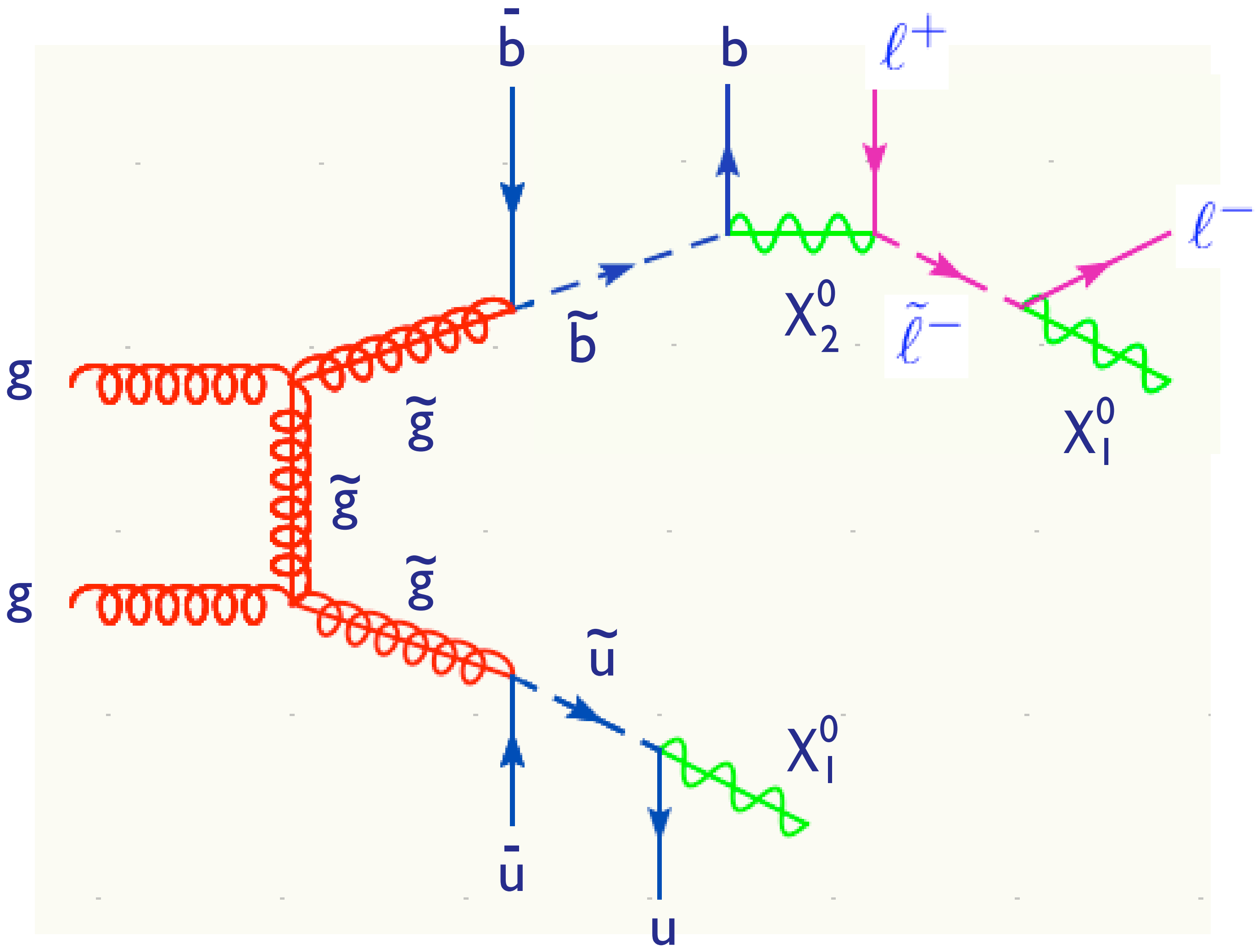
MC tools for hadron colliders

“An overview for SUSY & BSM hunters”

Fabio Maltoni

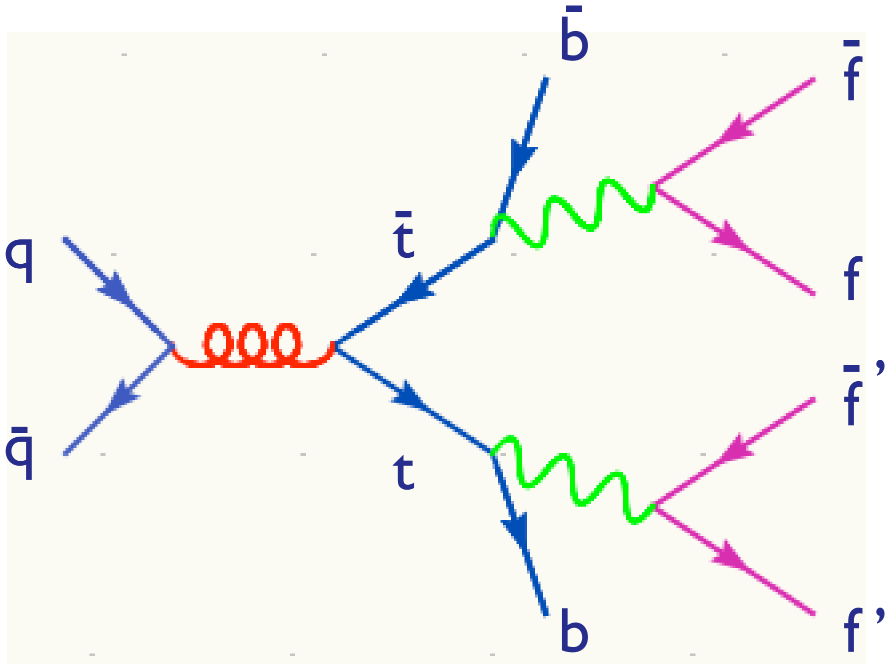
Center for Particle Physics and Phenomenology
Université Catholique de Louvain

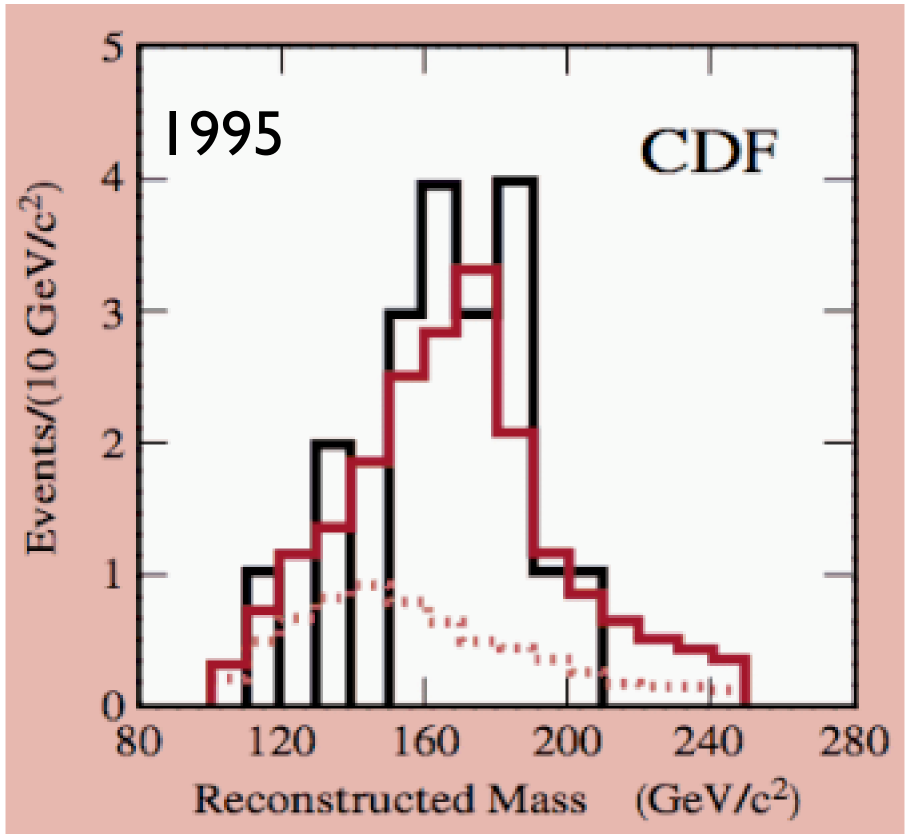
How are we going to discover SUSY?



Heavy states decaying in jets and leptons and $\not{E}_T$.

A lesson from the top





How did it go?

0. The only unknown was the top mass!

1. The experimentally easiest channel for triggering/ reconstruction/background-control was chosen.

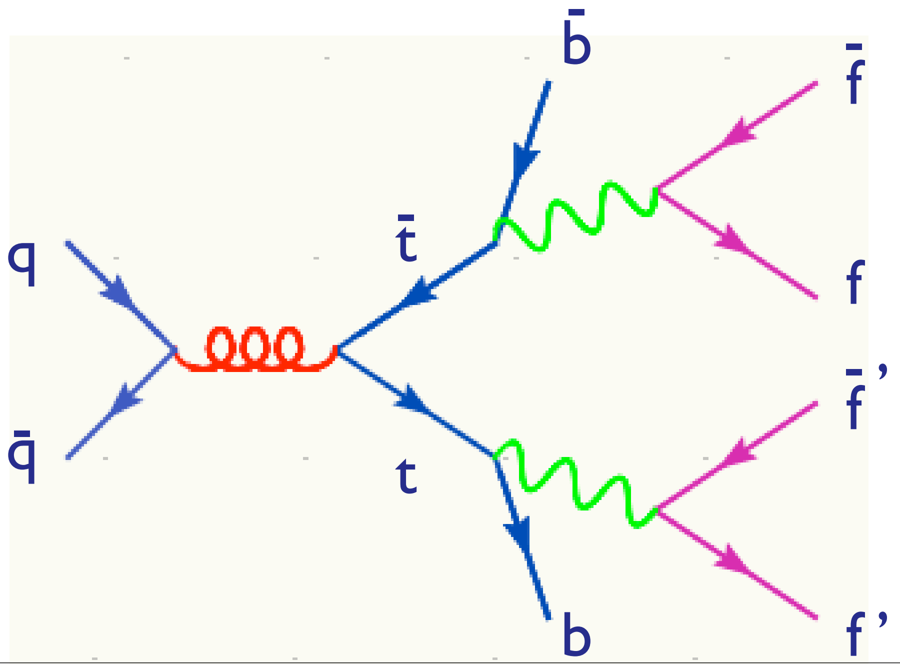
2. Mass reconstruction employed

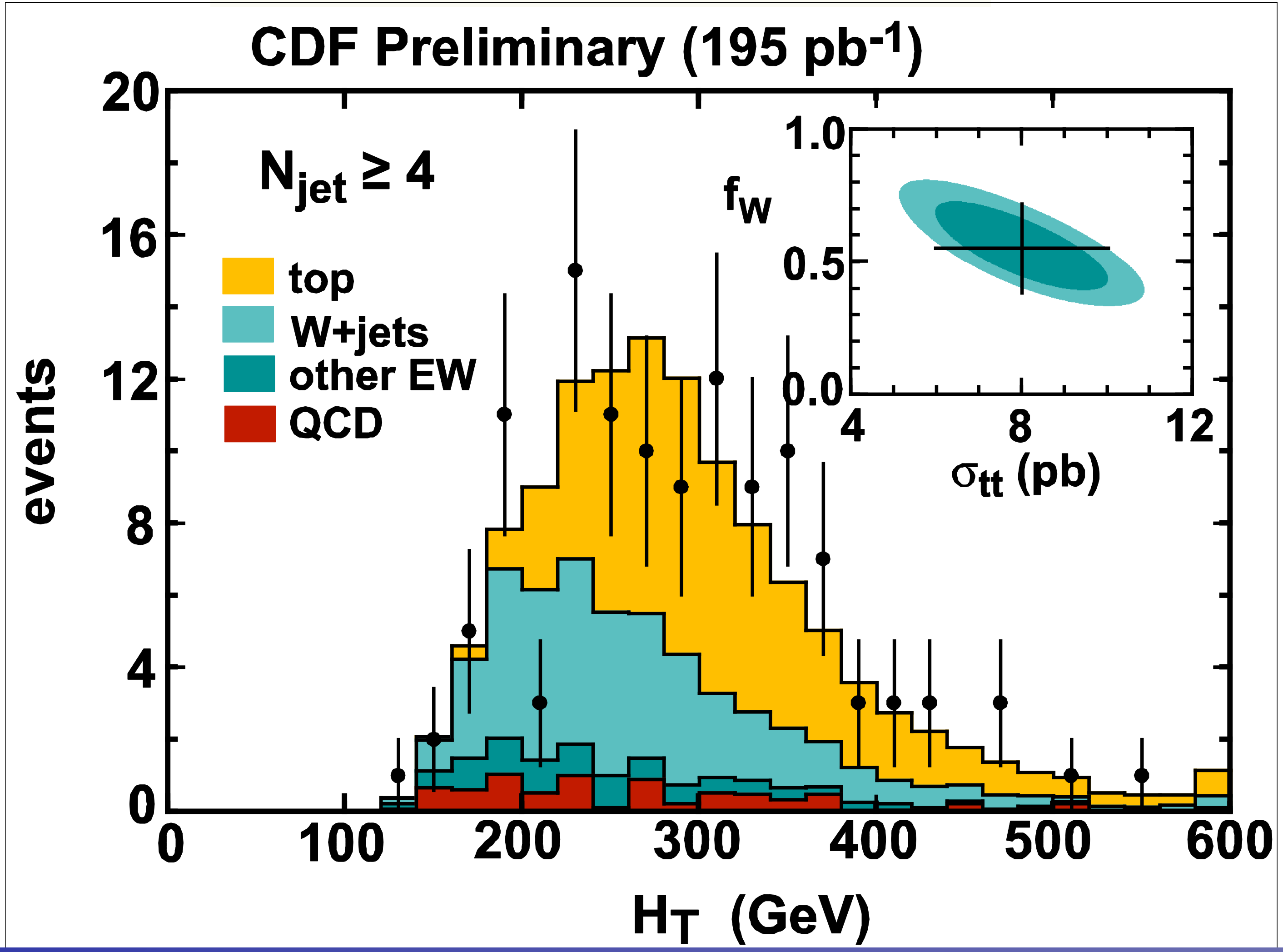
3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio’s.

4. Number of events consistent with the cross section expectation from QCD

Handful of events was enough!

A lesson from the top





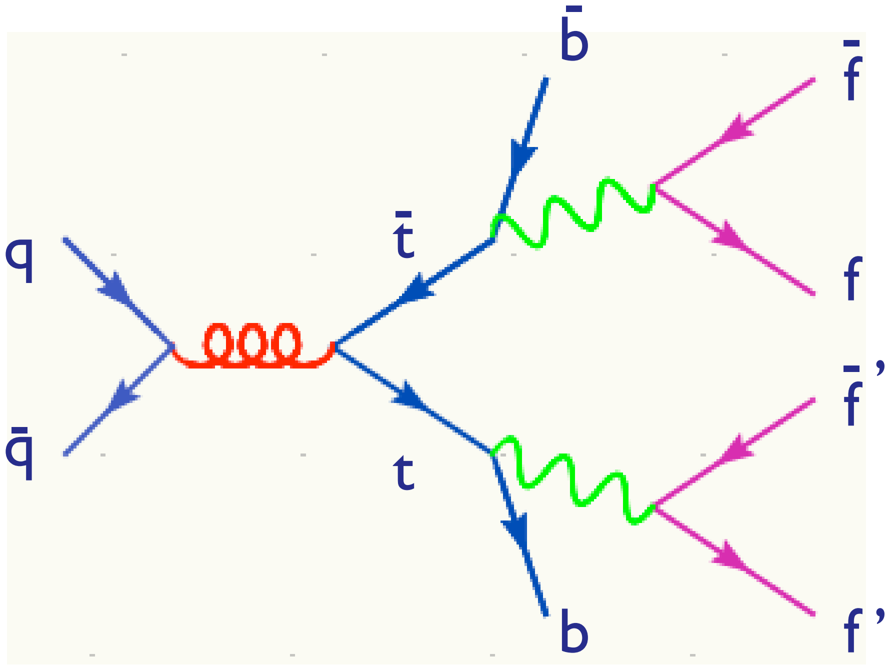
Immediately confirmed in Run II, also by the most inclusive measurements, H_T.

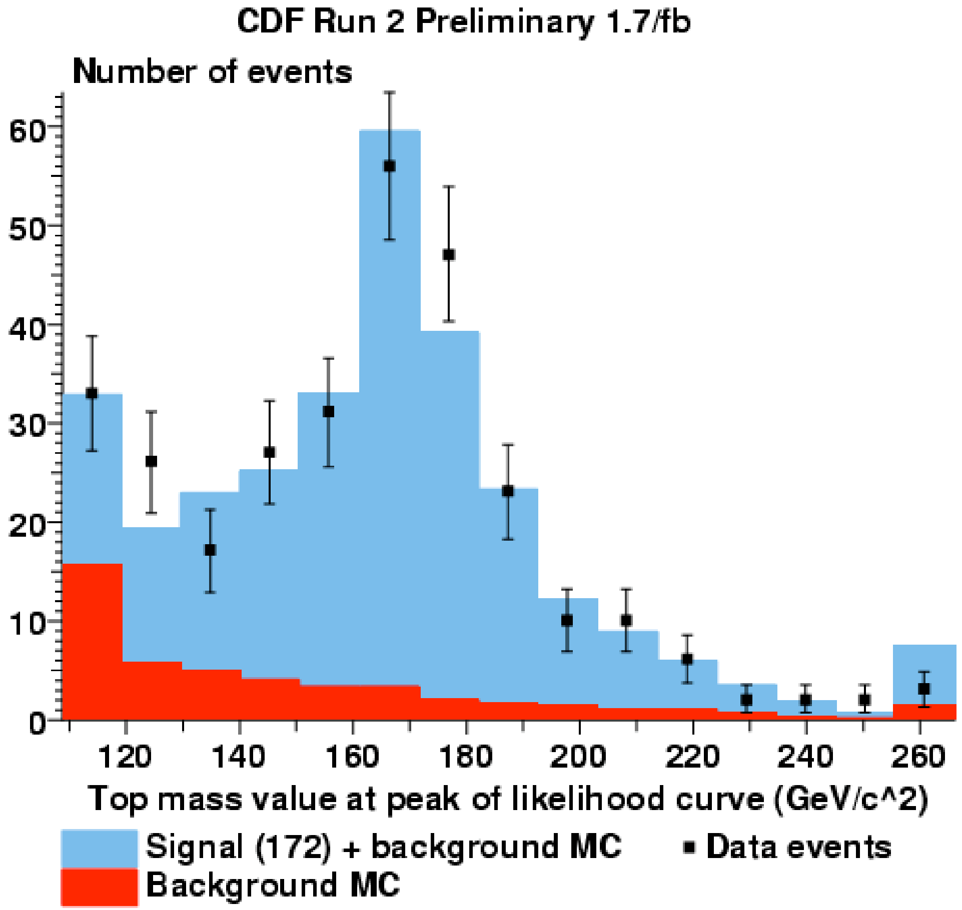
Other channels start to be considered as the statistics increases to have a consistent picture.

