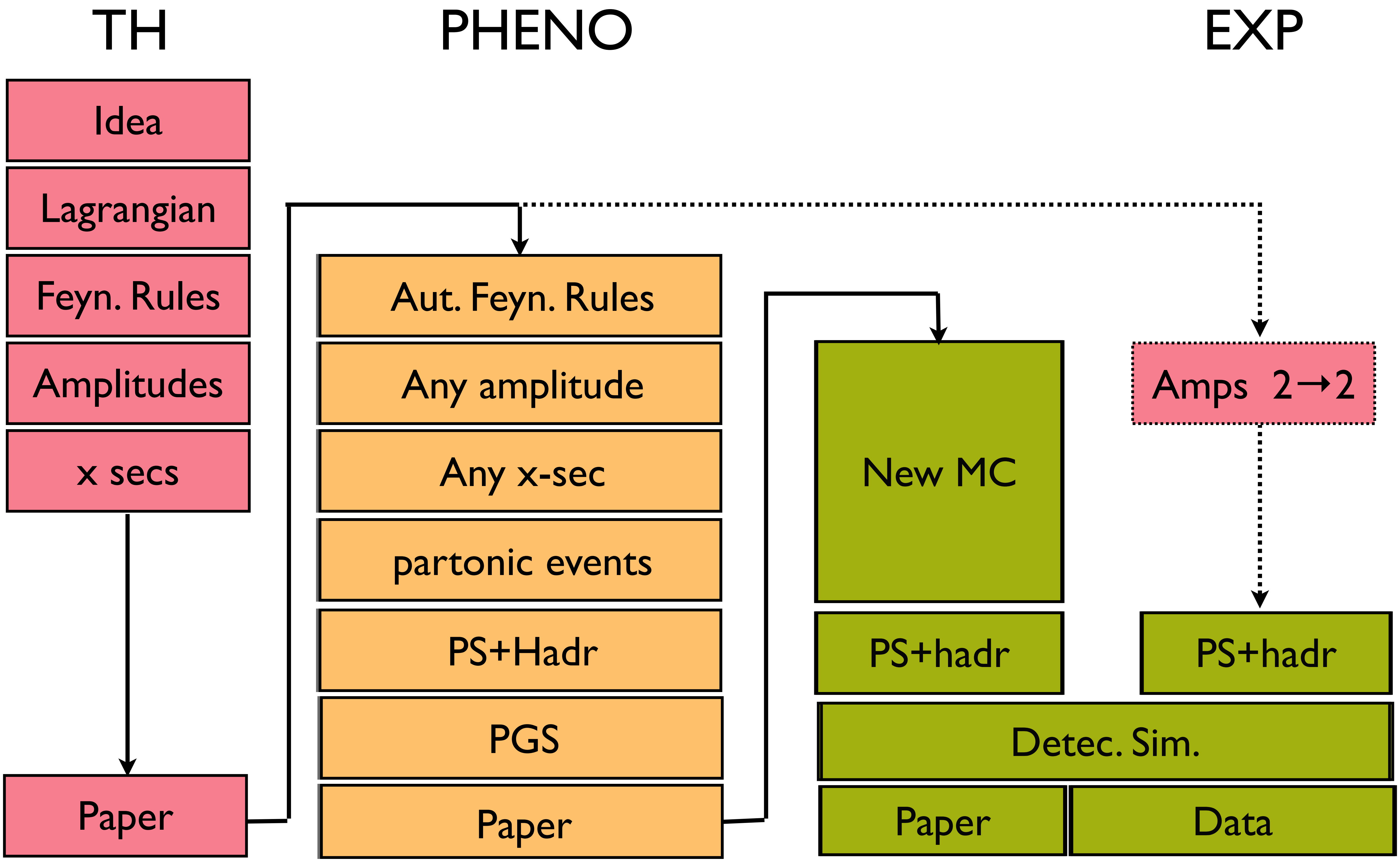

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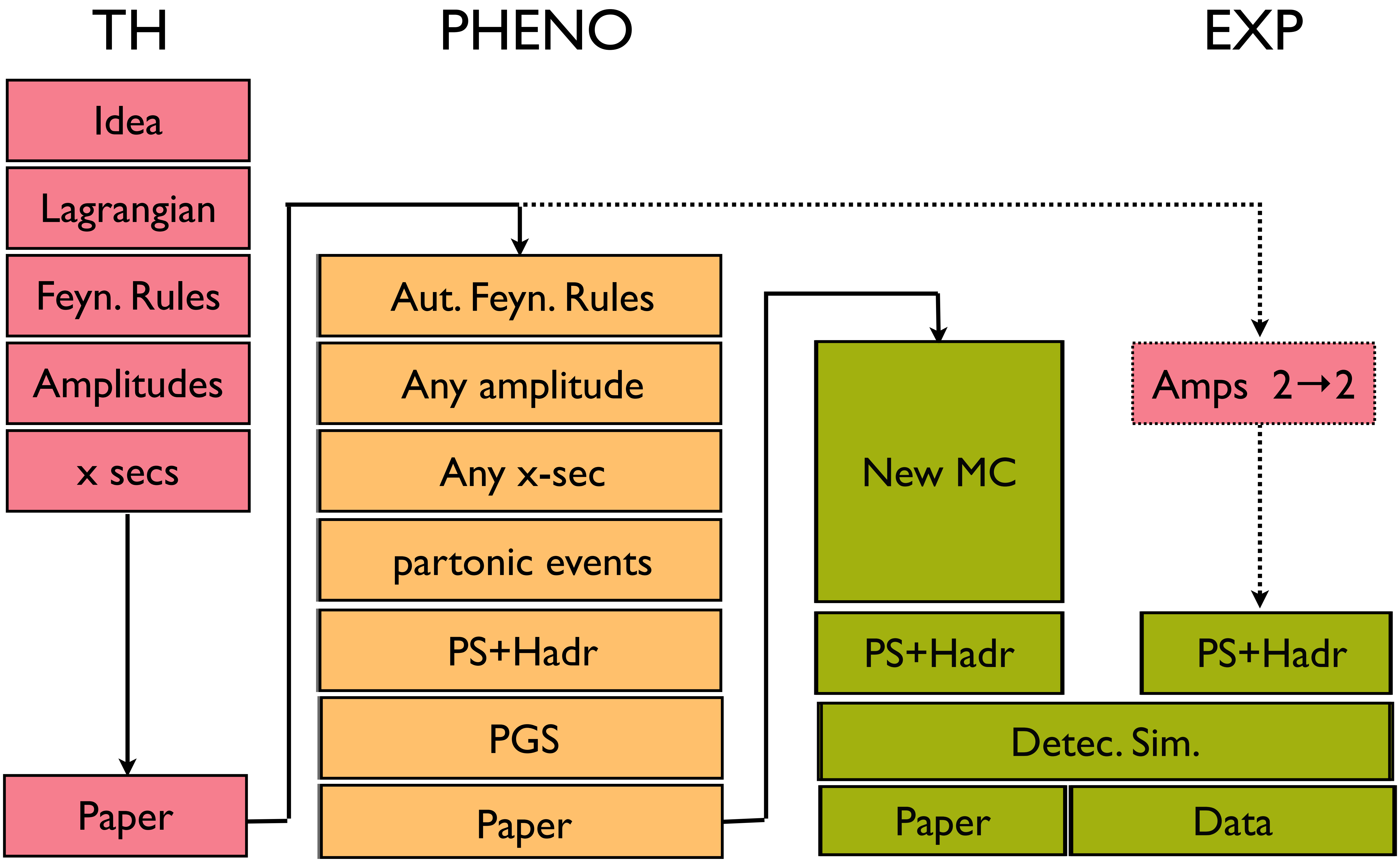


