SM (and BSM) simulations for the LHC

The path towards discoveries

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Two Burning Questions

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Do we understand and are we able to predict SM physics (QCD+EW) well enough to make discoveries at the LHC?

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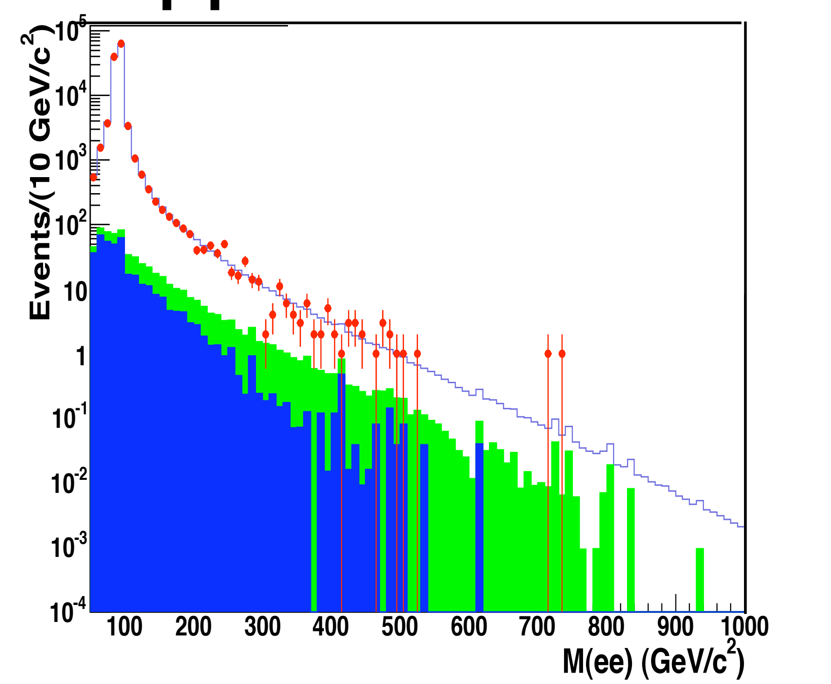
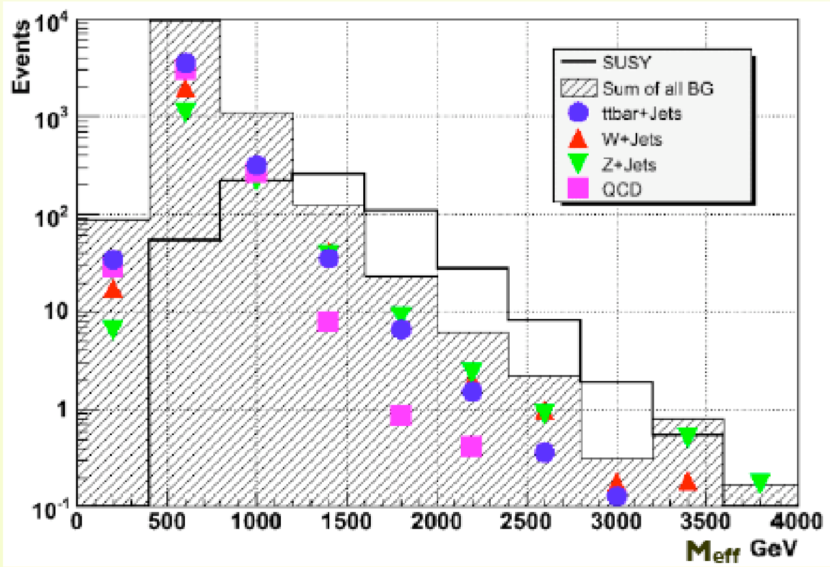
Will we be able to characterize the New Physics?

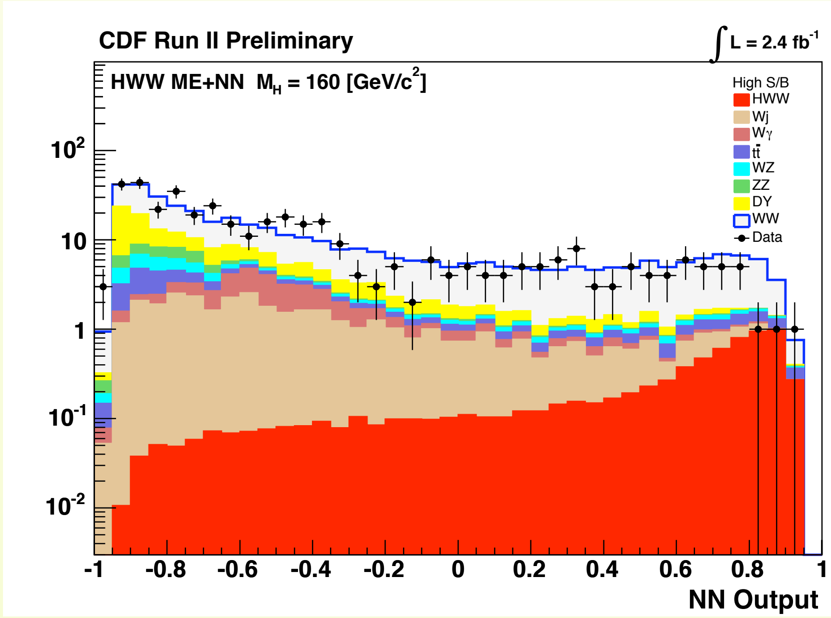
Discoveries at hadron colliders

[from M.L. Mangano, 2008]

peak	shape	rate
$pp \to Z' \to e^+e^-$	$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$	$pp \to H \to W^+W^-$



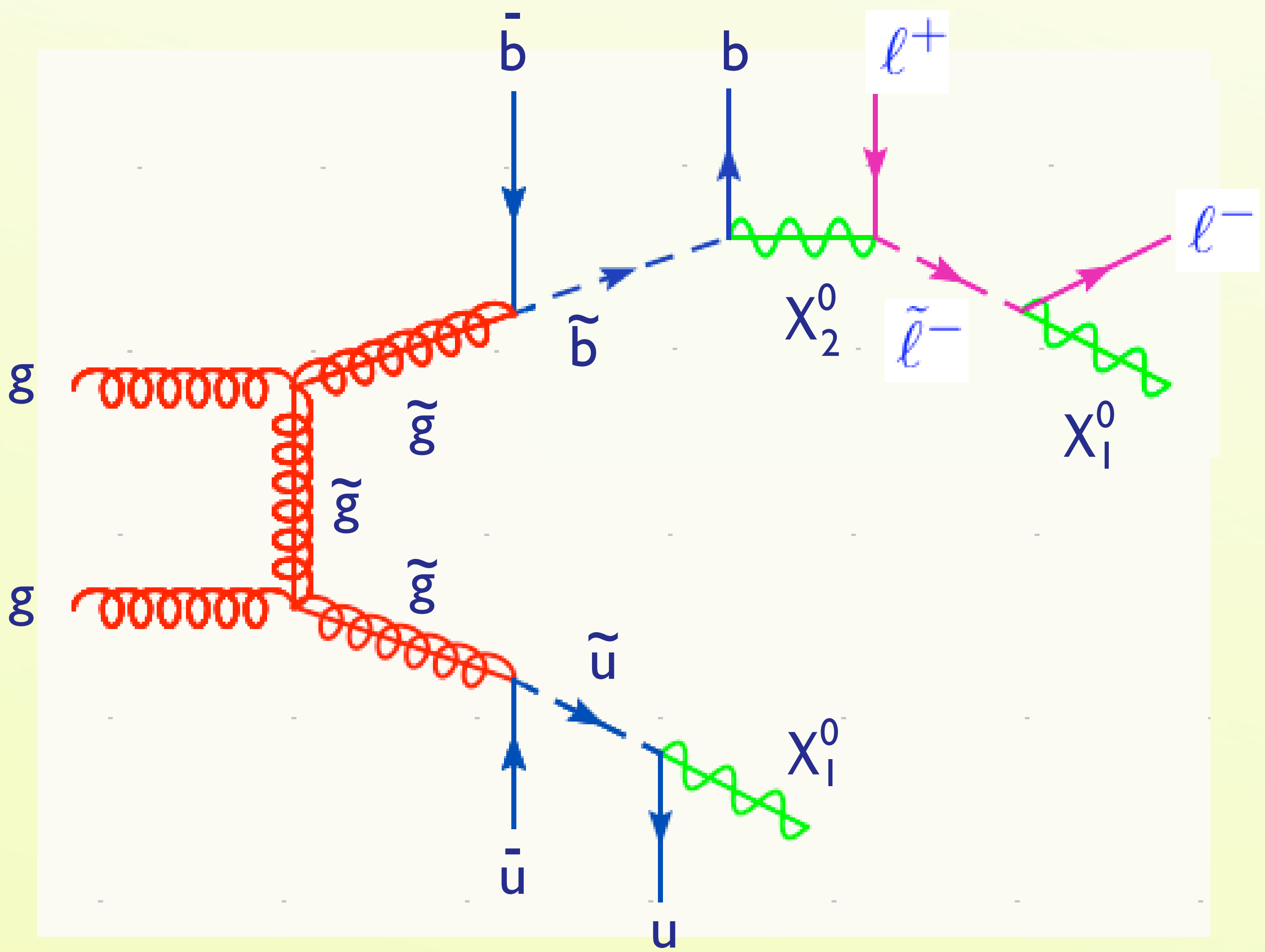




"easy"	hard	very hard
Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)	Background shapes needed. Flexible MC for both signal and backgroud tuned and validated with data.	Background normalization and shapes known very well. Interplay with 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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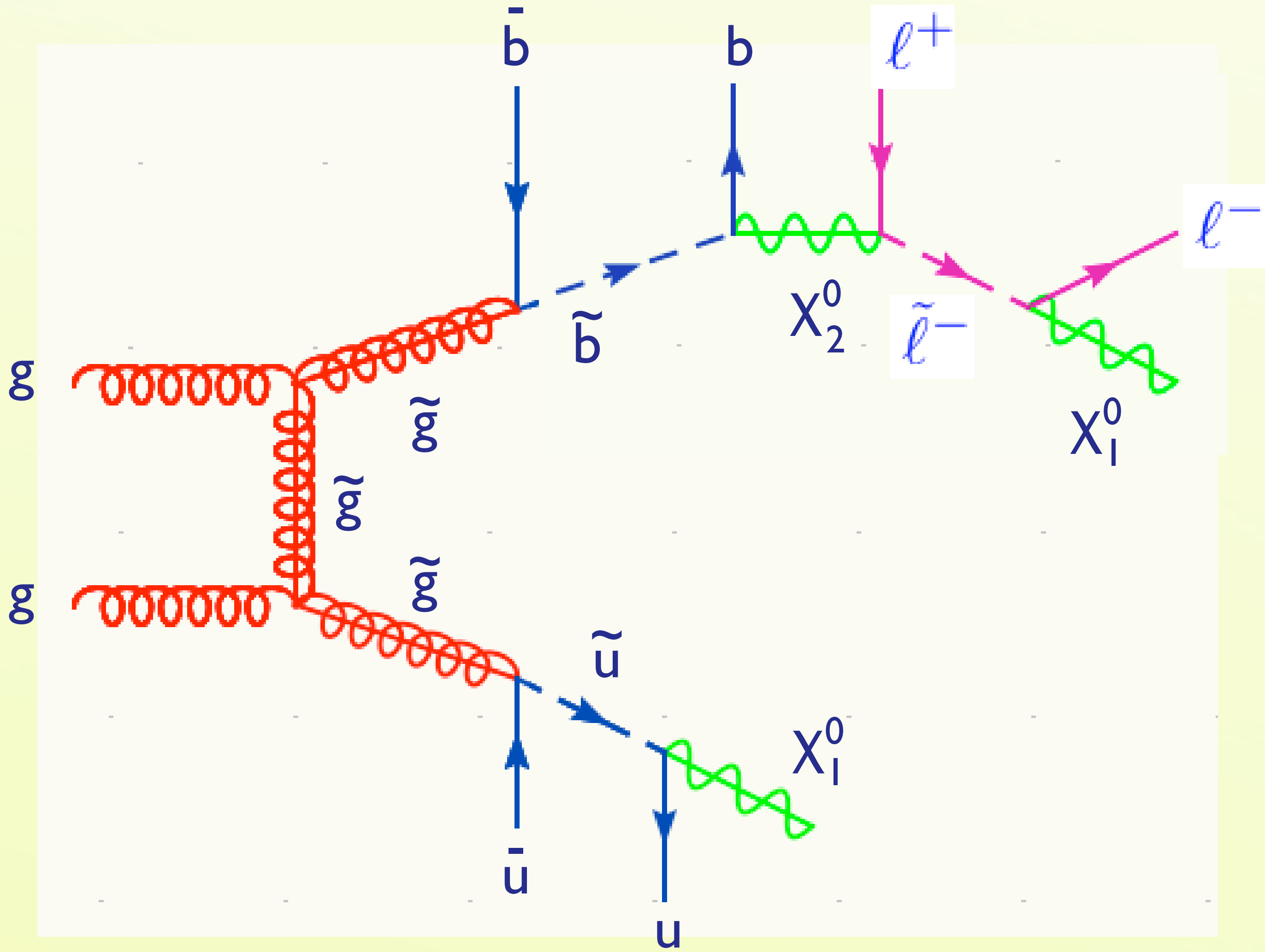
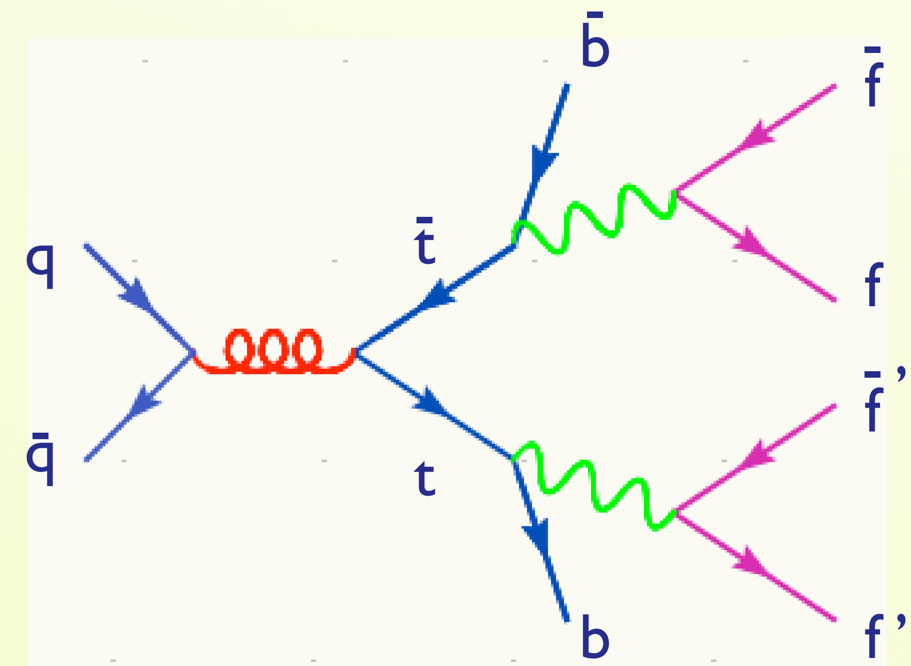


VS



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

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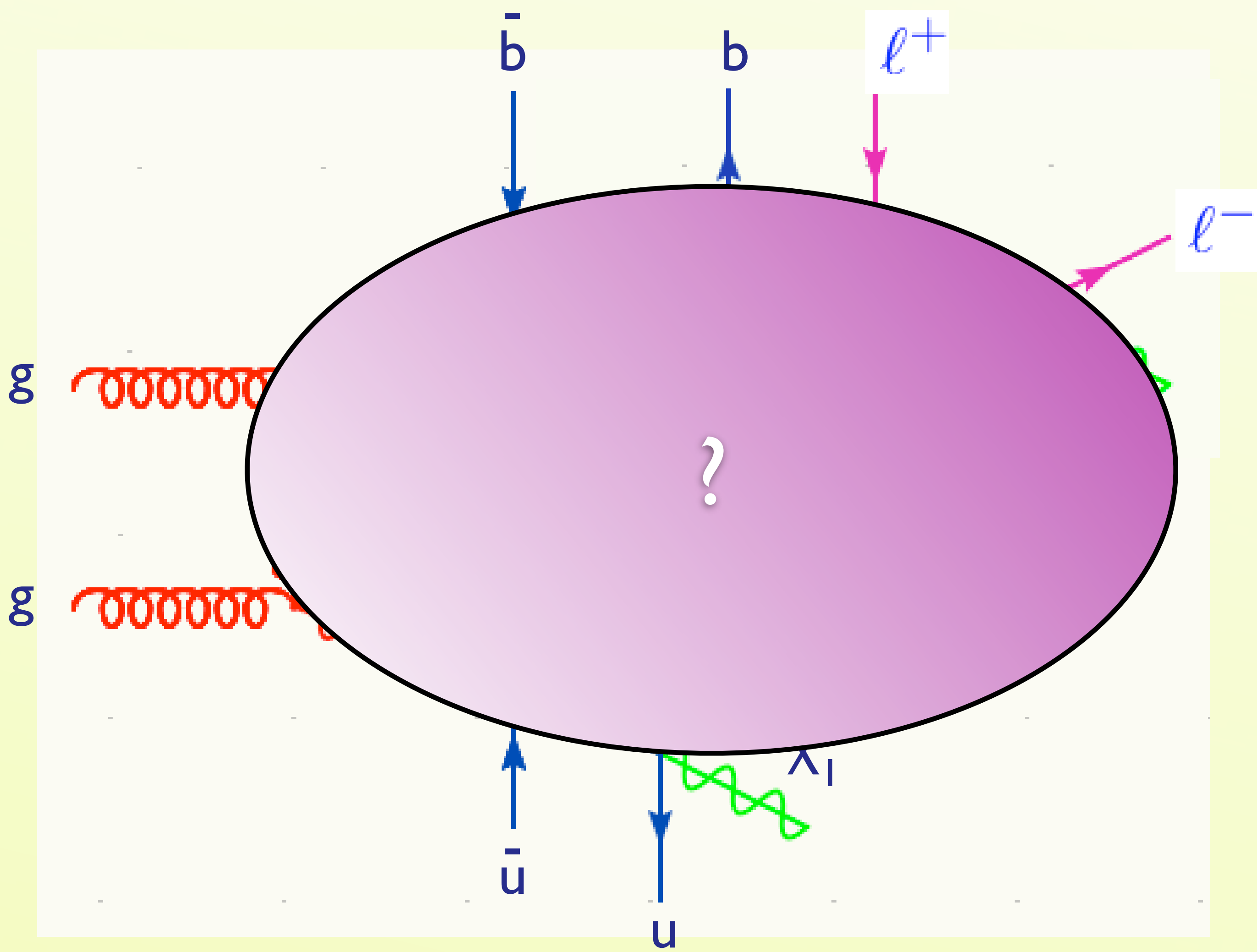

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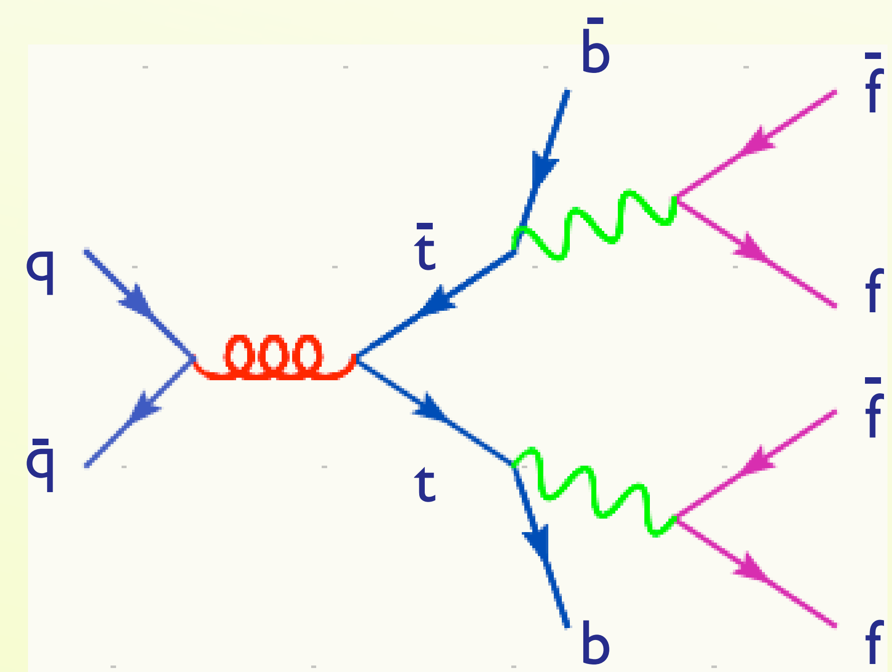
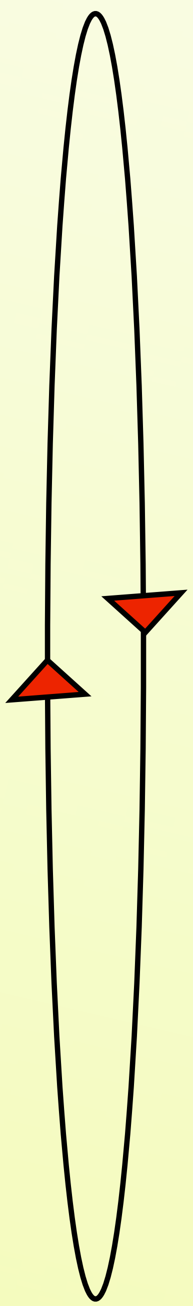


Follow the same approach of CDF in 1995 to establish first evidence of an excess wrt to SM-top and then consistency with SM top production [m_t=174, $t \to bl\nu$, $\sigma(tt)$] , works for the SM Higgs, but in general beware that... we don't know what to expect!

The path towards discoveries

LHC physics = QCD + ϵ



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

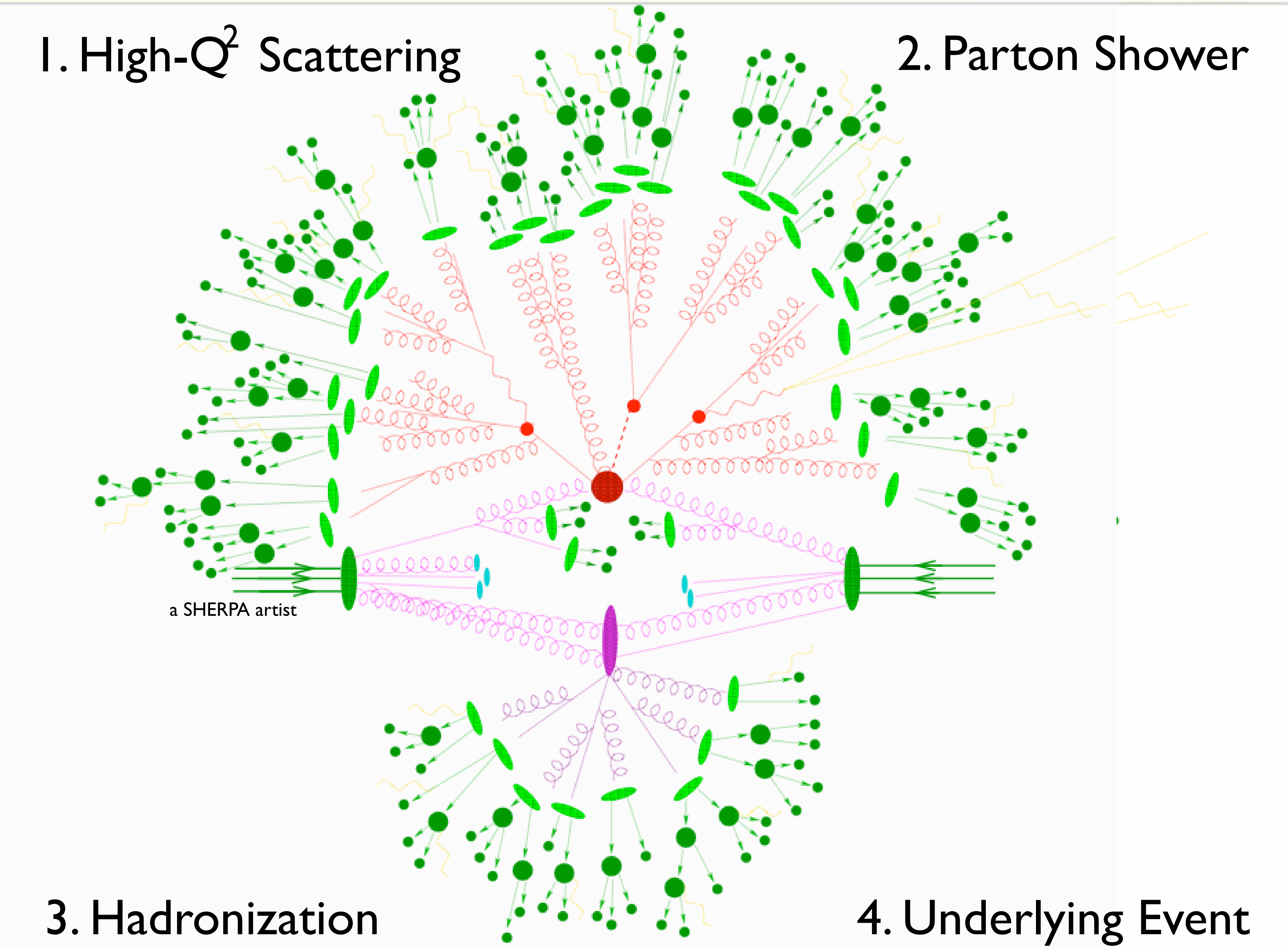
New regime for QCD. Exclusive description for rich and energetic final states with flexible MC to be validated and tuned to control samples. Shapes for multi-jet final states and normalization for key process important. Accurate predictions (NLO,NNLO) needed only for standard candle cross sections.