Cleaner and cleaner samples more exclusive studies:

1. W Polarization
2. BR’s ratio’s
3. Top Quark charge
4. Differential m_{tt} distribution
5. Search for new physics!!

A lesson from the top





Summary:

1. More than15-year long story

2. At all stages MC’s played a role.

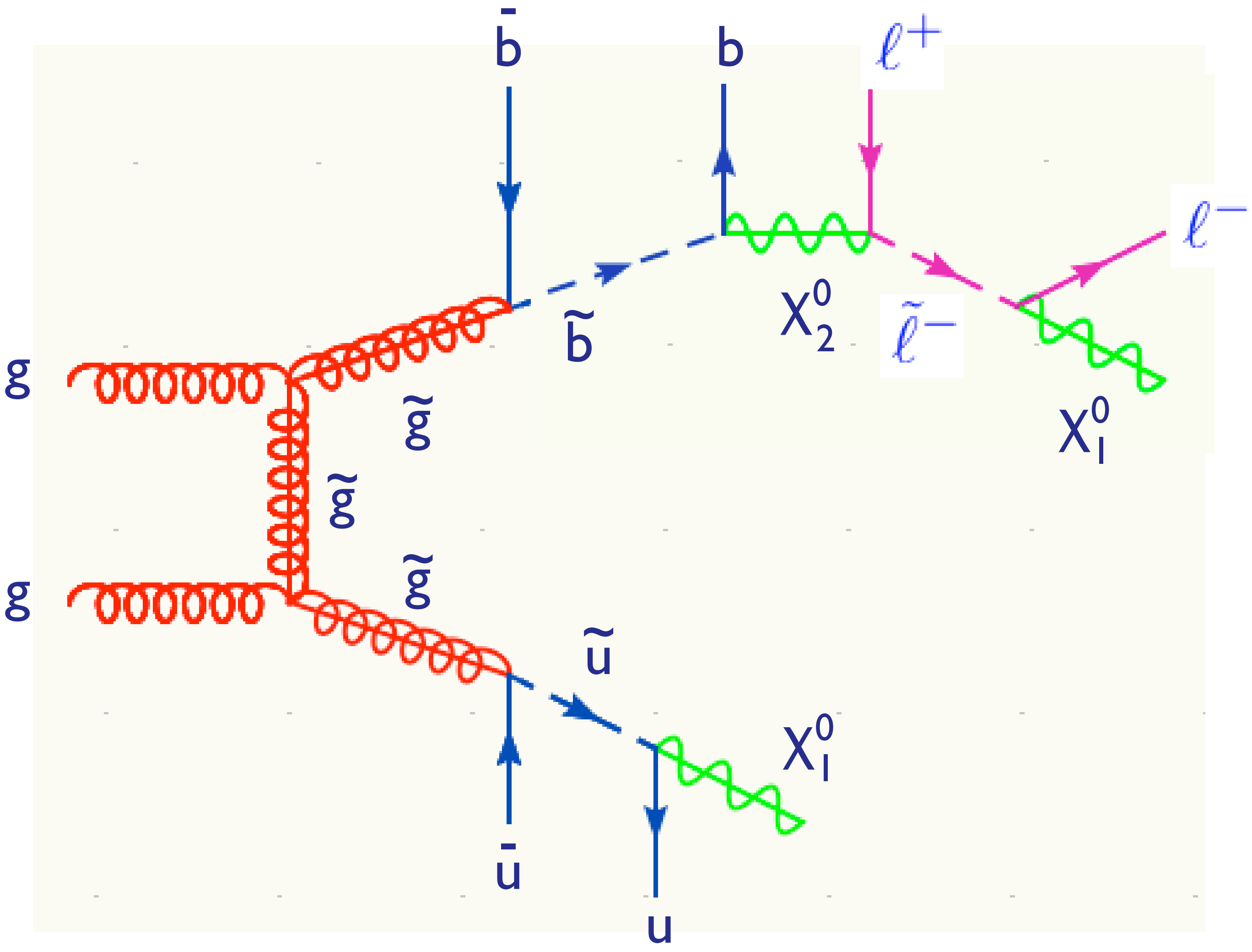
3. Now all studies, including the mass measurements, are strongly based on our simulation tools, i.e., matrix element methods.

More sophisticated analysis need more sophisticated MC’s...

Is this strategy directly applicable to new heavy state searches?

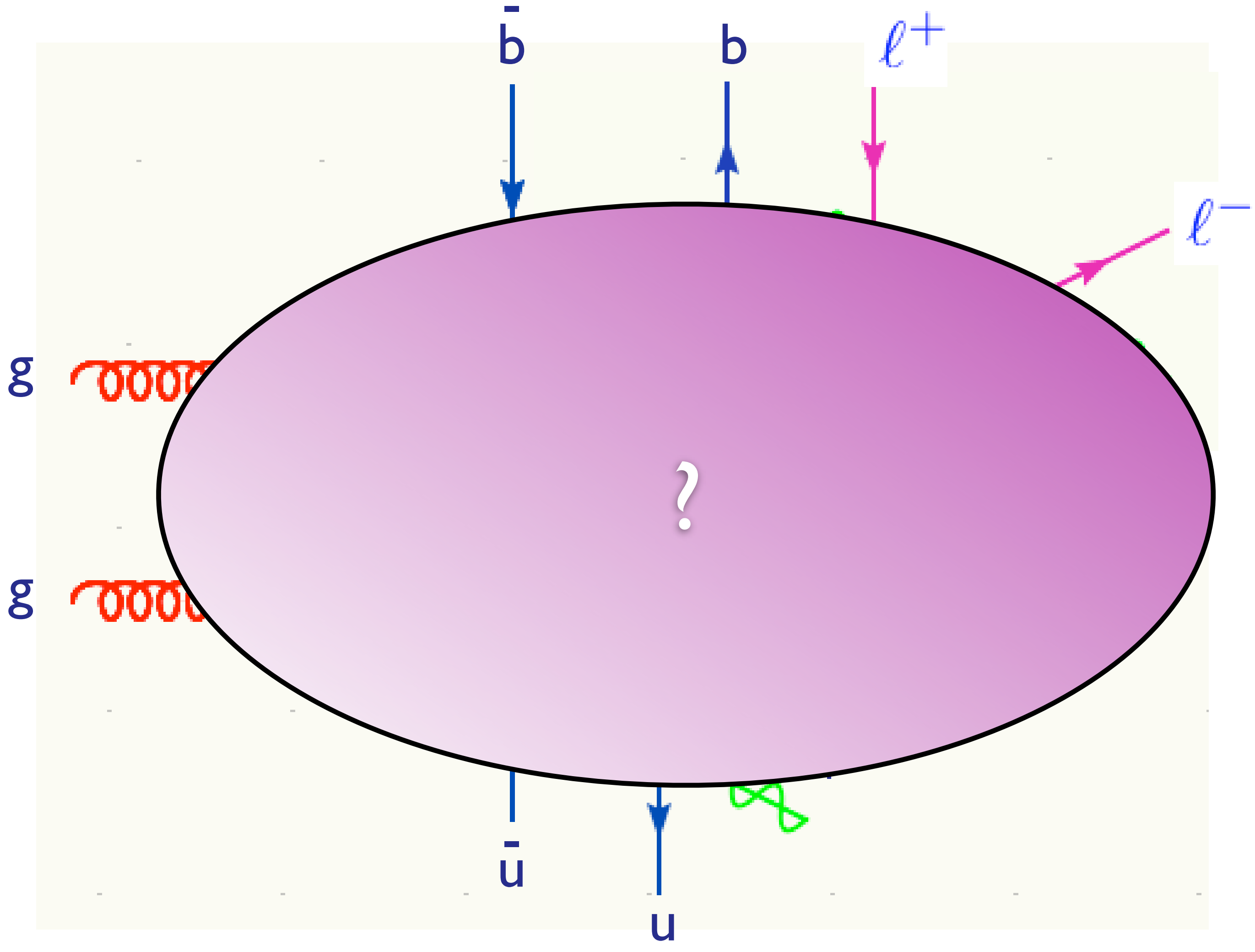
A lesson from the top

Susy inclusive searches are similar but more complicated final states.



A lesson from the top

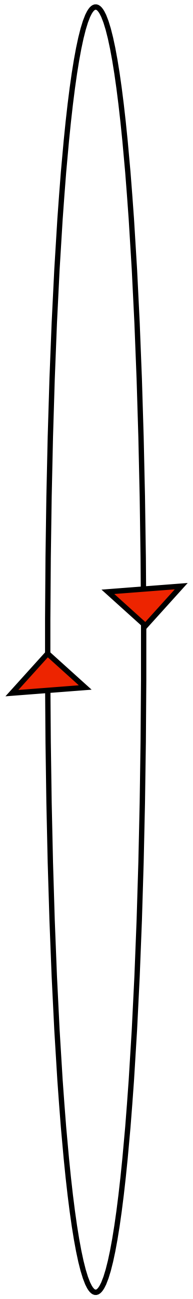
Susy inclusive searches are similar but more complicated final states.



The main difference is that we don't know what to expect!!

A minimal strategy for BSM & Tools

1. Find excess(es) over SM backgrounds

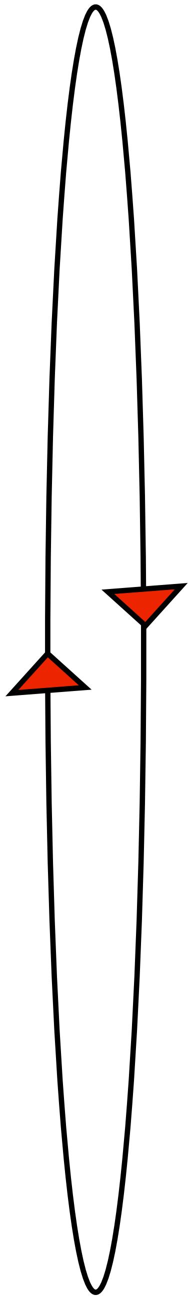


Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t)

Flexible MC to be validated and tuned to control samples.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

A minimal strategy for BSM & Tools



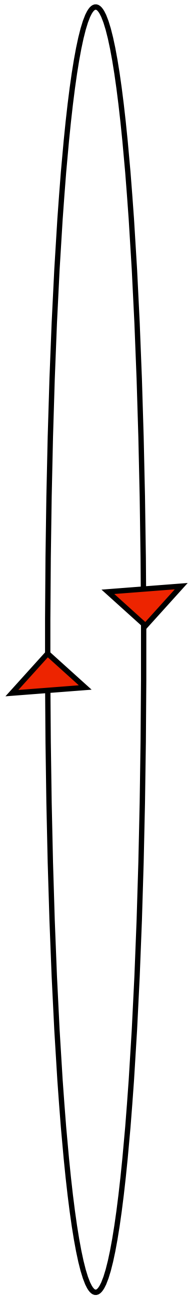
1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t)
Flexible MC to be validated and tuned to control samples.
Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).

Inverse problem tools (Ex: OSET)

A minimal strategy for BSM & Tools



1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t)

Flexible MC to be validated and tuned to control samples.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

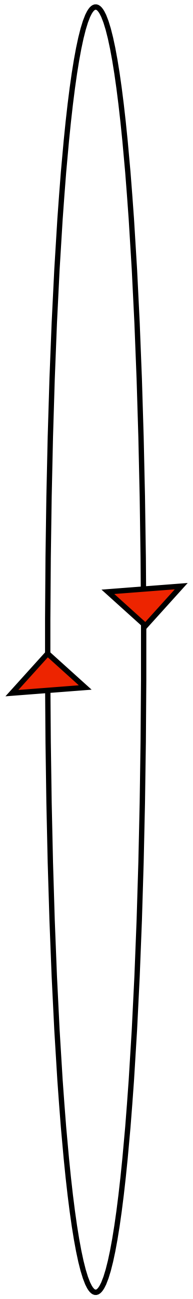
2. Identify a finite set of coarse models compatible with the excess(es).

Inverse problem tools (Ex: OSET)

3. Look for "predicted excesses" in other channels.

Simulation of any BSM signature: from models to events in an easy and fast way.

A minimal strategy for BSM & Tools



1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t).

Flexible MC to be validated and tuned to control samples.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).

Inverse problem tools (Ex: OSET)

3. Look for "predicted excesses" in other channels.

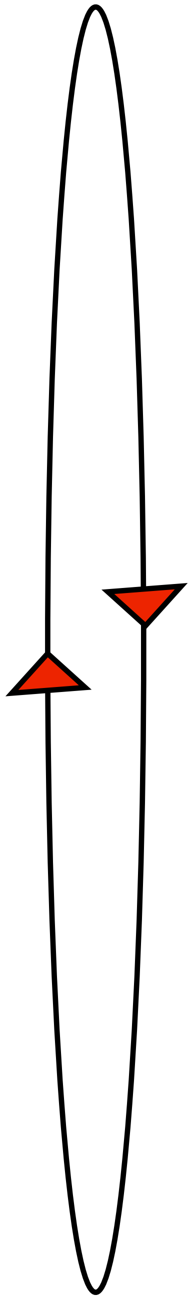
Simulation of any BSM signature: from models to events in an easy and fast way.

4. Refine

Accurate predictions for cross sections of selected models (Ex: SUSY) to identify couplings.

Accurate predictions for primary couplings (Ex: spectra calculators).

A minimal strategy for BSM & Tools



1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t).
Flexible MC to be validated and tuned to control samples.
Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).

Inverse problem tools (Ex: OSET)

3. Look for "predicted excesses" in other channels.

Simulation of any BSM signature: from models to events in an easy and fast way.

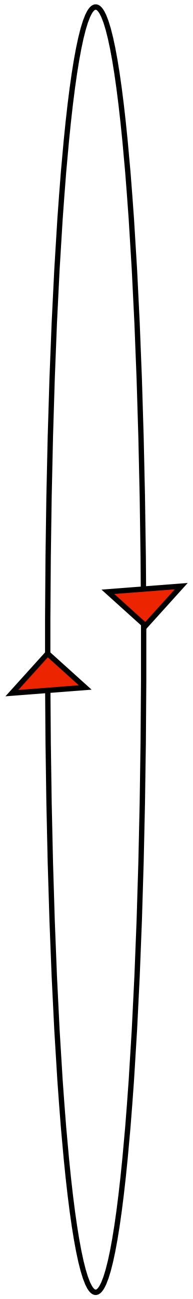
4. Refine

Accurate predictions for cross sections of selected models (Ex: SUSY) to identify couplings.
Accurate predictions for primary couplings (Ex: spectra calculators).

5. Perform more detailed studies to measure mass spectrum, quantum numbers, couplings.

Accurate ME based description for final state distributions which keeps all
the relevant information (Ex. decay chain with spin).

A minimal strategy for BSM & Tools



1. Find excess(es) over SM backgrounds
Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD particles (W,Z, photon,b,t).
Flexible MC to be validated and tuned to control samples.
Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).
Inverse problem tools (Ex: OSET)

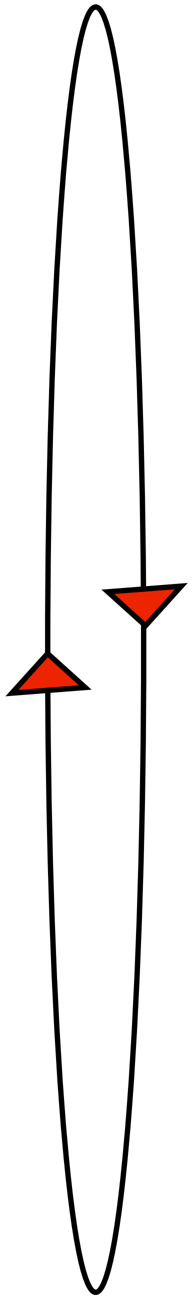
3. Look for "predicted excesses" in other channels.
Simulation of any BSM signature: from models to events in an easy and fast way.

4. Refine
Accurate predictions for cross sections of selected models (Ex: SUSY) to identify couplings.
Accurate predictions for primary couplings (Ex: spectra calculators).

5. Perform more detailed studies to measure mass spectrum, quantum numbers, couplings.
Accurate ME based description for final state distributions which keeps all the relevant information (Ex. decay chain with spin).

6. Refine
Off-shell effects, Matrix Element methods, Global fits (Ex: Sfitter)

What will be needed from TH?



1. Find excess(es) over SM backgrounds

Fully exclusive description for rich and energetic final states (multi-jets + EW and QCD part. (W,Z, photon,b,t)).

Flexible MC to be validated and tuned to control samples.

Accurate predictions (NLO,NNLO) for standard candles SM cross sections (with final state acceptance)

2. Identify a finite set of coarse models compatible with the excess(es).

Model building skills. Inverse problem tools (Ex: OSET).

3. Look for “predicted excesses” in other channels.

Simulation of any BSM signature: from models to events in an easy and fast way.

4. Refine

Accurate predictions for cross sections of selected models (Ex: SUSY) to identify couplings.

Accurate predictions for primary couplings (Ex: spectra calculators).

5. Perform more detailed studies to measure mass spectrum, quantum numbers, couplings.

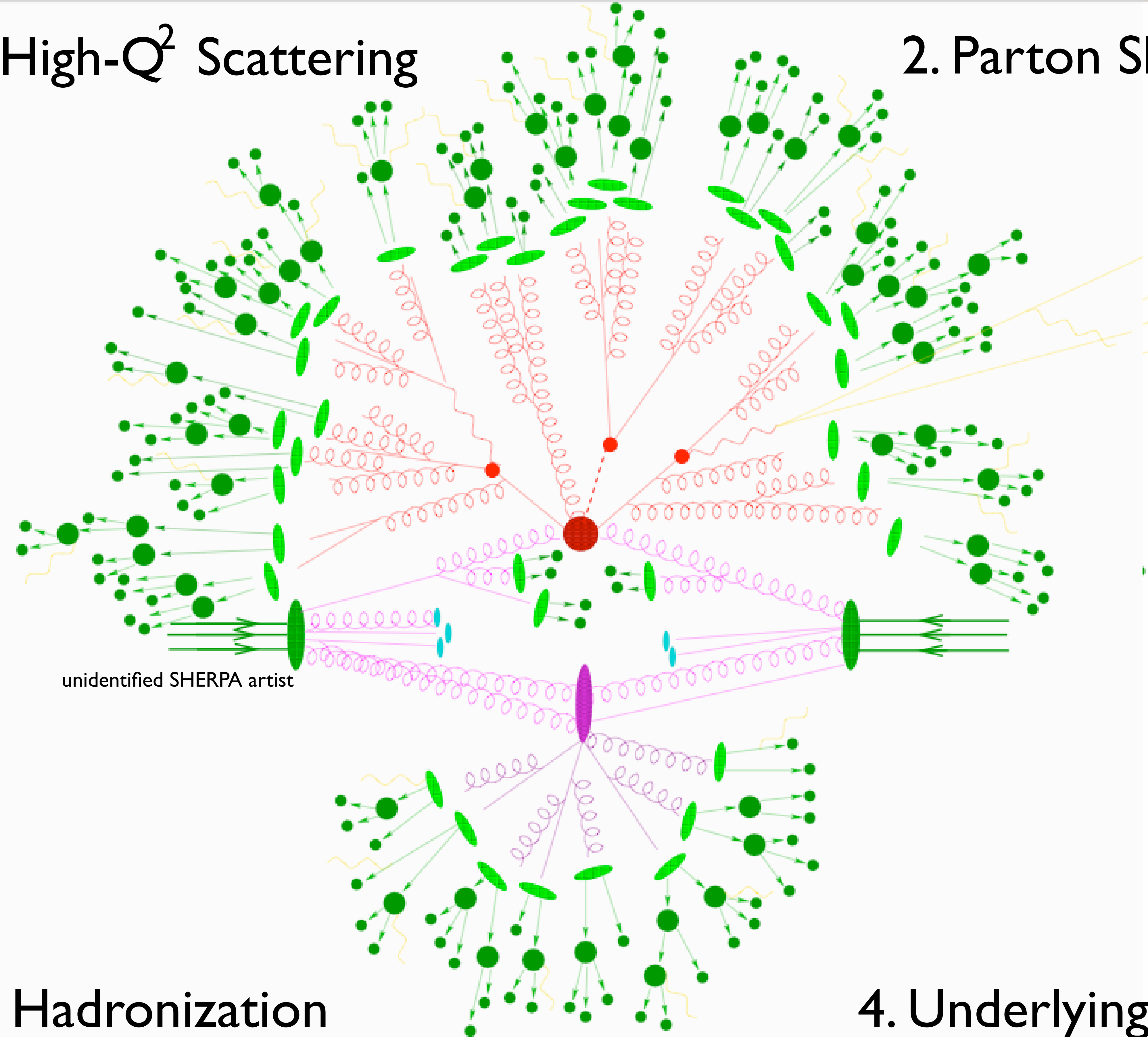
Accurate ME based description for final state distributions which keeps all the relevant information (Ex. decay chain with spin).