A Roadmap (with roadblocks) for BSM @ the LHC

TH

PHENO

EXP

Idea

Lagrangian

Aut. Feyn. Rules

Any amplitude

Any x-sec

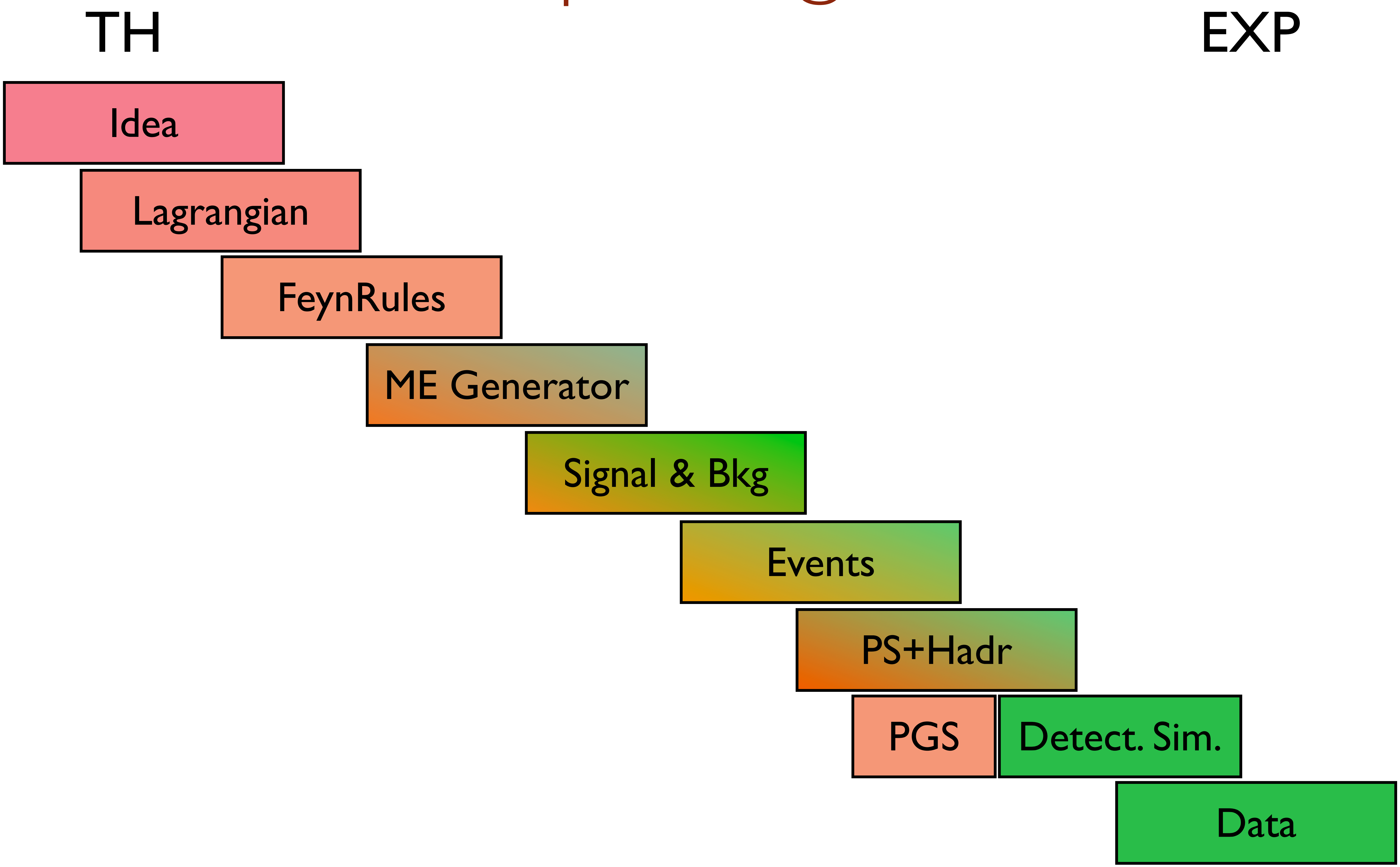
partonic events

PS+Hadr

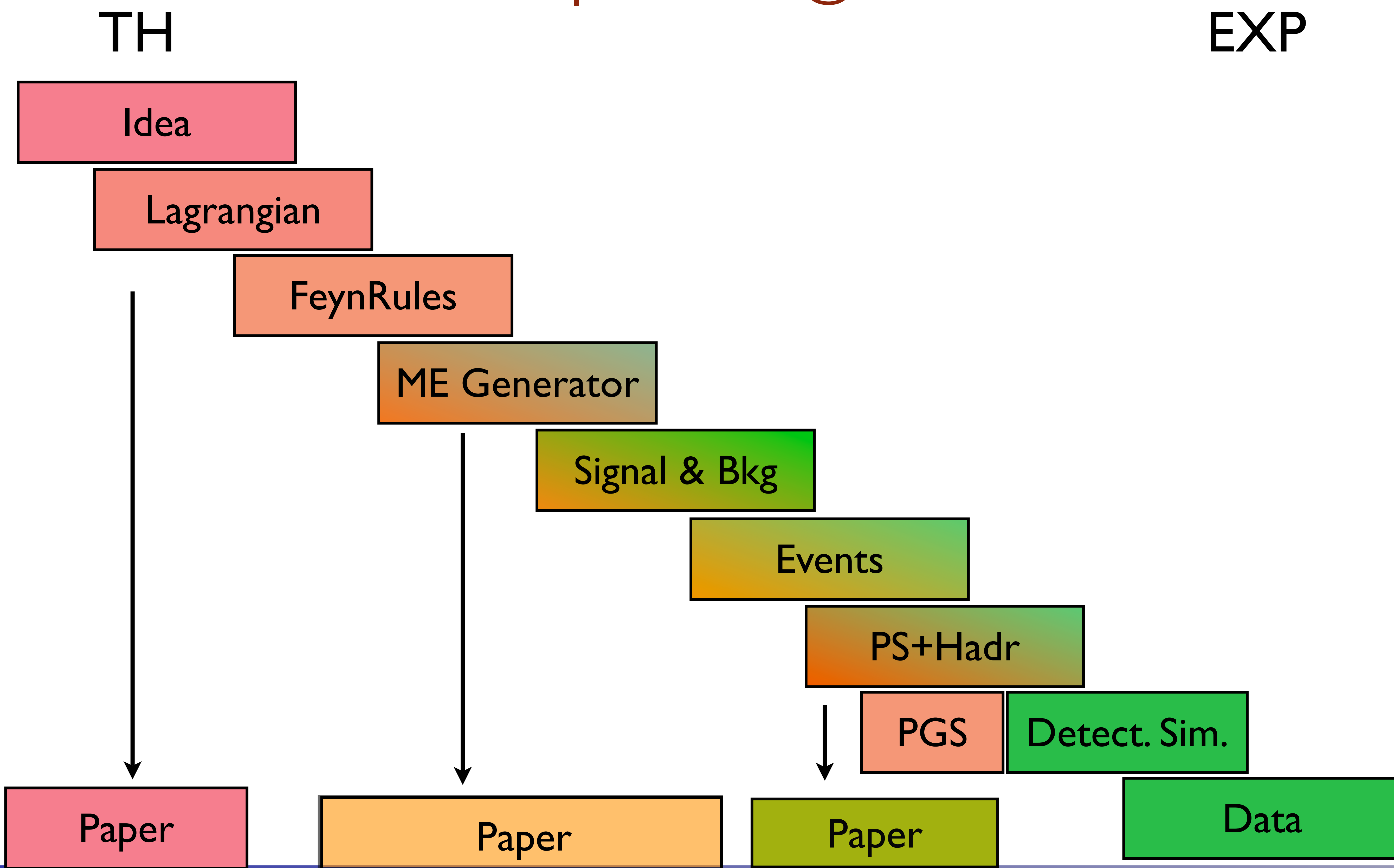
Detec. Sim.

Data

A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC



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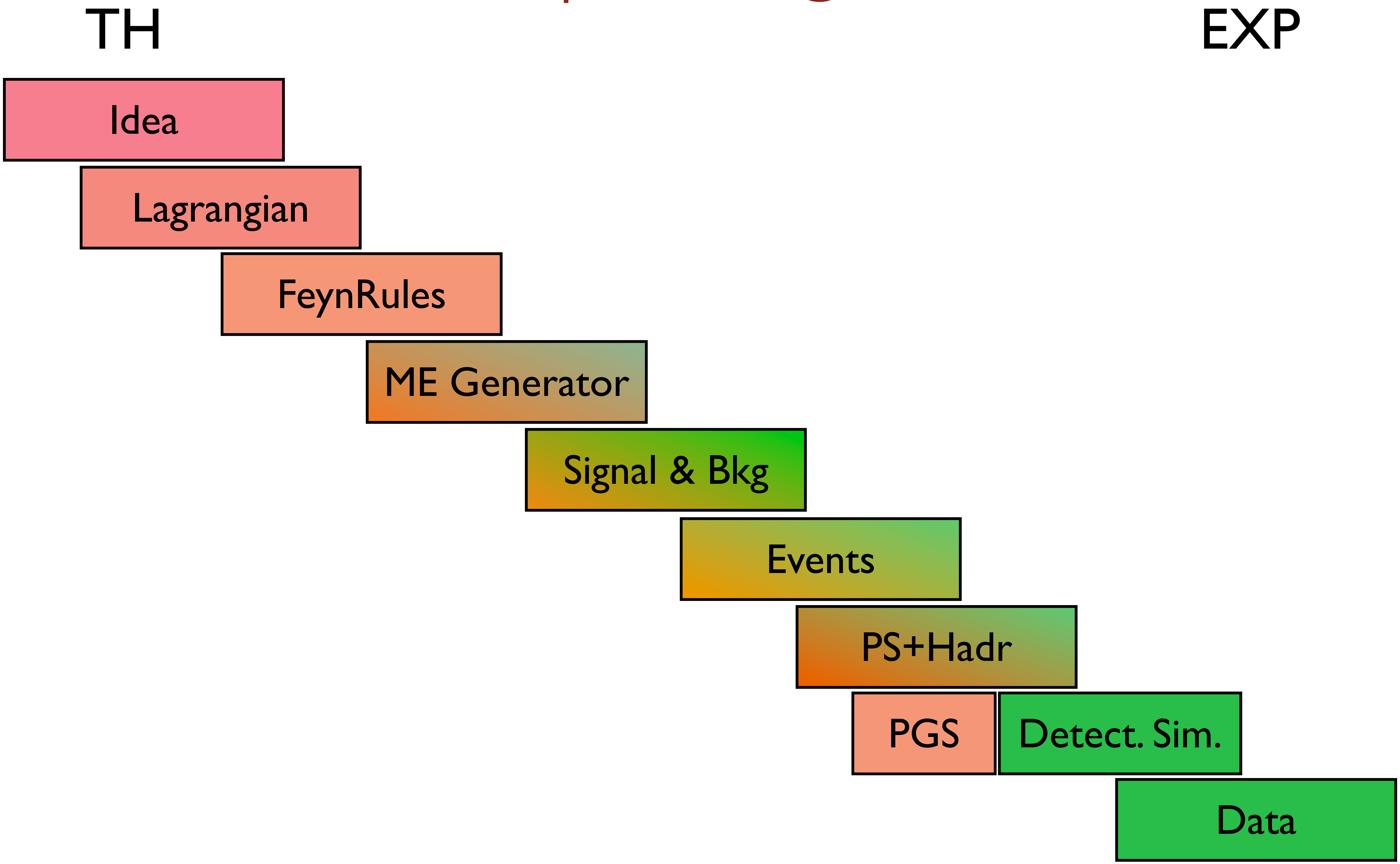

A Roadmap for BSM @ the LHC

TH

EXP

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

PS+Hadr

PGS | Detect. Sim.