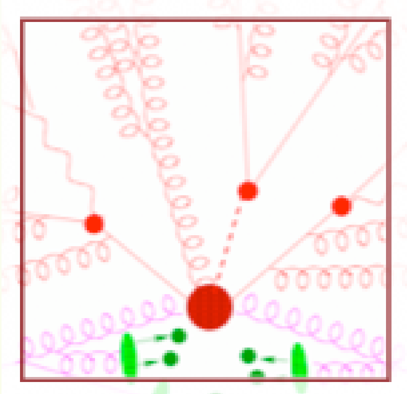
2. Identify excess(es) over SM

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.


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



How theorists (used to) make predictions?

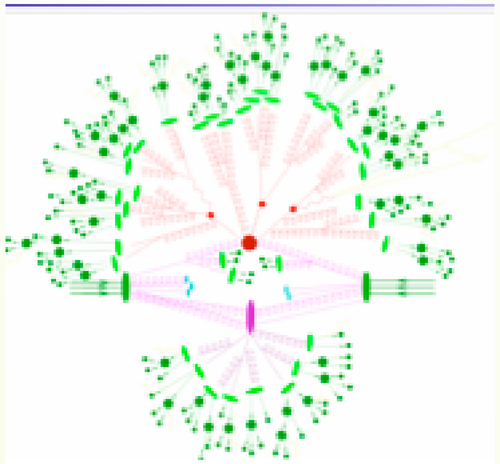
Evolution is unitary and universal: ignore it!
Focus on the high Q^2:

- For low parton multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  $\Rightarrow \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \ldots$
- For high parton multiplicity use the tree-level results

Comments:

1. The theoretical errors systematically decrease
2. A lot of new techniques and universal algorithms are developed
3. Final description only in terms of partons and calculation of IR safe observables ⇒ cannot be directly employed in experimental studies

How experimentalists (used to) make predictions?



Fully exclusive final state description for detector simulations more important ⇒ give up on the high Q^2 complexity.

- Describe final states with high multiplicities starting from $2 \to 1$ or $2 \to 2$ procs, using a parton shower, and then an hadronization model

Comments:

1. Very flexible and tunable tools. Good description of the data possible
2. Catches the bulk (log-enhanced) part of the cross section
3. Predictive power for normalization and kinematic distributions for high-pt multi-parton final states very limited

most known and used : PYTHIA, HERWIG

Matrix element vs Parton Shower

Matrix element	Shower MC
1. valid when partons are hard and well separated	1. based on subsequent soft/collinear splittings
2. fixed order calculation	2. resums large logs
3. only few partons	3. high multiplicities

New trends

Common Principle:

Avoid the weakest link! Balance the accuracy over the steps in the simulation chain. Improve not only the single steps but also their merging.

Two directions:

1. Matrix Elements + Parton Showers
Get fully exclusive description of many parton events correct at LO (LL) in all the phase space

ME+PS

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

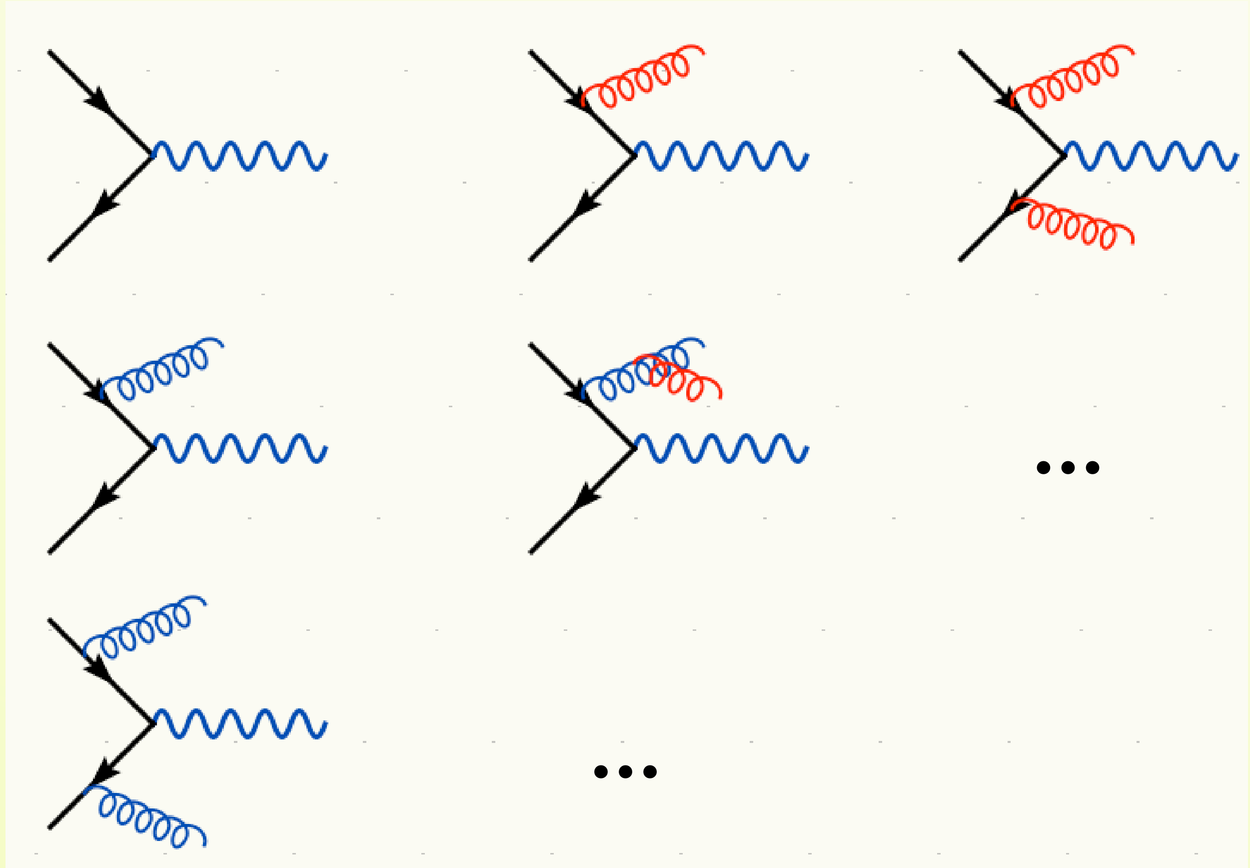
NLOwPS

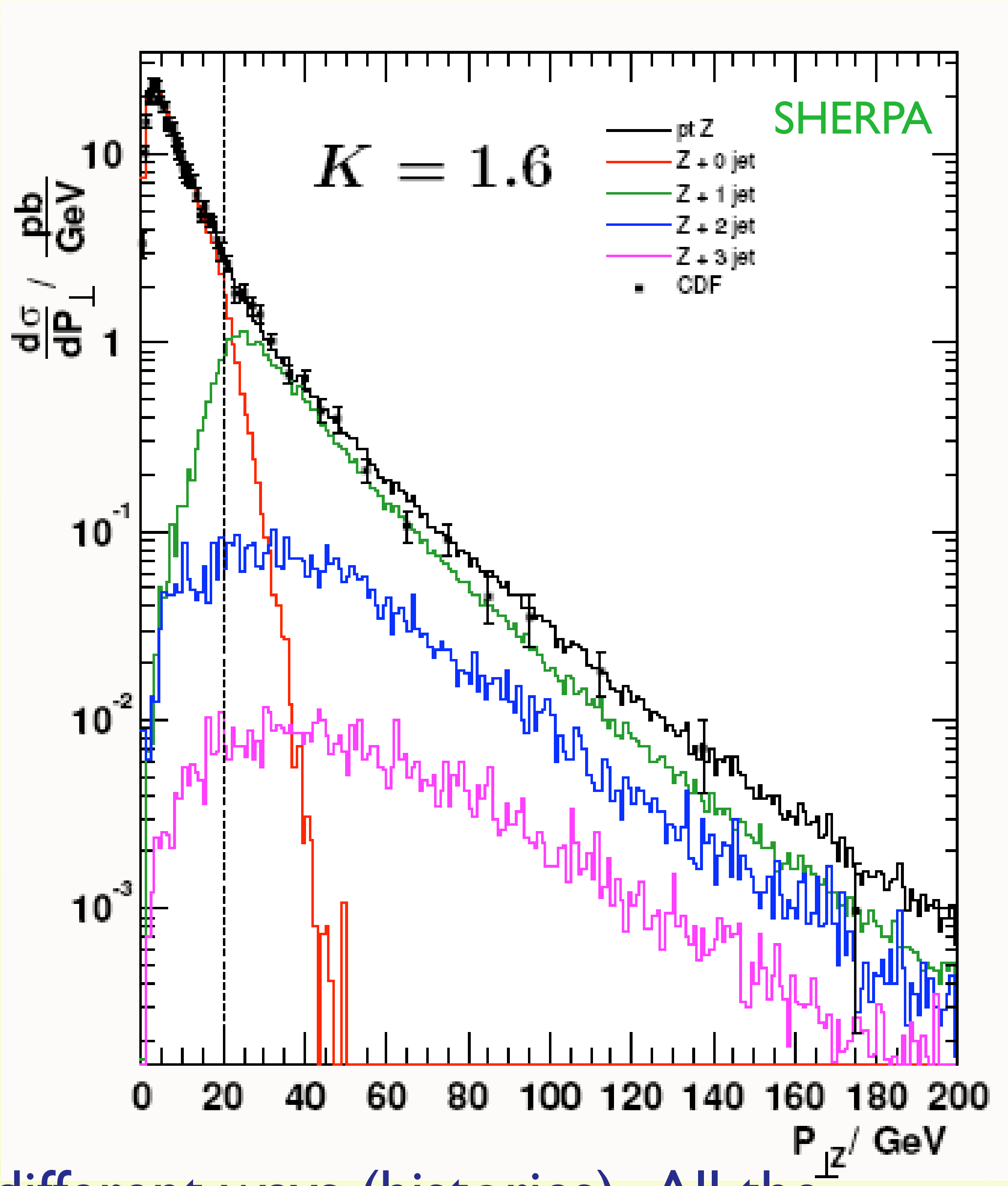
Merging fixed order with PS

[Mangano, 2003]
[Catani, Krauss, Kuhn, Webber,2003]

PS →

ME ↓

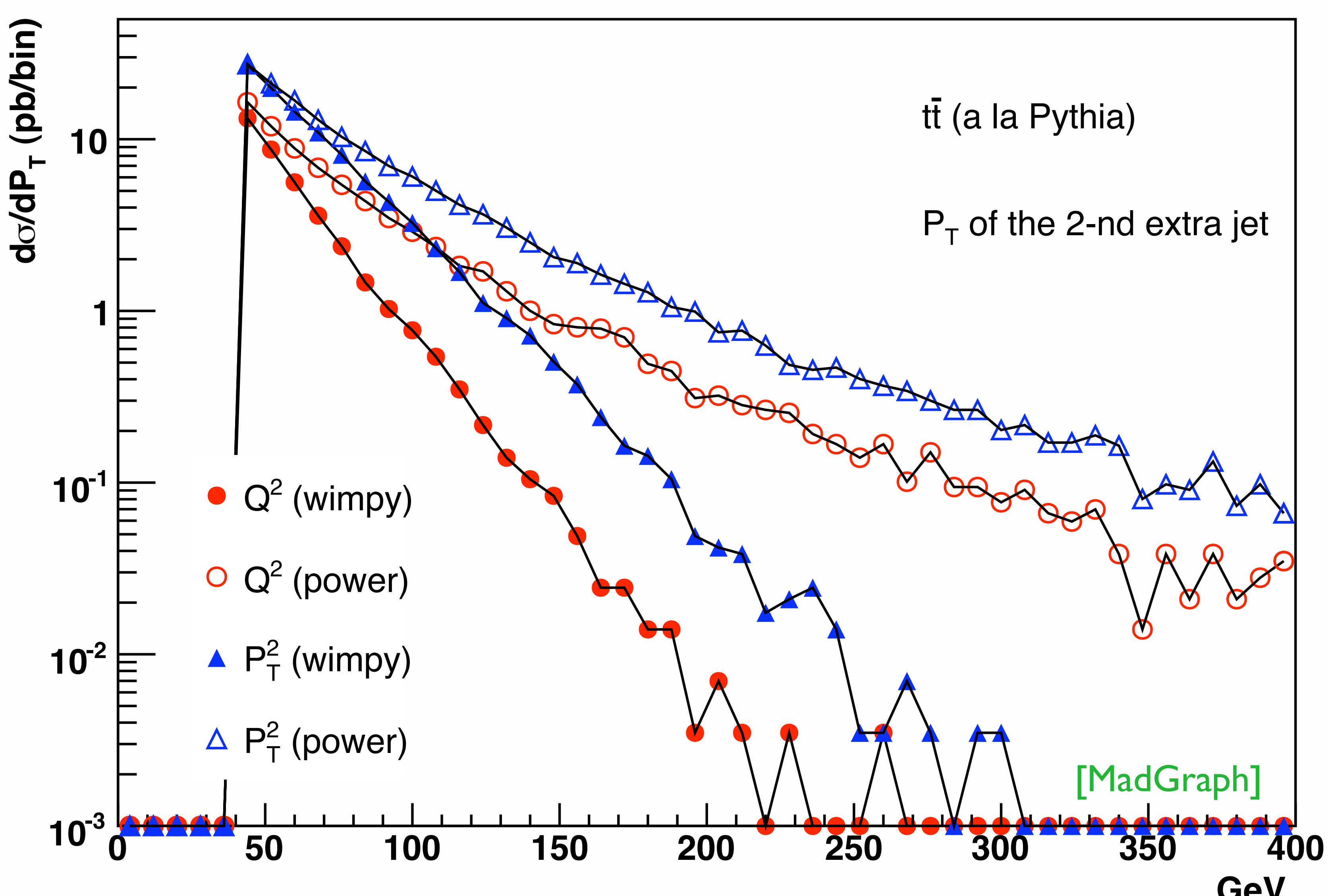




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

PS alone vs matched samples

A MC shower 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 not a good idea ⇒ problems in other regions/shapes, proc dependence.

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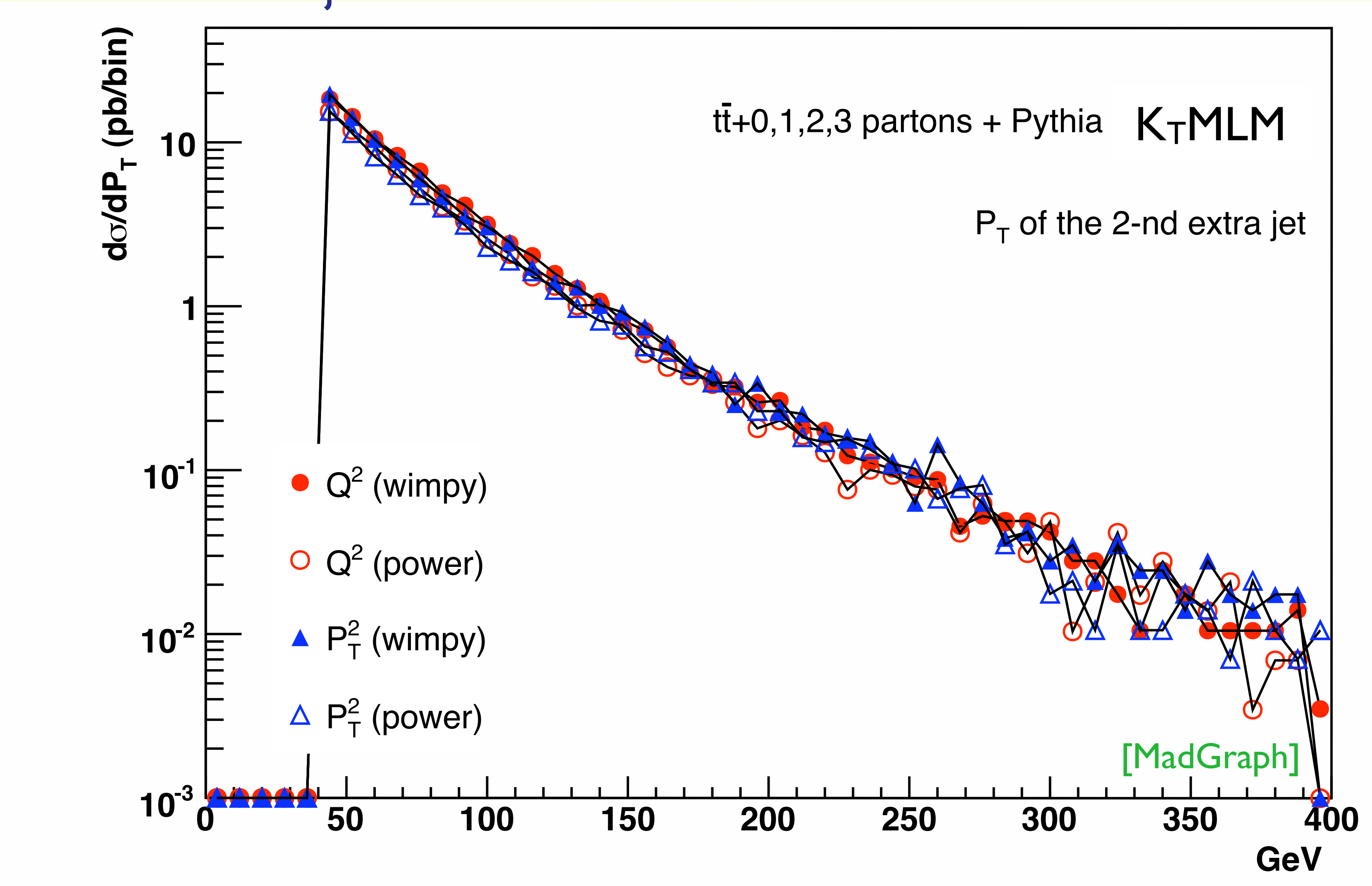
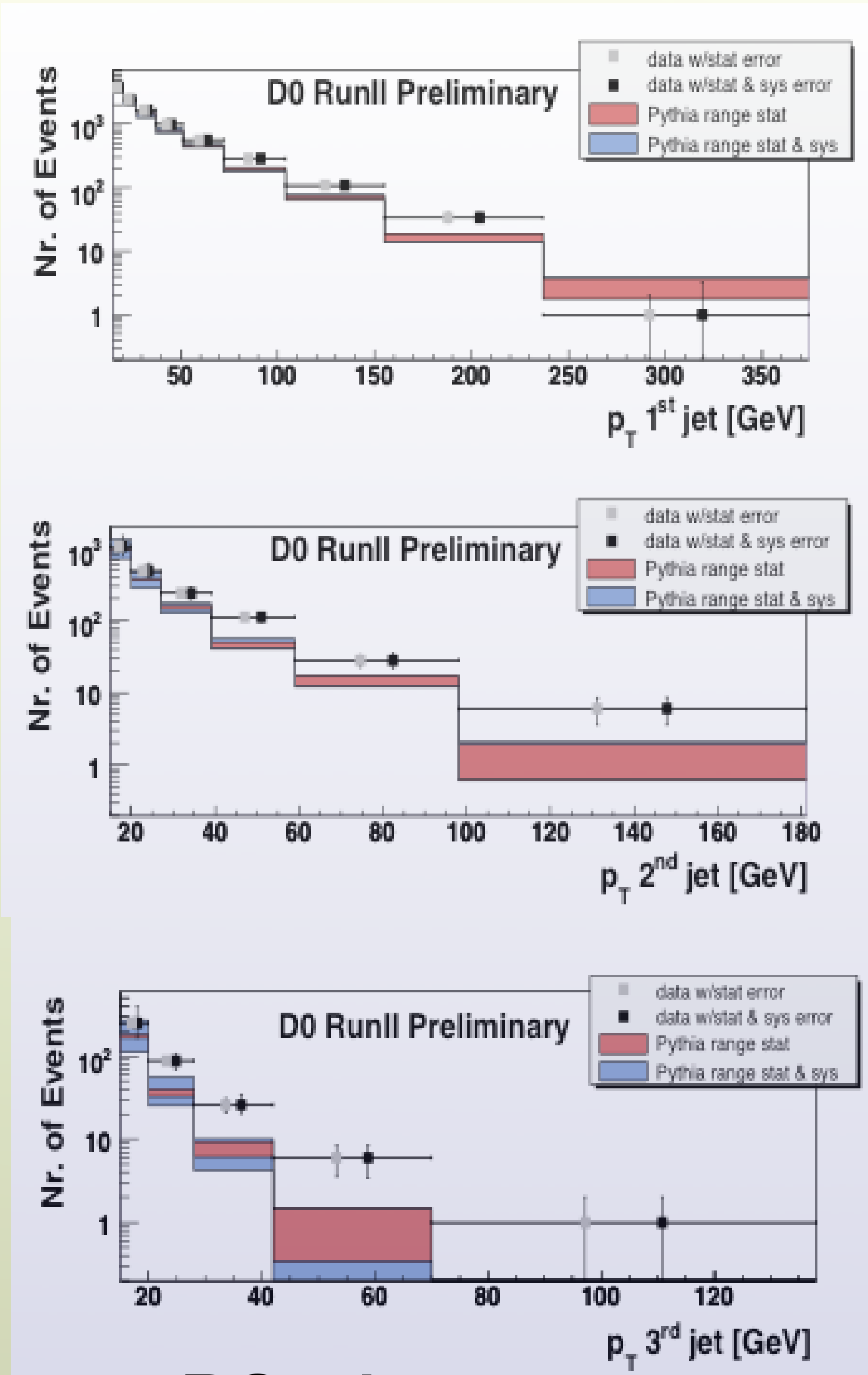
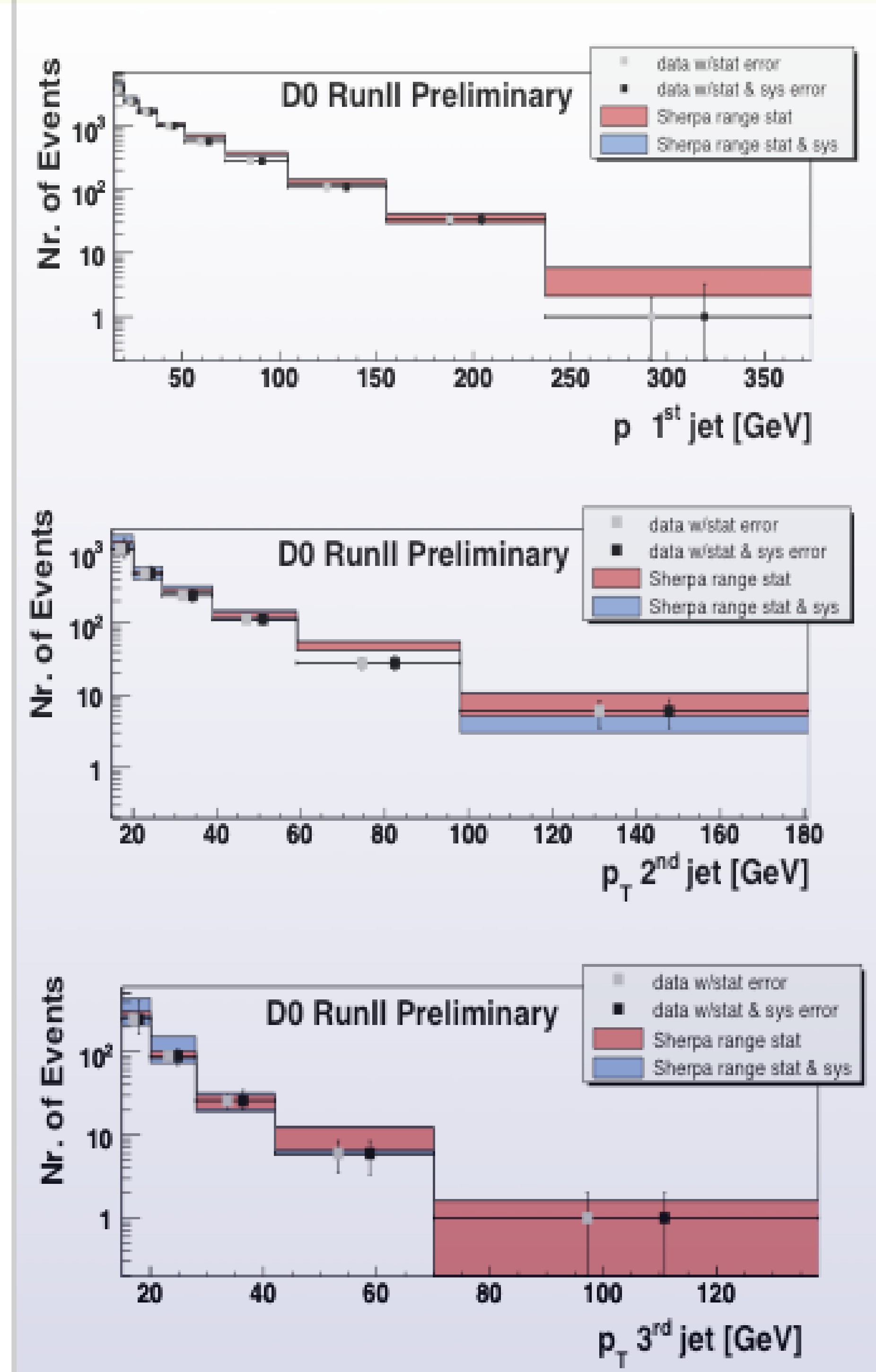