6. Refine

Off-shell effects, Matrix Element methods, Global fits (Ex: Sfitter)

Outline

- Matrix elements + Parton showers
- Matrix elements for BSM physics
- BSM at NLO
- Decay chains



1. High-Q^2 Scattering

2. Parton Shower

unidentified SHERPA artist

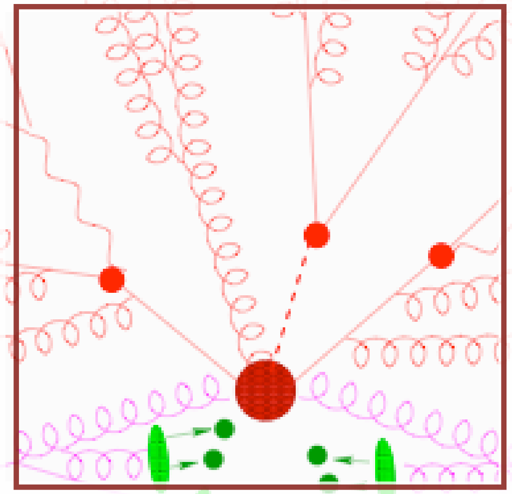
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



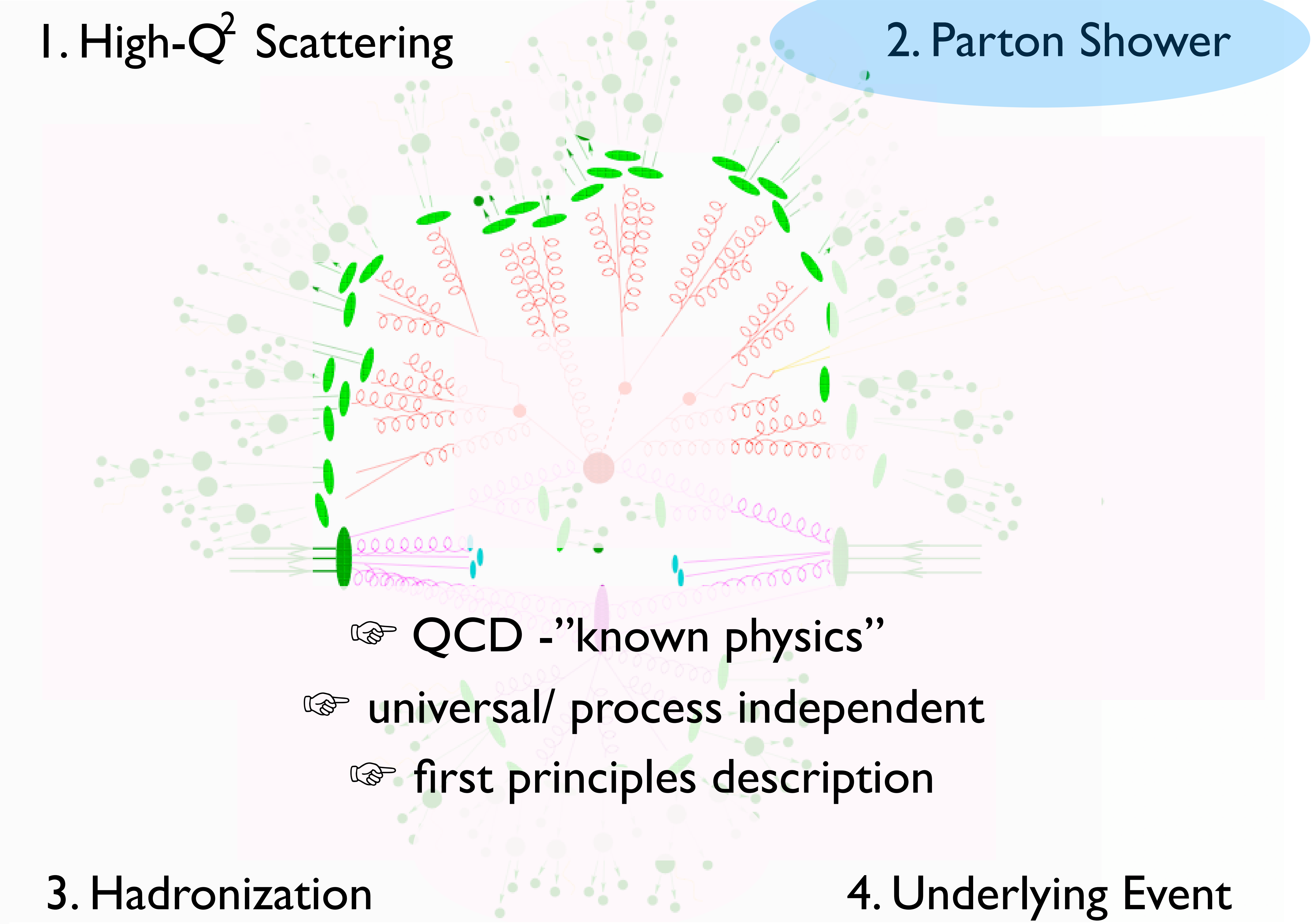
☞ process dependent

☞ first principles description

☞ it can be systematically improved

3. Hadronization

4. Underlying Event



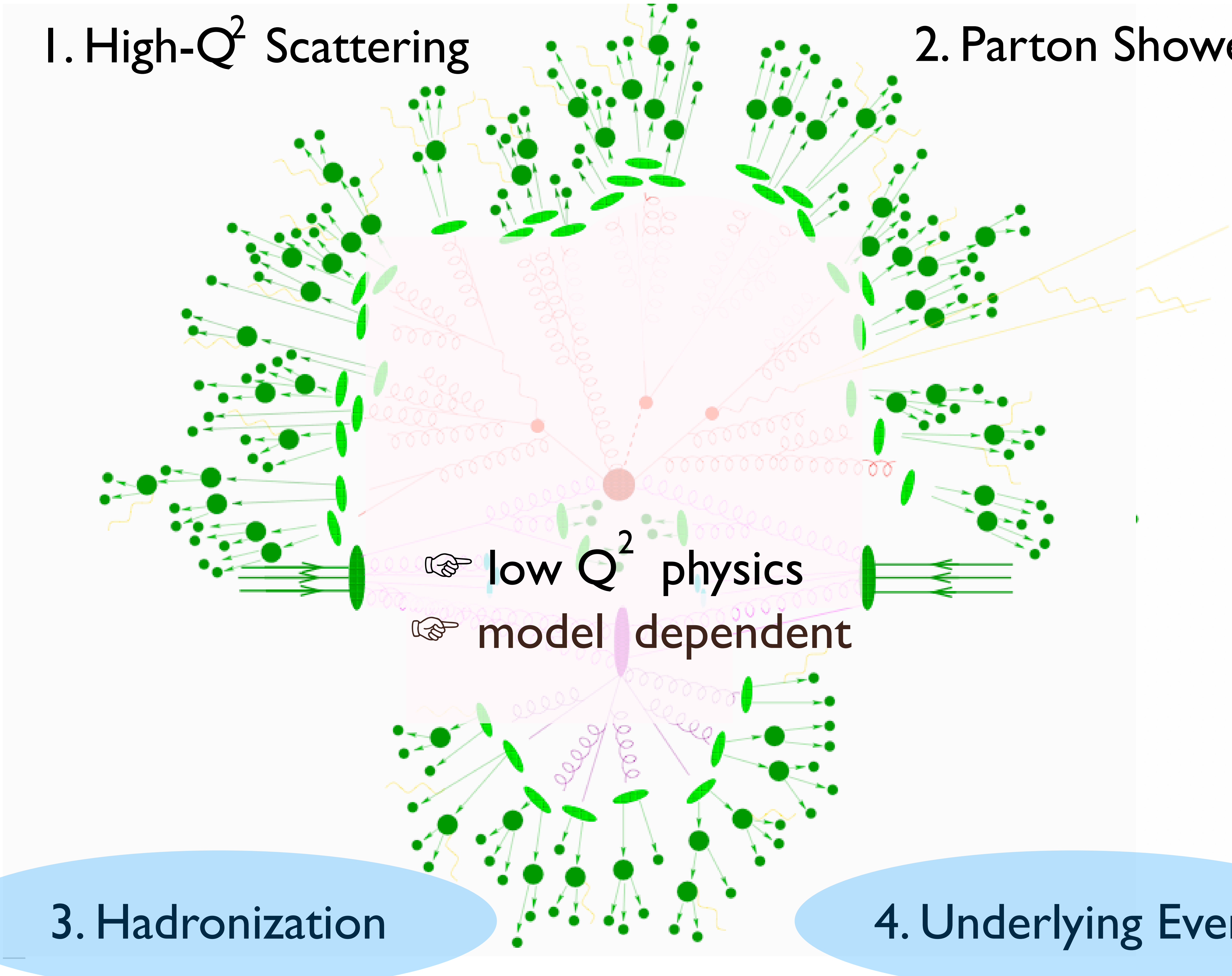
1. High-Q^2 Scattering

2. Parton Shower

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

3. Hadronization

4. Underlying Event



1. High-Q^2 Scattering

2. Parton Shower

☞ low Q^2 physics

☞ model dependent

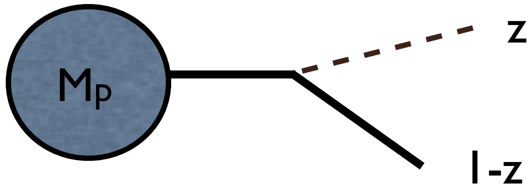
3. Hadronization

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

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.
- Significant and intense progress in the development of new showering algorithms with the final aim to go at NLO in QCD

  [Giele, Kosower, Skands, 2007; Krauss, Schumman, 2007]

most famous: PYTHIA, HERWIG
recent addition: SHERPA

Parton Shower MC event generators

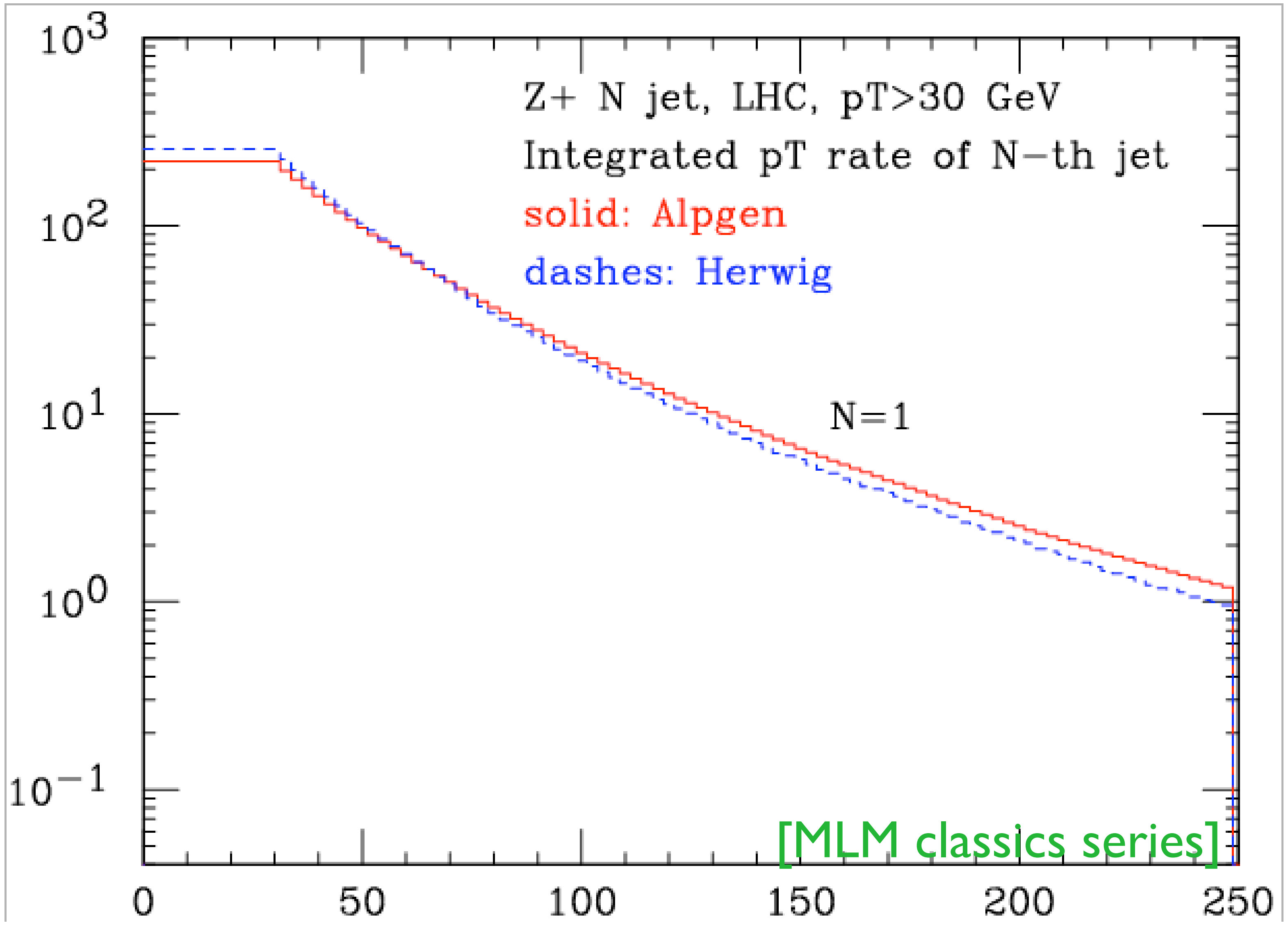
Two major limitations:

- Author's driven and limited library of processes in SM and some extensions including MSSM.
- Multi-parton processes are not well simulated.

Parton Shower MC event generators

Two major limitations:

- Author’s driven and limited library of processes in SM and some extensions including MSSM.
- Multi-parton processes are not well simulated.

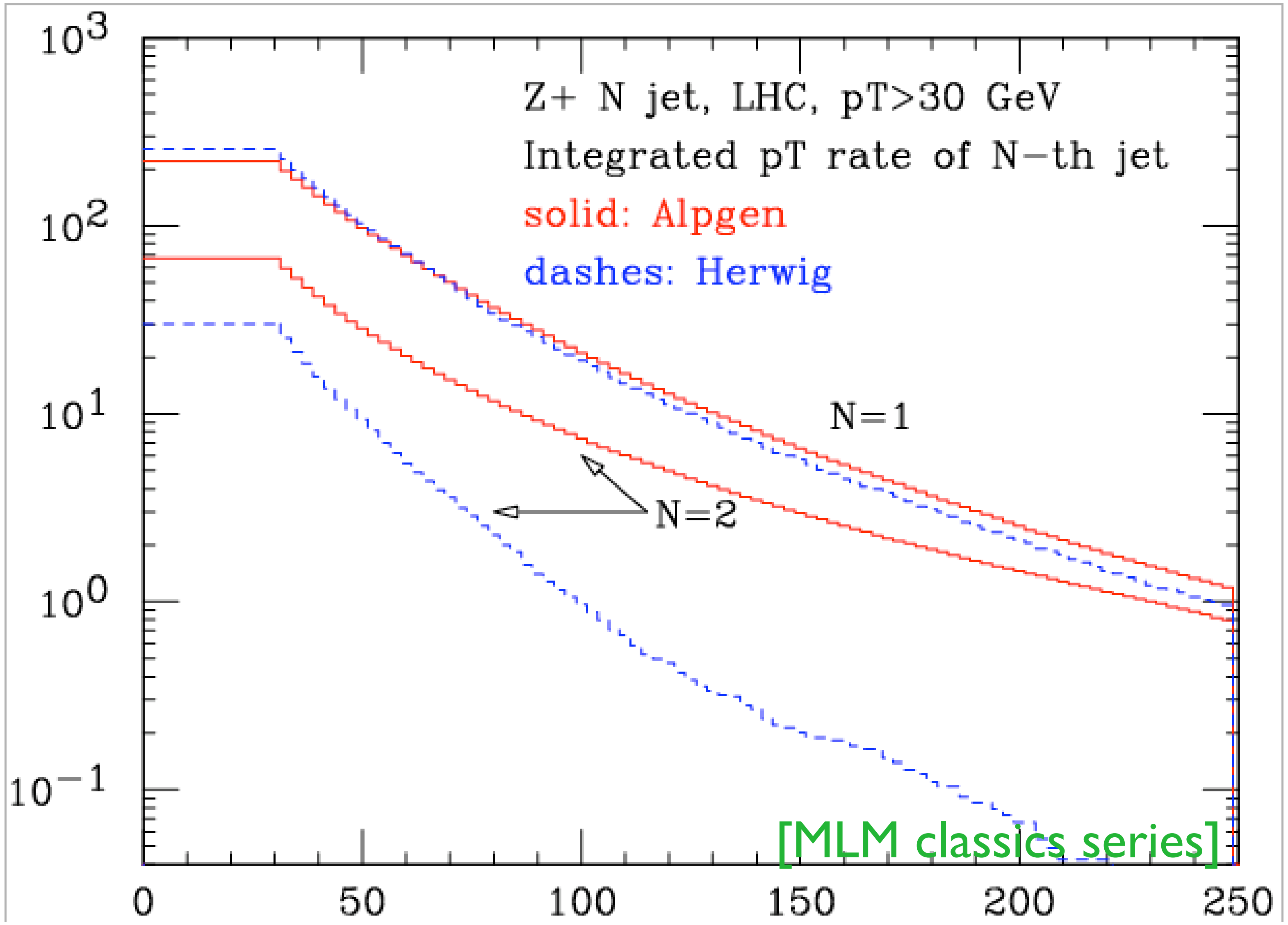


[MLM classics series]

Parton Shower MC event generators

Two major limitations:

- Author’s driven and limited library of processes in SM and some extensions including MSSM.
- Multi-parton processes are not well simulated.