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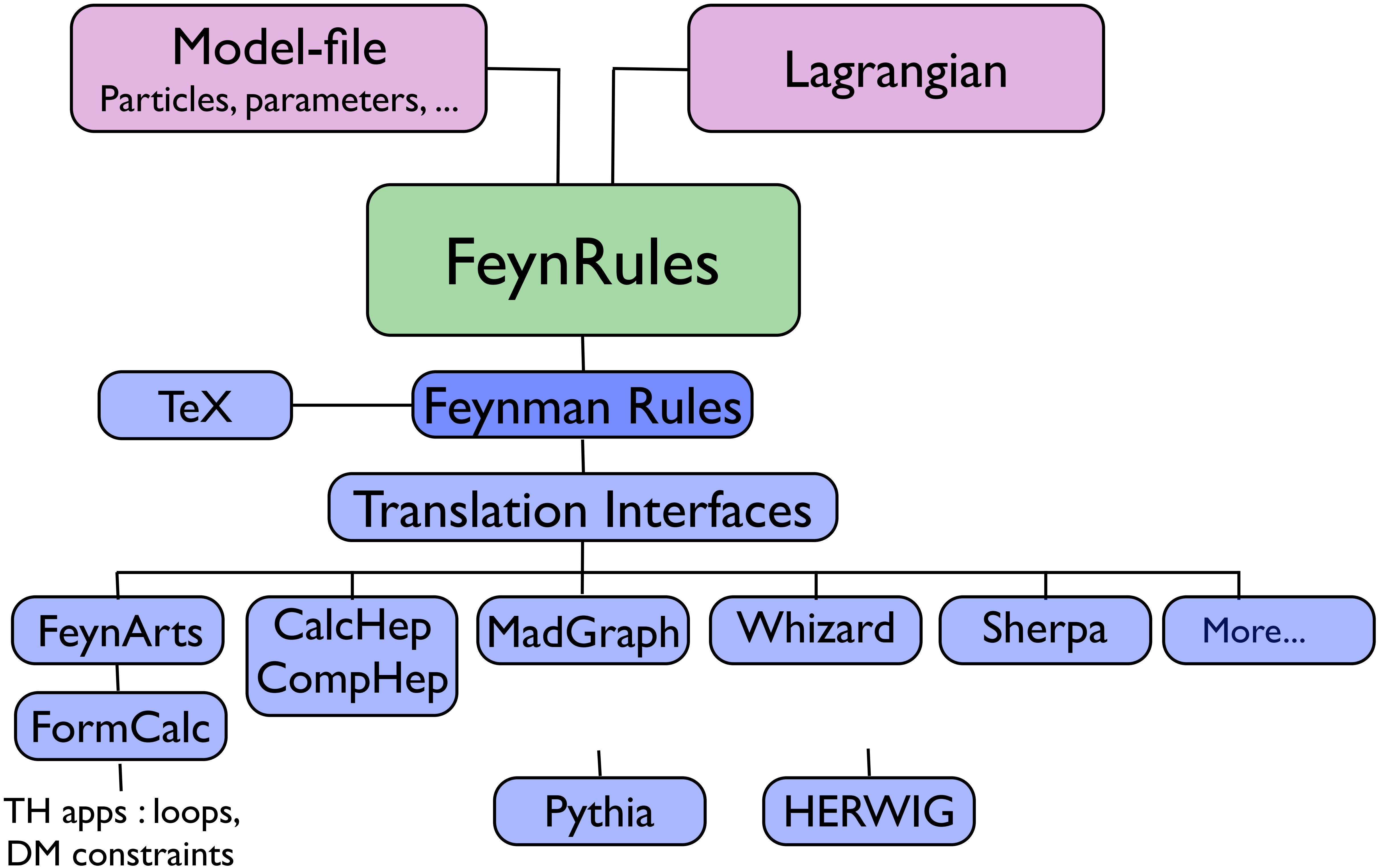
Complete automatization for tree-level based calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics. Automatization of NLO is very promising now...

The FeynRules Project

[Christensen, Duhr, 2008; Christensen, Duhr, Fuks, et al., 2009]



A look into the future

MadGraph 5 beta: released two weeks ago

Automatic NLOwPS in SM and BSM....

A look into the future

MadGraph 5 beta: released two weeks ago

Main points:

* New Matrix Element generator engine in Python
* Full flexibility for New Physics implementation through FeynRules
* Loops... NLO computations for SM and BSM!

Automatic NLOwPS in SM and BSM....

Improving our predictions

How we (used to) make predictions?

First way:

- For low multeplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  $\Rightarrow$ $\hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$

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

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

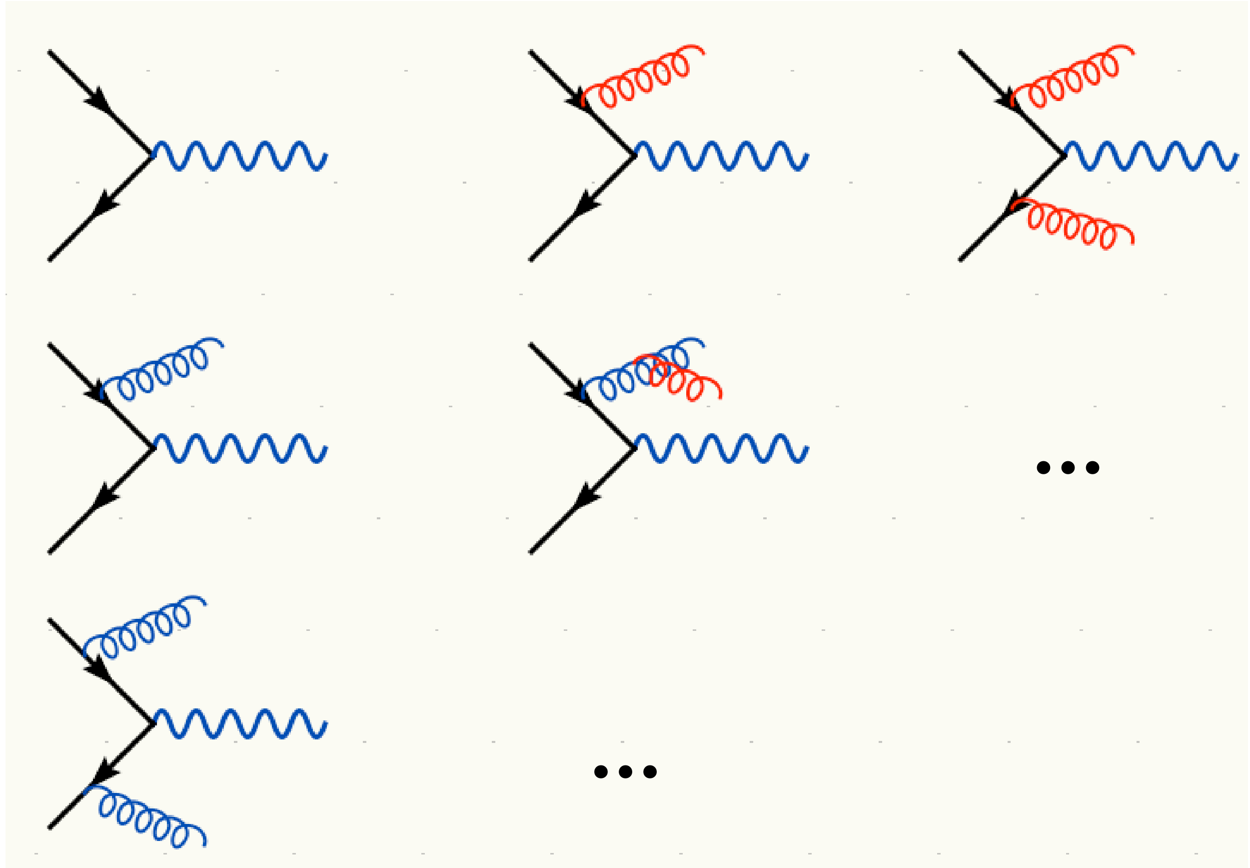
2. Get fully exclusive description of events correct at NLO in the normalization and distributions. NLOwPS