In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

PS alone vs matched samples : Z+jets at D0

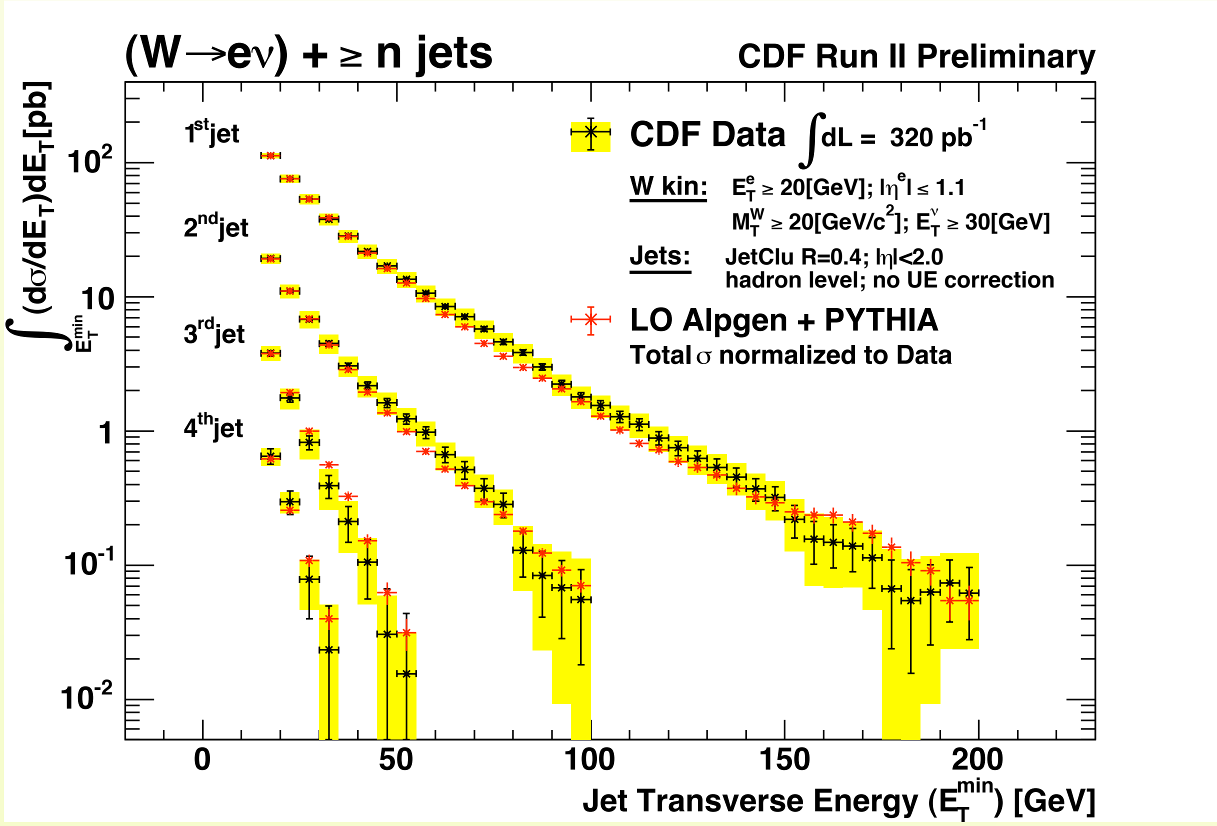


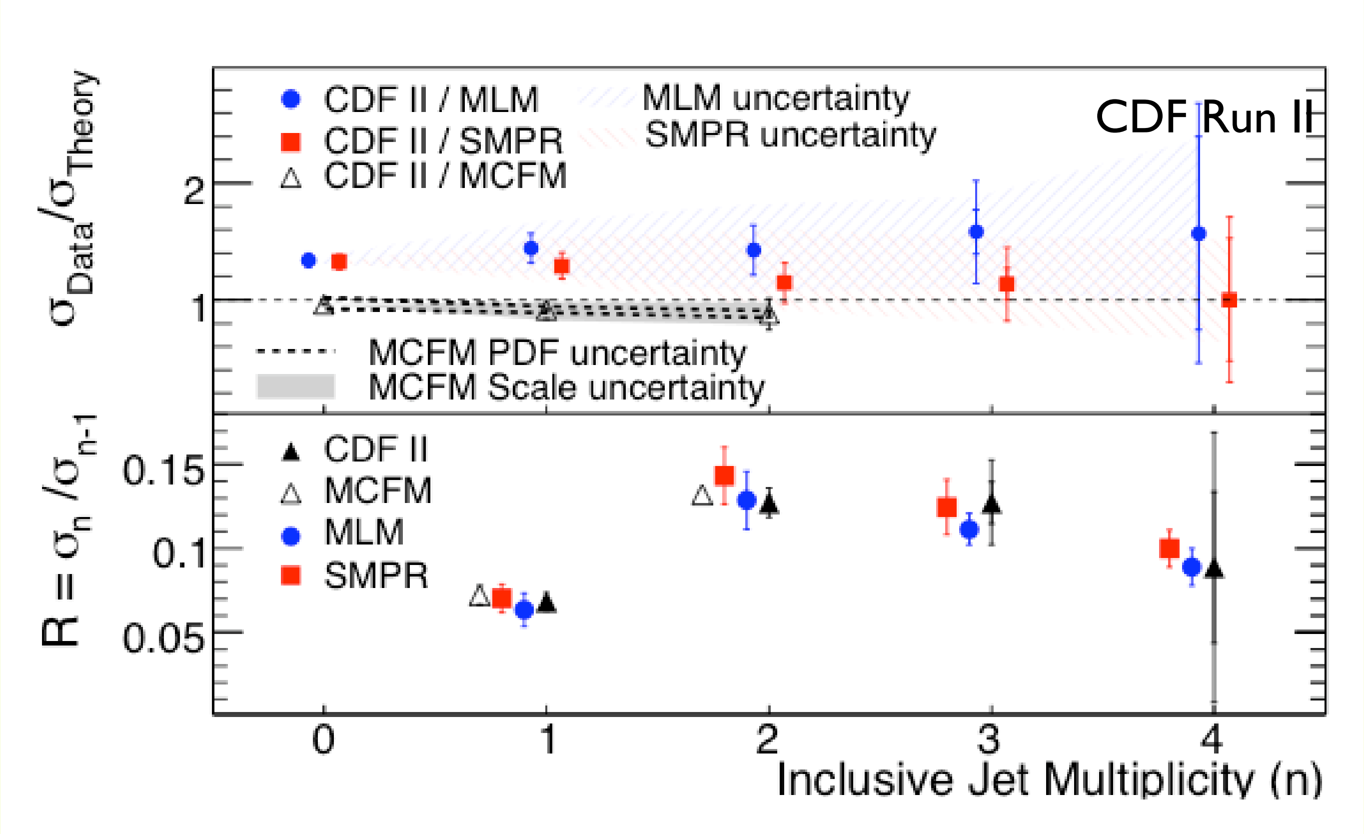
PS alone (Pythia)



ME+PS (SHERPA)

W+jets at CDF





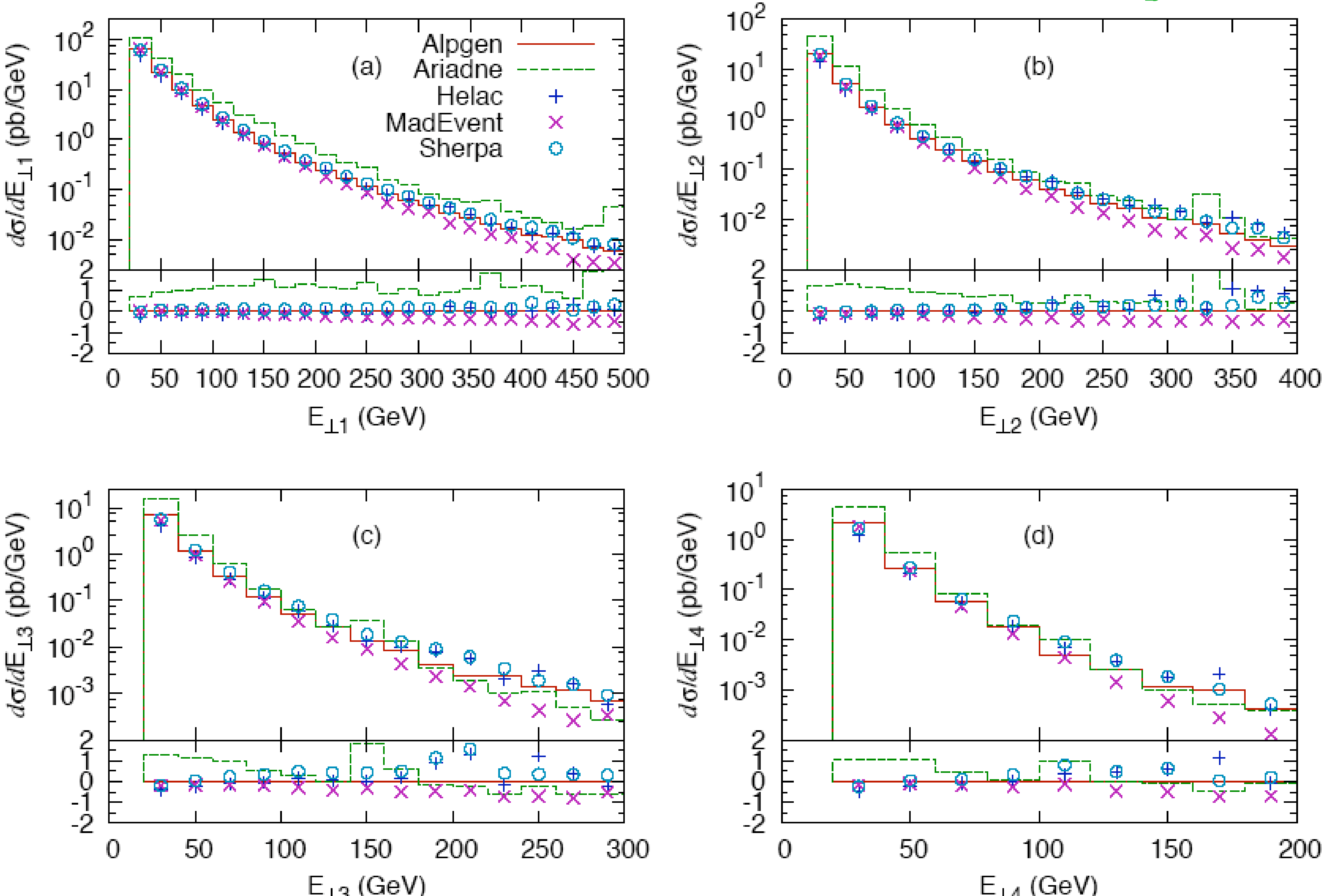
* Very good agreement in shapes (left) and in relative normalization (right).

* 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 @ LHC : MC comparison

[J. Alwall et al.,2007]

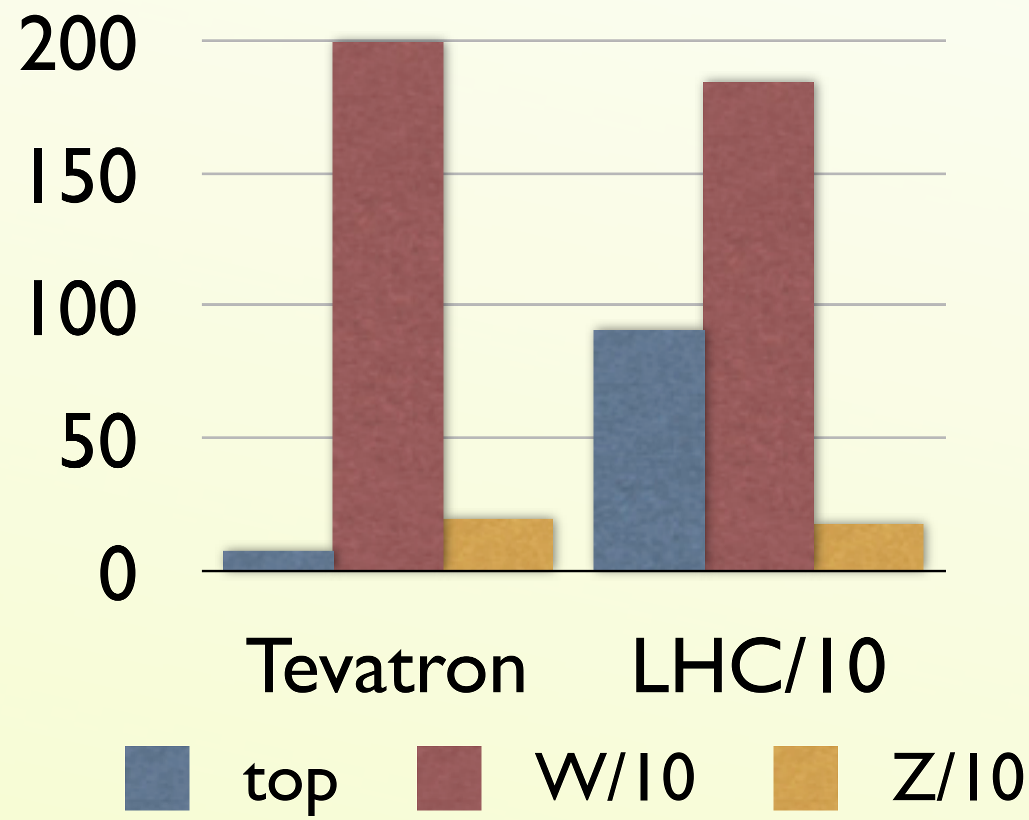


Cross sections : from Tevatron to the LHC

Total cross section for ttbar increases by a factor of 100, while Drell-Yan only by a factor of 10.

Top will be one of the major background to any new physics!

However, extra hard radiation is much easier at the LHC than at the Tevatron!



pb	tt	$W^{+-} \to e^{+-} \nu_e$ inclusive	$Z \to e^+ e^-$ inclusive	$W \to e^{+-} \nu_e$ + 4jets		$Z \to e^+ e^-$ + 4jets	
TeV	7.6	2000	200	0.98		0.096	
LHC	910	18500	1800	220	(20)	21	(2.1)
Gain	120	9	9	220	(21)	220	(22)

pt(j)>20 (50) GeV , |eta(j)|<3, DeltaR(jj)>0.7

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.

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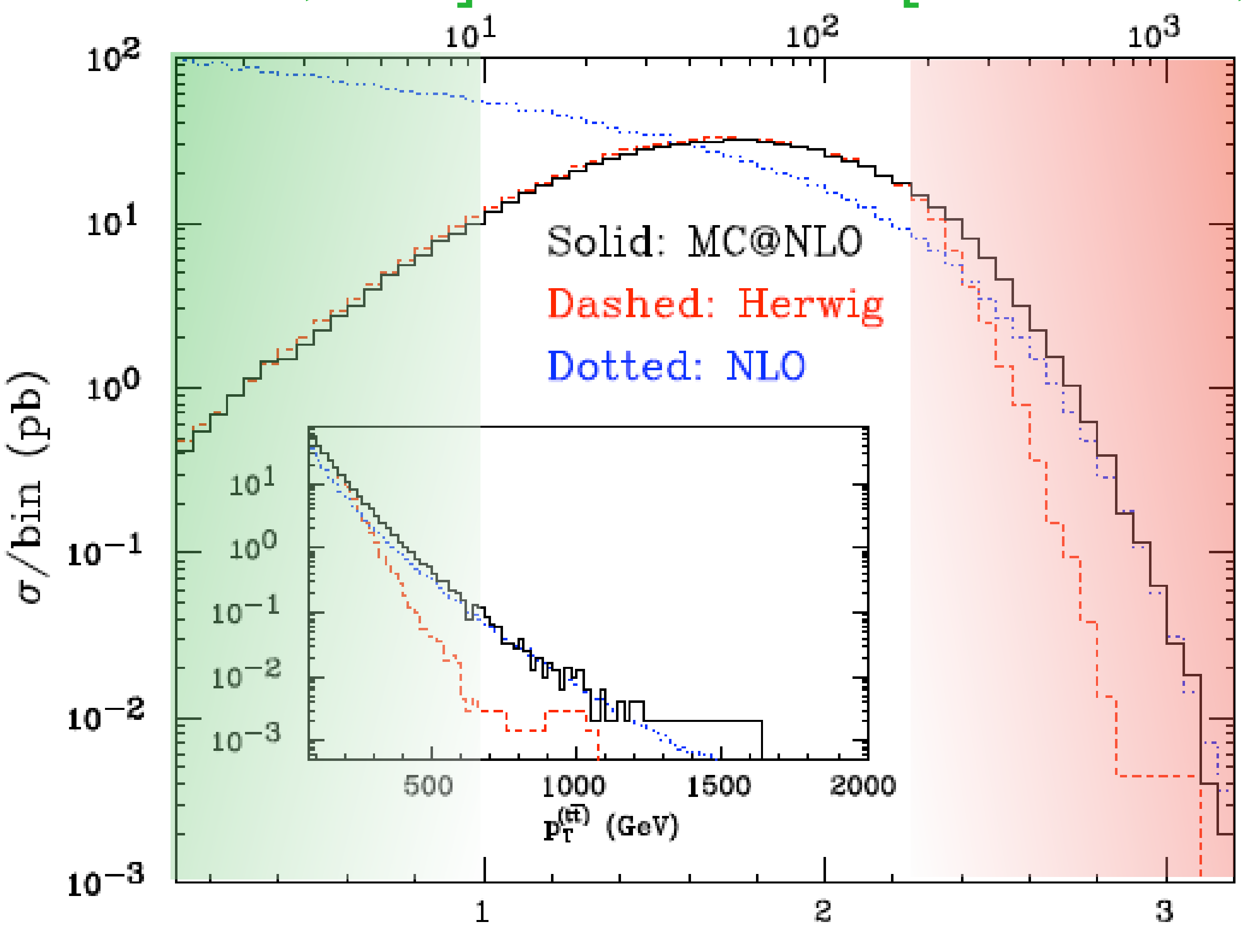

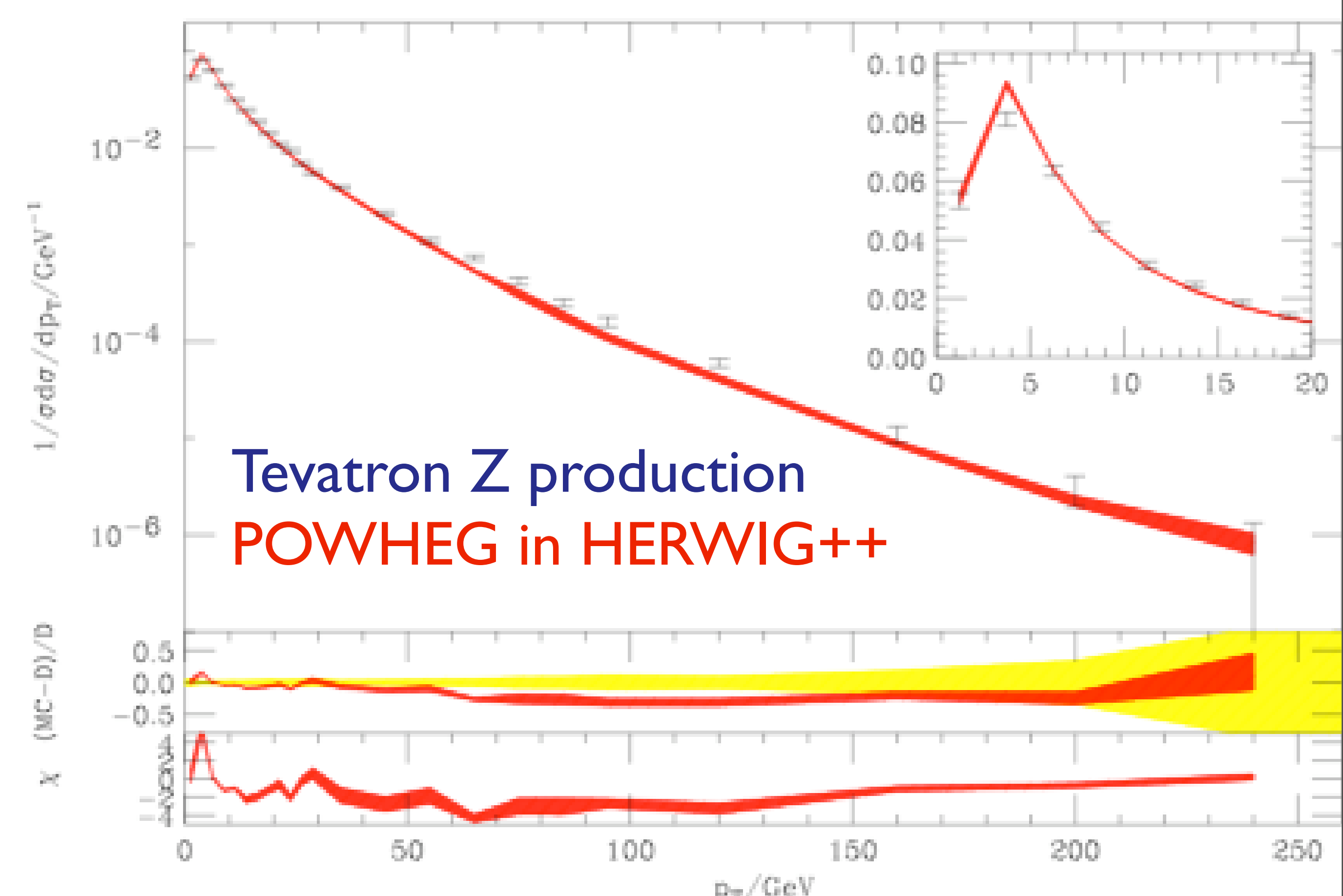

* Soft/Collinear resummation of the $p_T(tt) \to 0$ region.
* At high $p_T(tt)$ it approaches the tt+parton (tree-level) result.
* Normalization is FIXED and non trivial!!