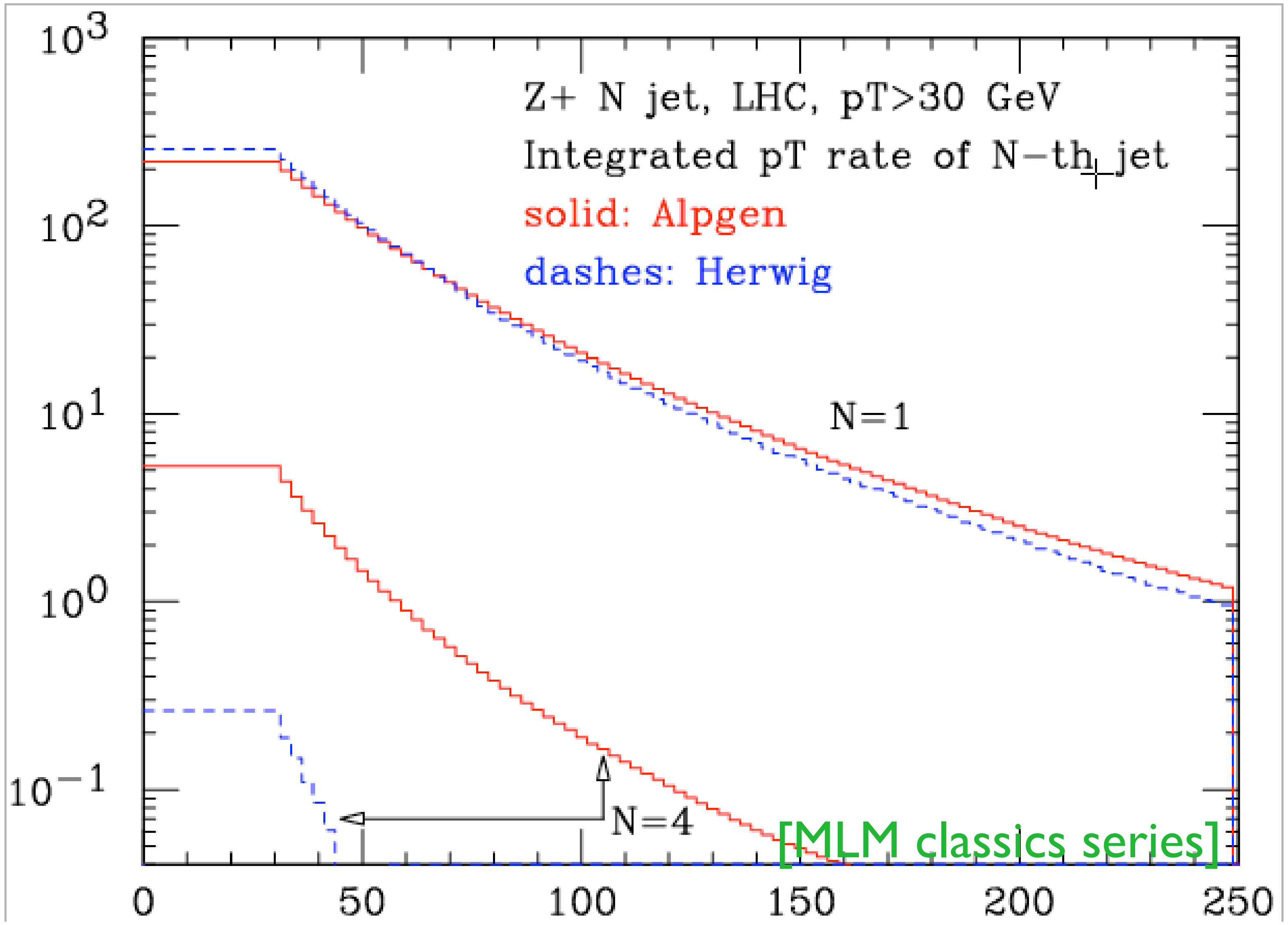


[MLM classics series]

Parton Shower MC event generators

Two major limitations:

- Author’s driven and limited library of processes in SM and some extensions including MSSM.
- Multi-parton processes are not well simulated.



[MLM classics series]

Parton Shower MC event generators

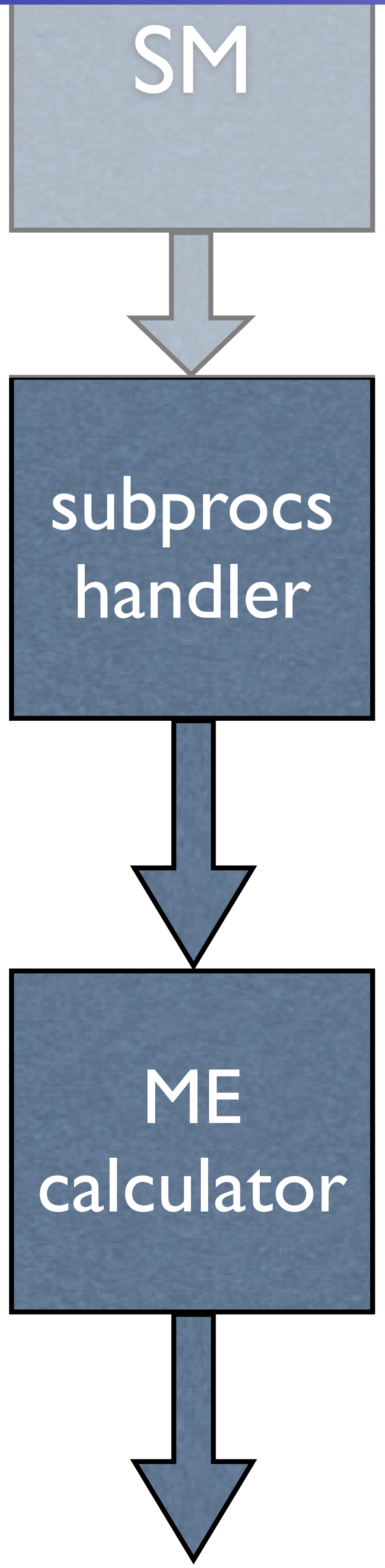
Two major limitations:

- Author’s driven and limited library of 2→2 processes in SM and some extensions including MSSM.
- Multi-parton processes are not well simulated.

The matrix element copernican revolution! [2001]

1. Outsource parton-level event generation to multi-purpose automatic matrix element codes
2. Pass events to PS in a standard format (Les Houches)
3. Perform a ME/PS merging to obtain accurate inclusive multi-jet samples (CKKW or MLM)

General structure

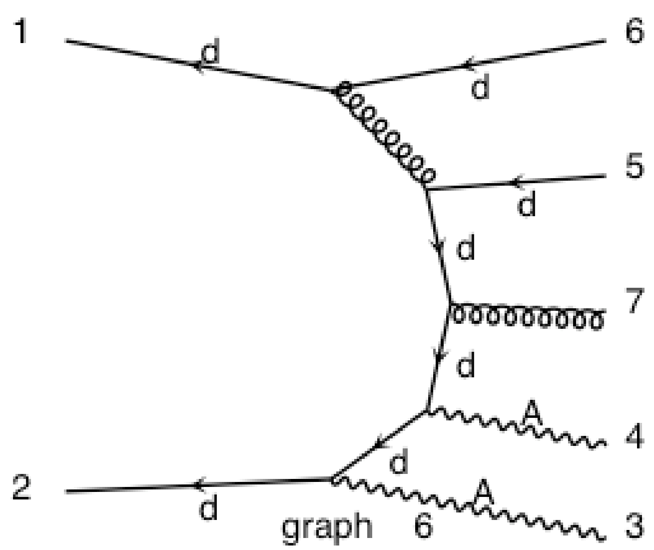


Includes all possible subprocess leading to a given multi-jet final state automatically or manually (done once for all)

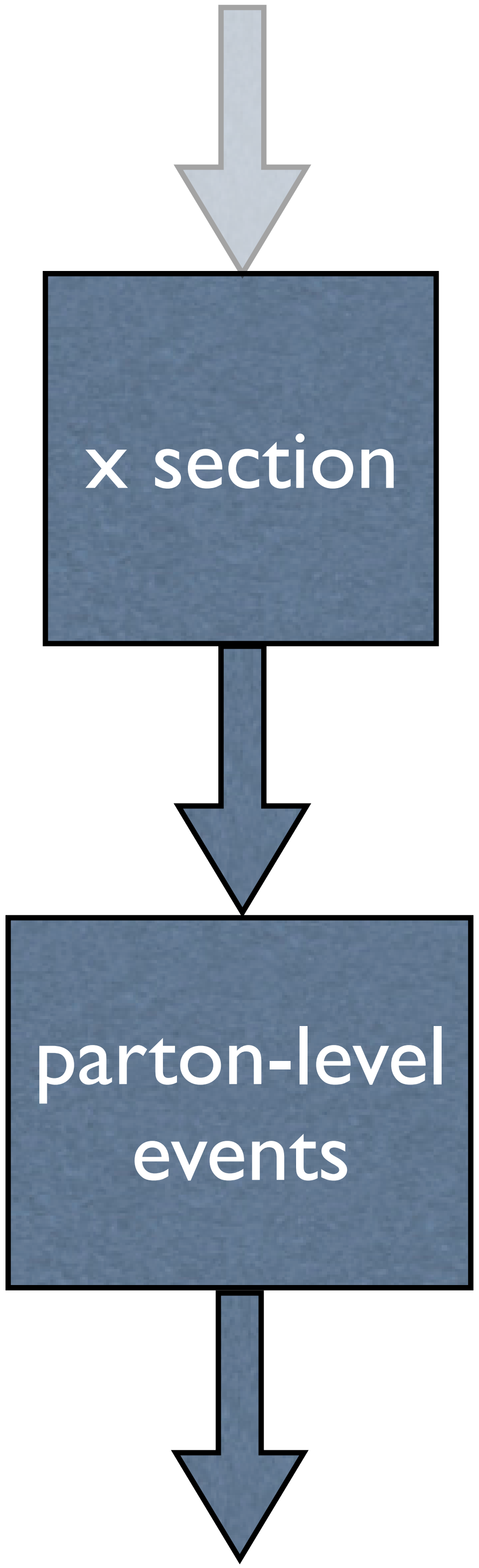
d~ d -> a a u u~ g
d~ d -> a a c c~ g
s~ s -> a a u u~ g
s~ s -> a a c c~ g

<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 [MadGraph, SHERPA], others have recursive relations to reduce the complexity to exponential [Alpgen,HELAC]. New approach from twistors [Comix].



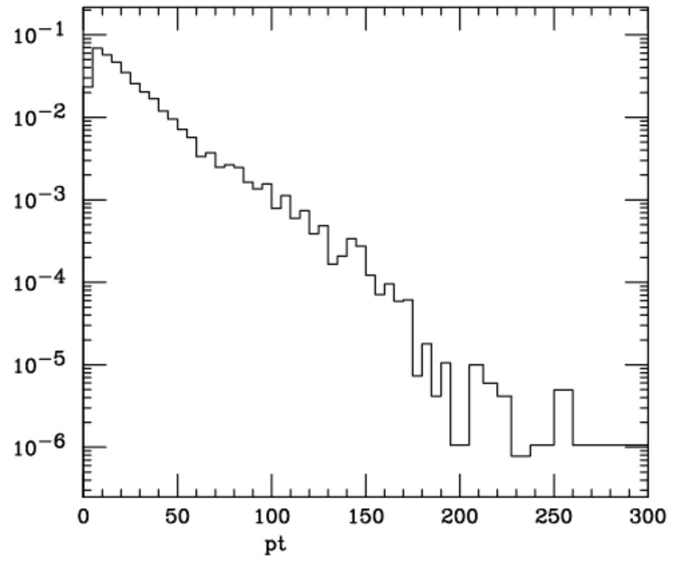
General structure



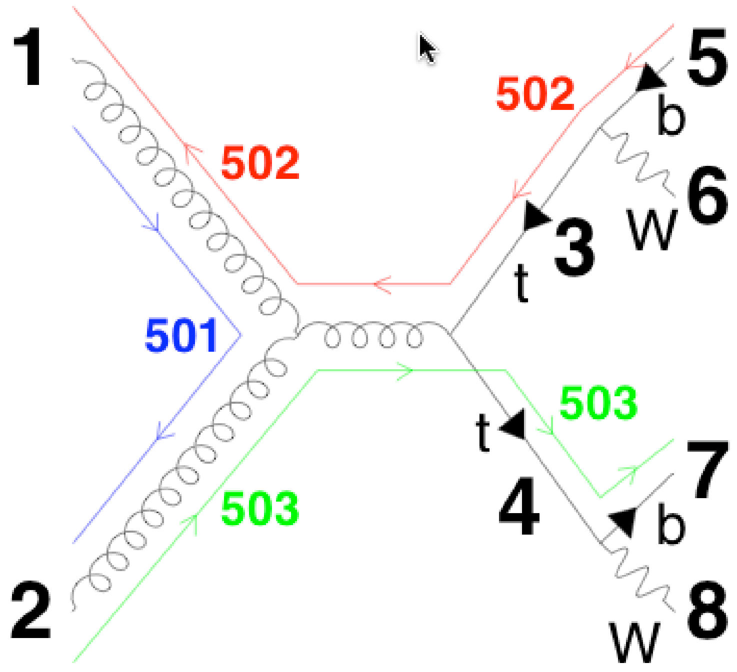
x section

parton-level events

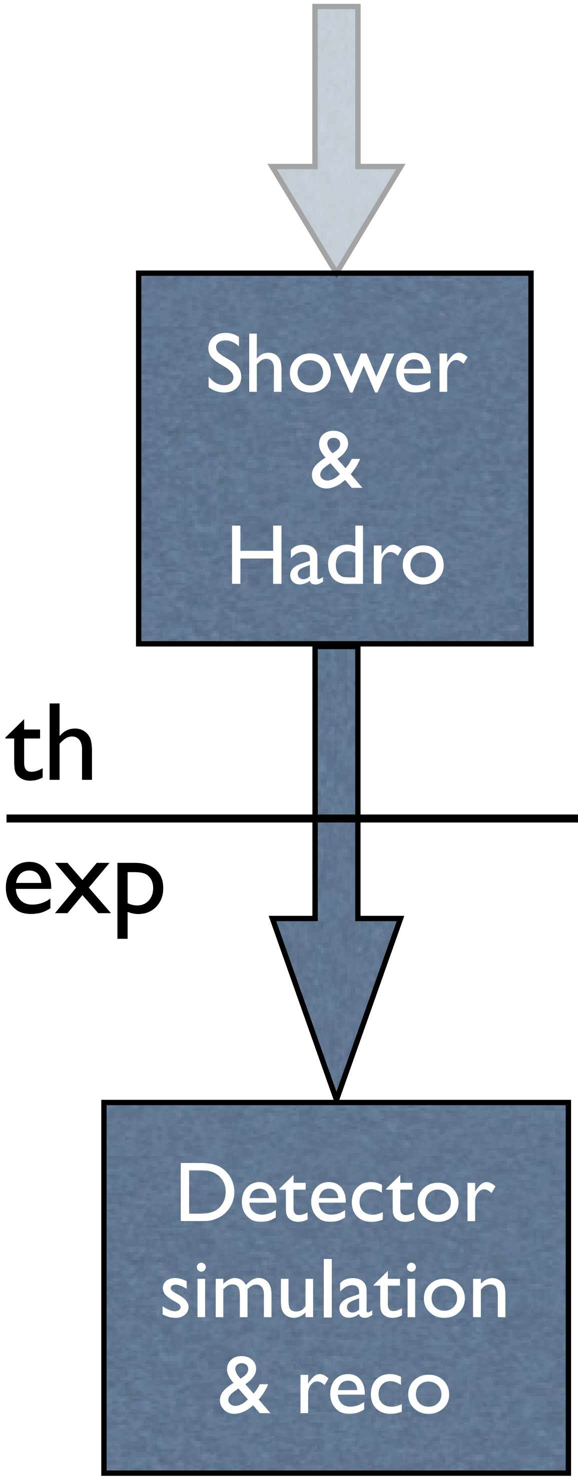
Integrate the matrix element over the phase space using a multi-channel technique and using parton-level cuts.



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.



General structure

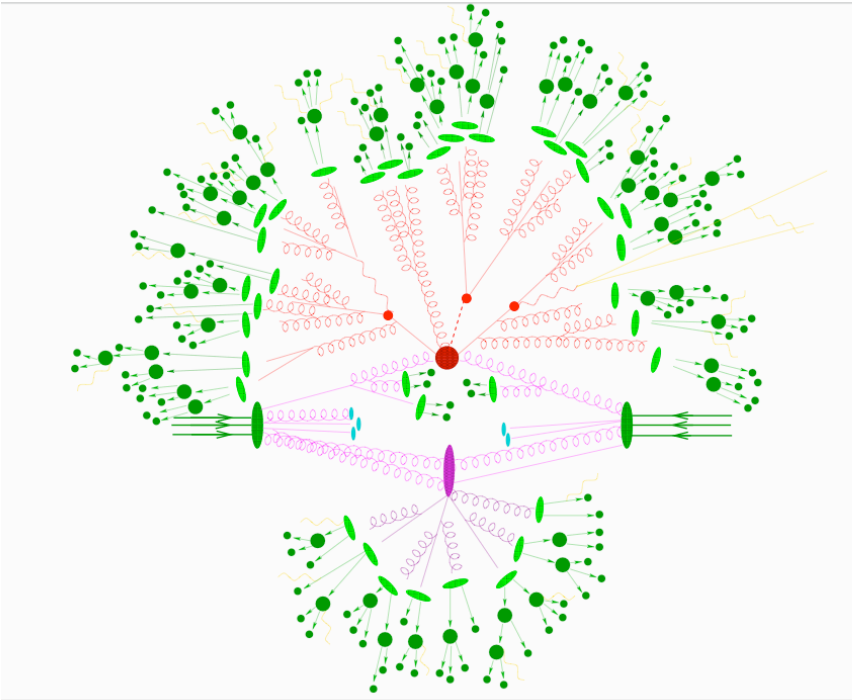


Shower & Hadro

th

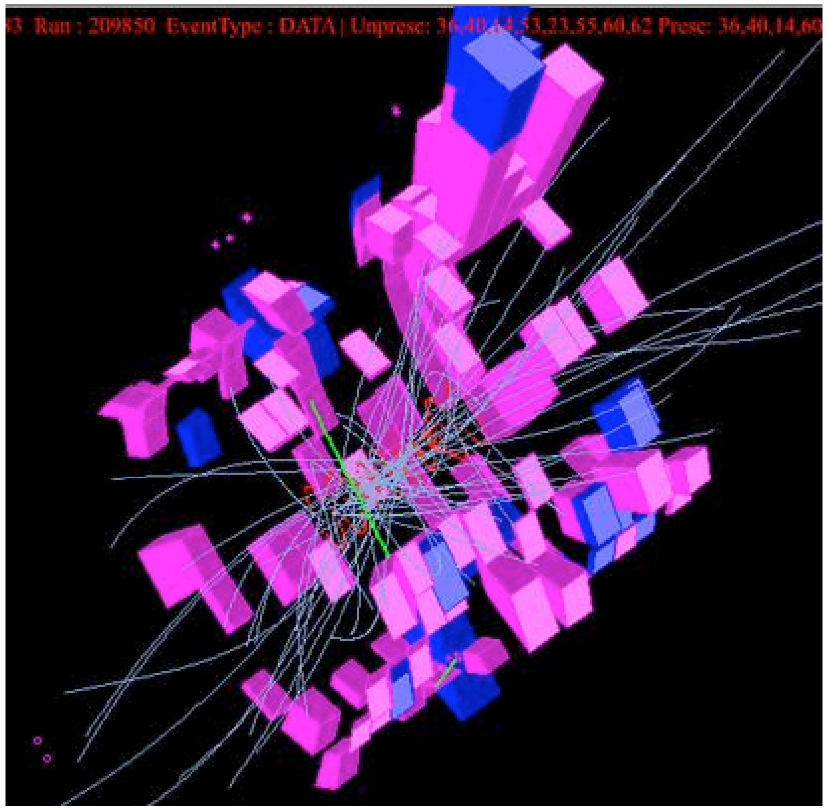
exp

Detector simulation & reco



Events in the LH format are passed to the showering and hadronization⇒

high multiplicity hadron-level events



Events in stdhep format are passed through fast or full simulation, and physical objects (leptons, photons, jet, b-jets, taus) are reconstructed.

New generation of ME based MC's

Multipurpose MC's, matrix element based. Matrix element creation is automatic or semi-automatic at tree level. Matching (when available) performed with the parton shower to produce inclusive multi-jet samples. Some codes are also suitable for BSM physics.