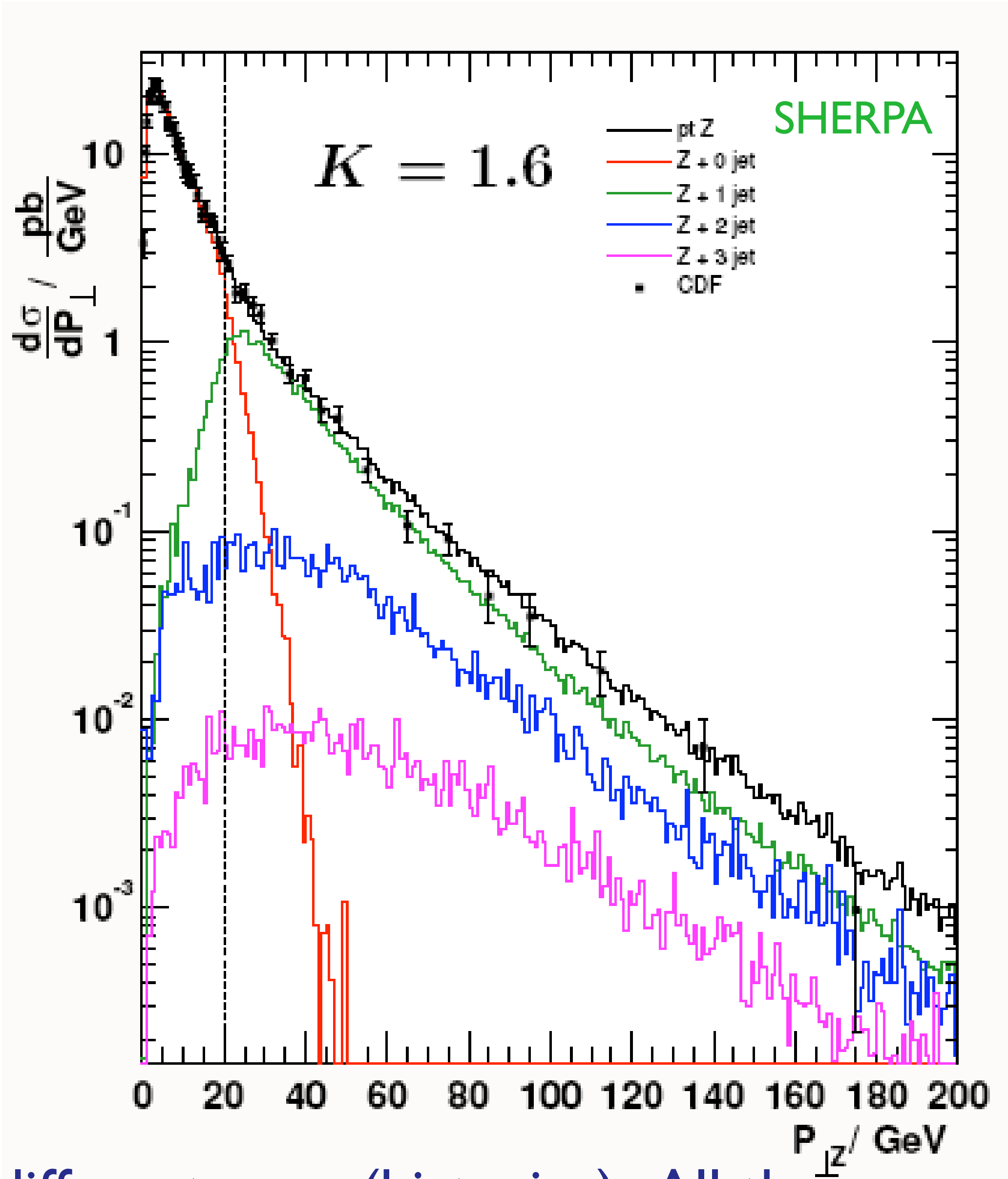
Merging fixed order with PS

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

PS →

ME ↓

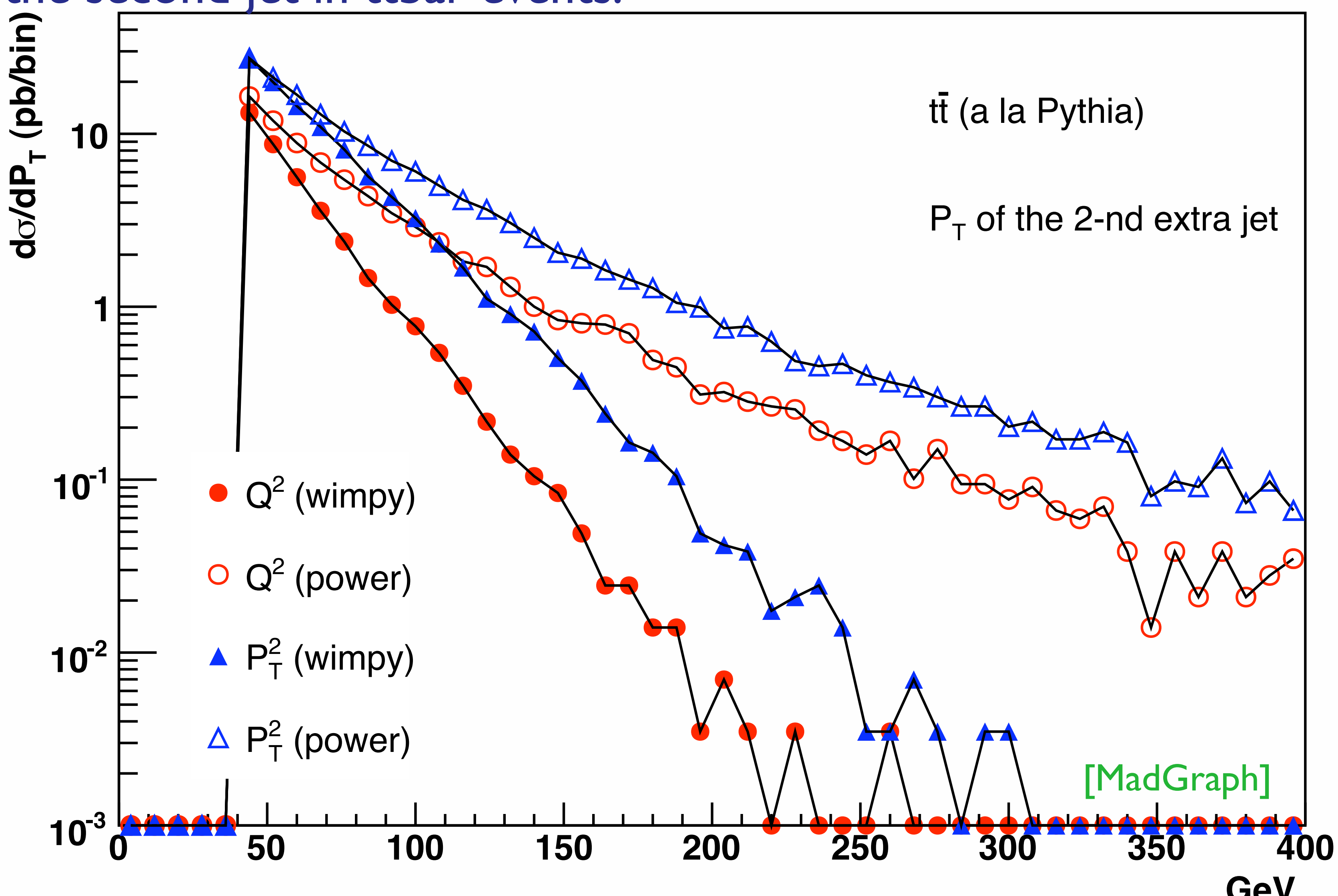




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

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.

PS alone vs matched samples

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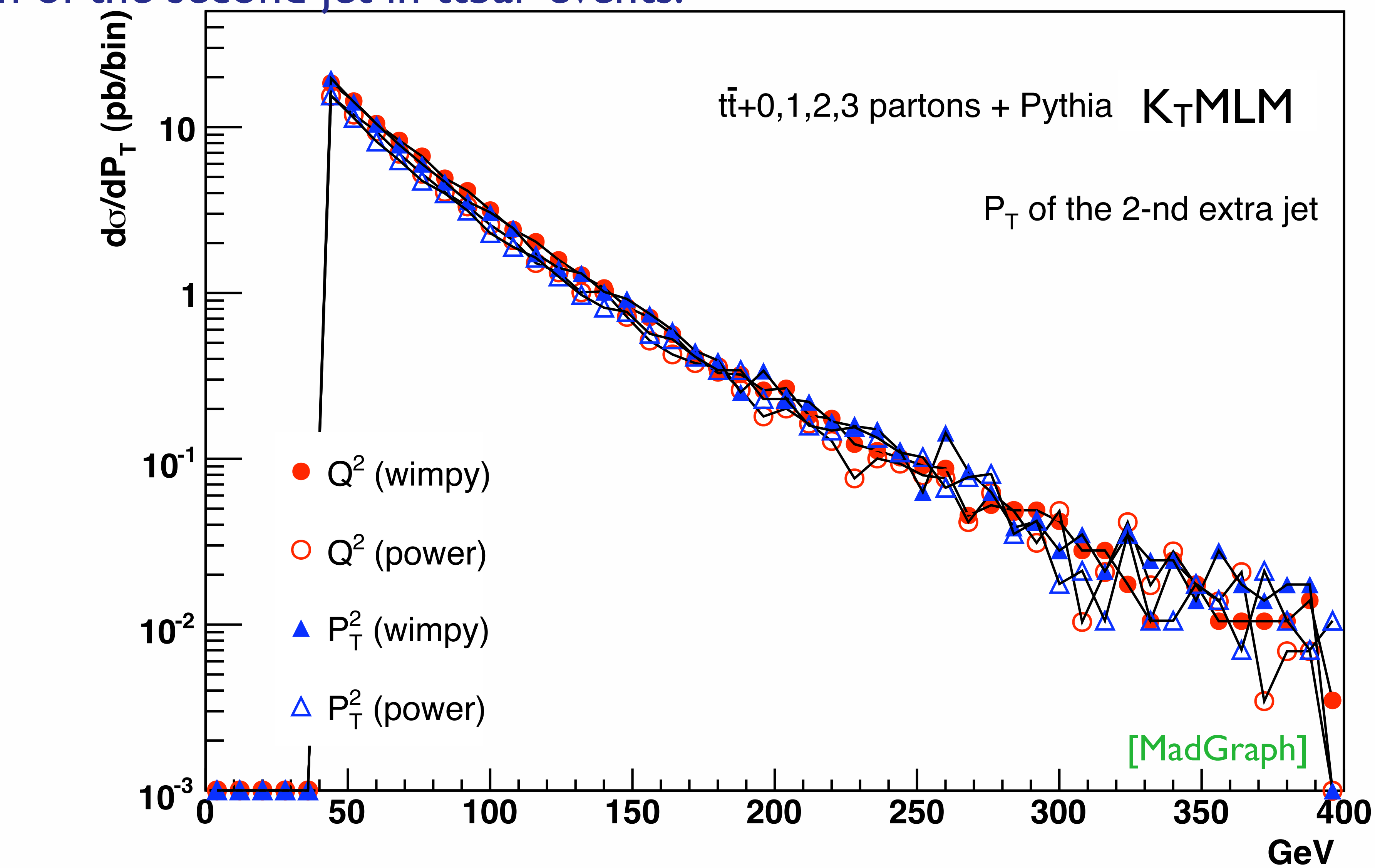
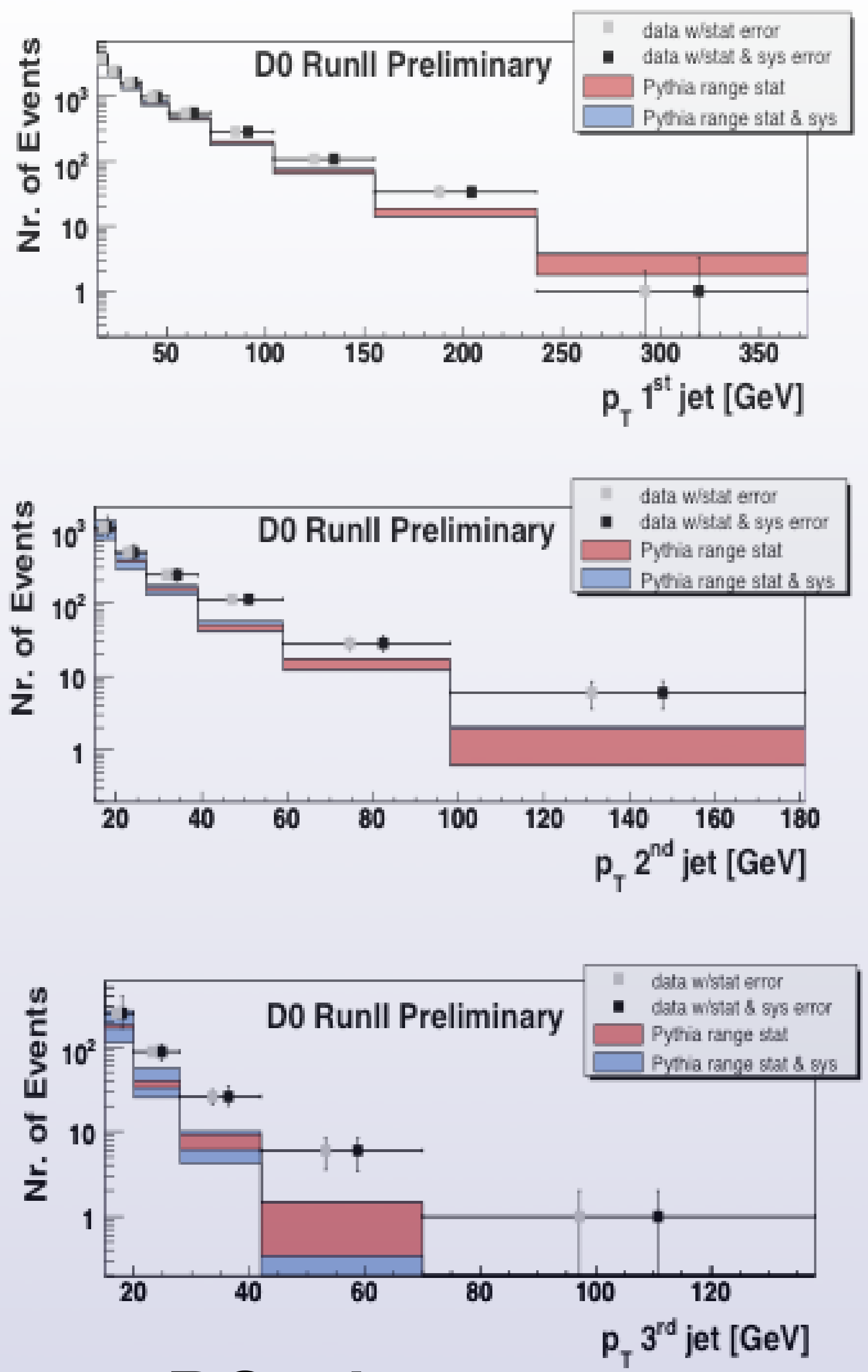
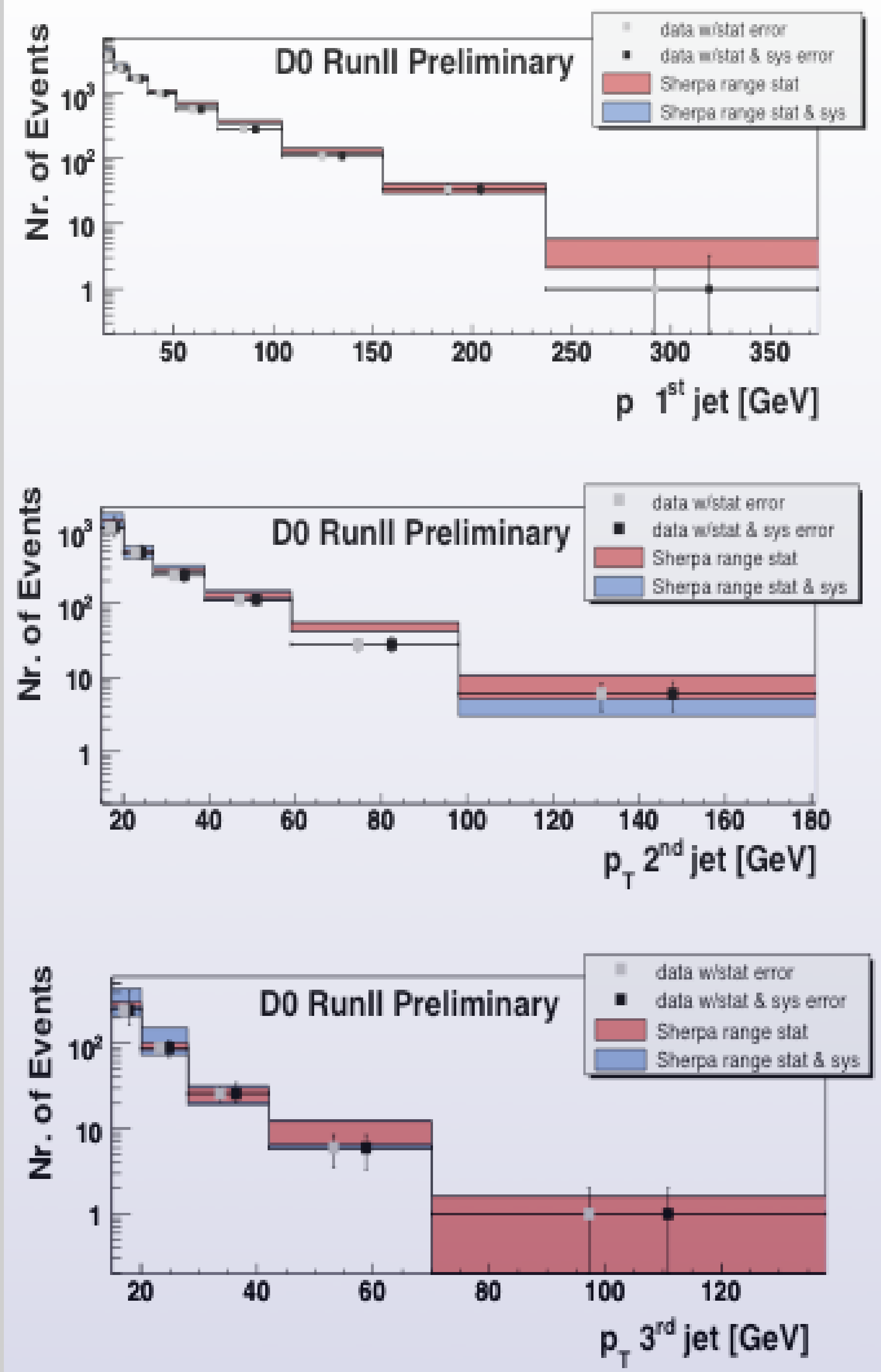