[Hamilton, Richardson, Tully, 2008; Alioli, Nason, Oleari, Re, 2008]

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 : SM

pp→ n particles

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1 2 3 4 5 6 7 8 9 10

complexity [n]

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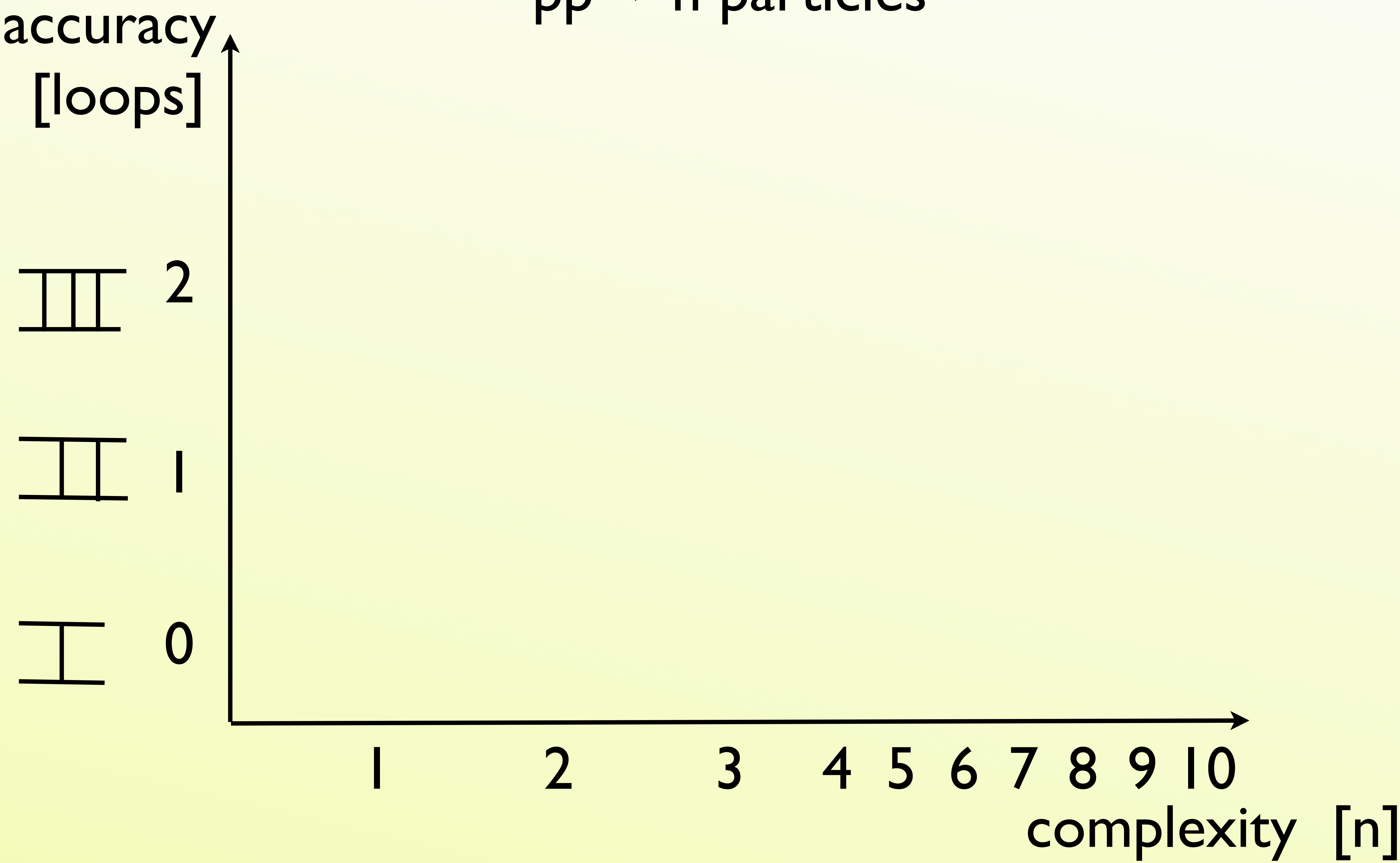

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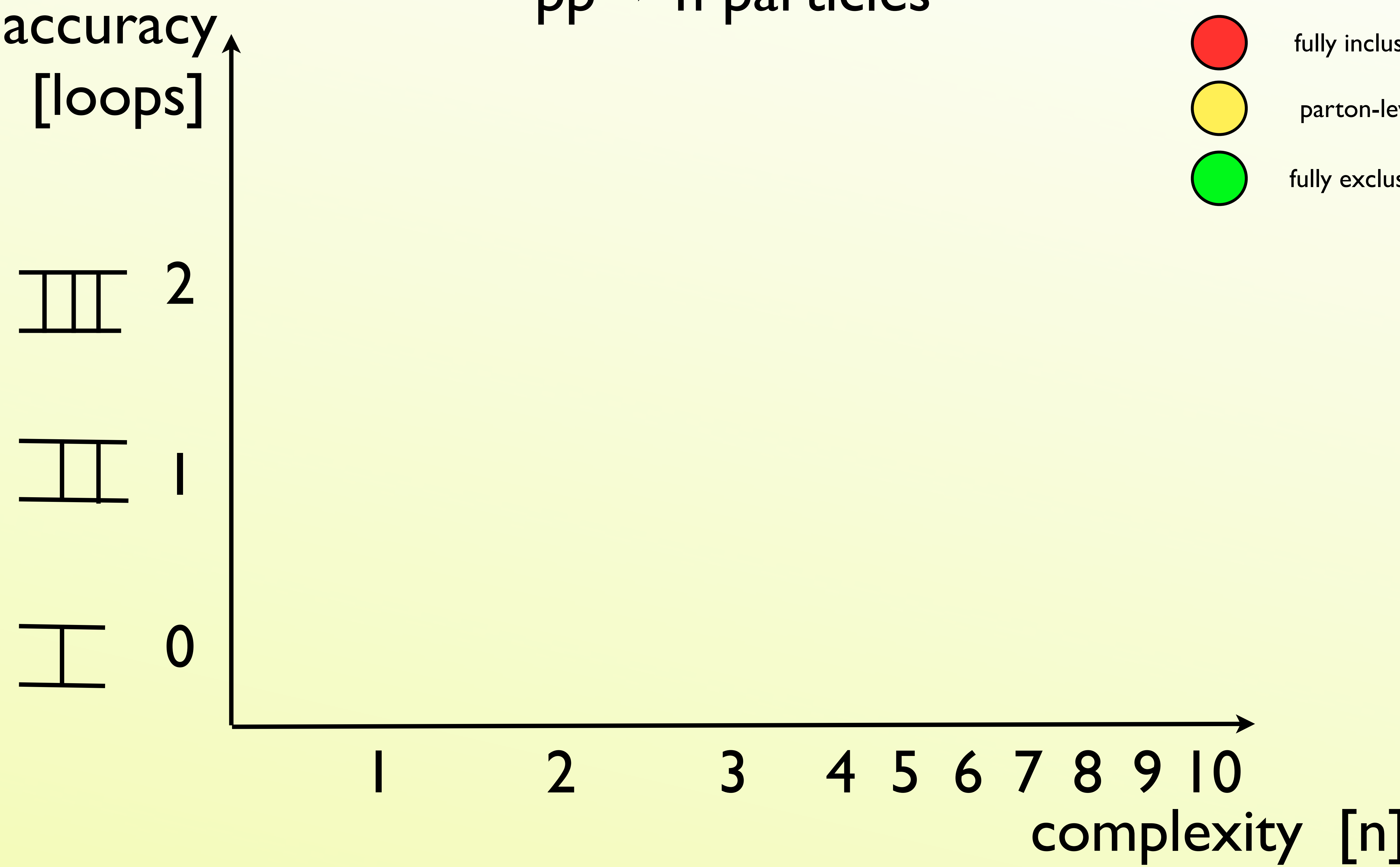

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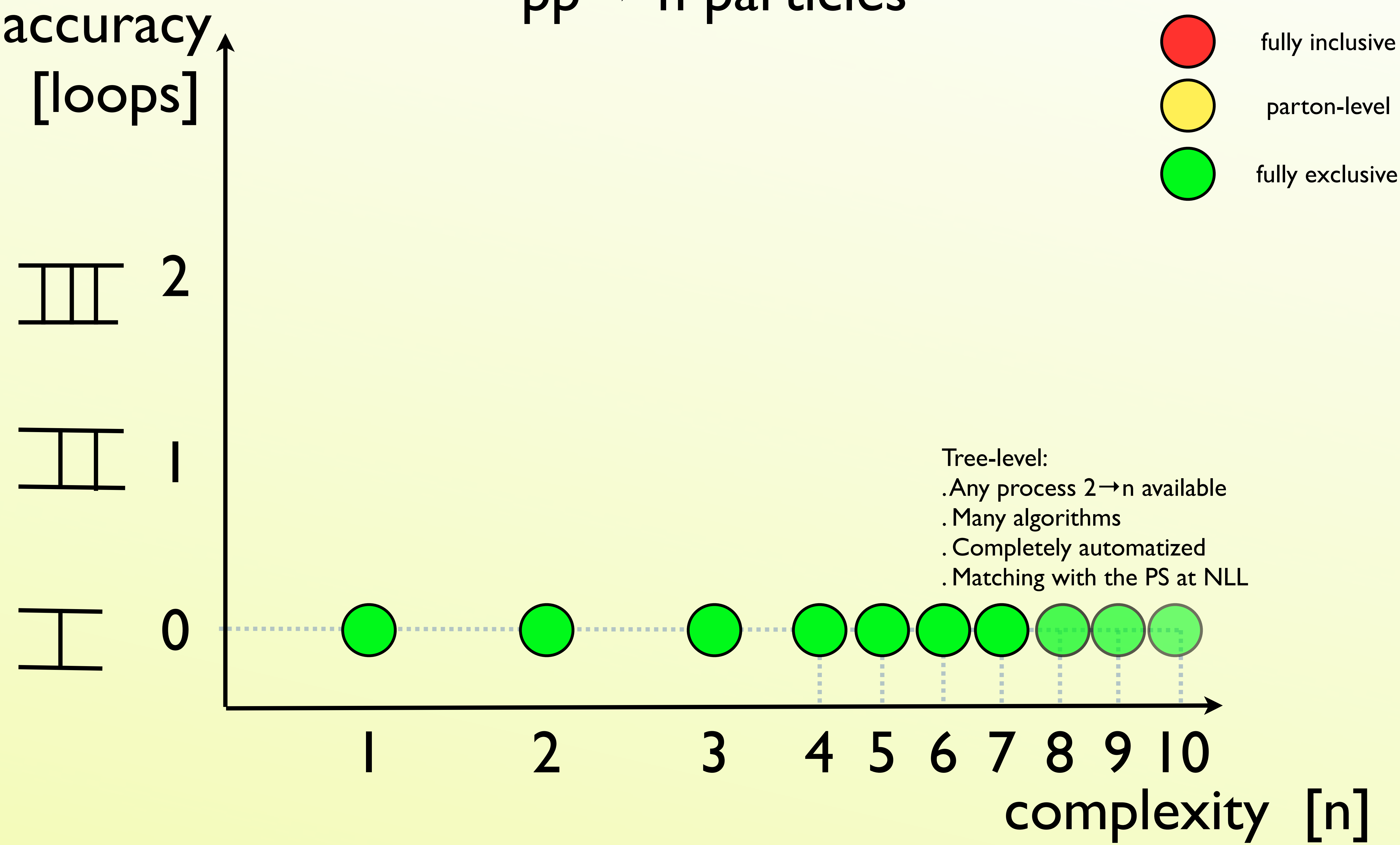

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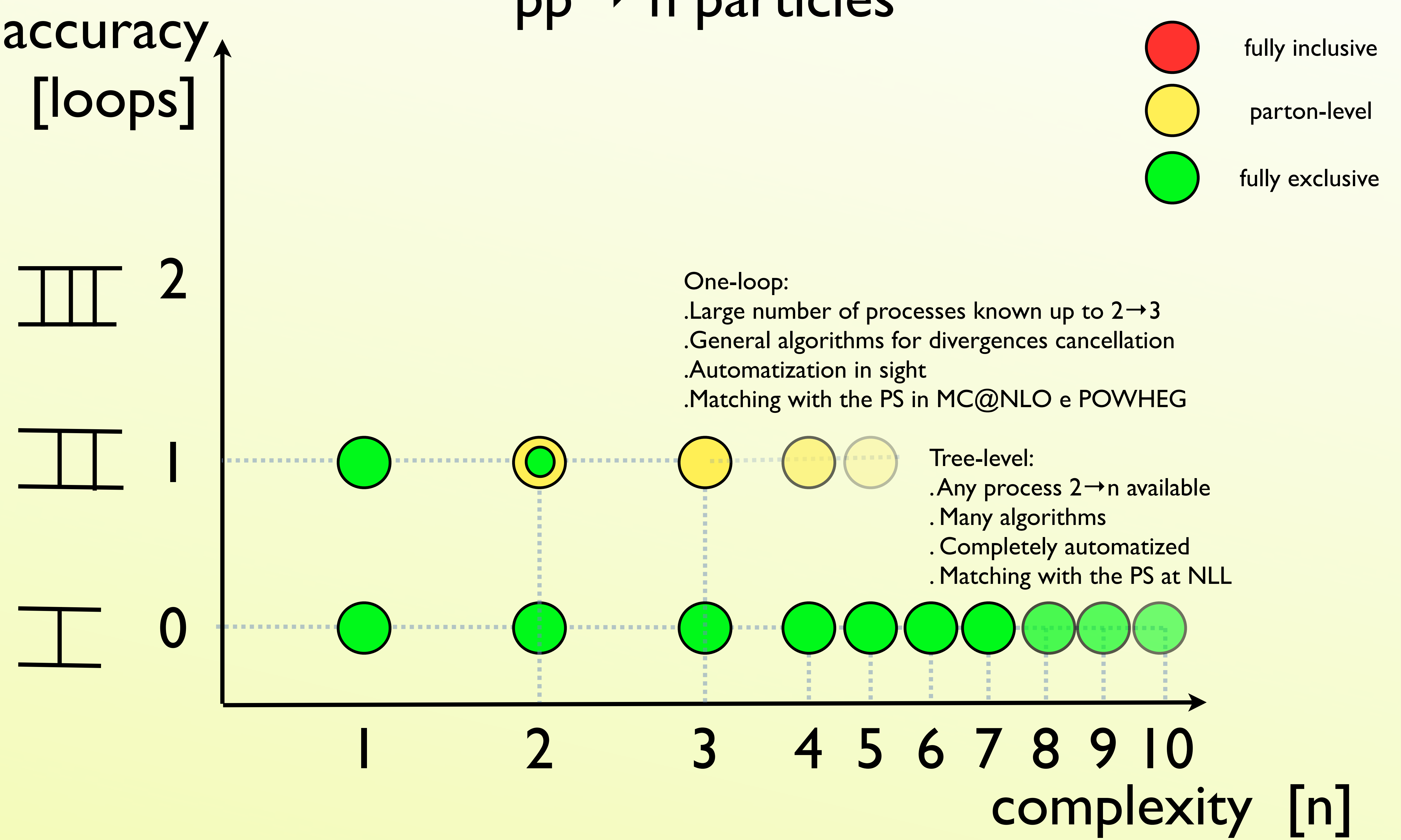

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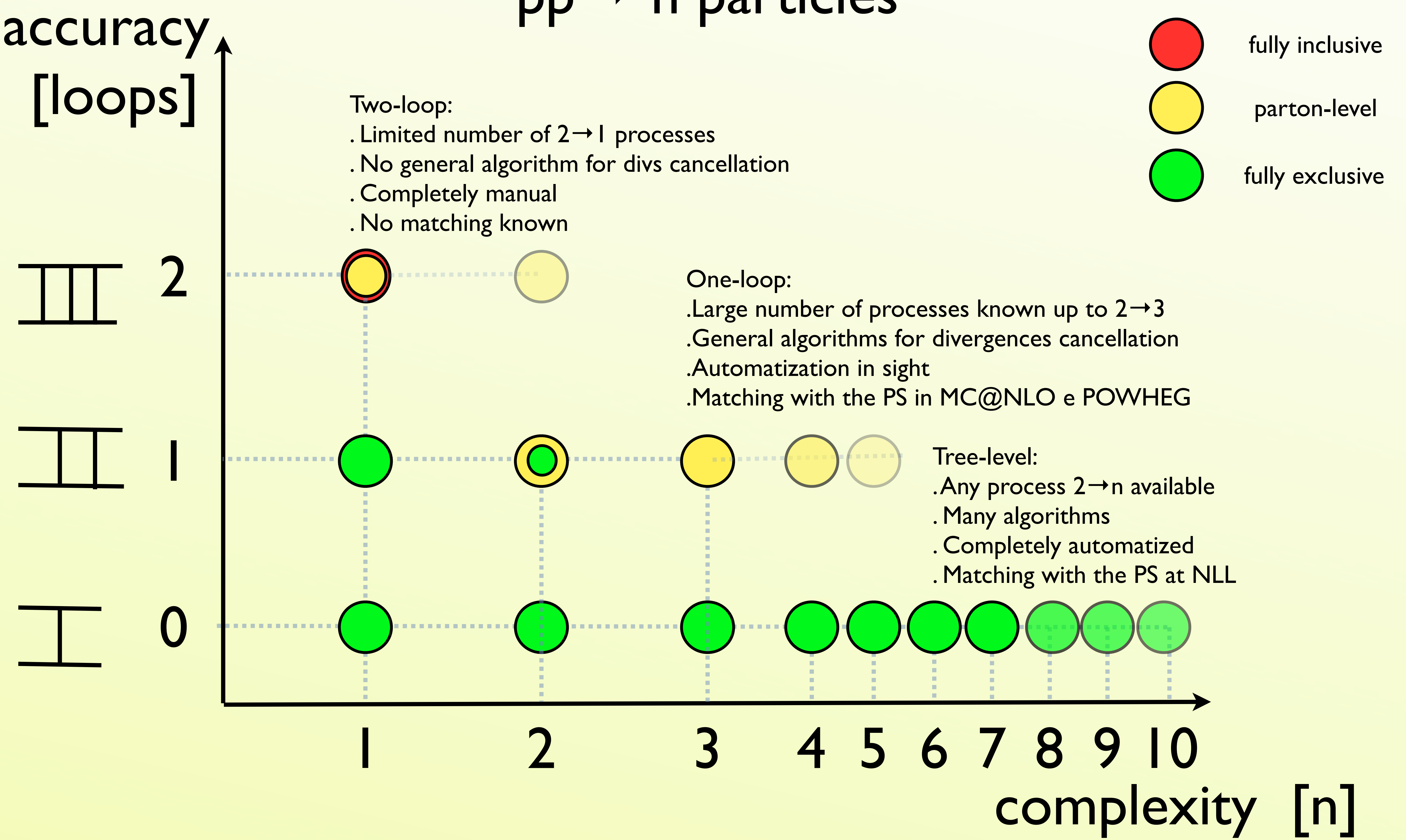

Kaizen approach

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Leading Order :

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

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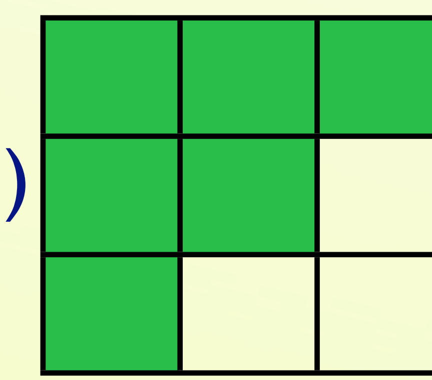
* General framework for interfacing to the shower (POWHEG)
* Impressive results in automatic 1-loop computations (BlackHat, Rocket, OPPP)



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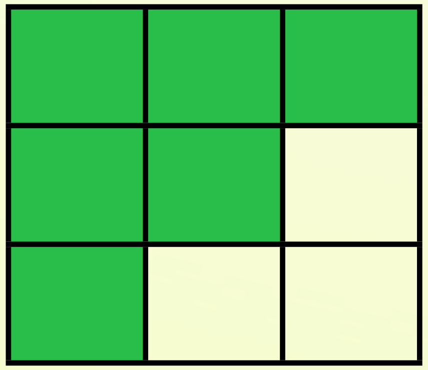

Solution in sight

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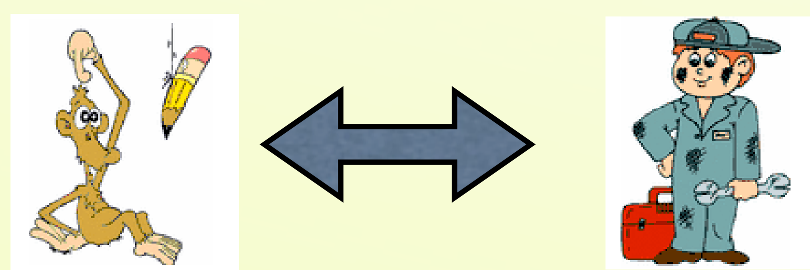

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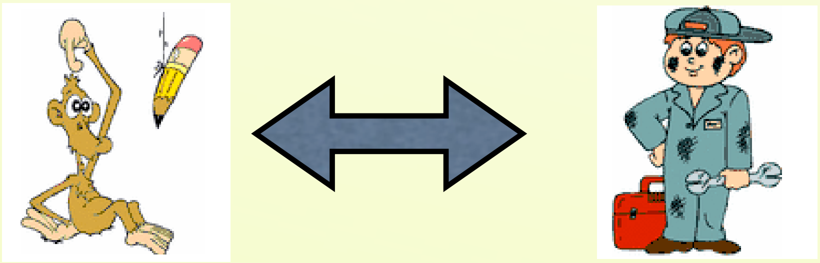

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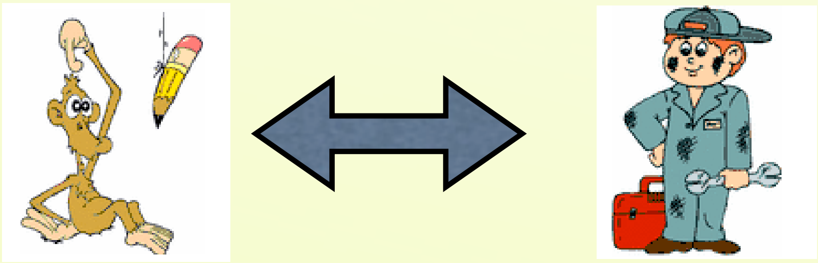