Code	Comments
Alpgen	Extendable library of procs. SM only. Optimized for multi-particle events. ME/PS matching a la MLM.
CompHep/CalcHEP	User's driven. Several models available and easy to insert new ones. No ME/PS matching. Squared amplitudes.
HELAC	User's driven. SM only. ME/PS matching a la MLM.
MadGraph	User's driven. Web based. Several models available and easy to insert new ones. ME/PS matching a la MLM.
SHERPA	User's driven. Several models available. Full showering and hadronization. ME/PS matching a la CKKW.

Updates on Alpgen by Piccinini and on SHERPA by Schumann

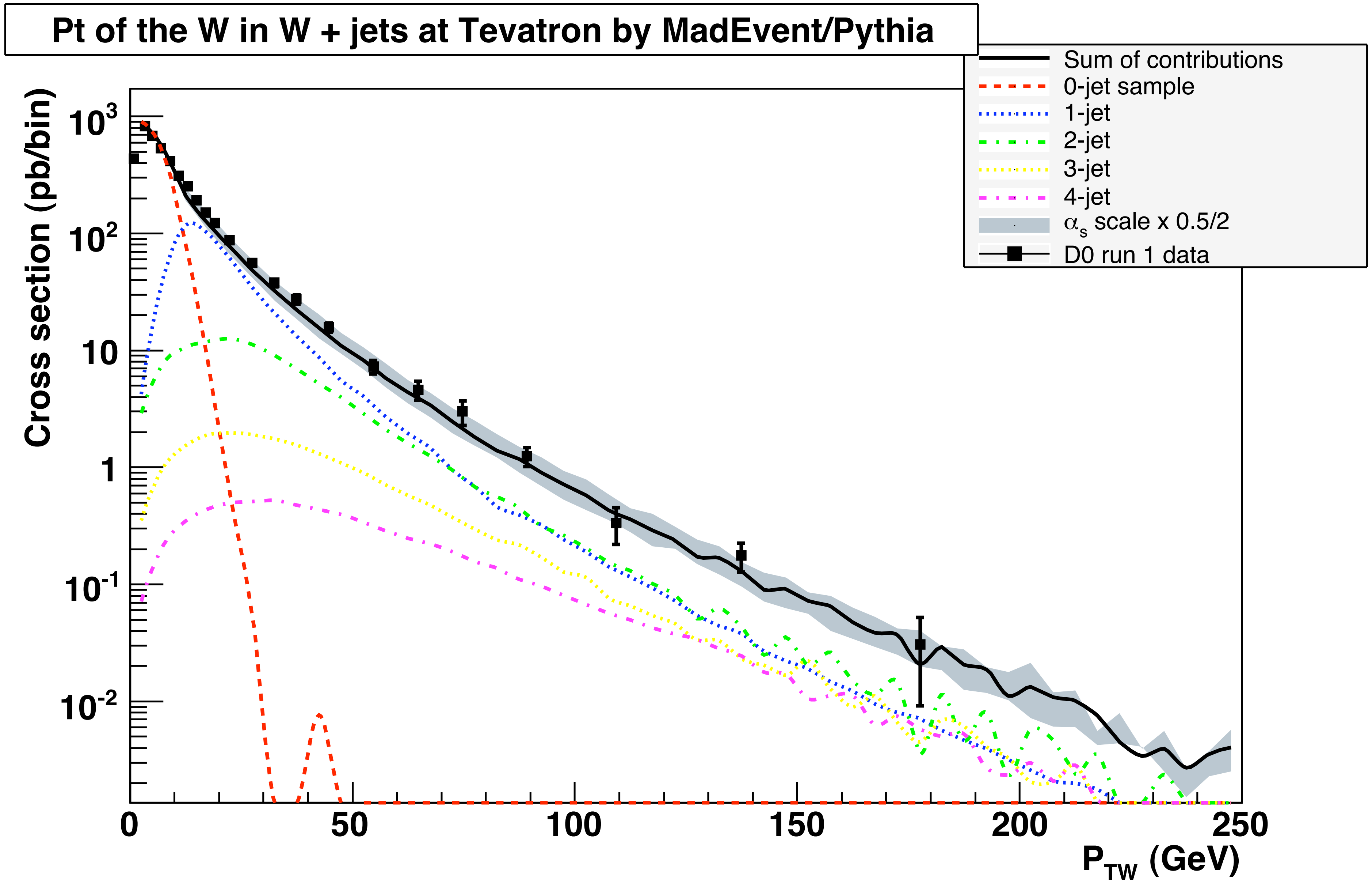
ME/PS merging

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 AA
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

Approaches are complementary!

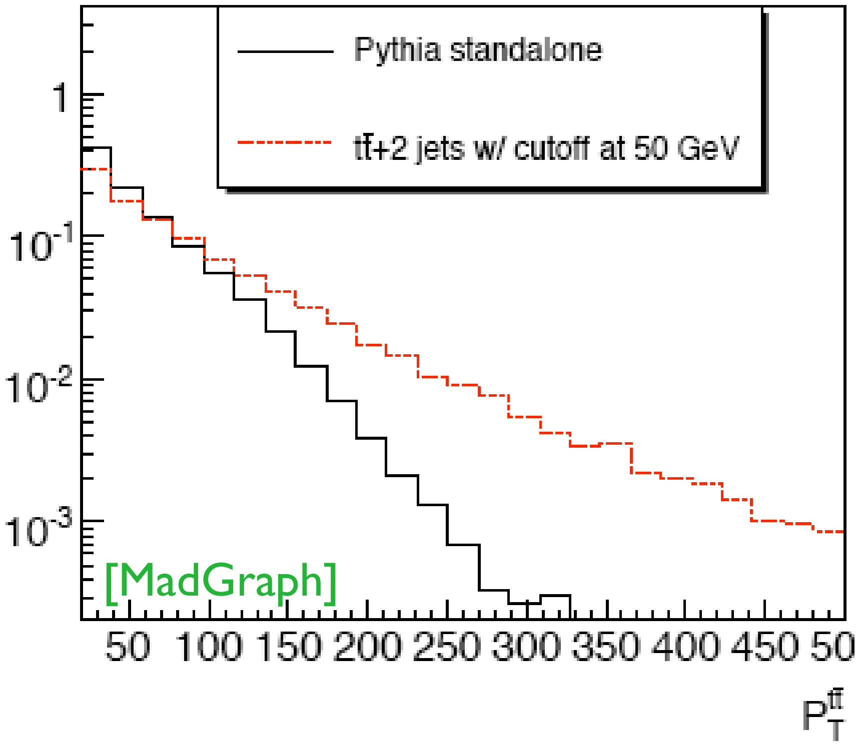
Two recipes available: CKKW and MLM

Matching: results



1. The most inclusive observable.
2. All parton multiplicities contribute.
3. Excellent agreement with TeV data (validation)

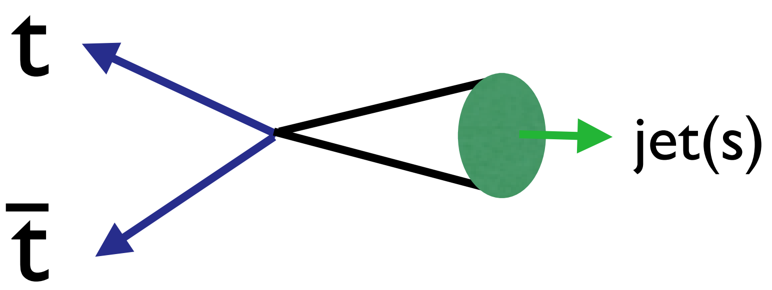
PS alone vs matched samples

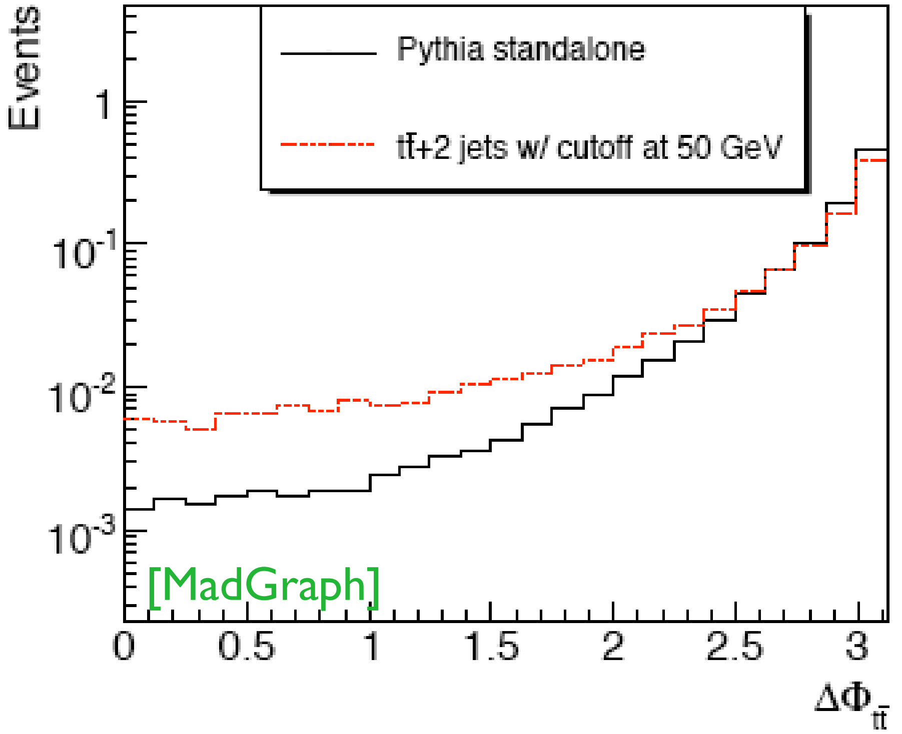


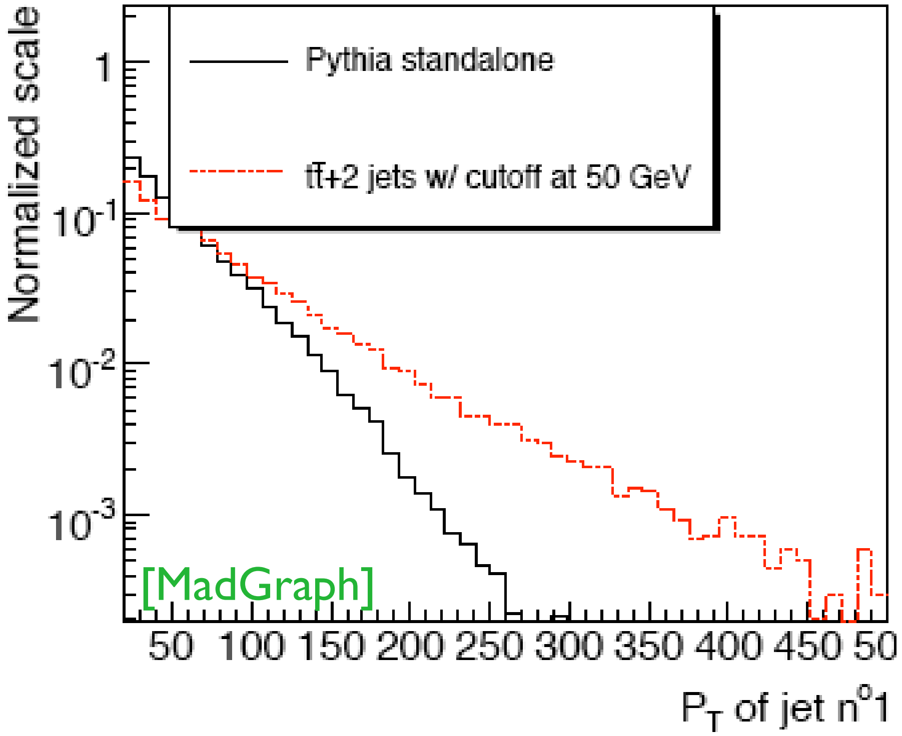
Comparison of key kinematical distributions of extra radiation between:

* t tbar + shower (Pythia)

* matched sample of t tbar + 0,1,2 partons with Qcut=50 GeV

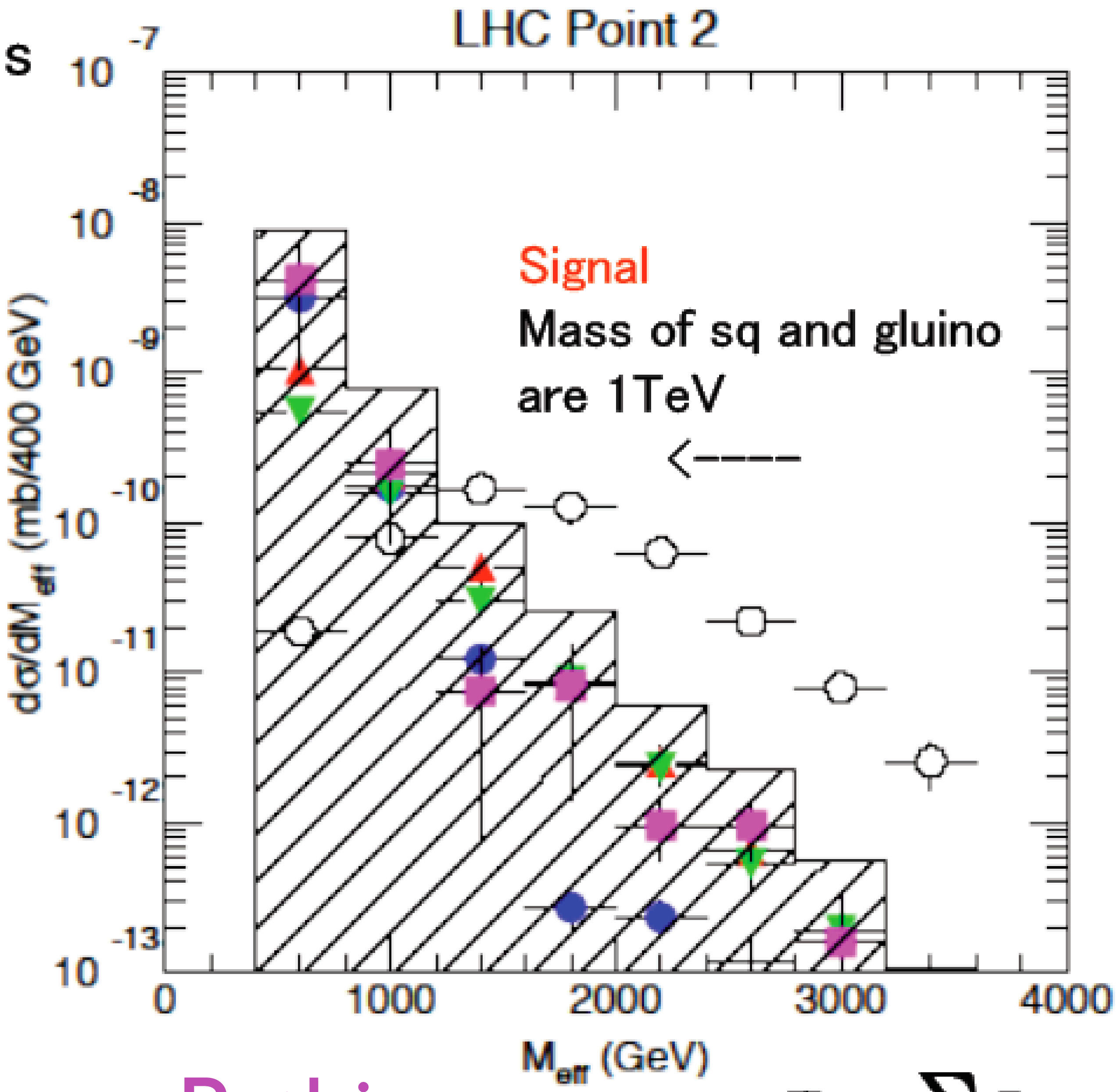






More on tt+jets comparisons and validation in Roberto Chierici's talk on Wed morning!