In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

PS alone vs matched samples : Z+jets at D0

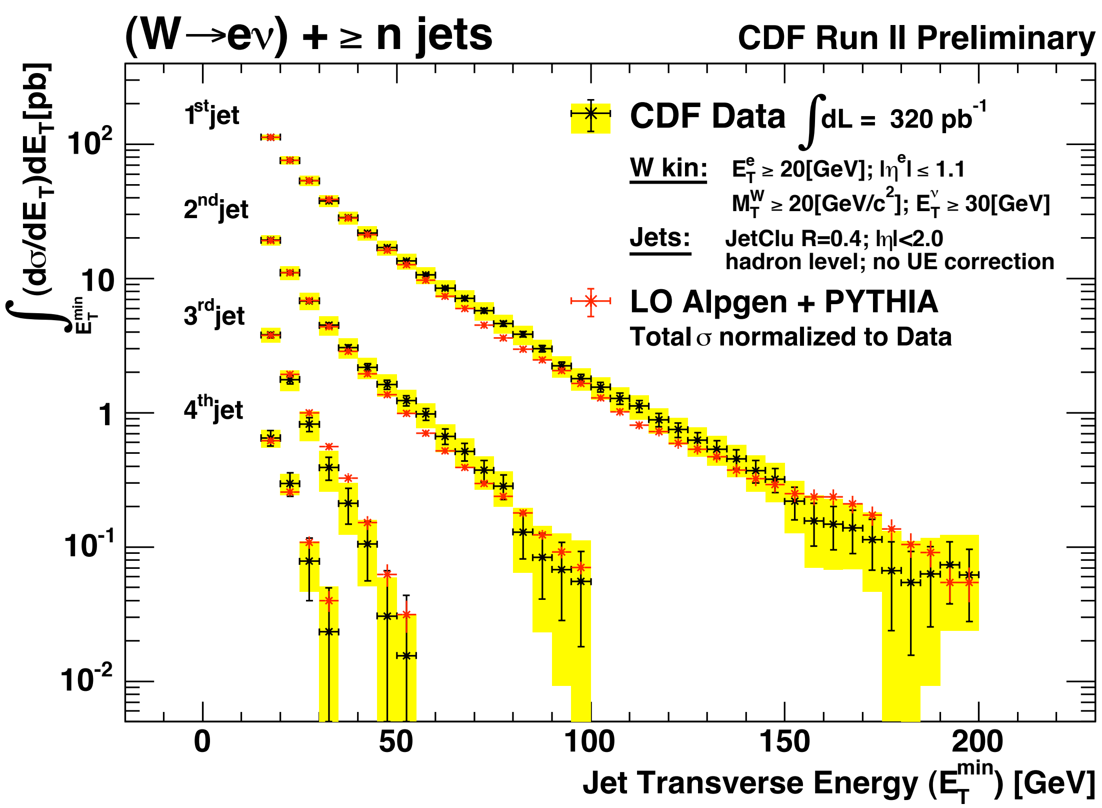


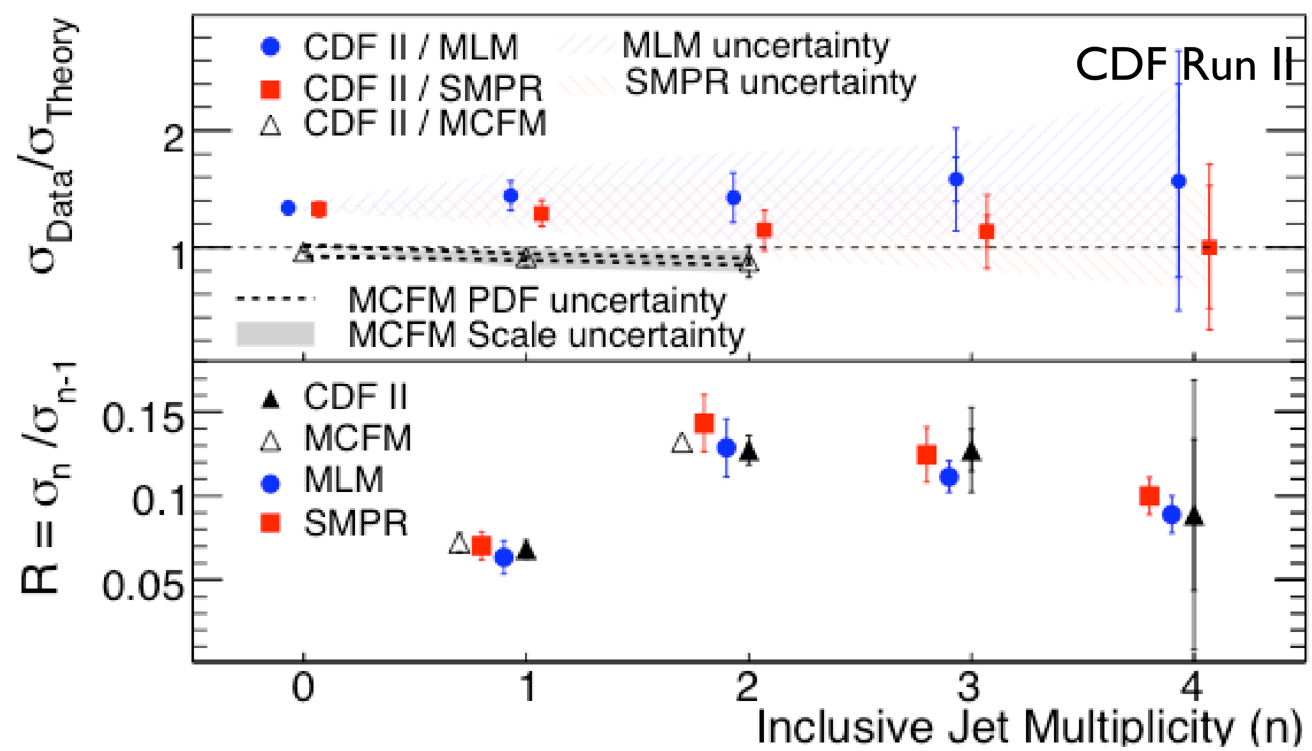
PS alone (Pythia)