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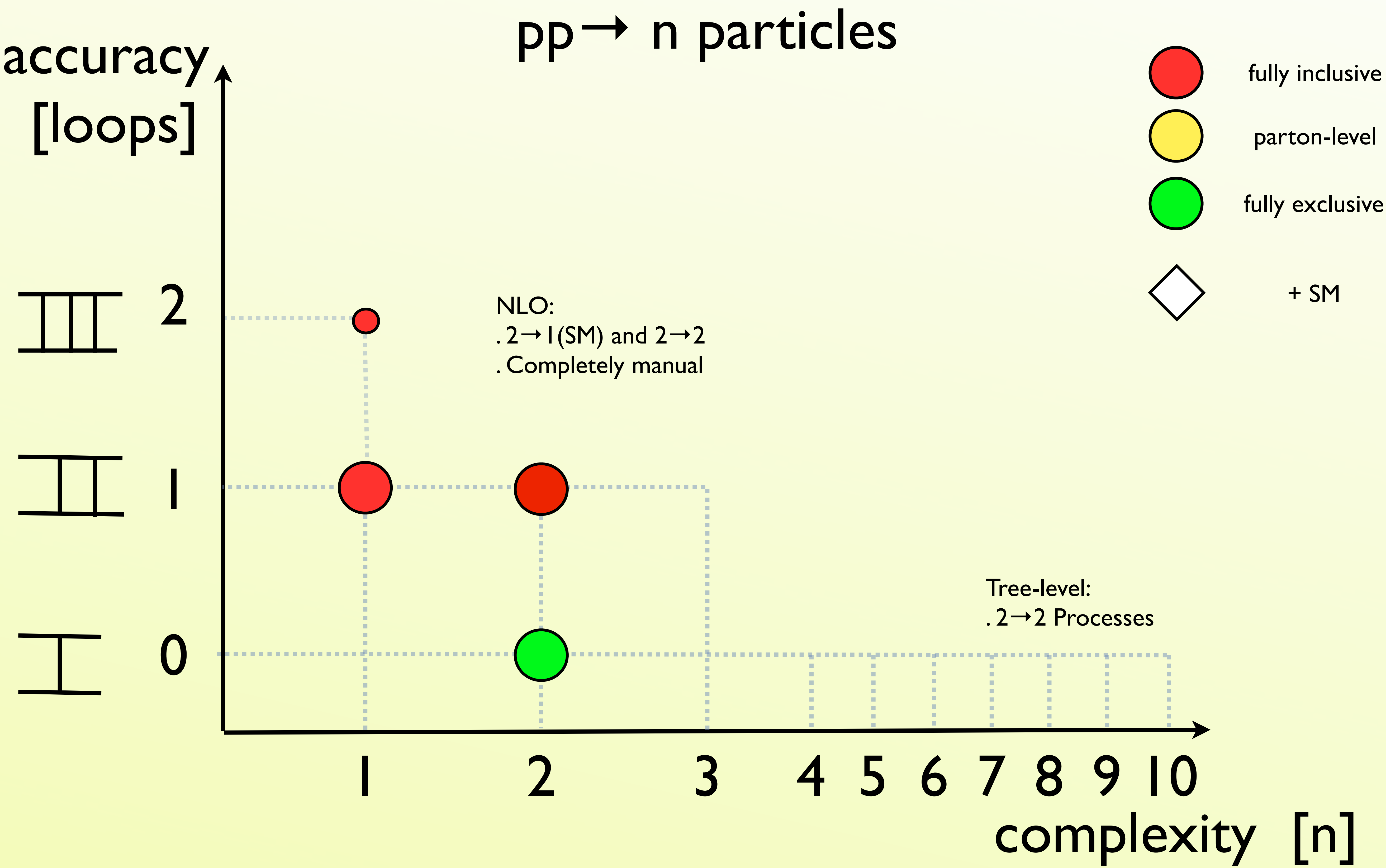
Status: BSM (a few years ago)



BSM simulations

- Matching is needed for generating inclusive samples with (LO) correct jet multiplicities.
- What about in for heavy new states?
  - very hard jets from decays
  - parton showers expected to be more accurate for larger masses
- Is this really the case or just common lore?
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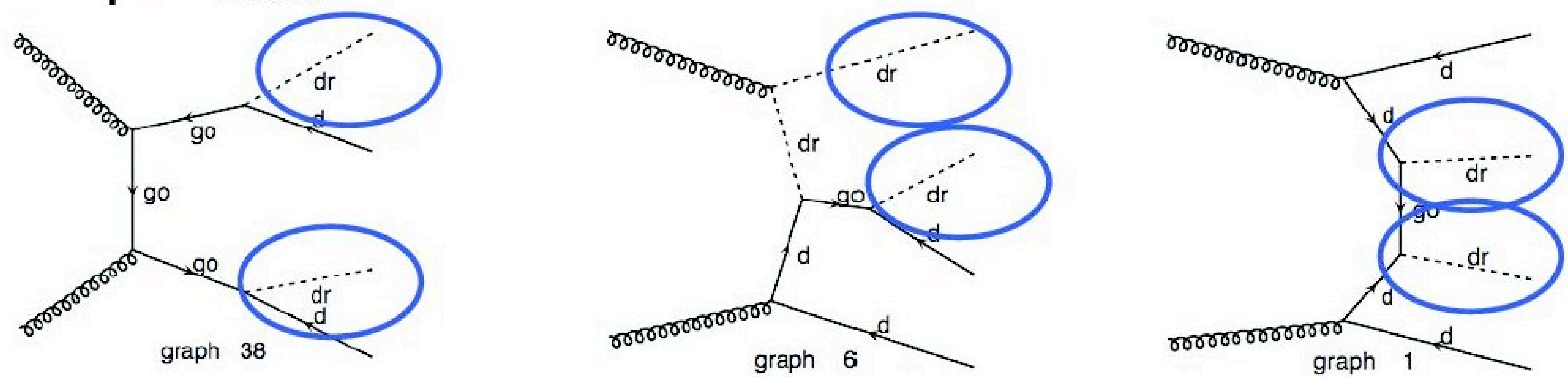
Let's look at a SUSY example : $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production!

Resonances double counting

[Alwall, de Visscher, FM, 2009]

A new* kind of problem arises when trying to combine samples with more partons.

Example: $\tilde{q}\tilde{q}jj$



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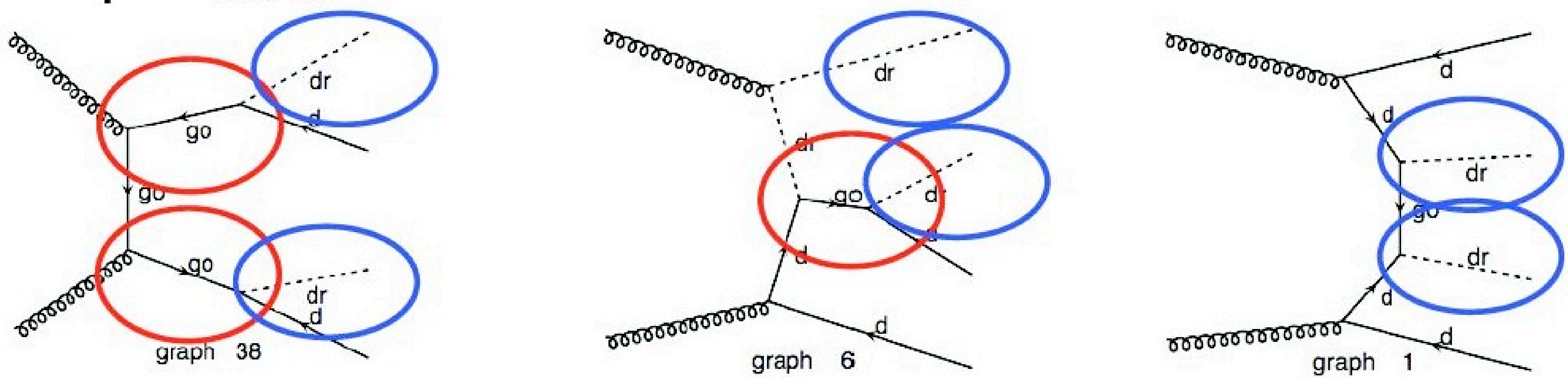

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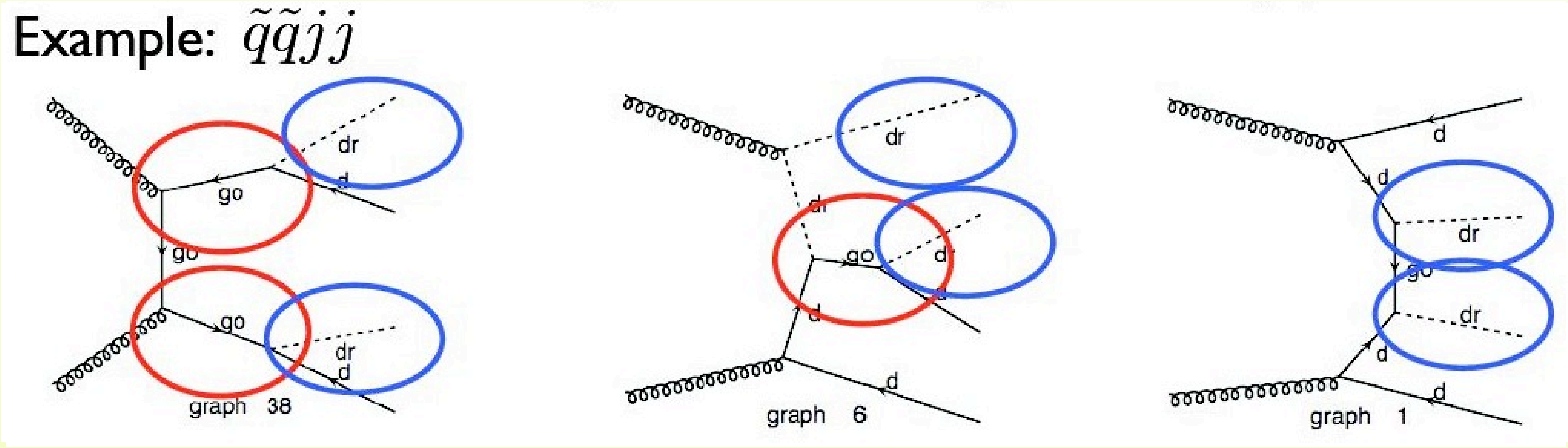

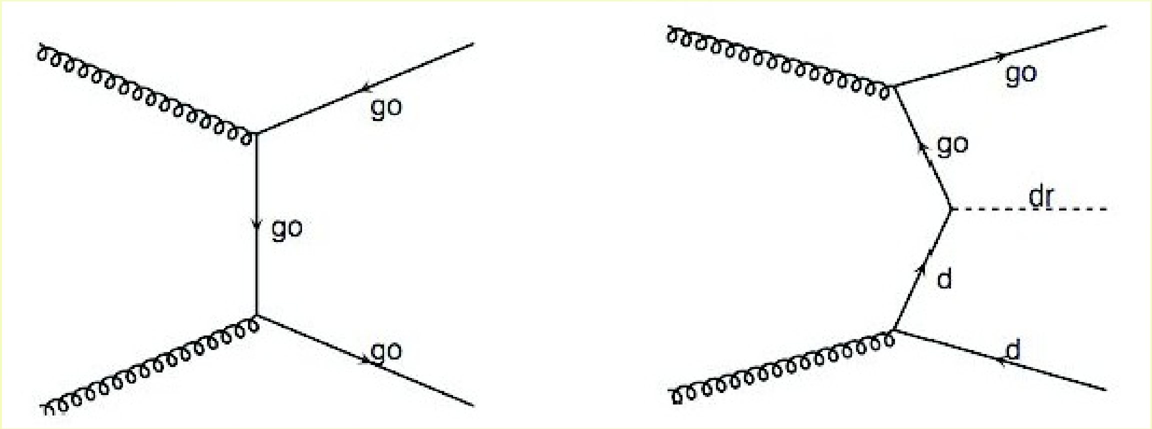

Double counting with gluino-gluino production and sucessive decays. Physics is clear, but technical problem.

Resonances double counting

Two solutions implemented and tested, which are exact in the NWA.

Resonances double counting

Two solutions implemented and tested, which are exact in the NWA.

1. Resonant event removal

```
<event>
 6   0  0.7992762E-04  0.9118800E+02  0.7816531E-02  0.1300000E+00
       21   -1     0     0  502  503  0.00000000000E+00  0.00000000000E+00  0.38916243784E+03  0.38916243784E+03  0.00000000000E+00 0.  1.
        1   -1     0     0  501    0  0.00000000000E+00  0.00000000000E+00 -0.16355197391E+04  0.16355197391E+04  0.00000000000E+00 0.  1.
  1000021    2     1     2  501  503 -0.22162854802E+03 -0.24366260777E+03 -0.12022753376E+04  0.13861620323E+04  0.60620830799E+03 0.  0.
       -1    1     3     3    0  503  0.18372150189E+02  0.27121177112E+02 -0.34707630298E+02  0.47725399437E+02  0.00000000000E+00 0. -1.
  2000001    1     3     3  501    0 -0.24000069821E+03 -0.27078378488E+03 -0.11675677073E+04  0.13384366329E+04  0.54522846200E+03 0. -1.
  2000001    1     1     2  502    0  0.22162854802E+03  0.24366260777E+03 -0.44081963594E+02  0.63852014456E+03  0.54522846200E+03 0. -1.
</event>
```

Resonances double counting

Two solutions implemented and tested, which are exact in the NWA.

1. Resonant event removal


```
<event>
 6   0  0.7992762E-04  0.9118800E+02  0.7816531E-02  0.1300000E+00
        21   -1    0    0  502  503  0.00000000000E+00  0.00000000000E+00  0.38916243784E+03  0.38916243784E+03  0.00000000000E+00 0.  1.
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   1000021    2    1    2  501  503 -0.22162854802E+03 -0.24366260777E+03 -0.12022753376E+04  0.13861620323E+04  0.60620830799E+03 0.  0.
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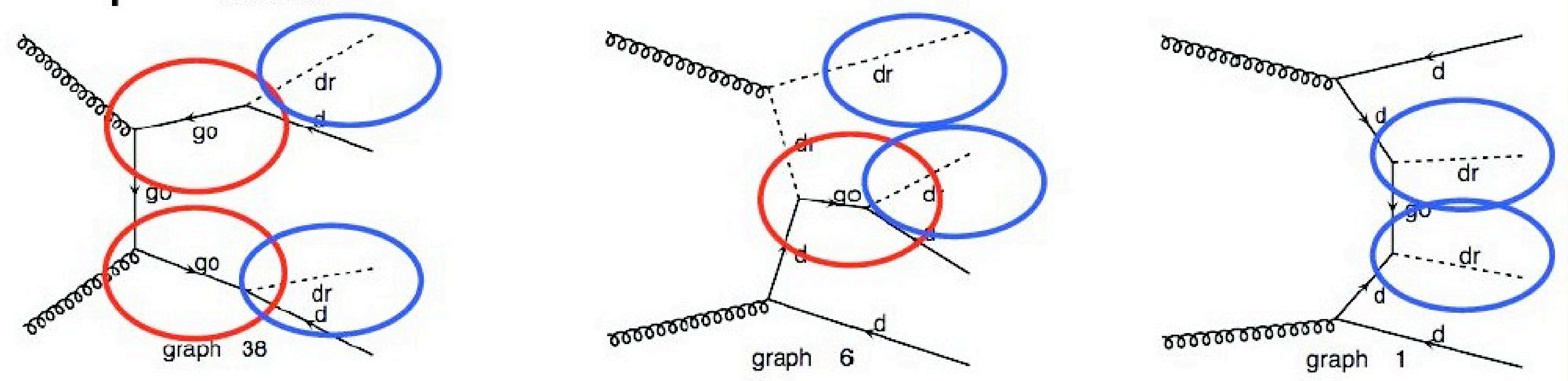
</event>
```