Inclusive SUSY searches at the LHC



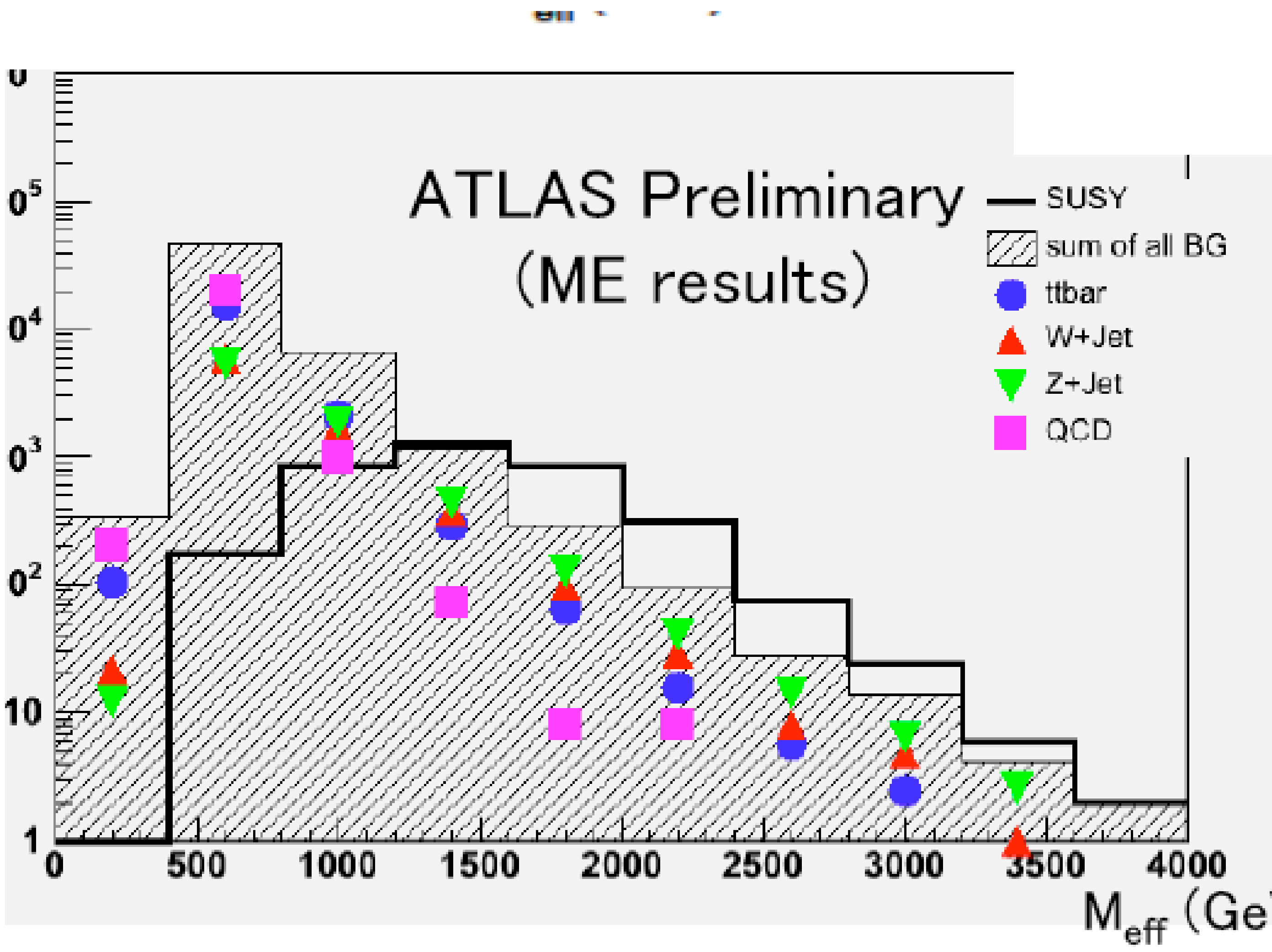
Signal

Mass of sq and gluino are 1TeV

<----

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

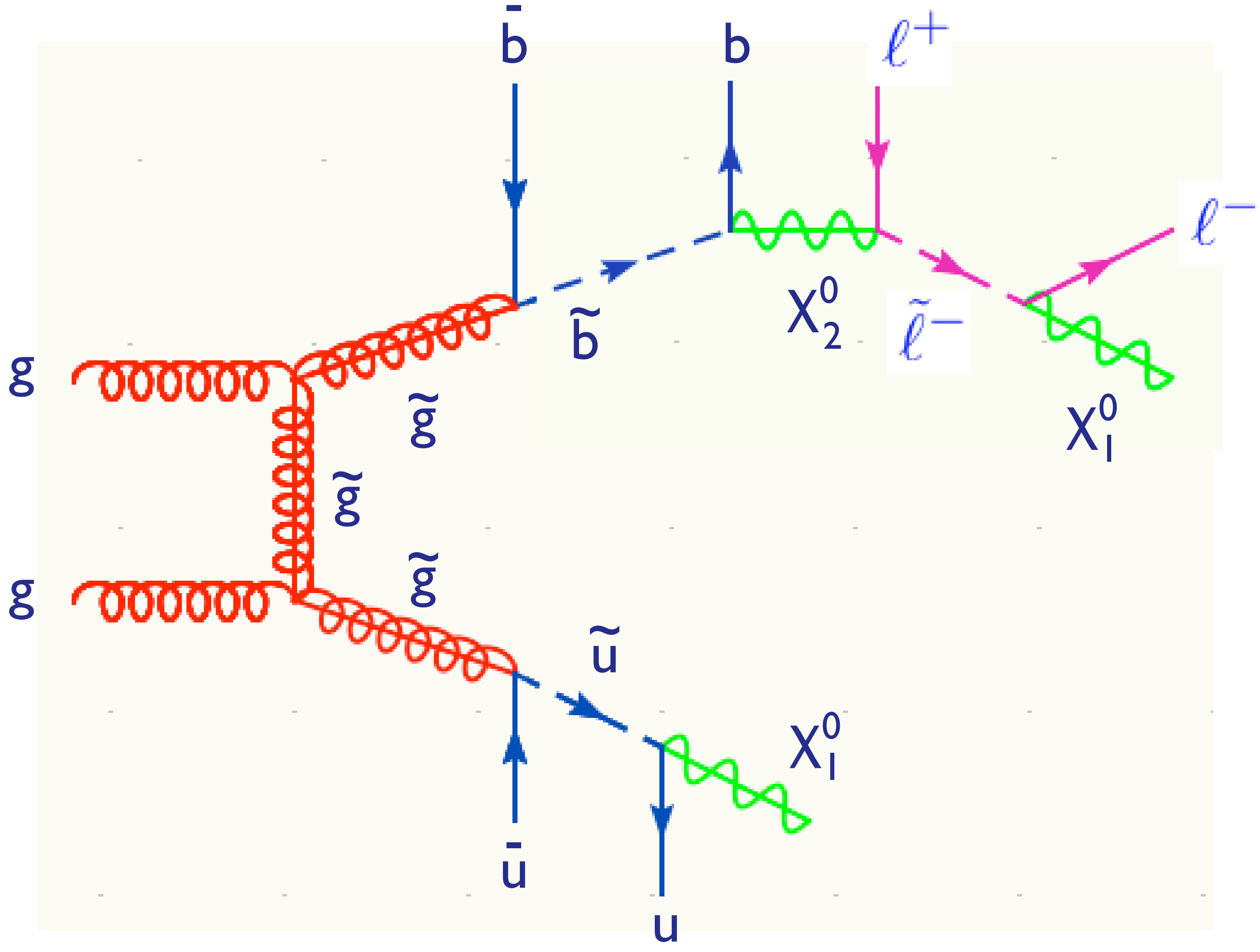
Pythia



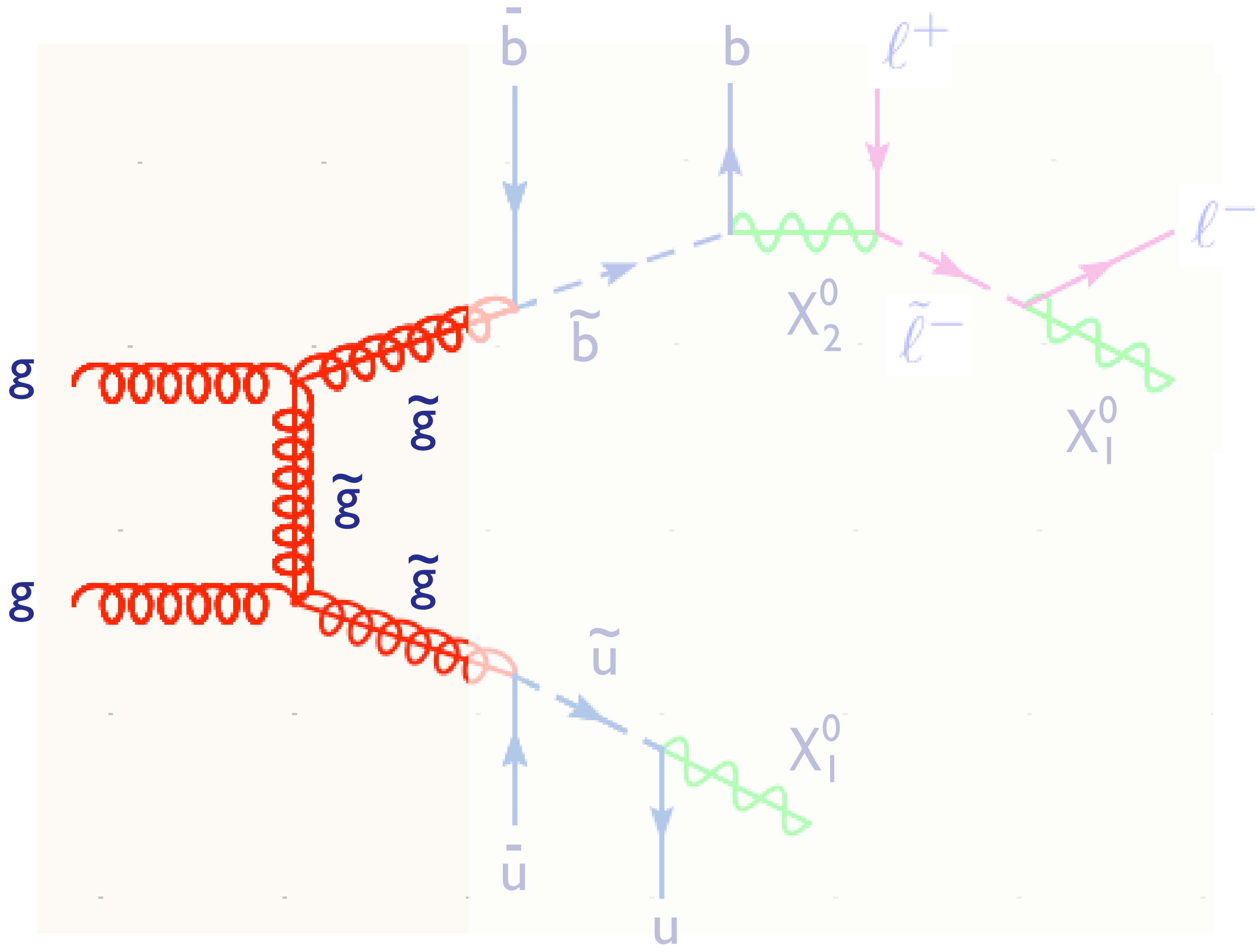
Alpgen+Pythia

See Mangano's talk at SUSY07 for a detailed "anatomy" of these results

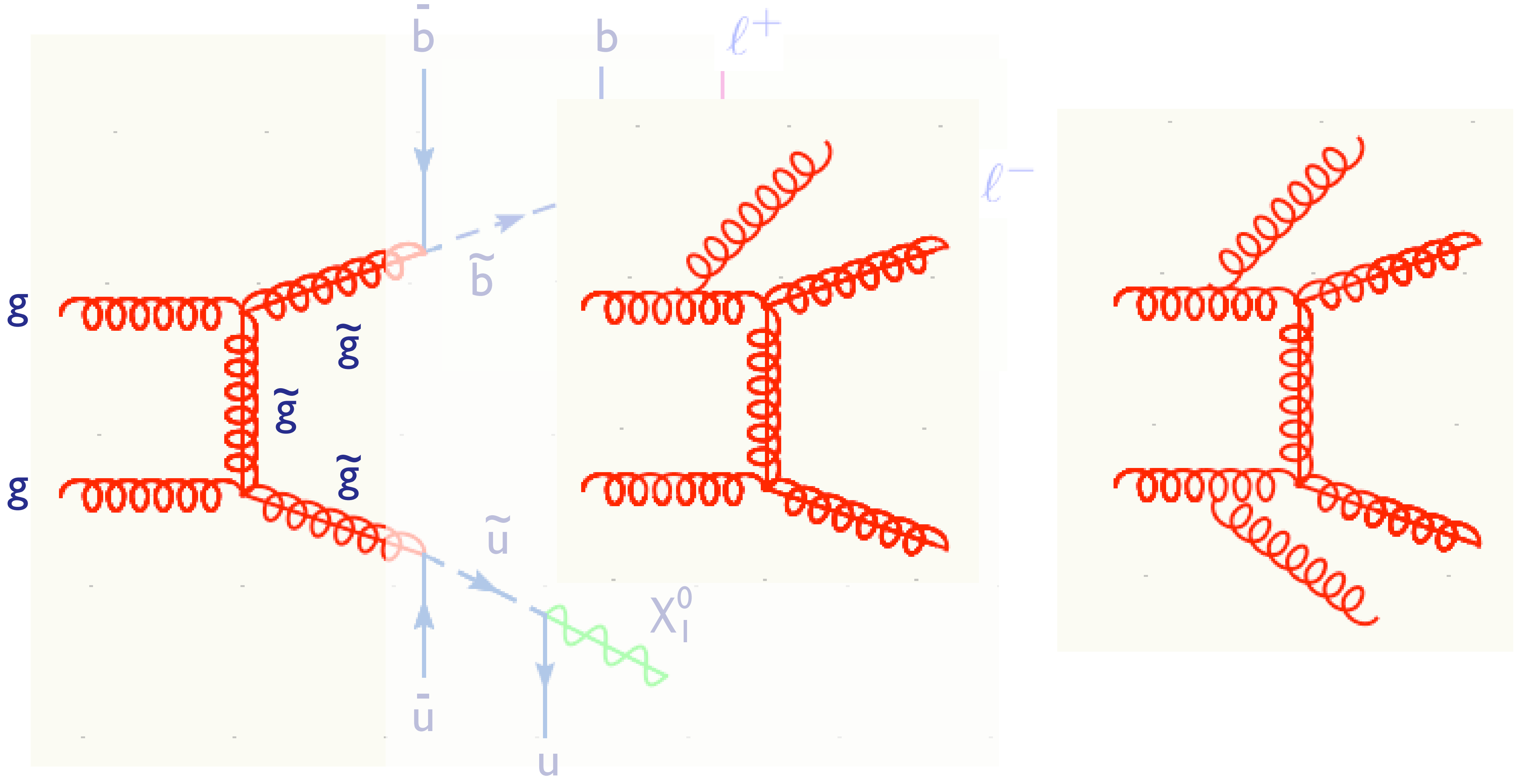
ME/PS merging in SUSY



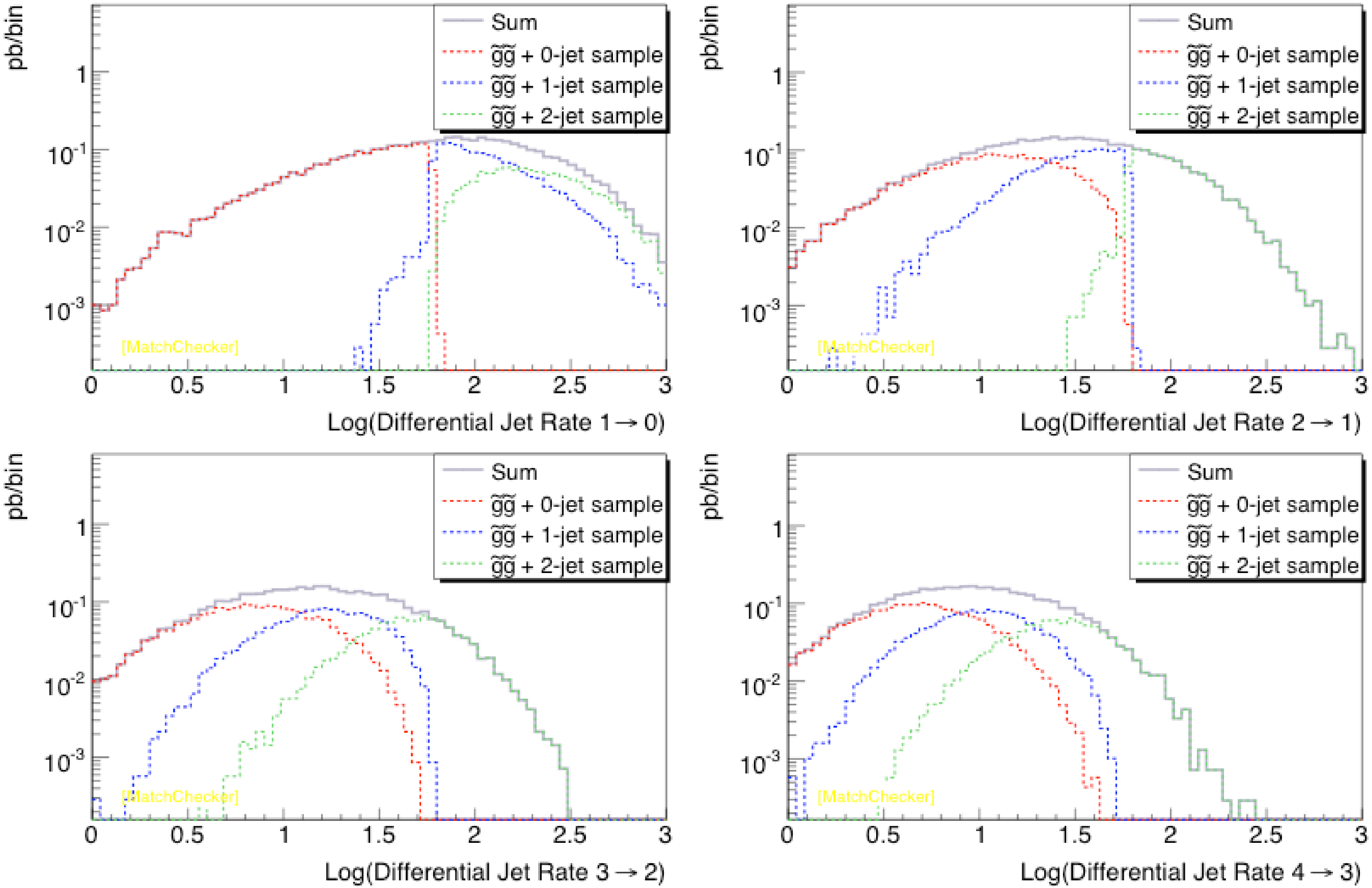
ME/PS merging in SUSY



ME/PS merging in SUSY



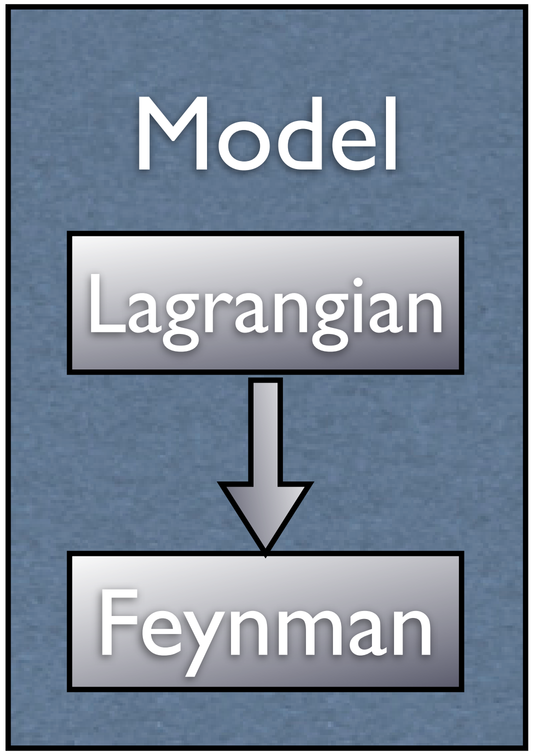
$\tilde{g}\tilde{g}$ + jets: inclusive sample validation plots



Jet rates are smooth
SUSY double counting problem solved

More on ME&PS and SUSY in de Visscher's talk tomorrow

Add-on for BSM



Model

Lagrangian

Feynman

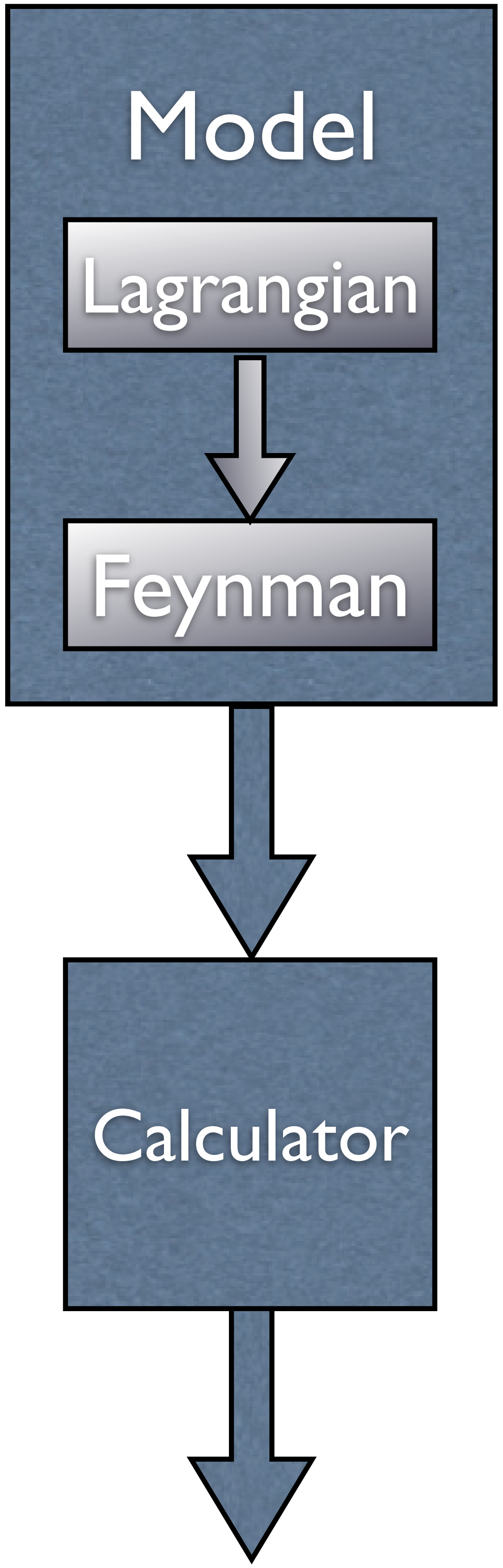
Invent a model, renormalizable or not, with new physics. Write the Lagrangian and (now get) the Feynman Rules.

The particles content, the type of interactions and the analytic form of the couplings in the Feynman rules define the model at tree level.

SUSY, Little Higgs, Higgsless, GUT, Extra dimensions (flat, warped, universal,...)

See Hahn's and Duhr's talks tomorrow

Add-on for BSM



Les Houches interface

Invent a model, renormalizable or not, with new physics. Write the Lagrangian and (now get) the Feynman Rules.