ME+PS (SHERPA)

W+jets at CDF





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

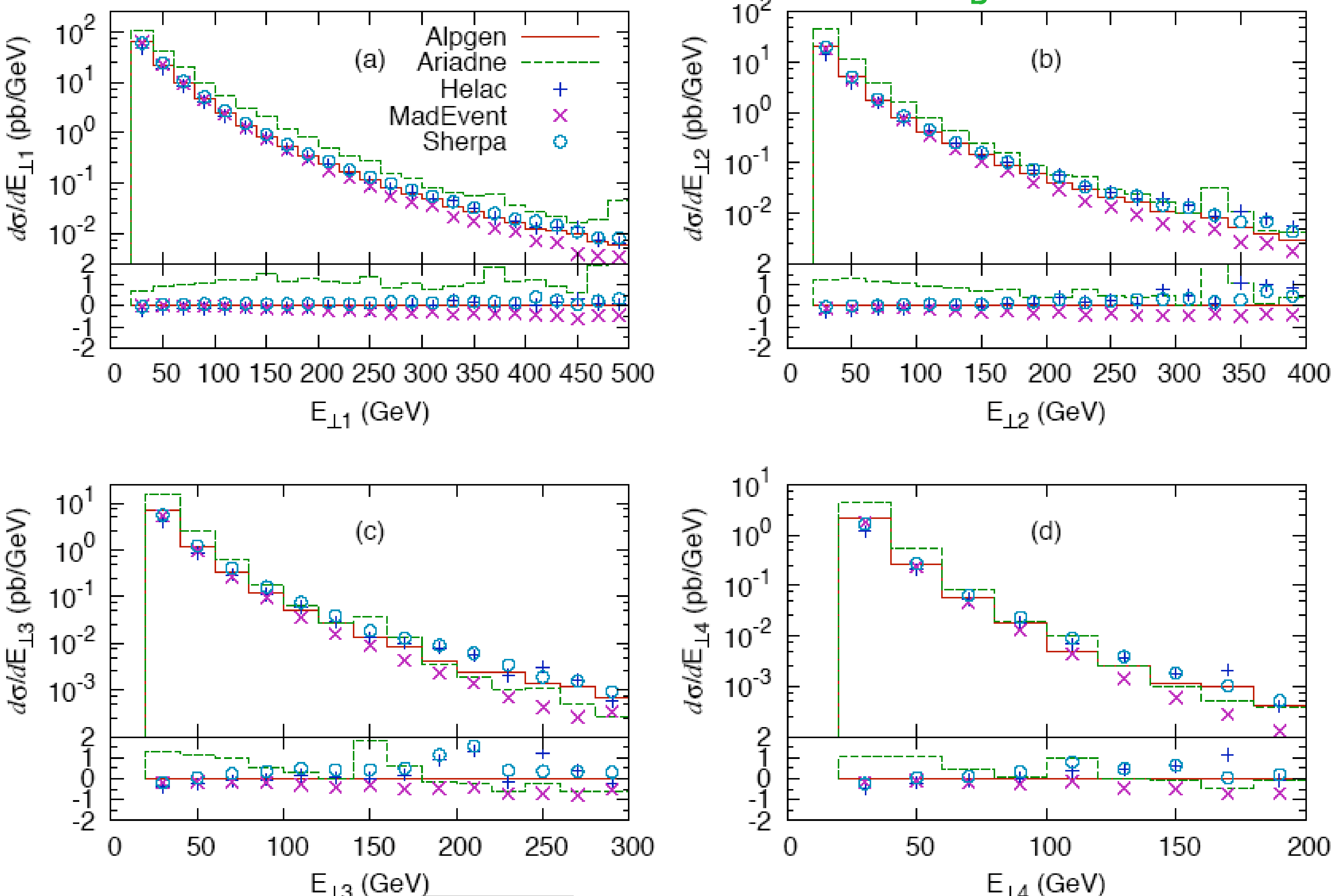
* NLO rates in outstanding agreement with data.

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

W+ jets: first comparison

$W^{\pm}$ + jets comparison plots: Jet E_T for LHC

[J. Alwall et al., arXiv:0706.2569]



NLOwPS

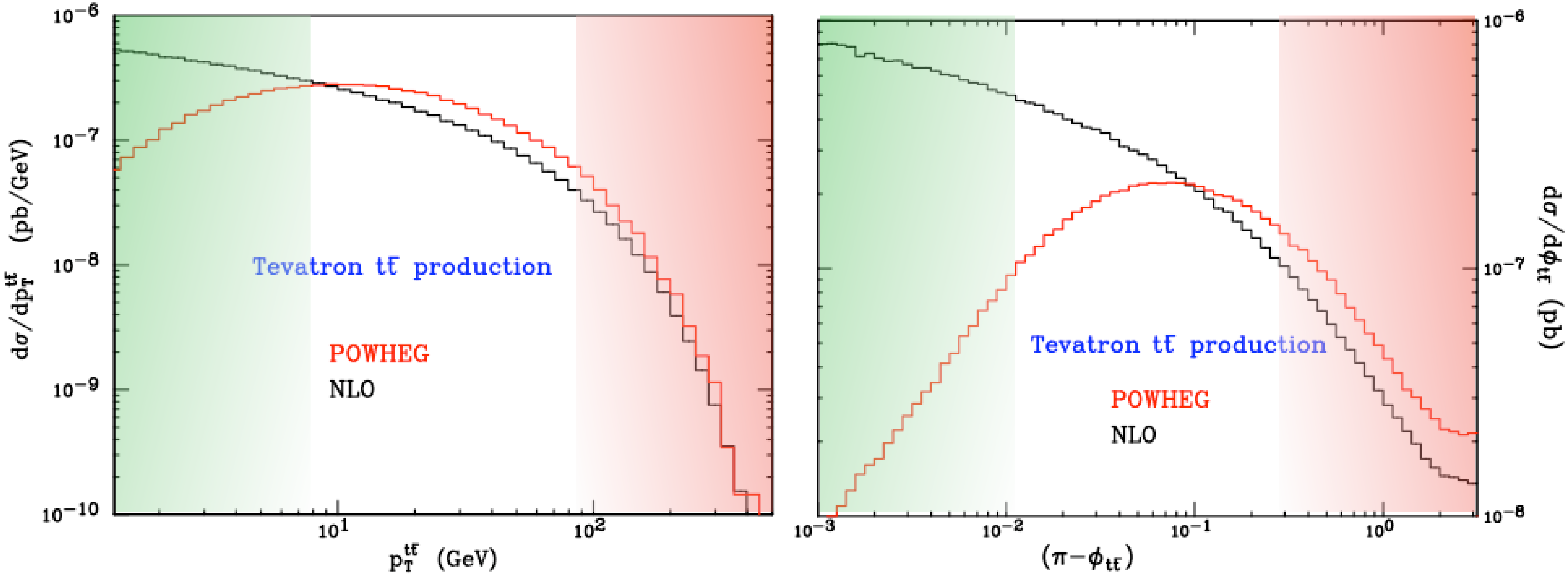
Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

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.

Status

pp→ n particles

Status

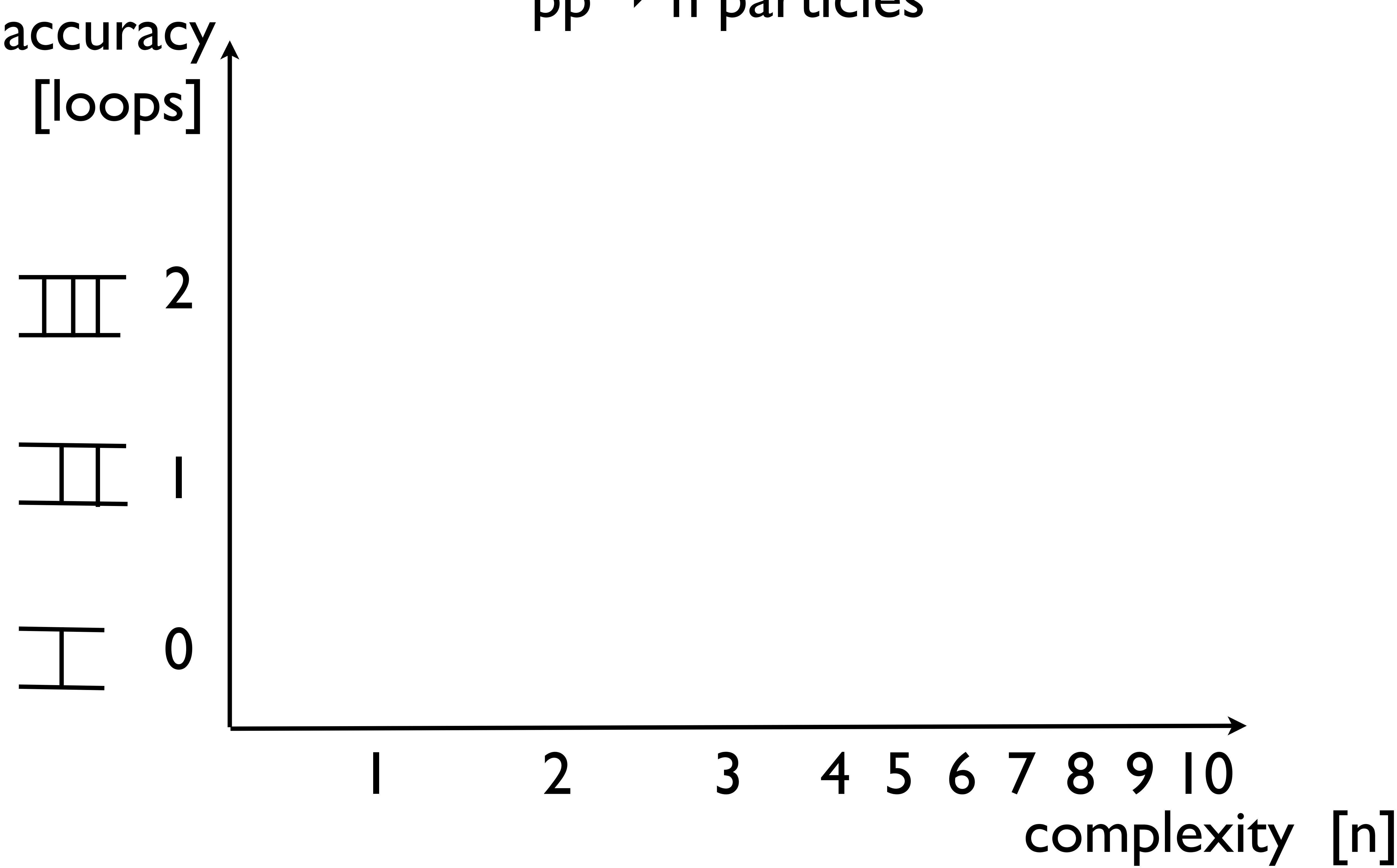
pp→ n particles

1 2 3 4 5 6 7 8 9 10

complexity [n]