2. Resonant diagram removal

Example: $\tilde{q}\tilde{q}jj$



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  2000001     1     1     2  502    0  0.22162854802E+03  0.24366260777E+03 -0.44081963594E+02  0.63852014456E+03  0.54522846200E+03 0. -1.
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        21    -1     0     0   502   503  0.00000000000E+00  0.00000000000E+00  0.38916243784E+03  0.38916243784E+03  0.00000000000E+00 0.  1.
         1    -1     0     0   501     0  0.00000000000E+00  0.00000000000E+00 -0.16355197391E+04  0.16355197391E+04  0.00000000000E+00 0.  1.
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</event>
```

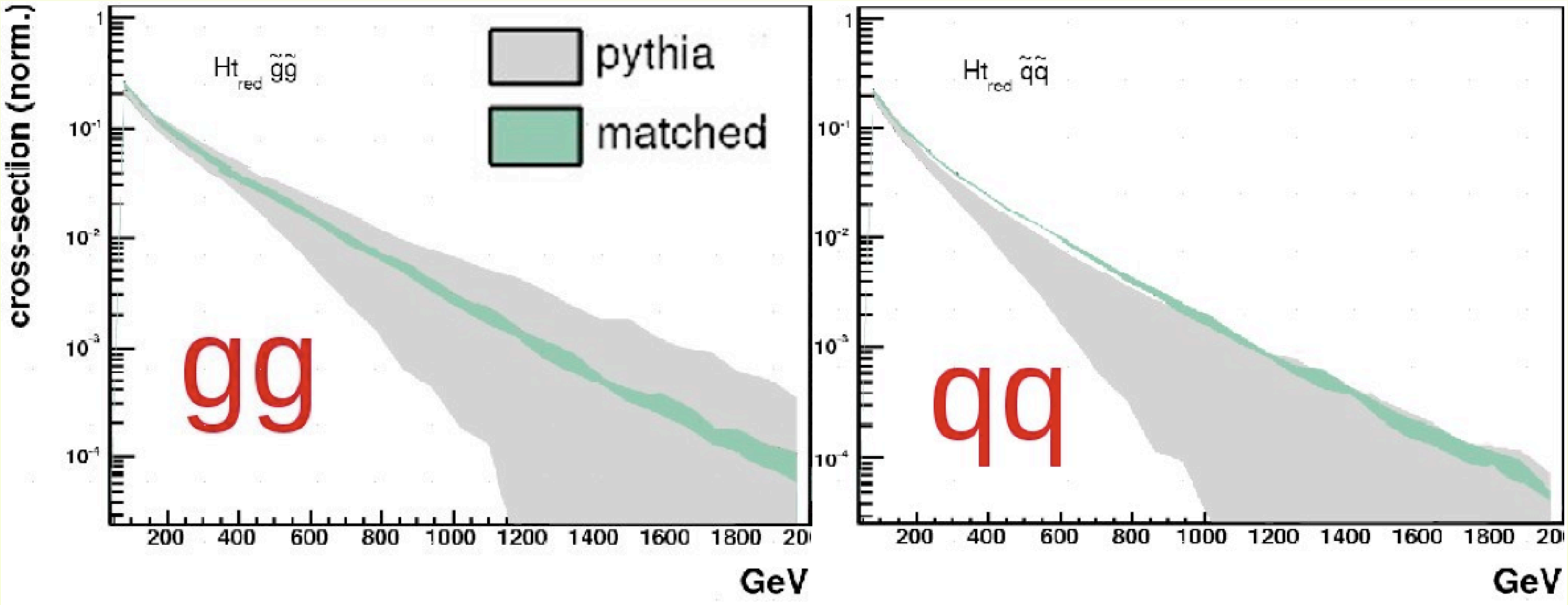

2. Resonant diagram removal

Example: $\tilde{q}\tilde{q}jj$

Results are very much independent on the subtraction method.

Initial state dependence: gg vs qq

600 GeV gluino vs squark pair production at the LHC



No single tune for the shower can reproduce both channels.

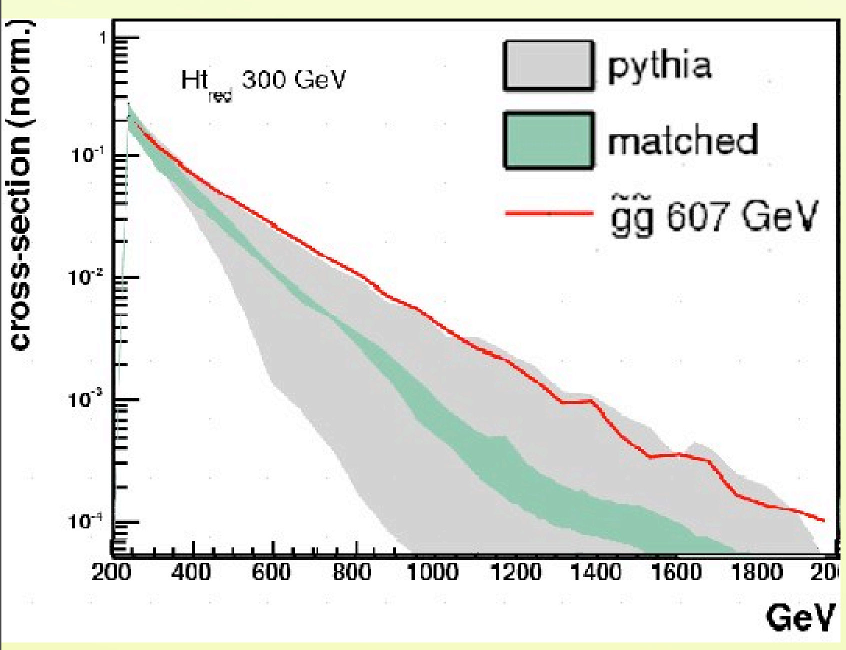
Mass scale dependence of the radiation pattern

1. Overall scale of SUSY can be difficult to measure in presence of missing E_T.
2. The “amount” of radiation depends on the overall scale of the event as expected

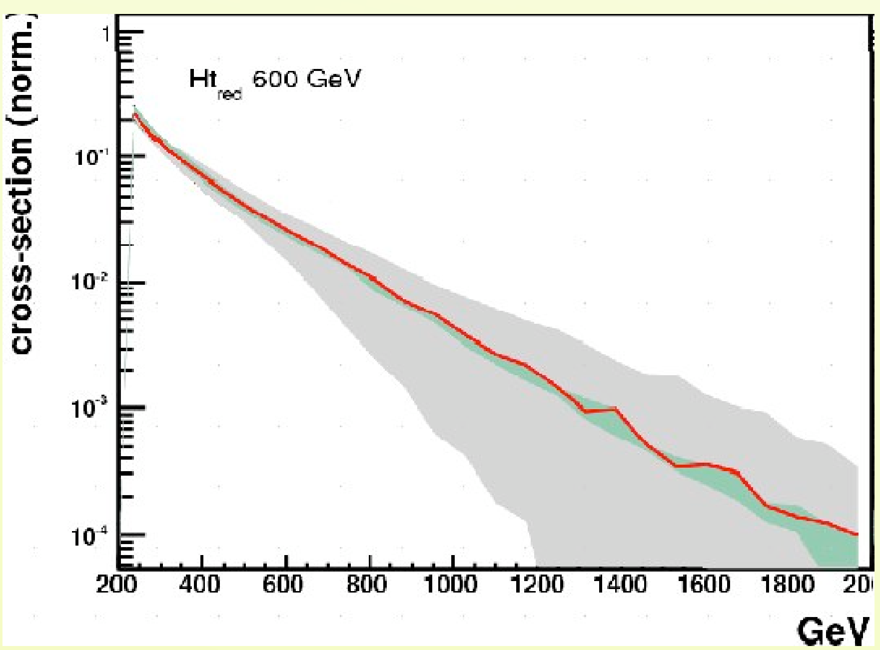
Q: can we use the “amount of radiation” to measure the overall scale?

Example: (Stable) gluino pair production at the LHC. The hard jets H_T.

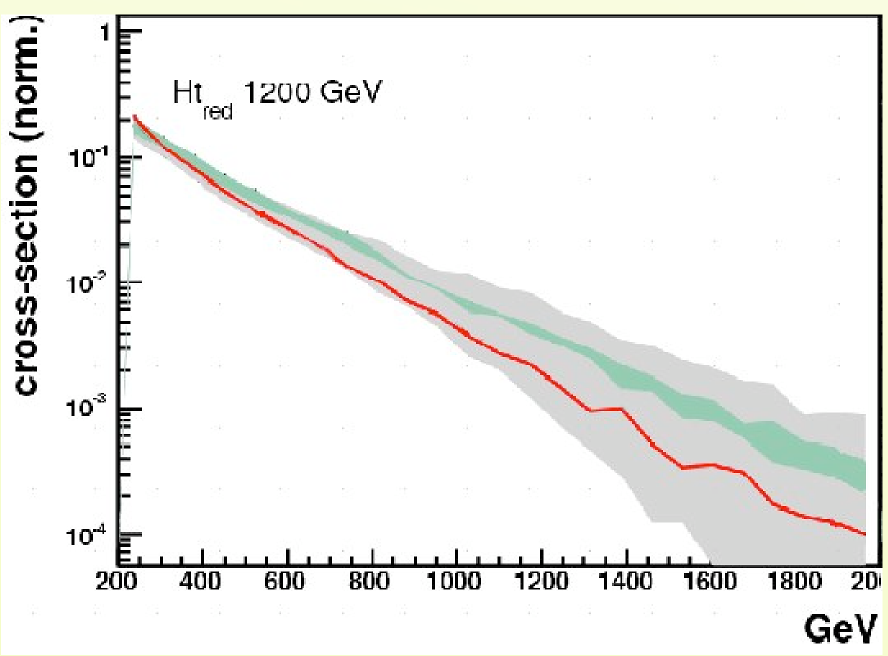
300 GeV



600 GeV



1200 GeV



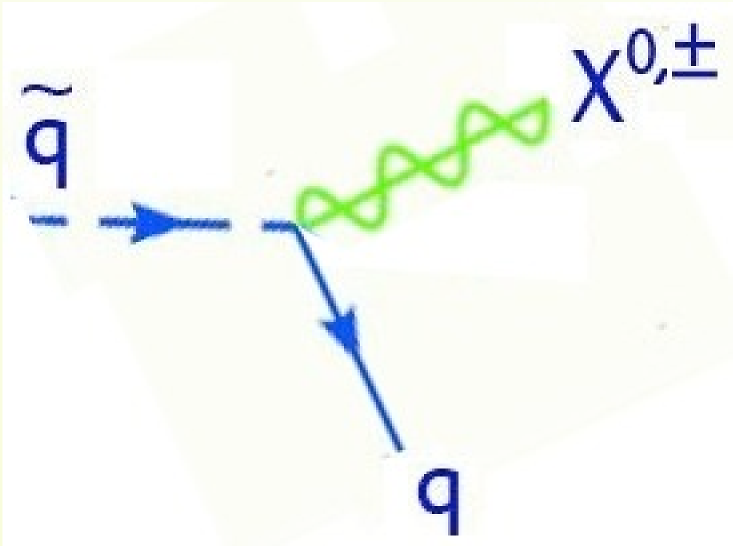
Matched predictions are in principle predictive enough to allow such a study.

Squark/gluino separation

Squark decay:

quark + weak gaugino

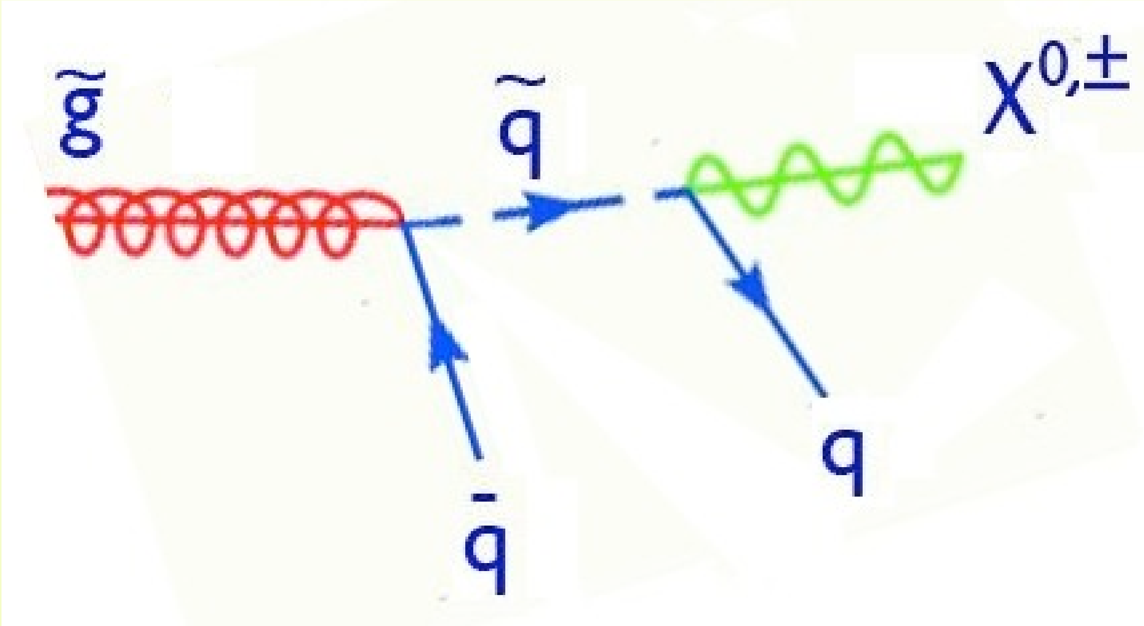
1 Jet



Gluino decay:

2 quarks + weak gaugino

2 Jets

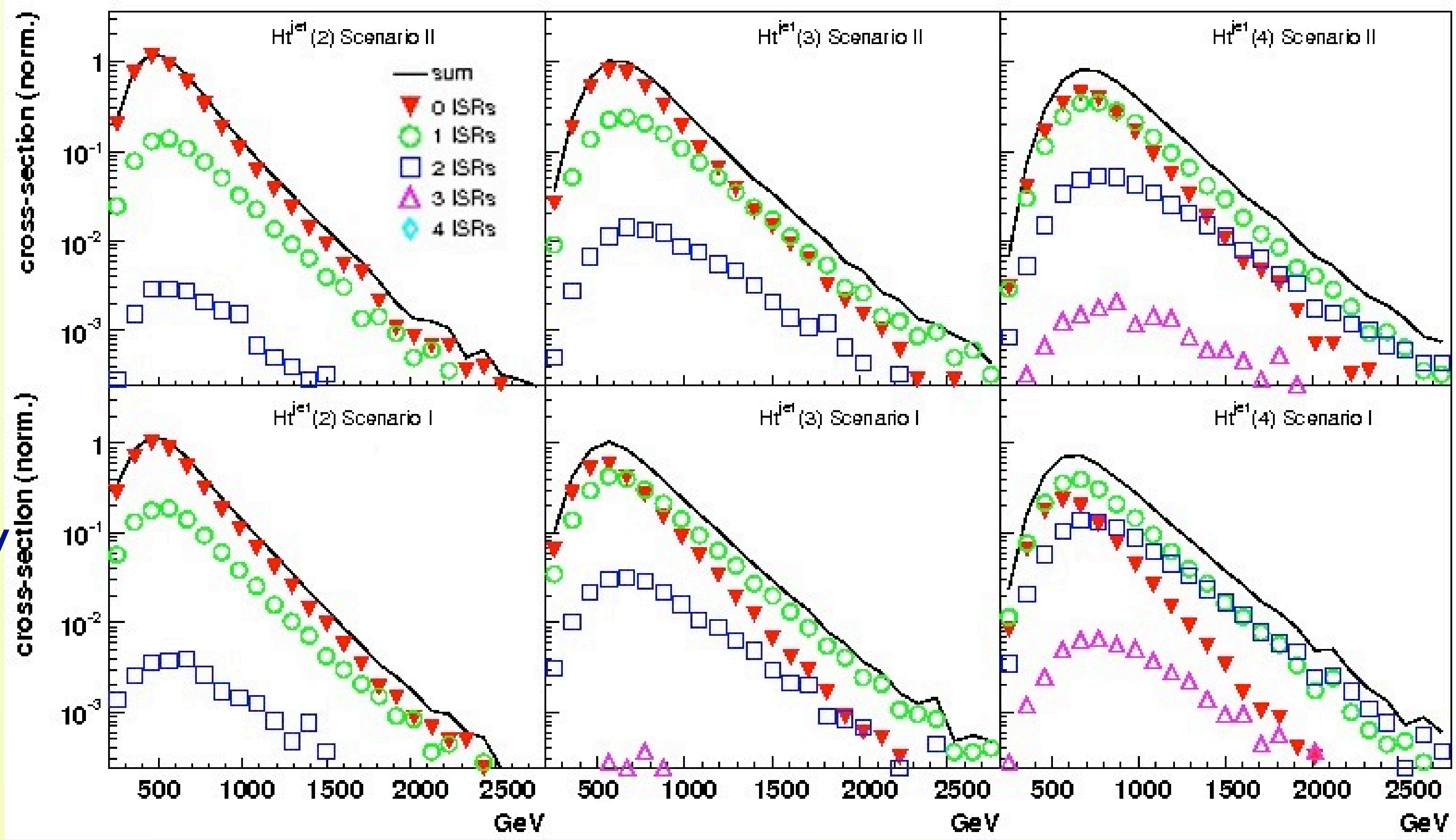


Squark/gluino separation

600 GeV gluino pair production at the LHC

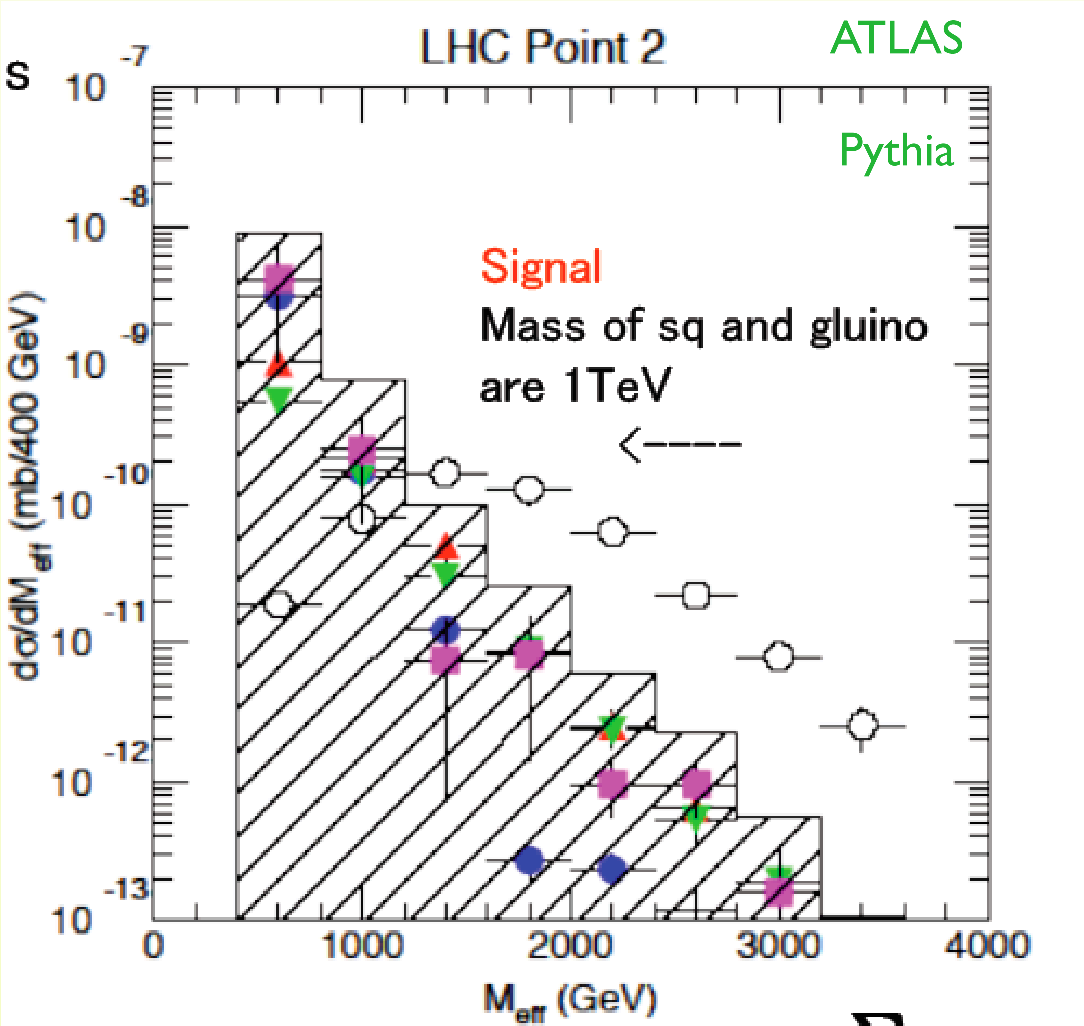
Gluino
3 body decay

Mg - Mq=50 GeV