The particles content, the type of interactions and the analytic form of the couplings in the Feynman rules define the model at tree level.

SUSY, Little Higgs, Higgsless, GUT, Extra dimensions (flat, warped, universal,...)

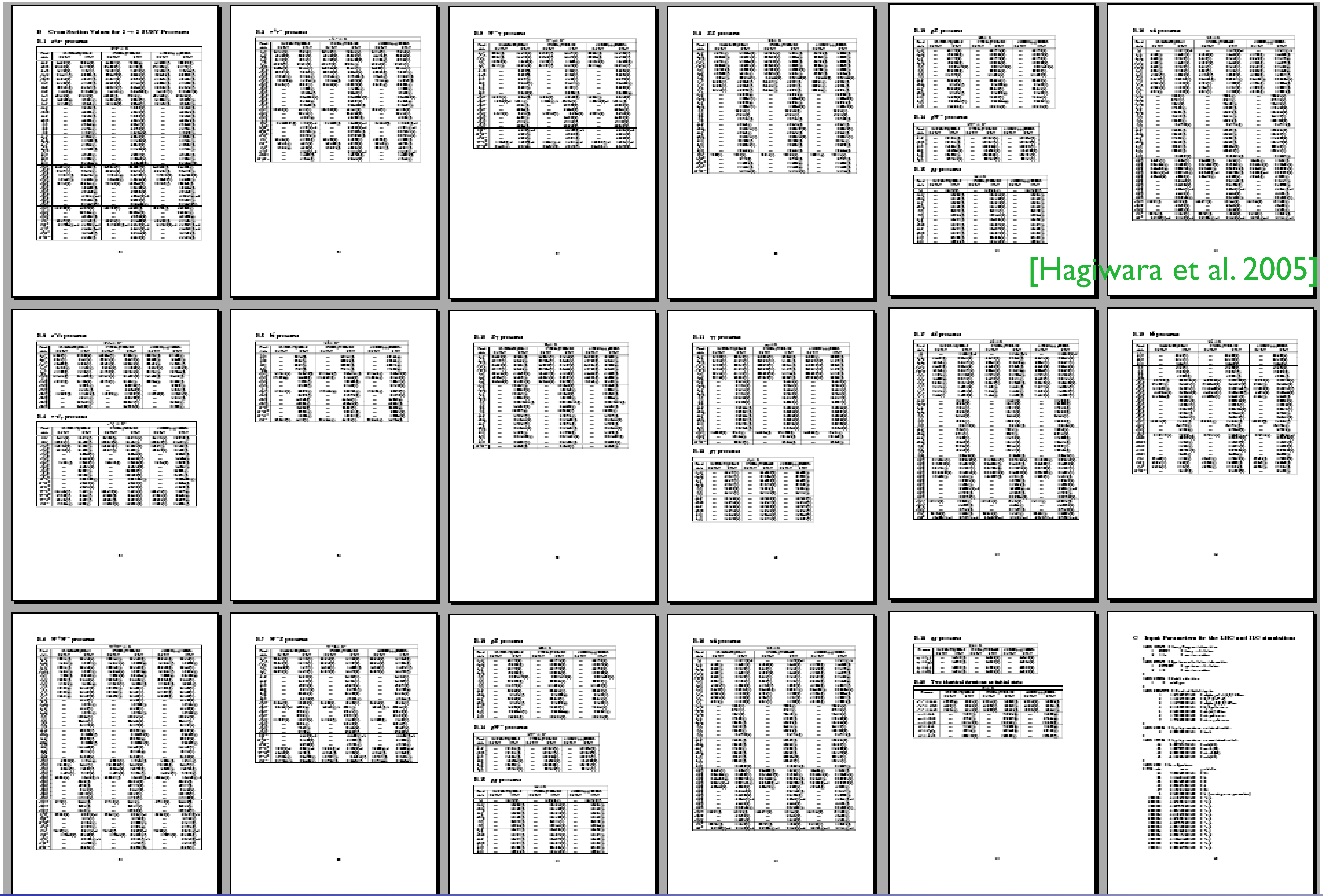
See Hahn's and Duhr's talks tomorrow

Parameters Calculator.
Given the "primary" couplings, all relevant quantities are calculated: masses, widths and the values of the couplings in the Feynman rules.

Caution: tree-level relations have to be satisfied to avoid gauge violations and/or wrong branching ratios.

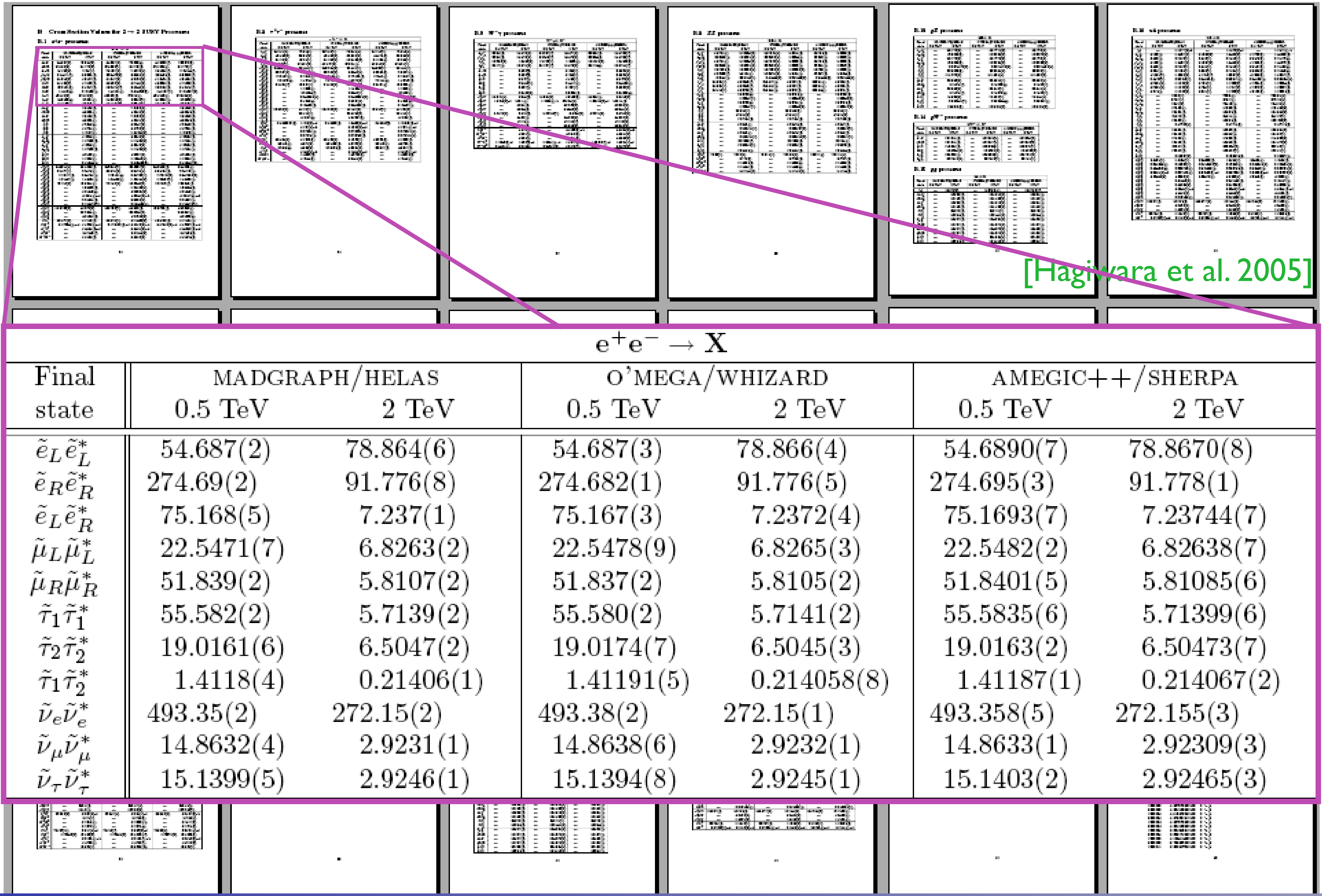
FeynHiggs, ISAJET, NMHDecay, SOFTSUSY, SPHENO, SUSPECT, SDECAY...

MadGraph/Sherpa/Whizard SUSY comparison



[Hagiwara et al. 2005]

MadGraph/Sherpa/Whizard SUSY comparison

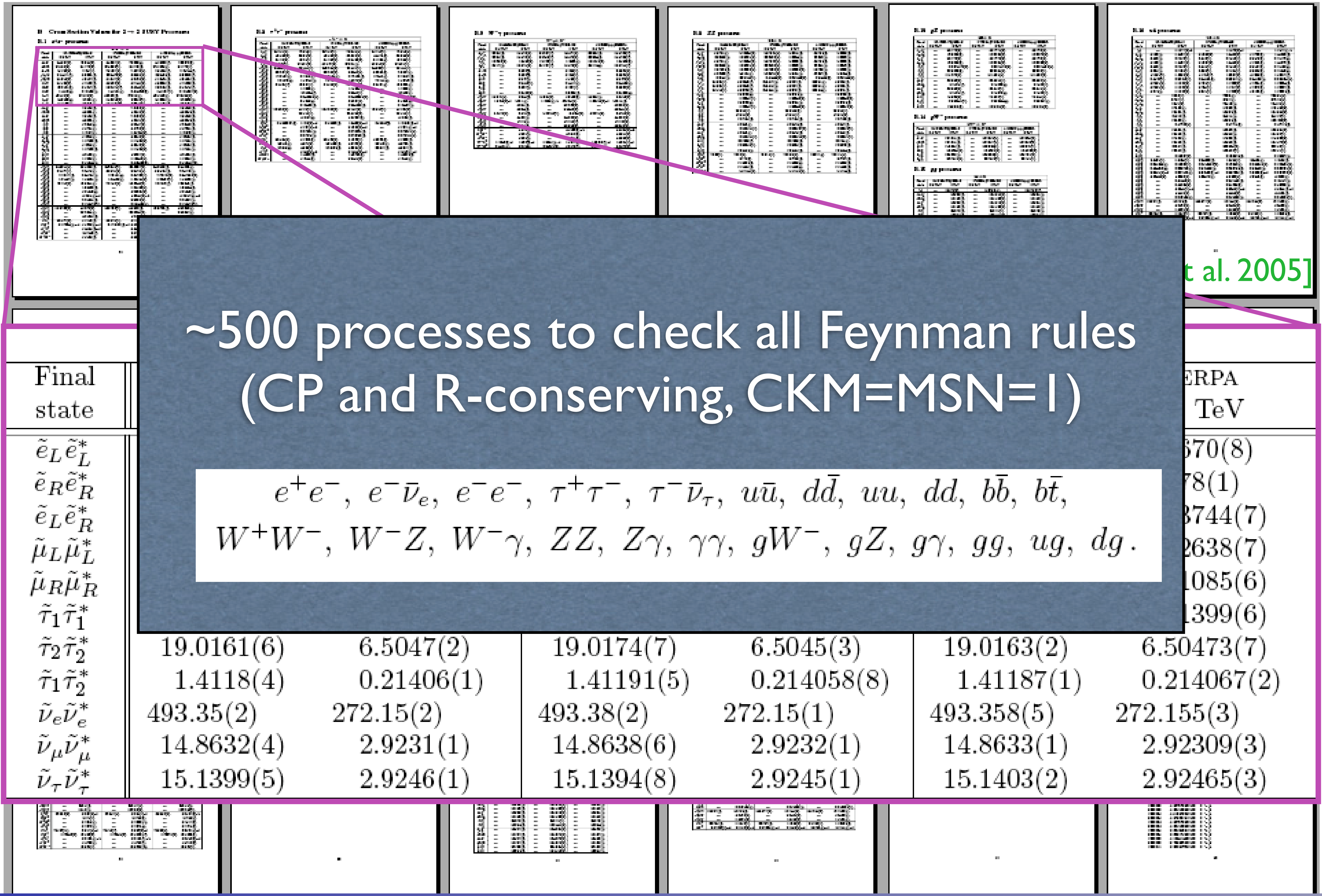


[Hagiwara et al. 2005]

$e^+e^- \to X$

Final state	MADGRAPH/HELAS 0.5 TeV	MADGRAPH/HELAS 2 TeV	O'MEGA/WHIZARD 0.5 TeV	O'MEGA/WHIZARD 2 TeV	AMEGIC++/SHERPA 0.5 TeV	AMEGIC++/SHERPA 2 TeV
$\tilde{e}_L\tilde{e}_L^*$	54.687(2)	78.864(6)	54.687(3)	78.866(4)	54.6890(7)	78.8670(8)
$\tilde{e}_R\tilde{e}_R^*$	274.69(2)	91.776(8)	274.682(1)	91.776(5)	274.695(3)	91.778(1)
$\tilde{e}_L\tilde{e}_R^*$	75.168(5)	7.237(1)	75.167(3)	7.2372(4)	75.1693(7)	7.23744(7)
$\tilde{\mu}_L\tilde{\mu}_L^*$	22.5471(7)	6.8263(2)	22.5478(9)	6.8265(3)	22.5482(2)	6.82638(7)
$\tilde{\mu}_R\tilde{\mu}_R^*$	51.839(2)	5.8107(2)	51.837(2)	5.8105(2)	51.8401(5)	5.81085(6)
$\tilde{\tau}_1\tilde{\tau}_1^*$	55.582(2)	5.7139(2)	55.580(2)	5.7141(2)	55.5835(6)	5.71399(6)
$\tilde{\tau}_2\tilde{\tau}_2^*$	19.0161(6)	6.5047(2)	19.0174(7)	6.5045(3)	19.0163(2)	6.50473(7)
$\tilde{\tau}_1\tilde{\tau}_2^*$	1.4118(4)	0.21406(1)	1.41191(5)	0.214058(8)	1.41187(1)	0.214067(2)
$\tilde{\nu}_e\tilde{\nu}_e^*$	493.35(2)	272.15(2)	493.38(2)	272.15(1)	493.358(5)	272.155(3)
$\tilde{\nu}_\mu\tilde{\nu}_\mu^*$	14.8632(4)	2.9231(1)	14.8638(6)	2.9232(1)	14.8633(1)	2.92309(3)
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	15.1399(5)	2.9246(1)	15.1394(8)	2.9245(1)	15.1403(2)	2.92465(3)

MadGraph/Sherpa/Whizard SUSY comparison



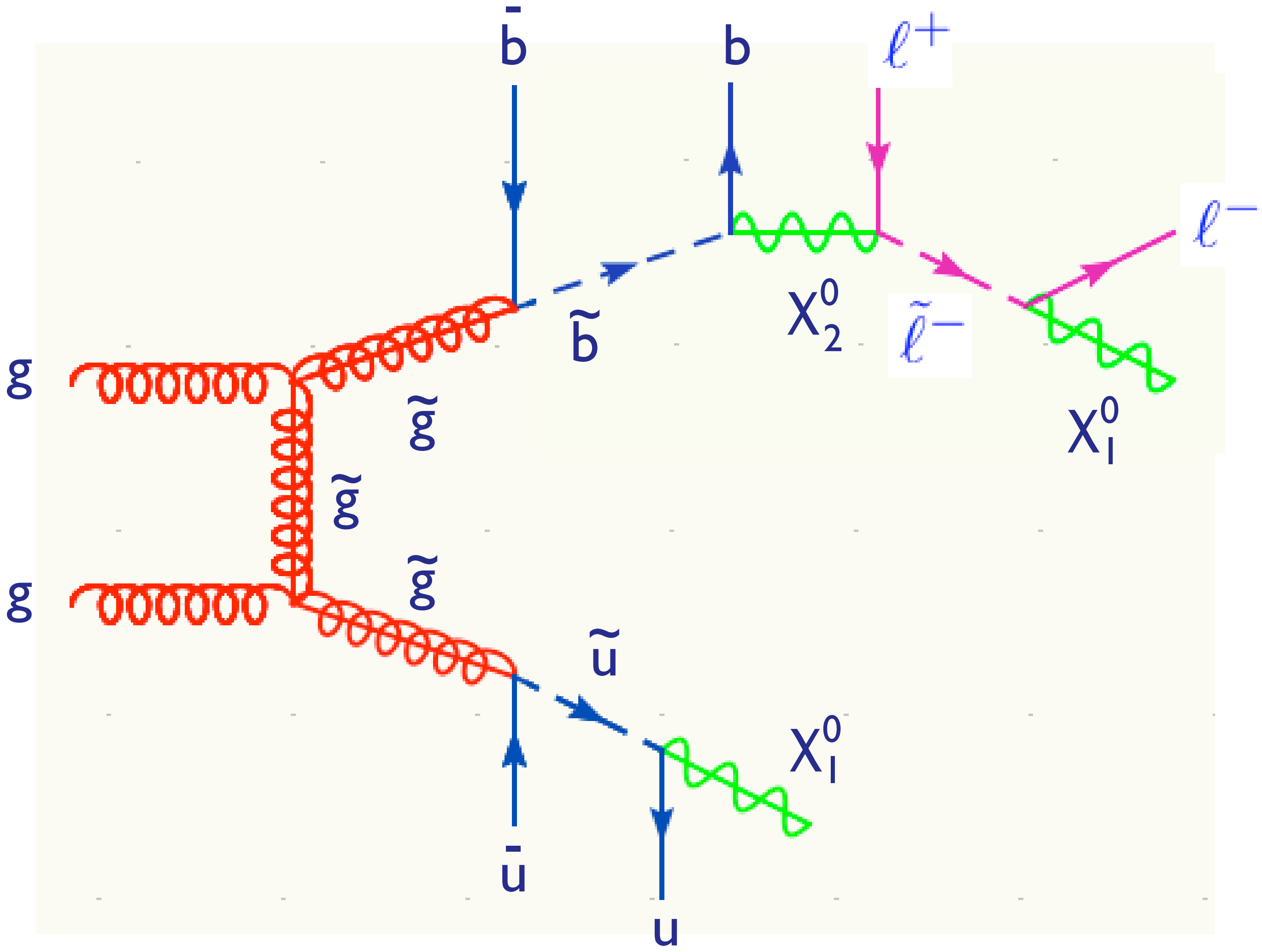
t al. 2005]

~500 processes to check all Feynman rules (CP and R-conserving, CKM=MSN=1)