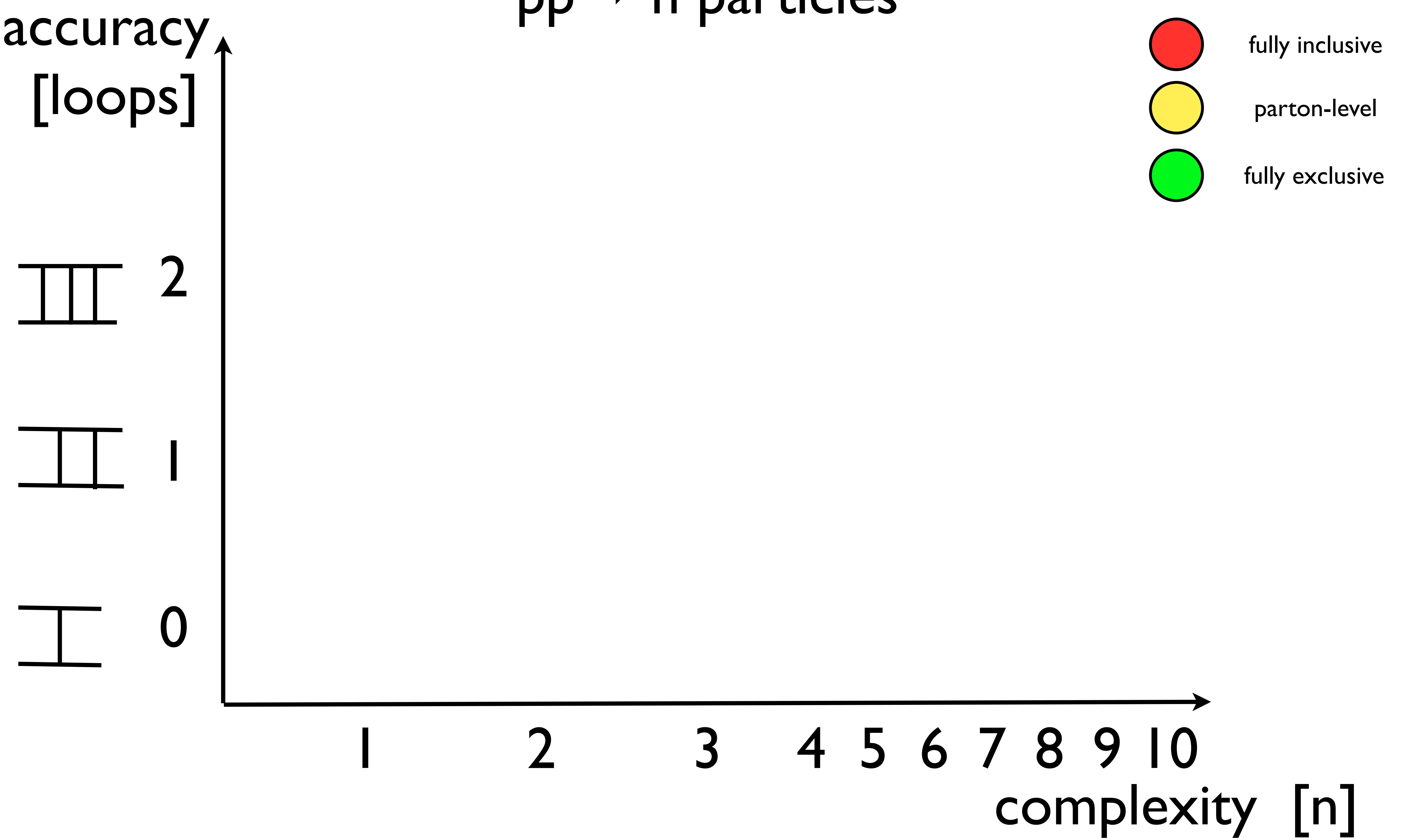
Status

pp$\to$ n particles



Status

pp→ n particles



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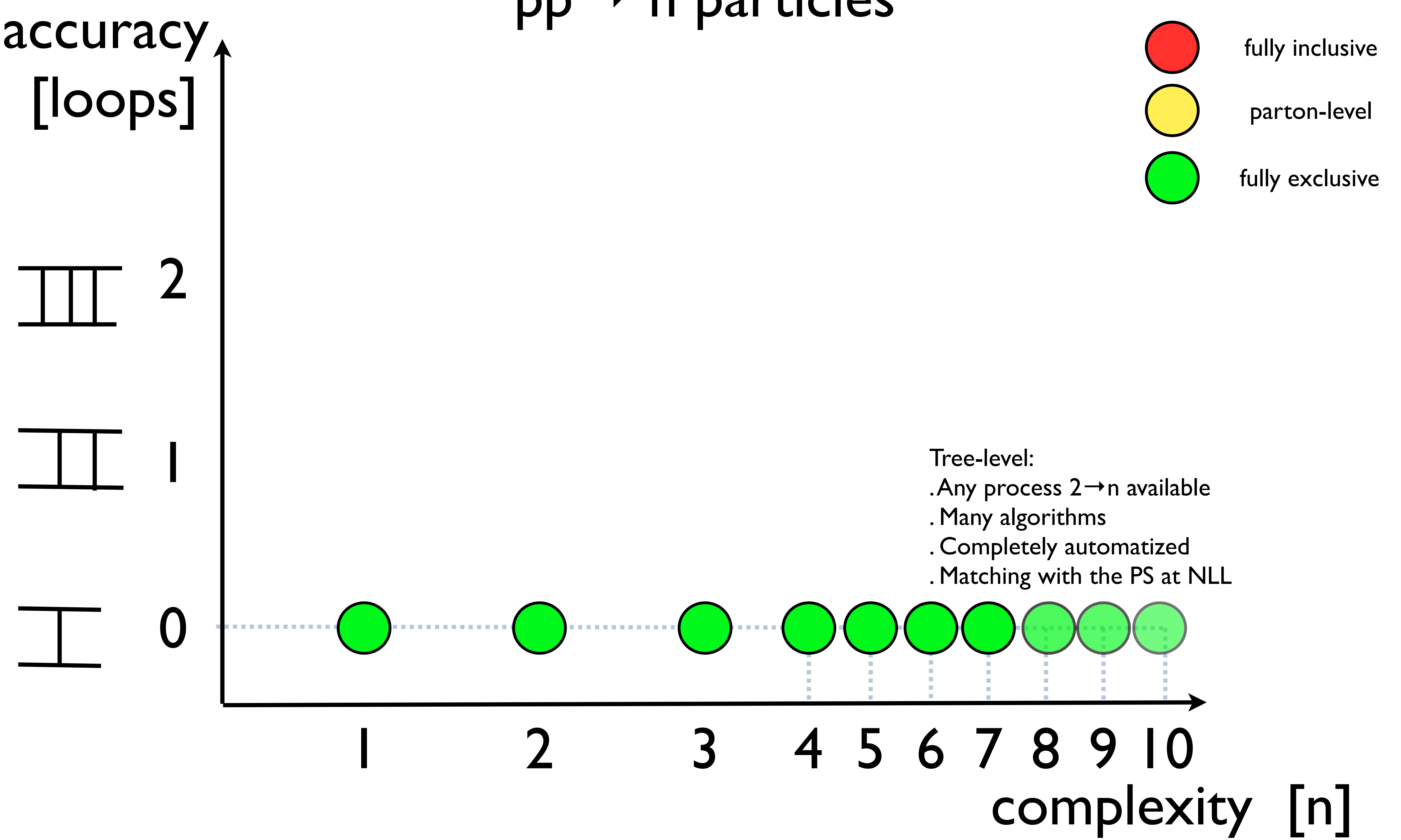