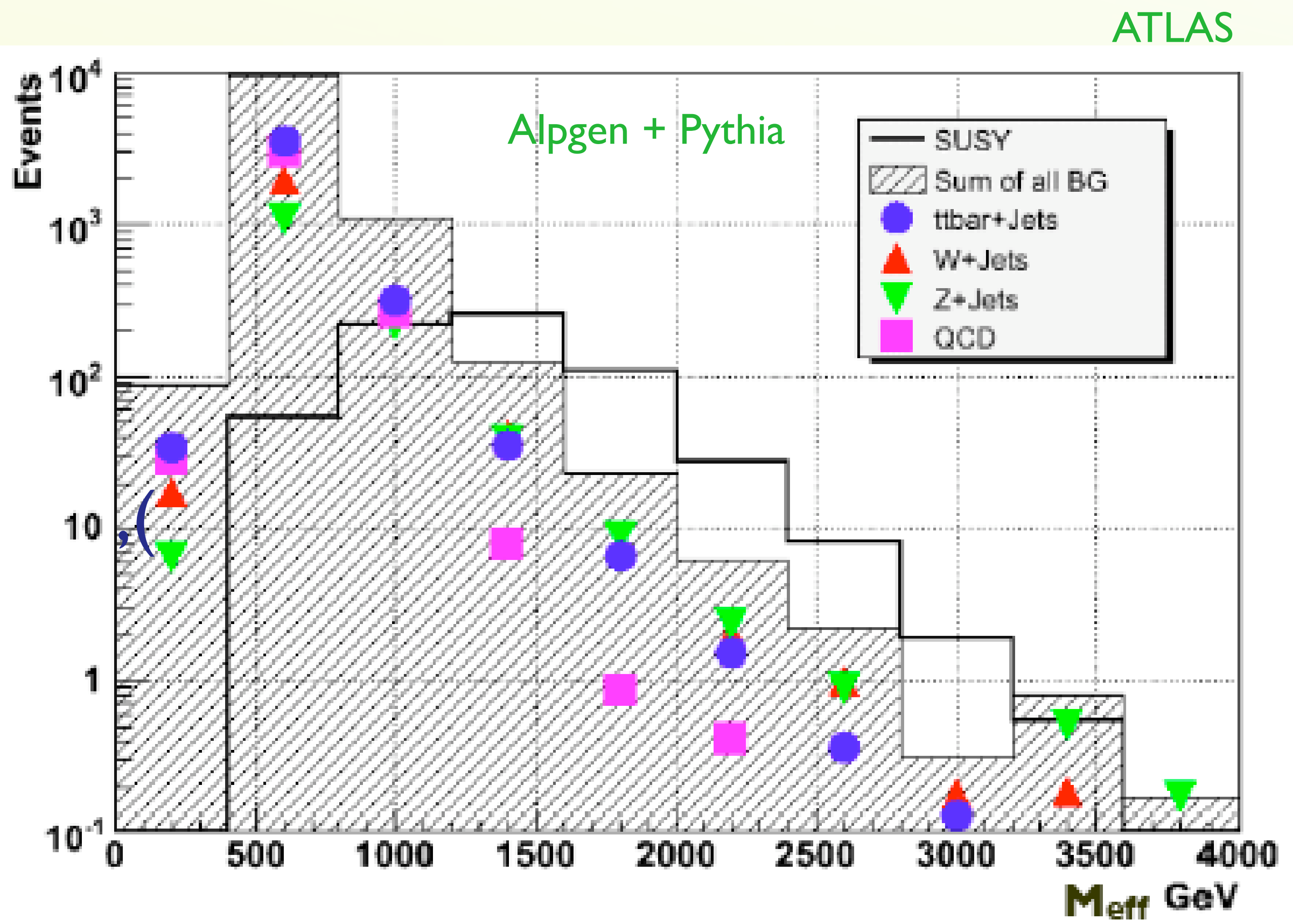


$H_T(n) = \sum_n p_T(j)$ $H_T(2)$ $H_T(3)$ $H_T(4)$

BSM @ LHC : far and recent past



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

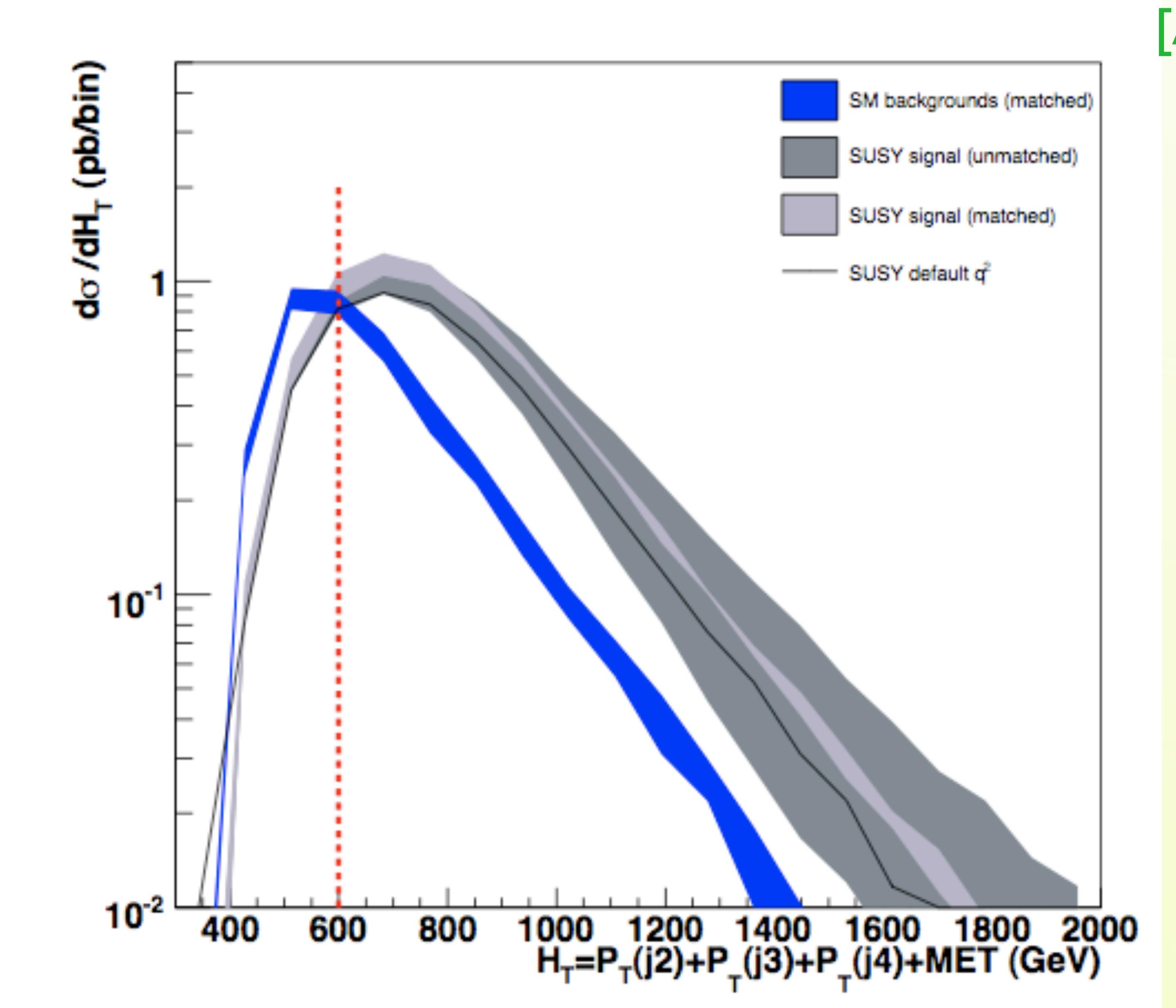


Signal: SUSY inclusive. Background: t tbar+jets,(Z,W)+jets, QCD jets.

With more realistic simulations life's harder! MC's help in indentifying and understanding the possible sources of backgrounds and eventually model the data better. Need for validation, control samples and robust extrapolations.

BSM @ LHC : present

[Alwall, de Visscher, FM, 2009]

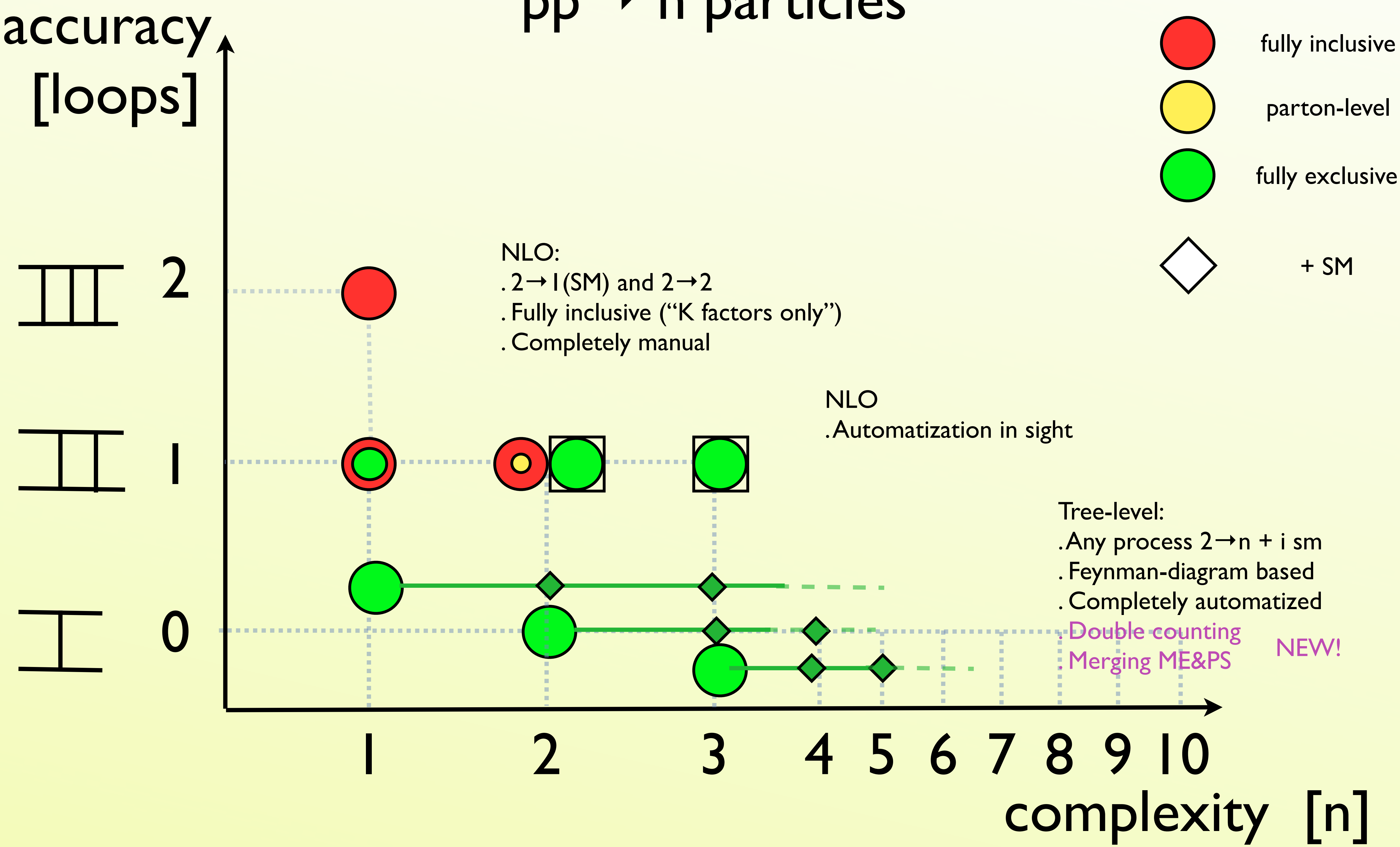


Both signal and background matched!

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

BSM : status and outlook

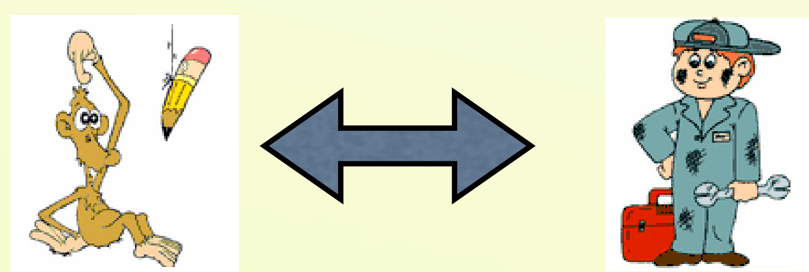
pp→ n particles



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).



2. Once models are available in multipurpose MC's, new detailed studies are possible that allow to bring to the BSM signatures the same level of sophistication achieved for the SM.

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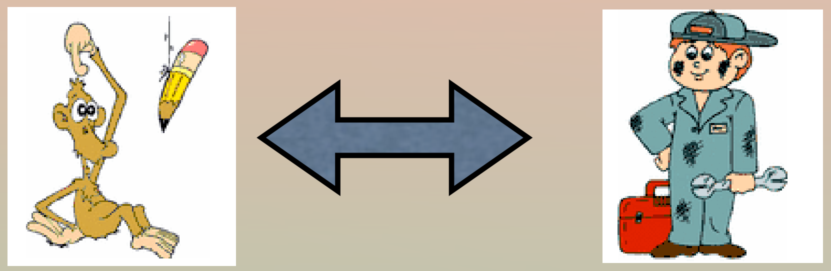

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A Roadmap (with roadblocks) for BSM @ the LHC

TH

EXP

Idea

Data

A Roadmap (with roadblocks) for BSM @ the LHC

TH

EXP

Idea

?

Data

A Roadmap (with roadblocks) for BSM @ the LHC

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Idea

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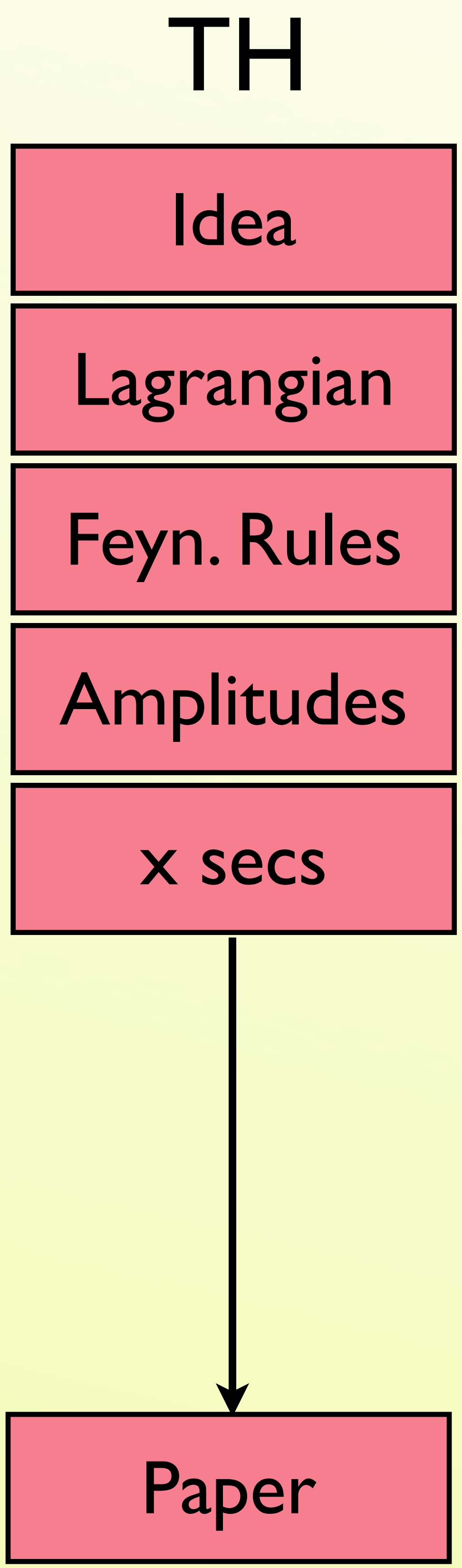
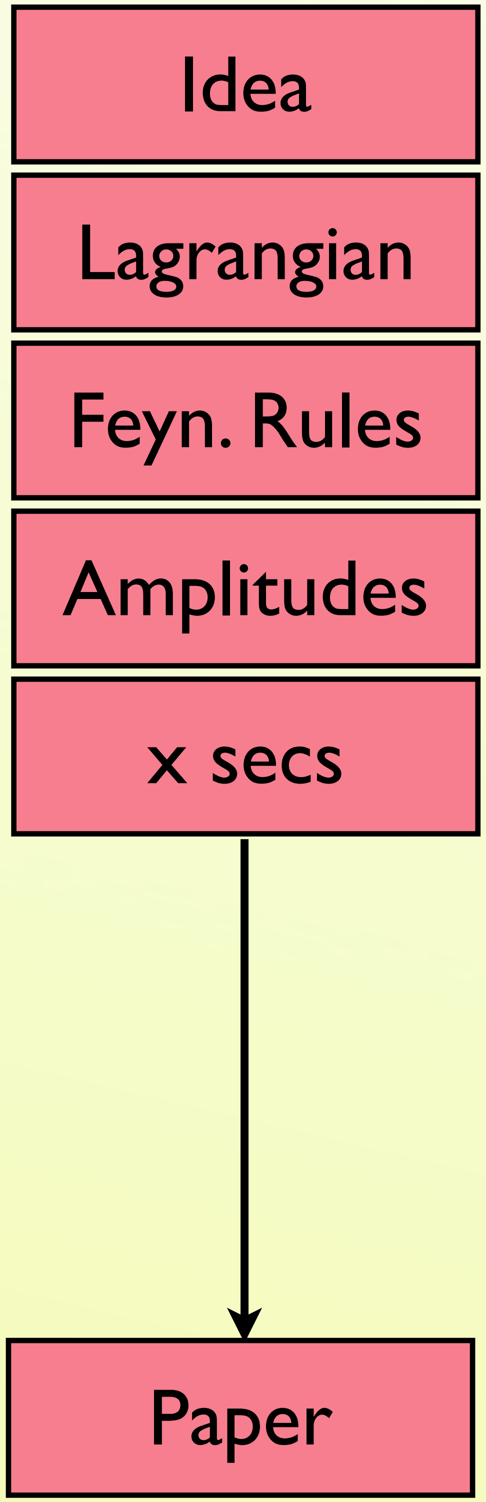


A Roadmap (with roadblocks) for BSM @ the LHC

TH PHENO



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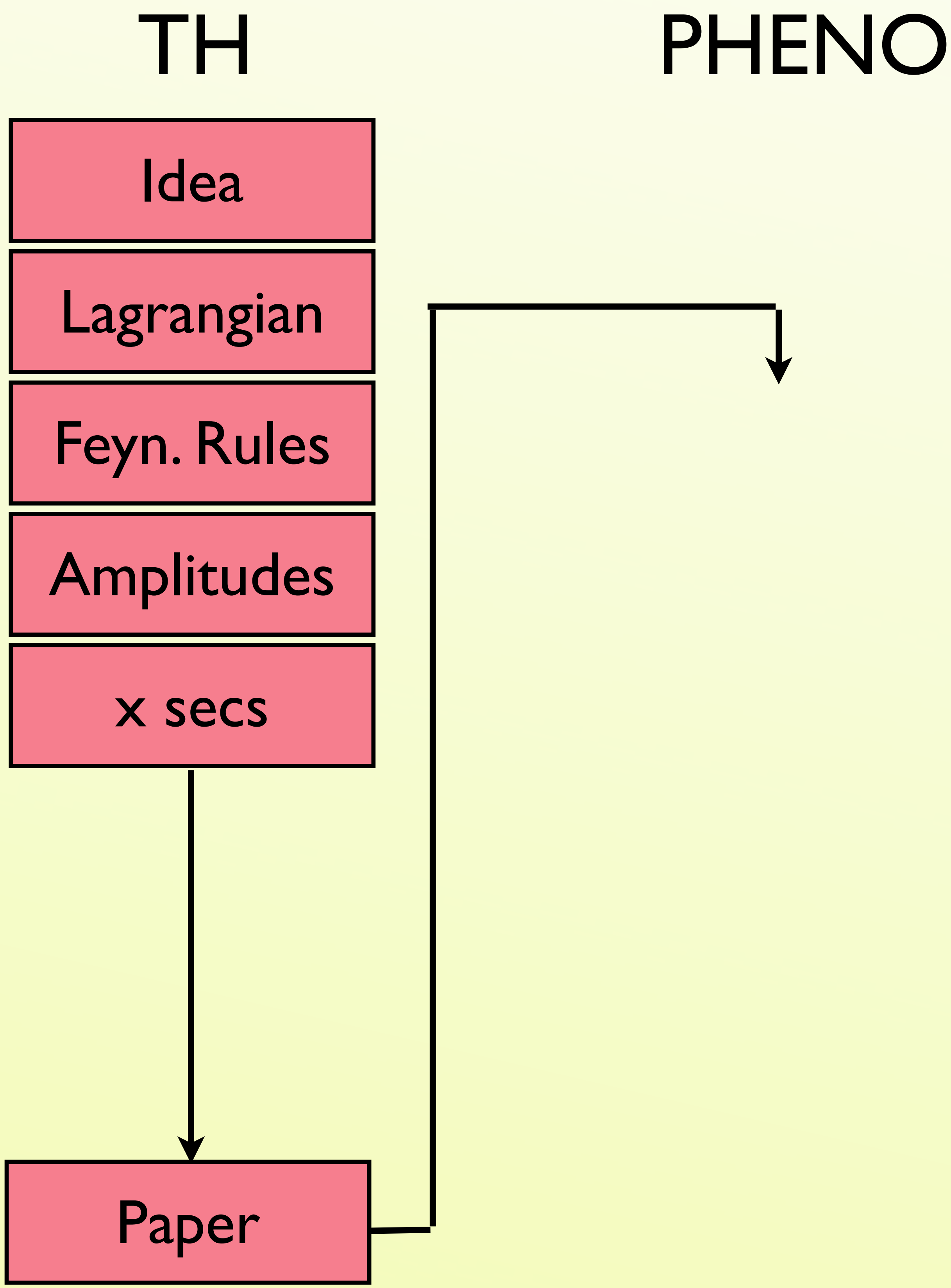

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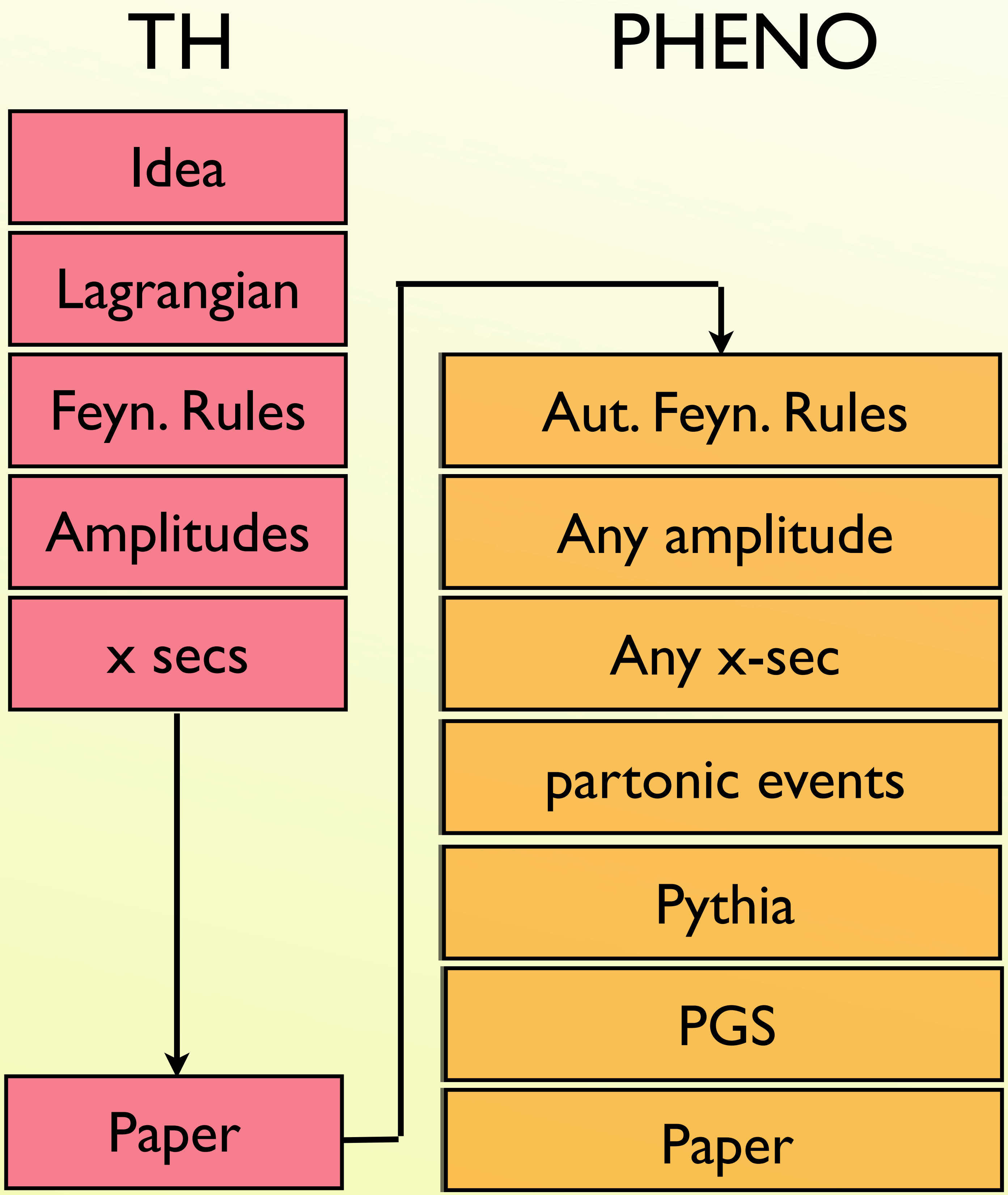
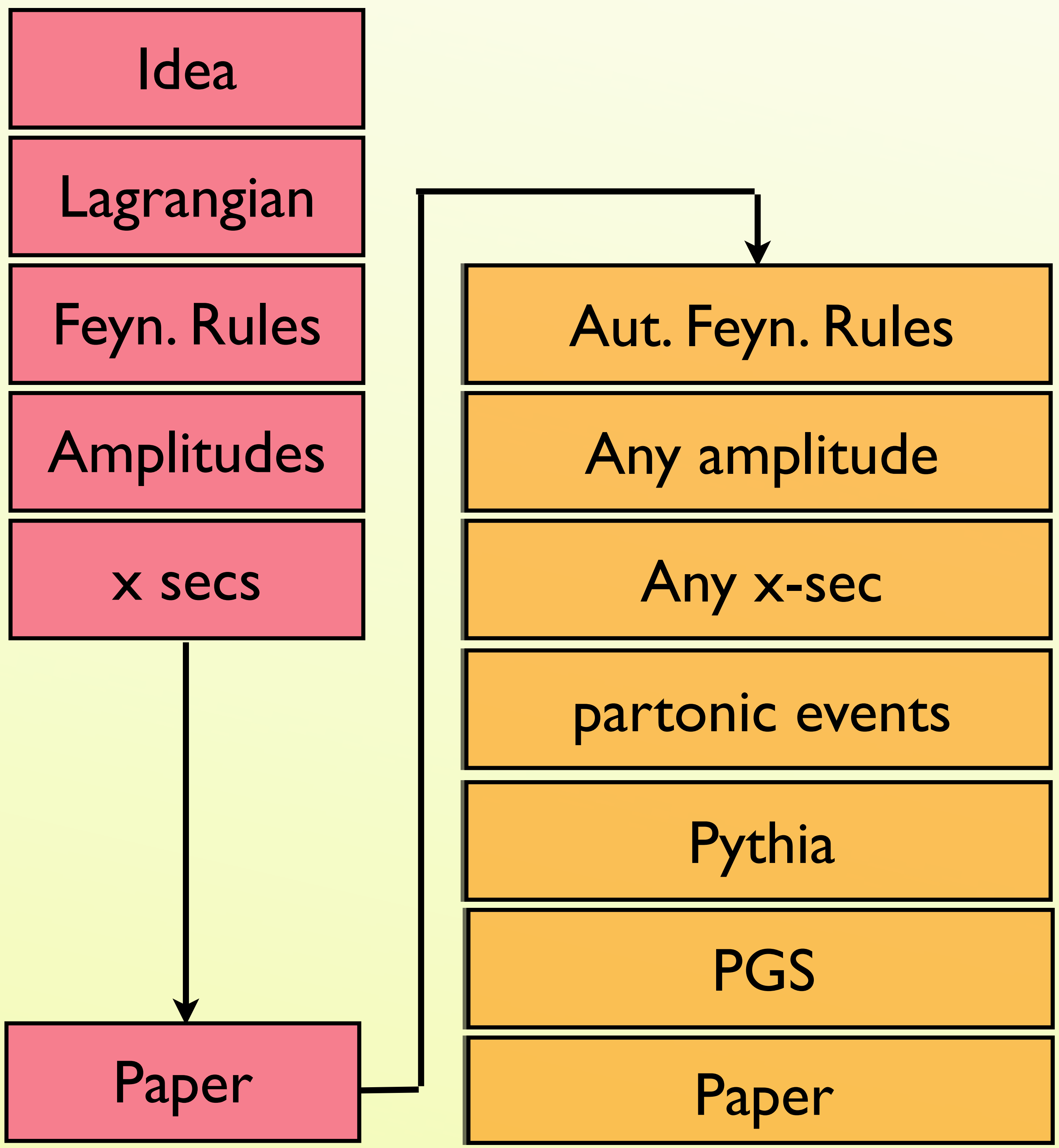


A Roadmap (with roadblocks) for BSM @ the LHC

TH | PHENO | EXP



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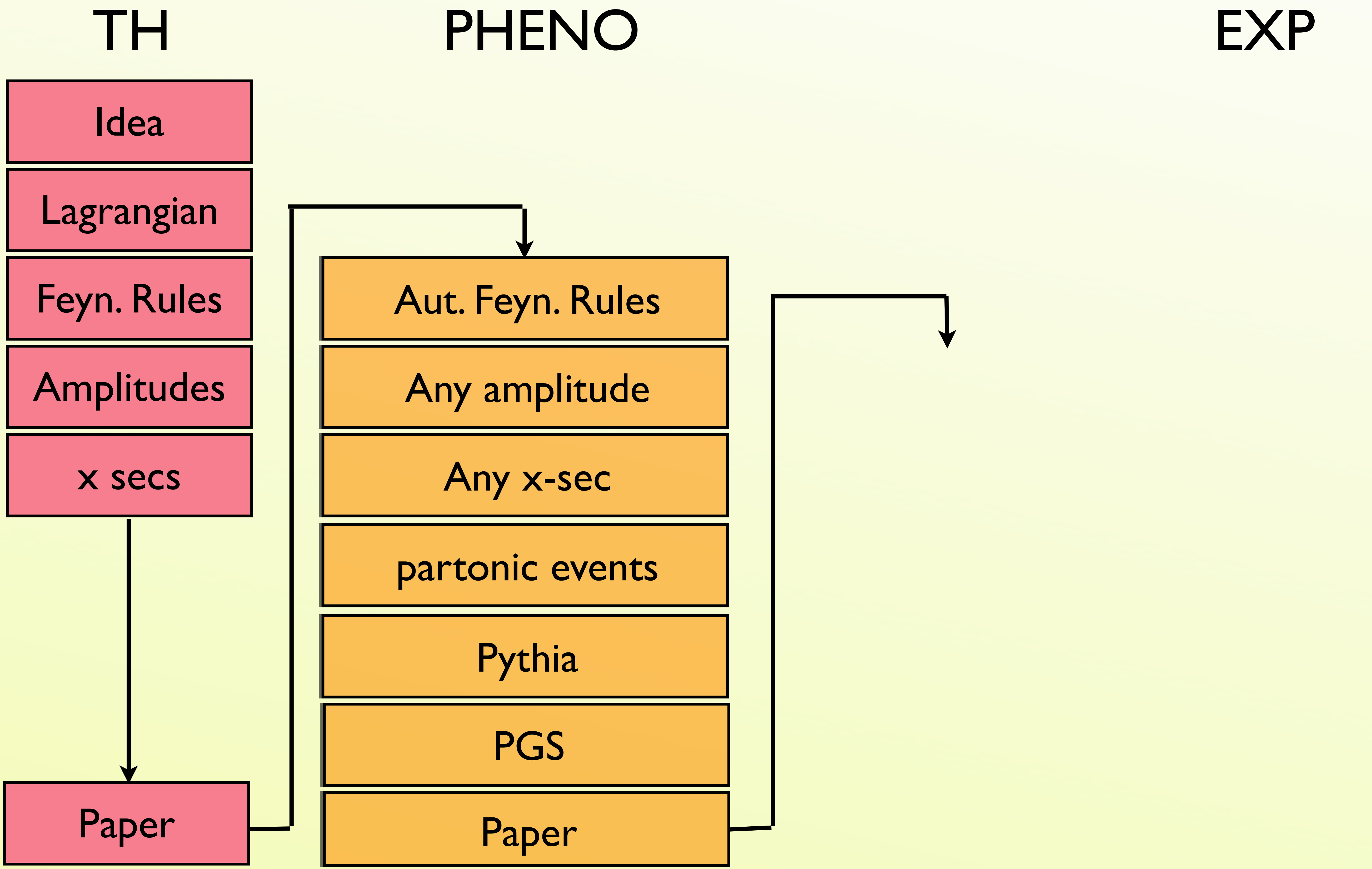

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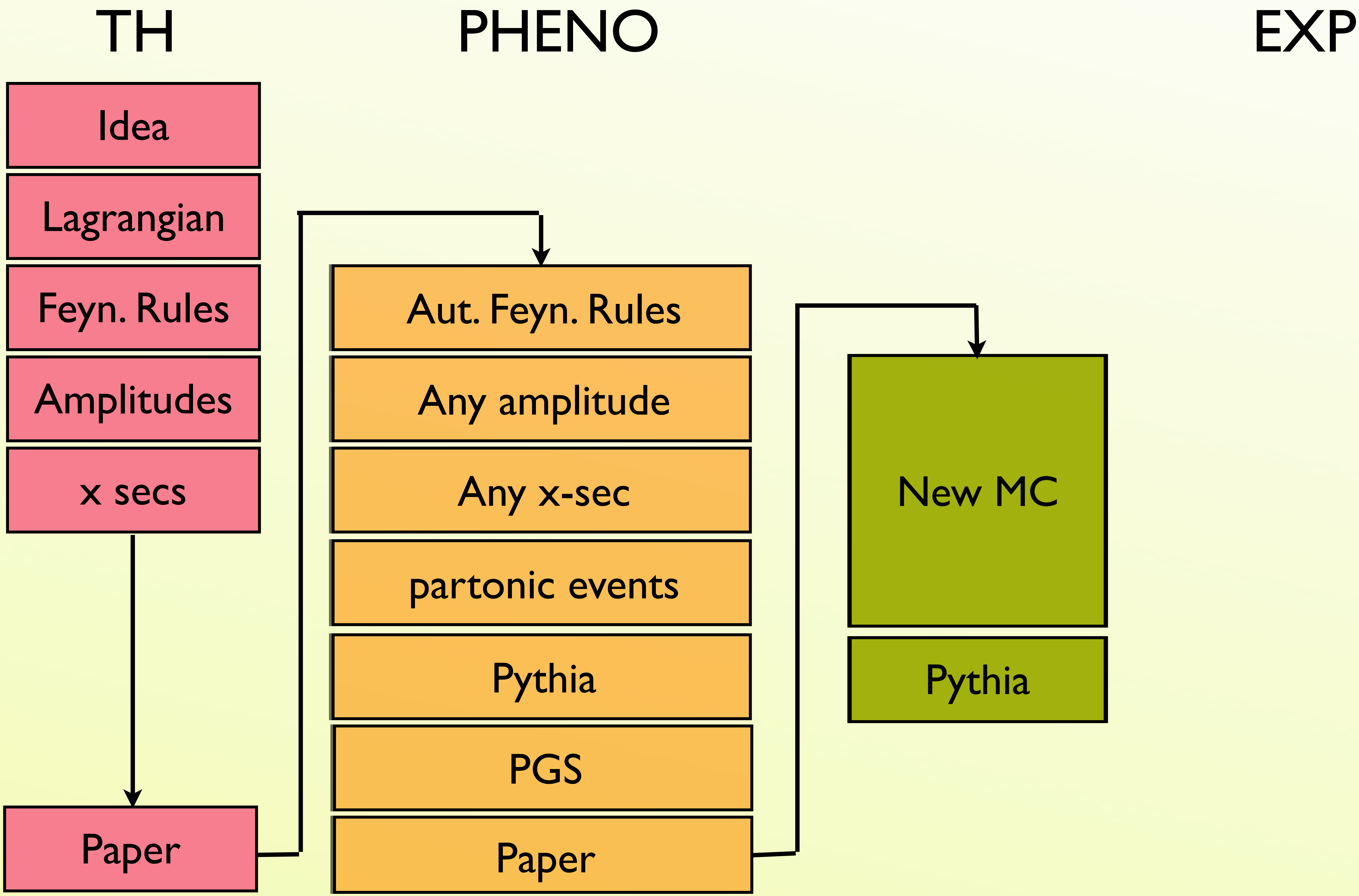

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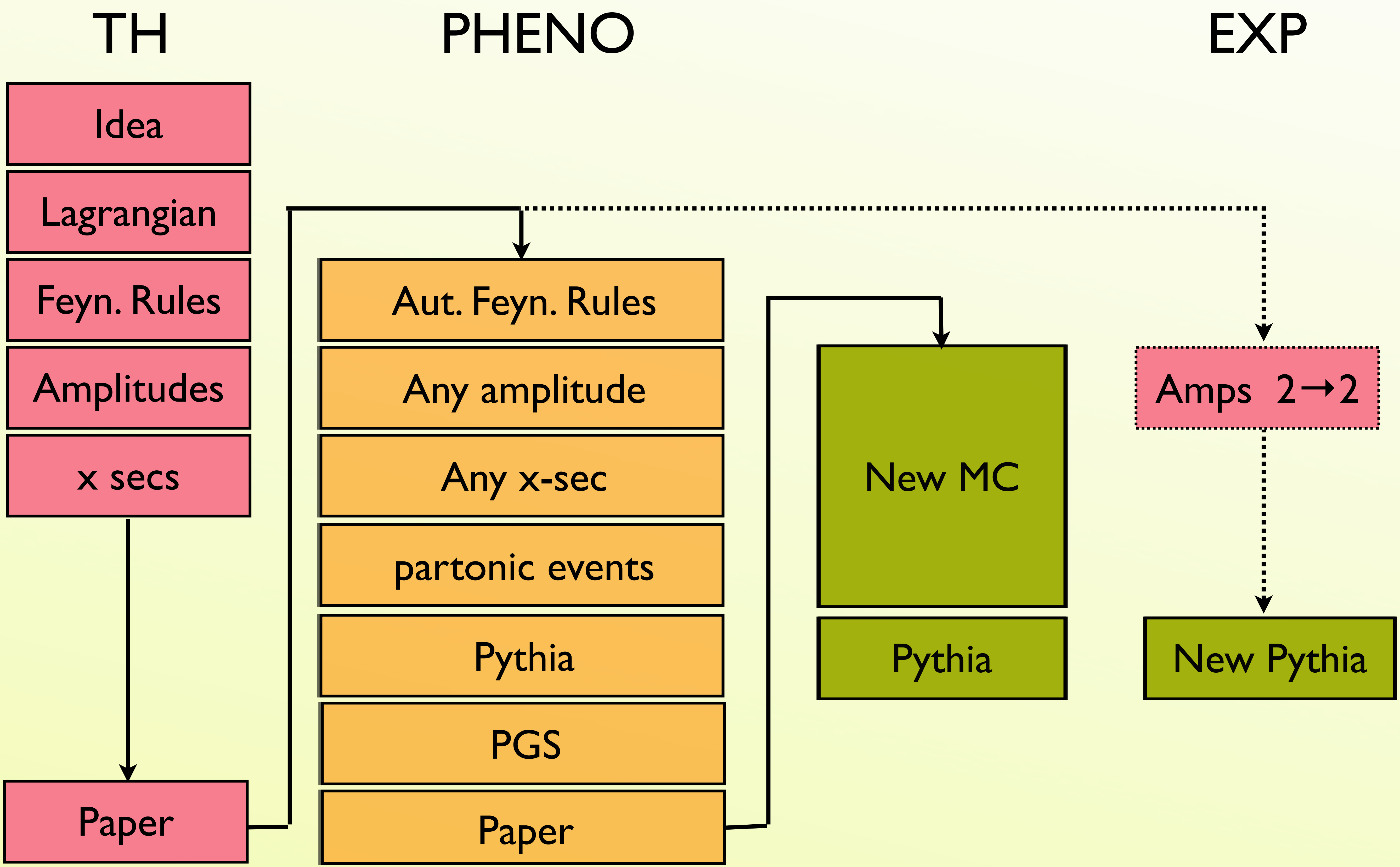

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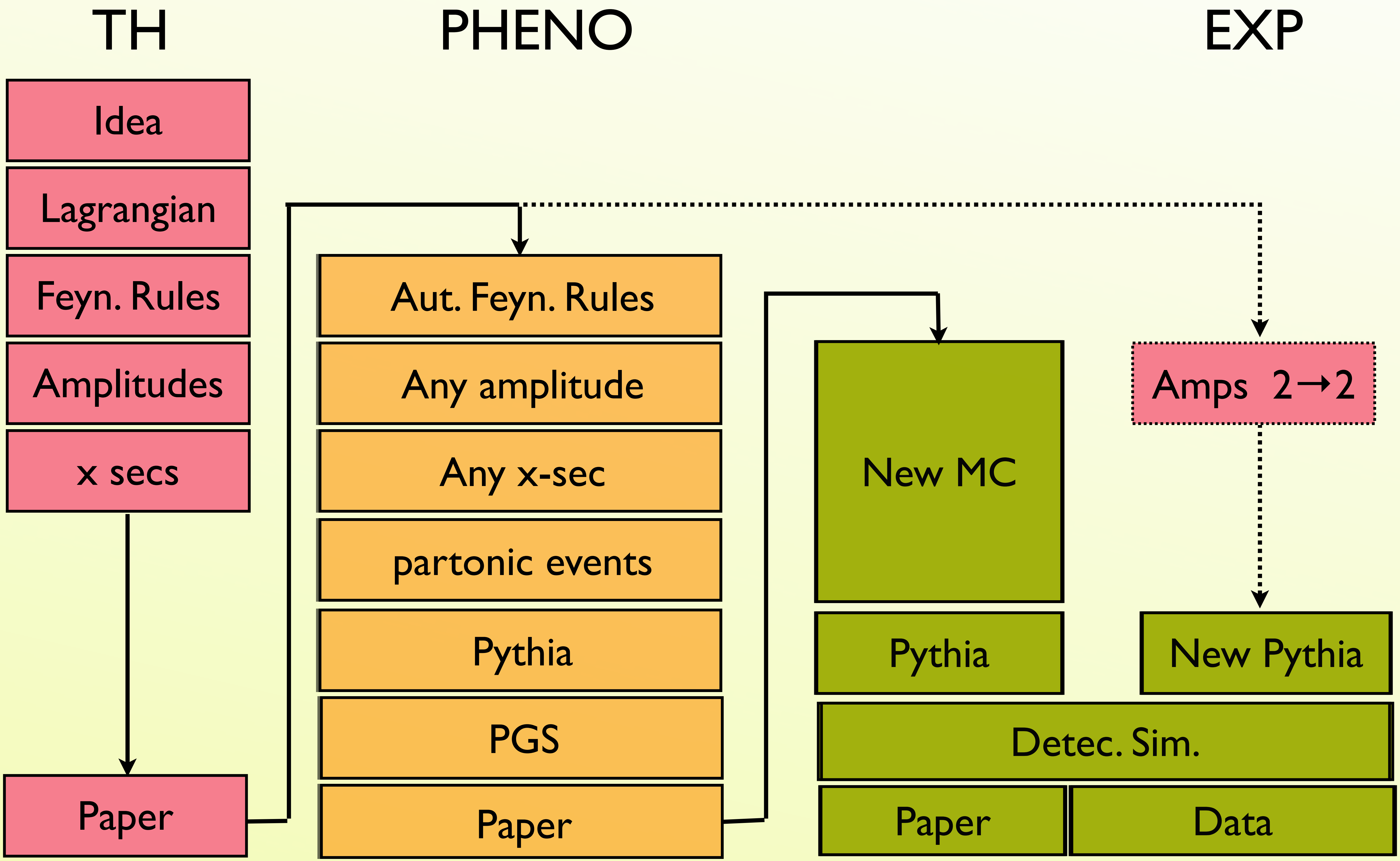
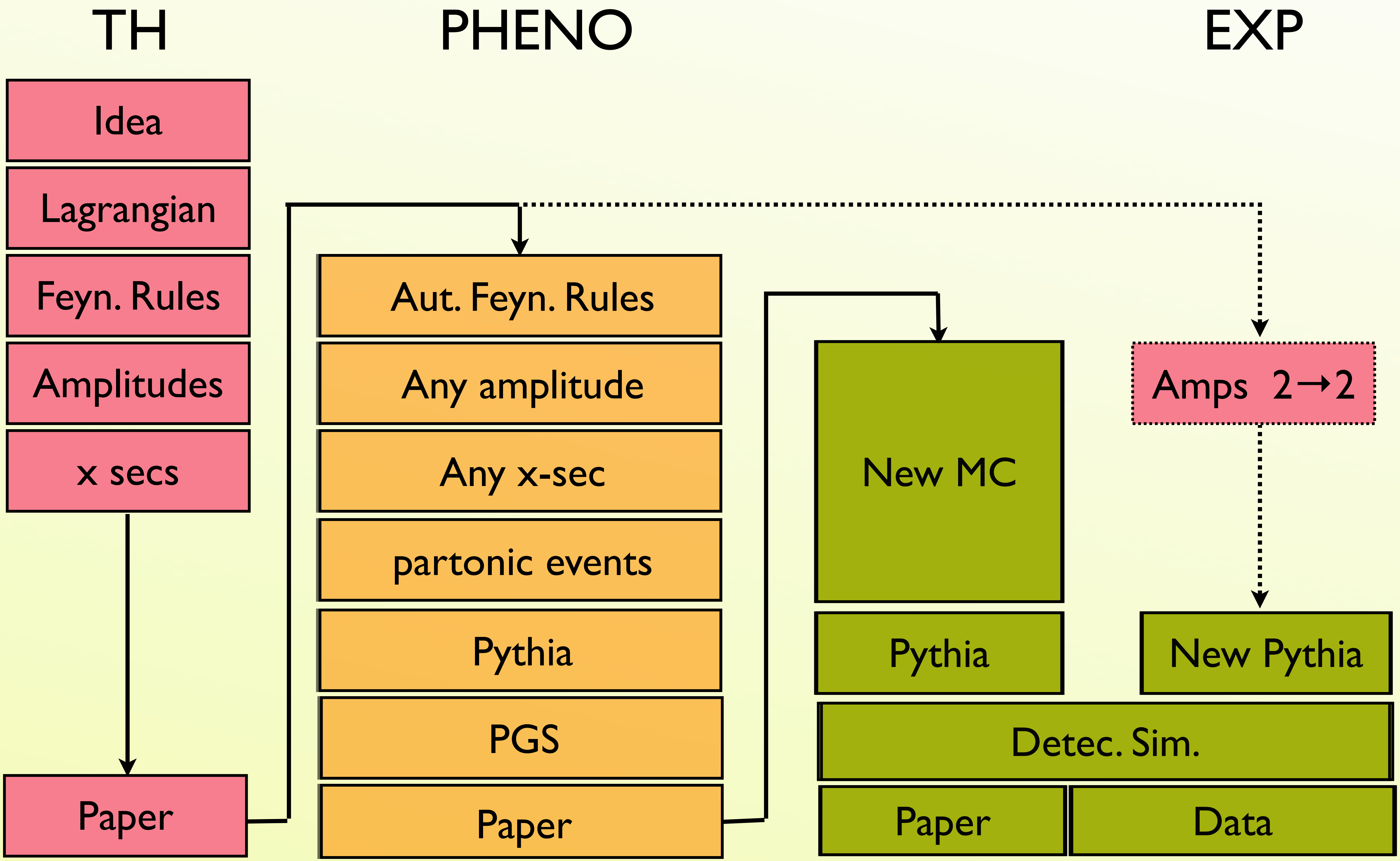


A Roadmap (with roadblocks) for BSM @ the LHC

- 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

- Idea
- Lagrangian

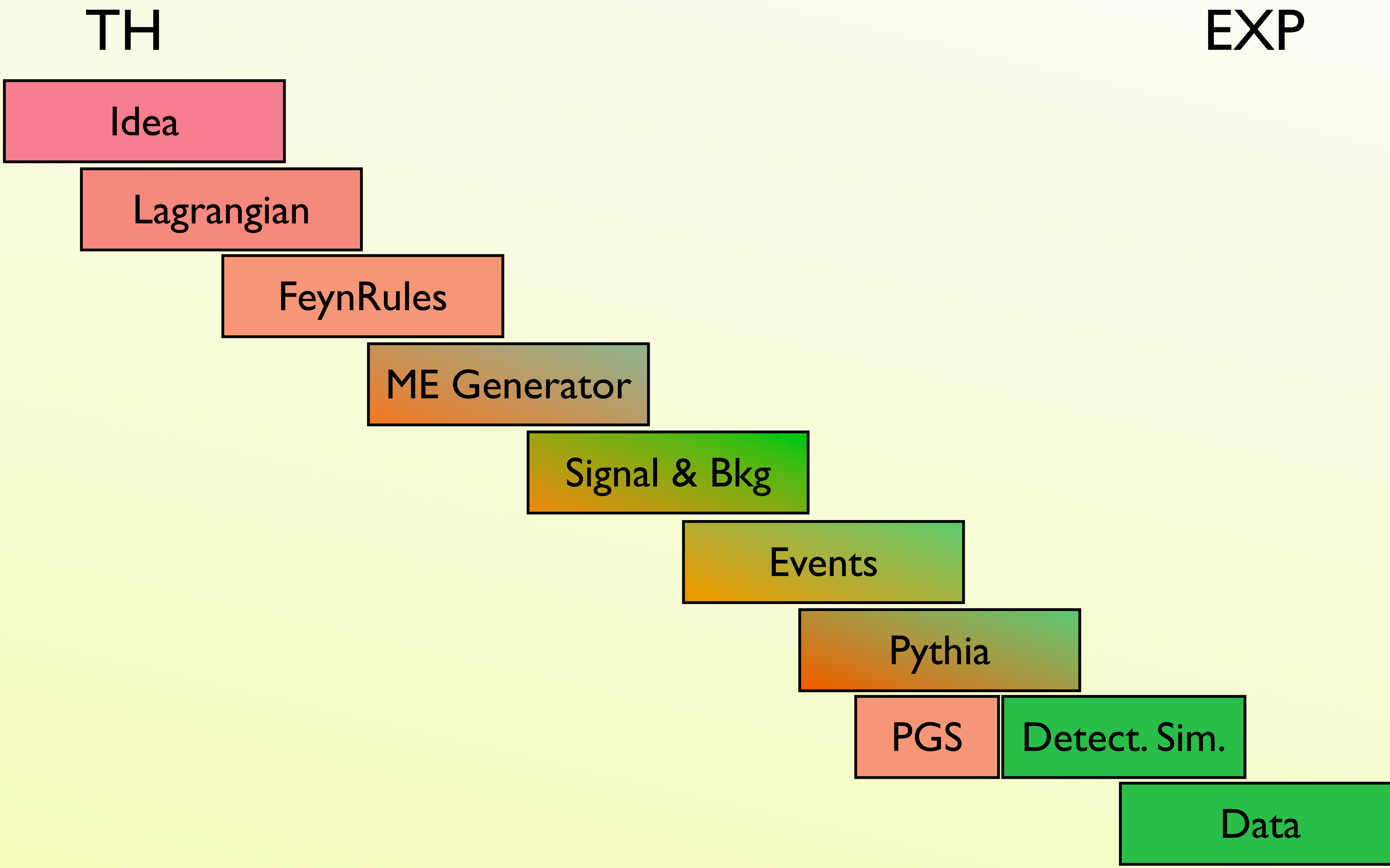
PHENO

- Aut. Feyn. Rules
- Any amplitude
- Any x-sec
- partonic events

EXP

- Pythia
- Detec. Sim.
- Data

A Roadmap for BSM @ the LHC



A Roadmap for BSM @ the LHC

TH

EXP

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

Idea

Lagrangian

FeynRules

ME Generator

Signal & Bkg

Events

Pythia

PGS | Detect. Sim.

Data

A Roadmap for BSM @ the LHC

TH → **EXP**

- Idea
- Lagrangian
- FeynRules
- ME Generator
- Signal & Bkg
- Events
- Pythia
- PGS | Detect. Sim.
- Data

- One path for all
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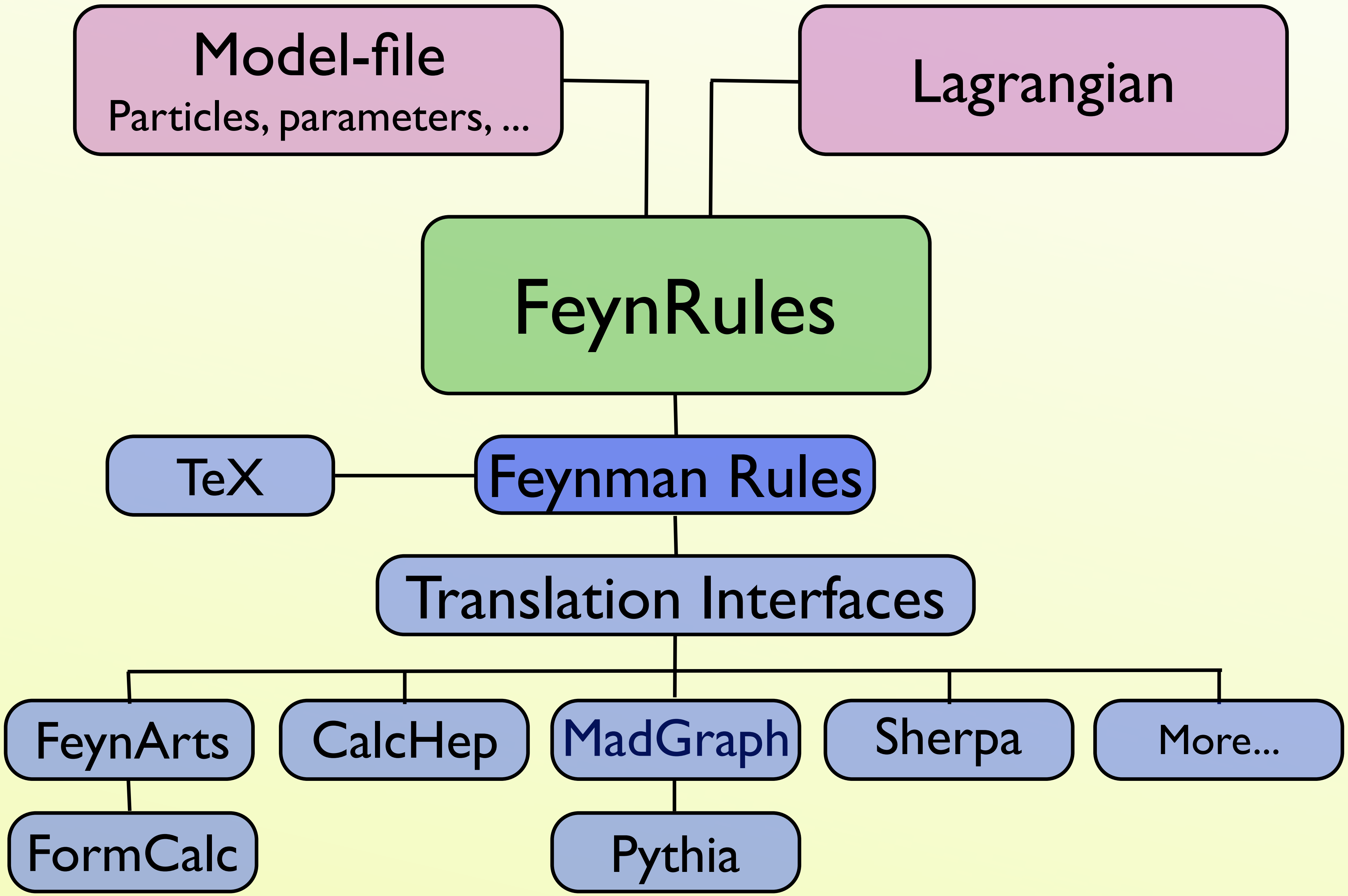
- It works top-down and bottom-up

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., in progress]



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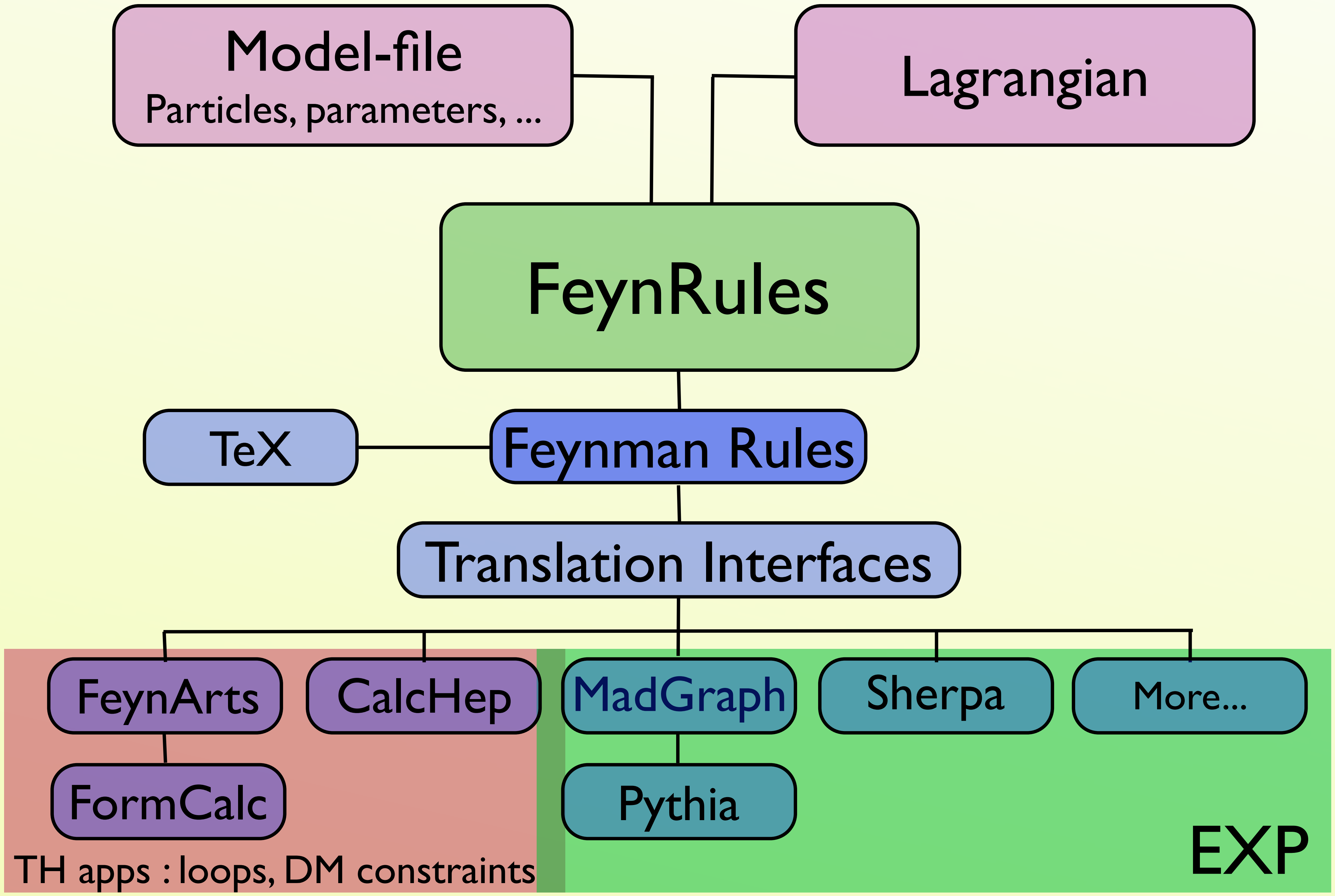

Conclusions

- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.

- A new generation of tools and techniques has been is available. Among the most useful is the matching between fixed-order and parton-shower both at tree-level and at NLO.

- Fully efficient and flexible BSM simulation chain being completed. Same level of sophistication as SM processes attained.

- 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.


Let's sharpen our swords:
the LHC is finally coming!

Credits

I am particularly grateful to the MadGraph and FeynRules teams for continuous, lively and fruitful work during the past and the next exciting years!