Status

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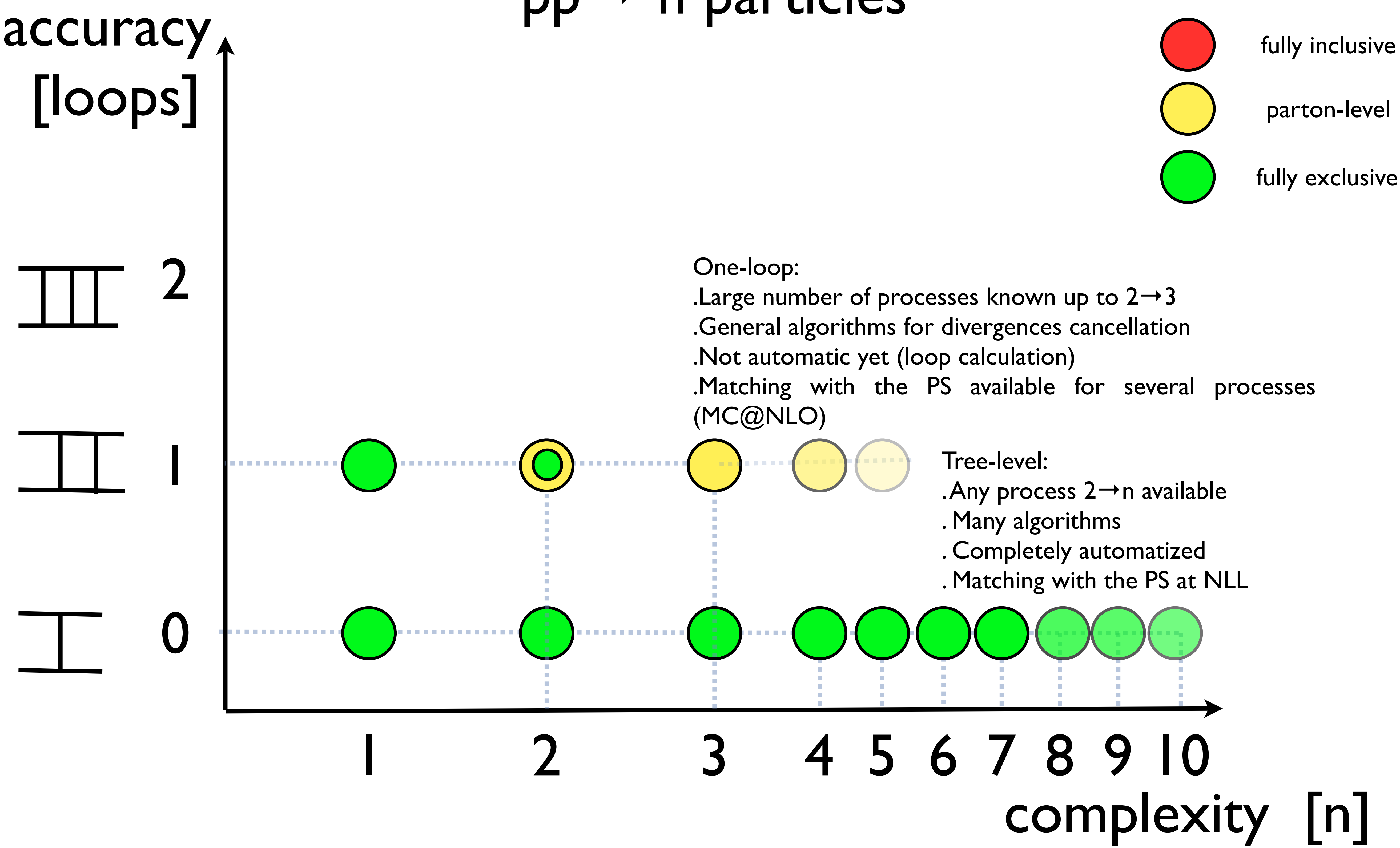
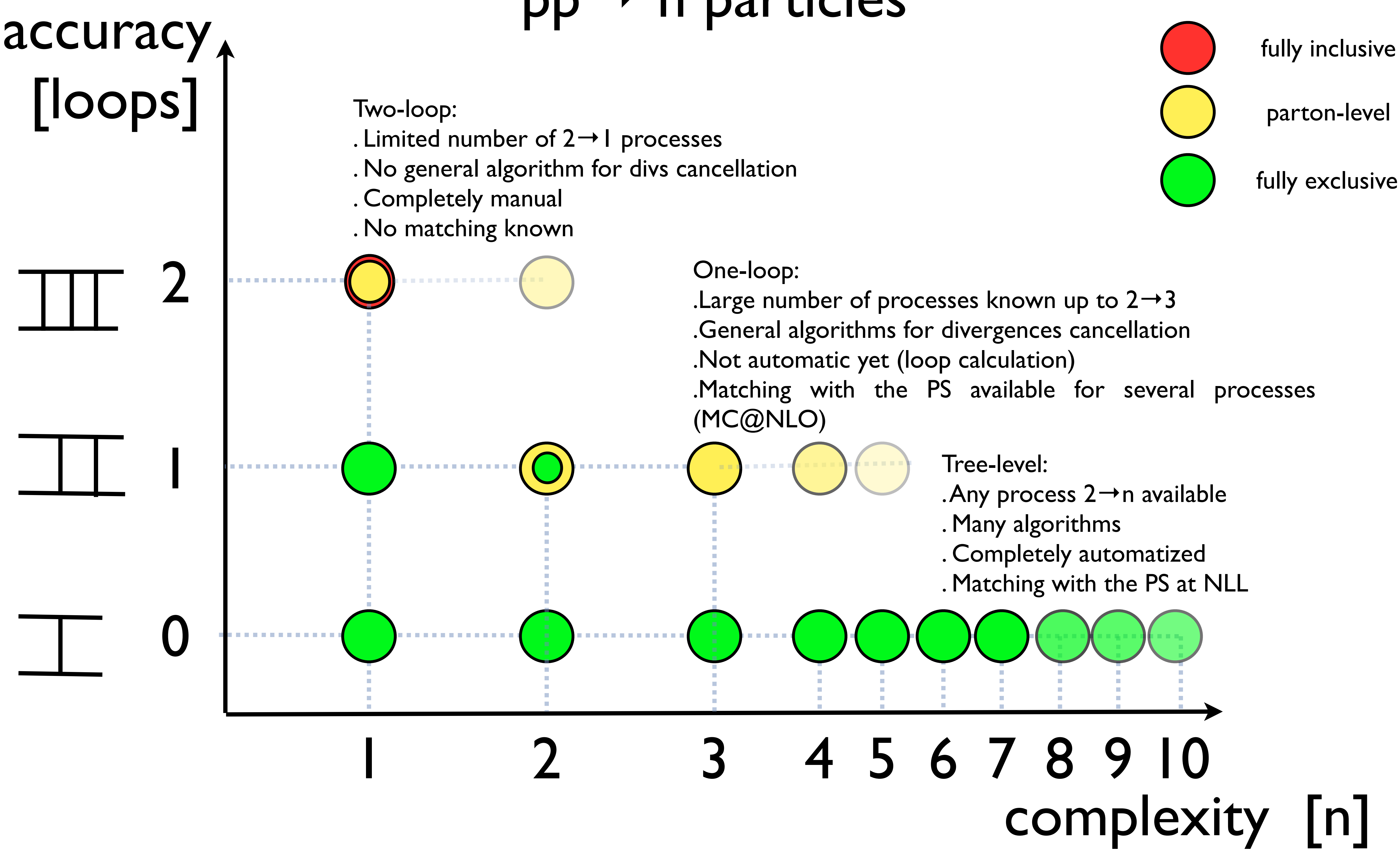


Status

pp→ n particles



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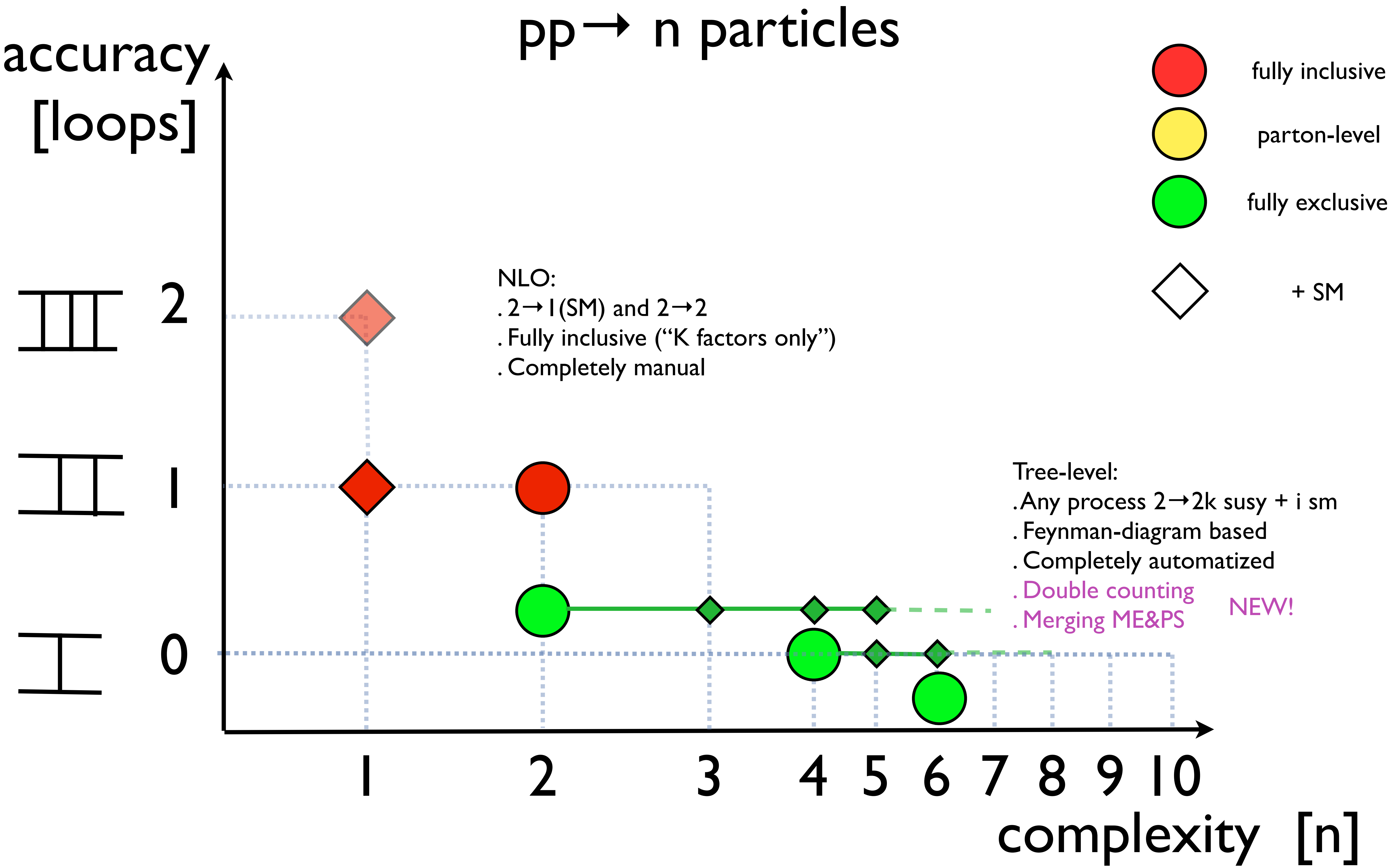
pp→ n particles
accuracy [loops]
2
1
0
fully inclusive
parton-level
fully exclusive
+ SM
NLO:
. 2→1(SM) and 2→2
. Fully inclusive (“K factors only”)
. Completely manual
Tree-level:
.Any process 2→2k susy + i sm
. Feynman-diagram based
. Completely automatized
. Double counting
. Merging ME&PS
NEW!
1 2 3 4 5 6 7 8 9 10
complexity [n]