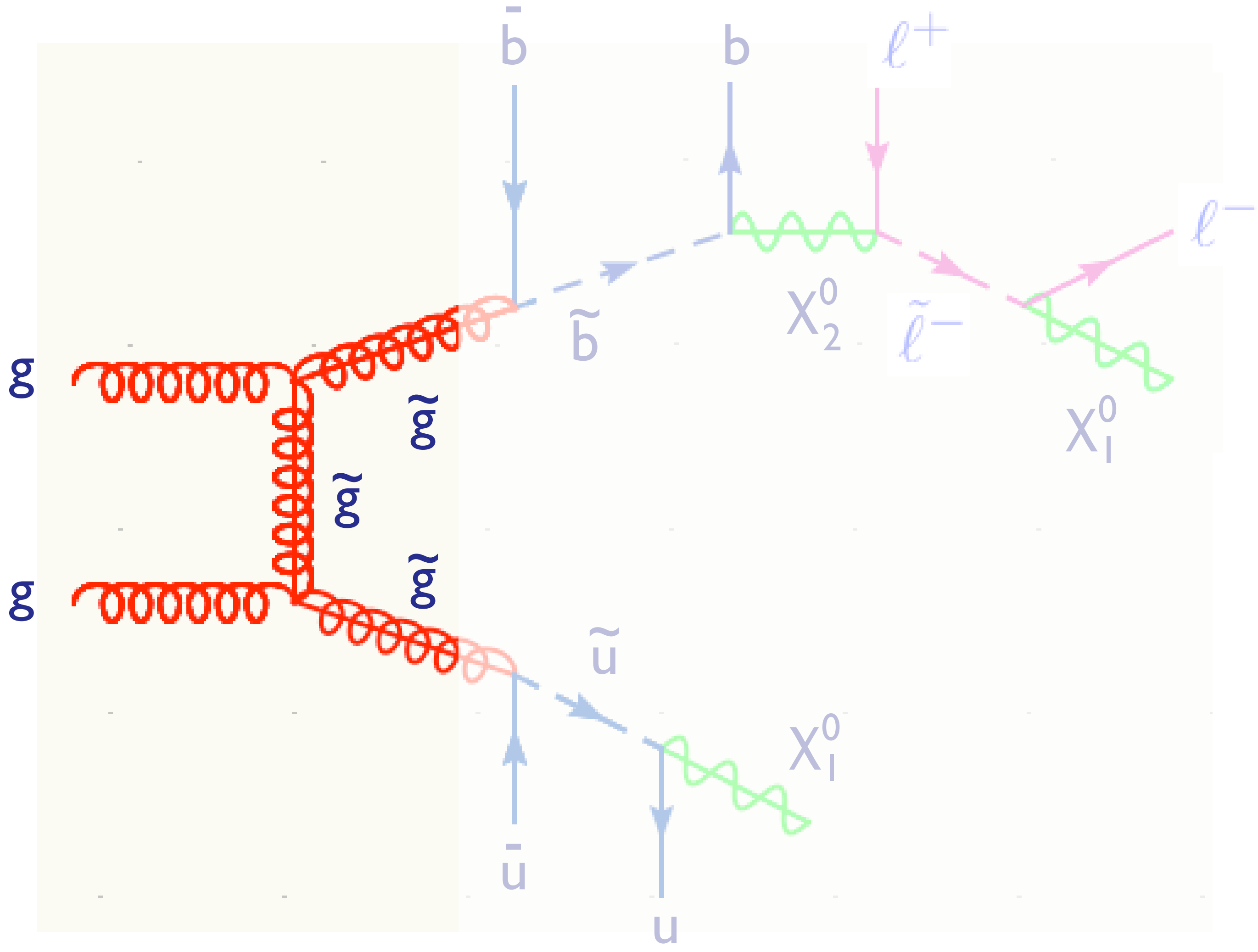
$$e^+e^-,\ e^-\bar\nu_e,\ e^-e^-,\ \tau^+\tau^-,\ \tau^-\bar\nu_\tau,\ u\bar u,\ d\bar d,\ uu,\ dd,\ b\bar b,\ b\bar t,$$
$$W^+W^-,\ W^-Z,\ W^-\gamma,\ ZZ,\ Z\gamma,\ \gamma\gamma,\ gW^-,\ gZ,\ g\gamma,\ gg,\ ug,\ dg\,.$$

Final state						ERPA TeV
$\tilde e_L\tilde e_L^*$						70(8)
$\tilde e_R\tilde e_R^*$						78(1)
$\tilde e_L\tilde e_R^*$						3744(7)
$\tilde\mu_L\tilde\mu_L^*$						2638(7)
$\tilde\mu_R\tilde\mu_R^*$						1085(6)
$\tilde\tau_1\tilde\tau_1^*$						1399(6)
$\tilde\tau_2\tilde\tau_2^*$	19.0161(6)	6.5047(2)	19.0174(7)	6.5045(3)	19.0163(2)	6.50473(7)
$\tilde\tau_1\tilde\tau_2^*$	1.4118(4)	0.21406(1)	1.41191(5)	0.214058(8)	1.41187(1)	0.214067(2)
$\tilde\nu_e\tilde\nu_e^*$	493.35(2)	272.15(2)	493.38(2)	272.15(1)	493.358(5)	272.155(3)
$\tilde\nu_\mu\tilde\nu_\mu^*$	14.8632(4)	2.9231(1)	14.8638(6)	2.9232(1)	14.8633(1)	2.92309(3)
$\tilde\nu_\tau\tilde\nu_\tau^*$	15.1399(5)	2.9246(1)	15.1394(8)	2.9245(1)	15.1403(2)	2.92465(3)

NLO cross sections



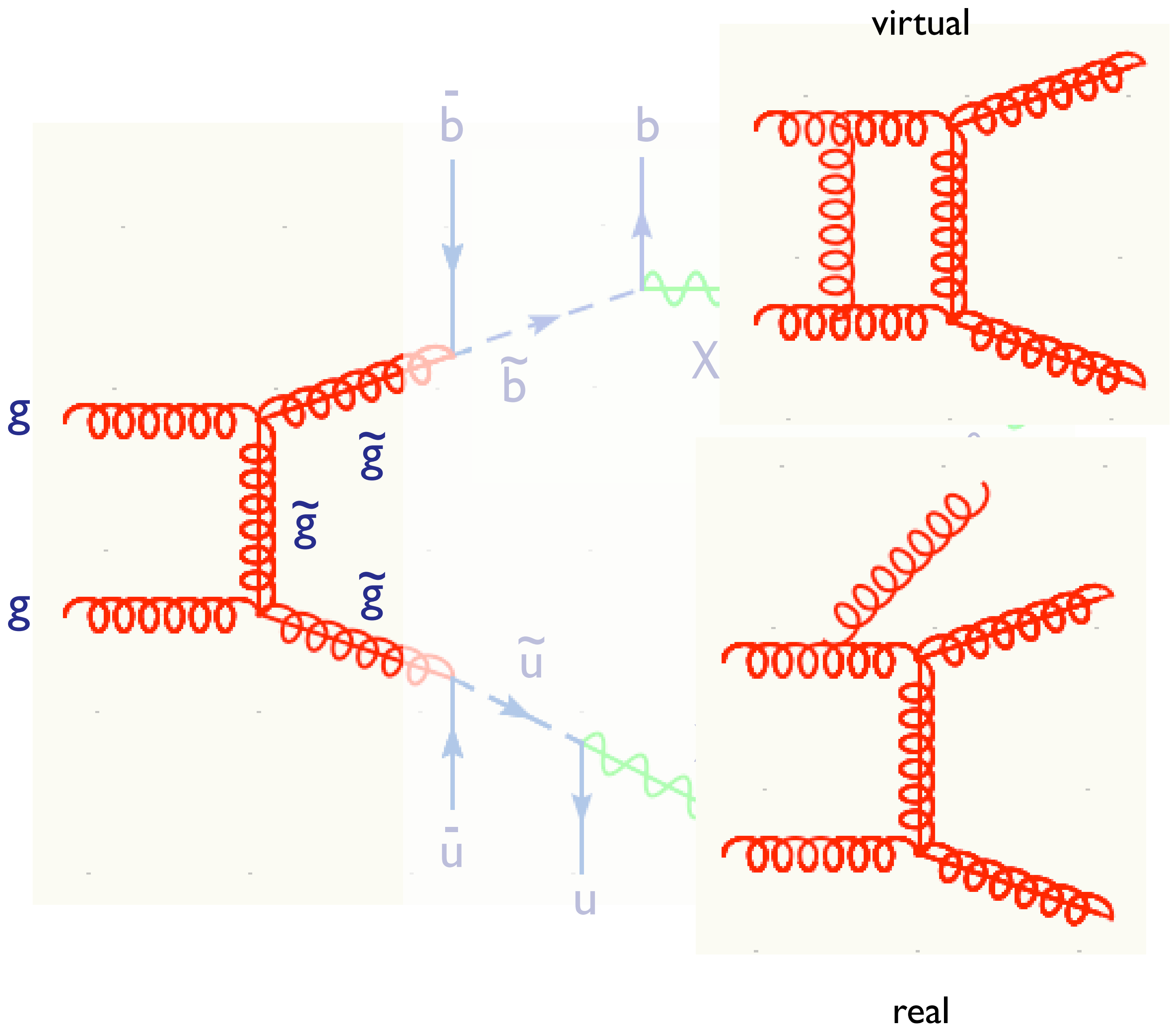
NLO cross sections



NLO cross sections

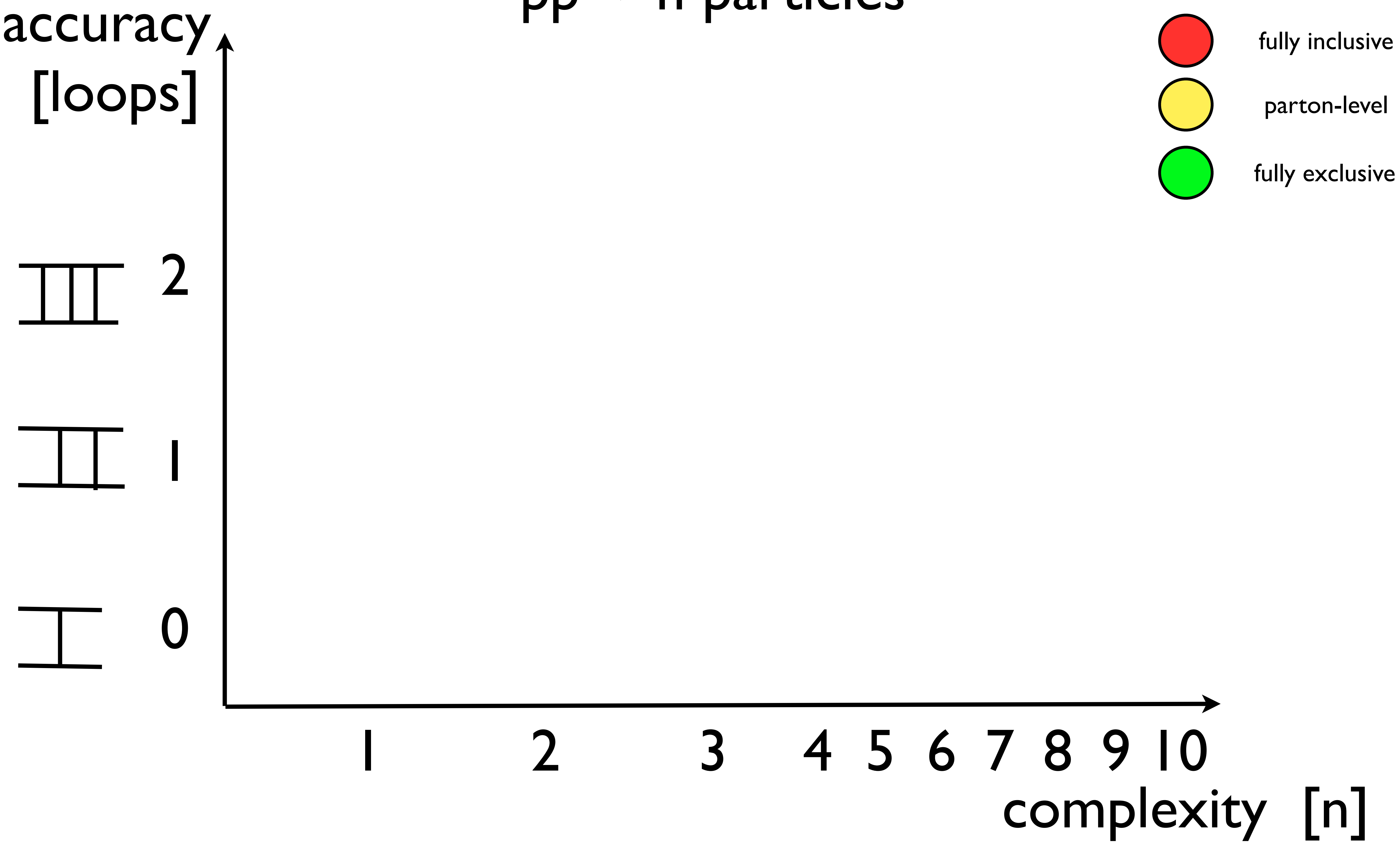
Include higher order terms int the fixed-order calculations

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



Status: SM

pp→ n particles



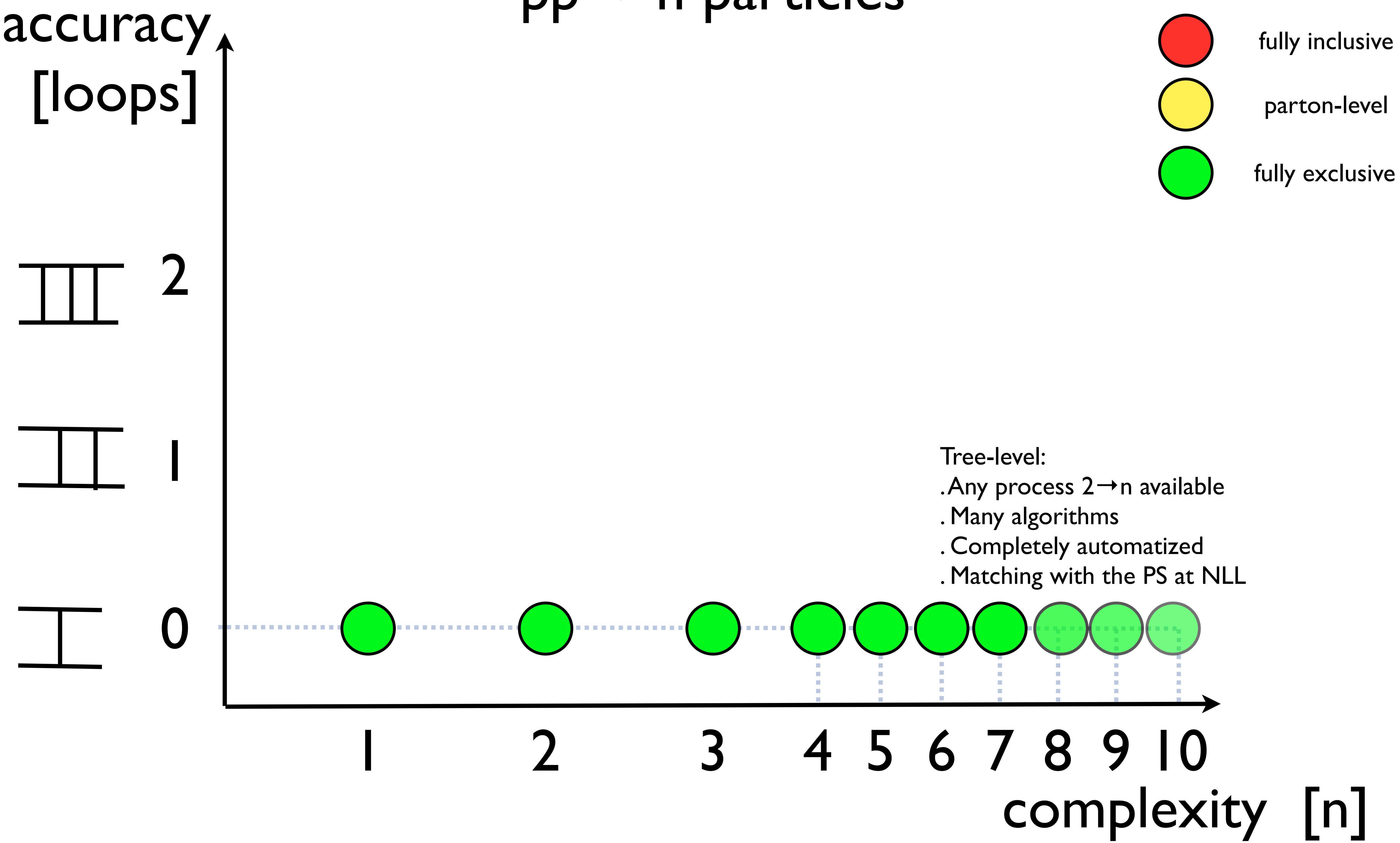
🔴 fully inclusive

🟡 parton-level

🟢 fully exclusive

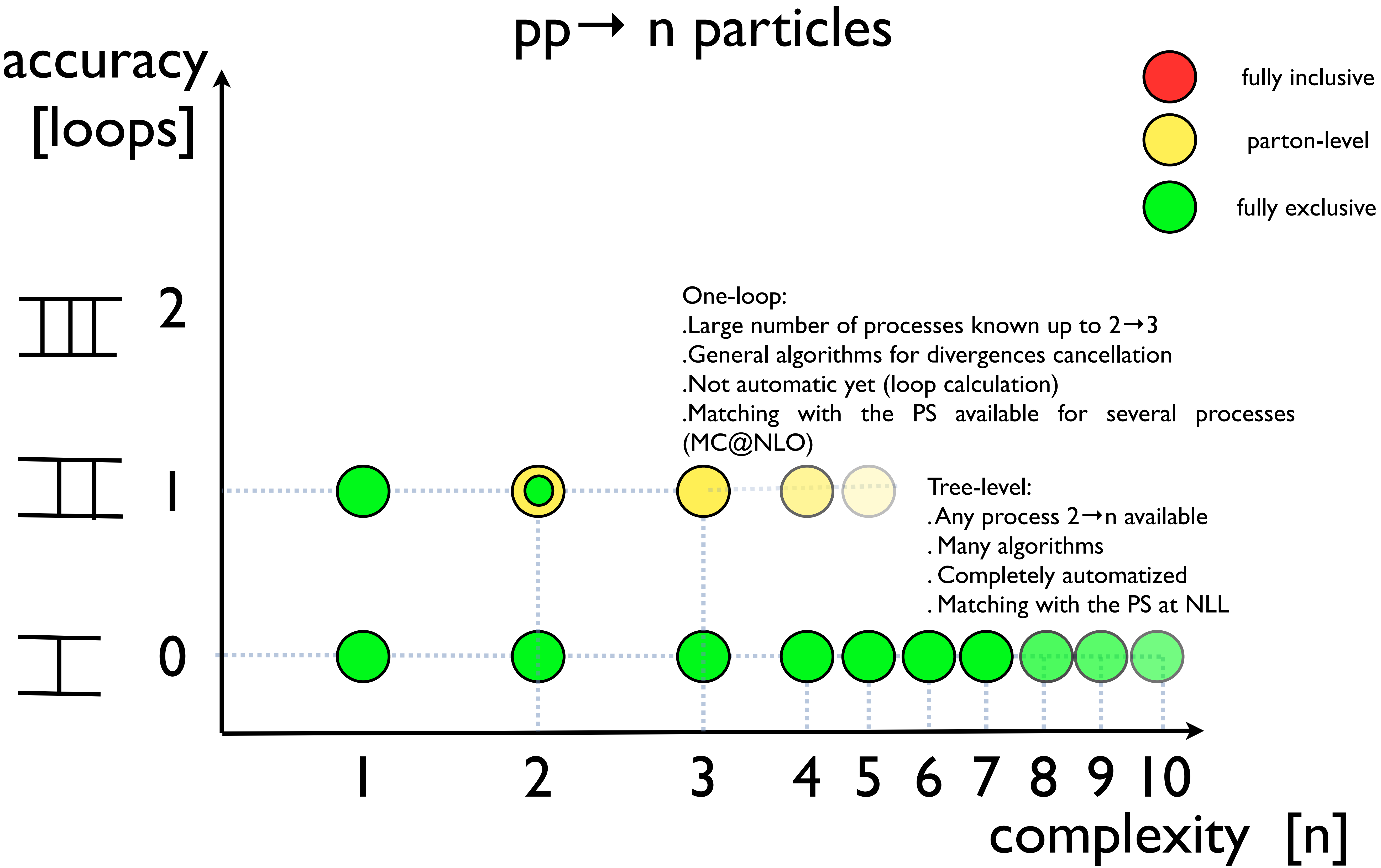
Status: SM

pp→ n particles



Tree-level:
- .Any process 2→n available
- . Many algorithms
- . Completely automatized
- . Matching with the PS at NLL

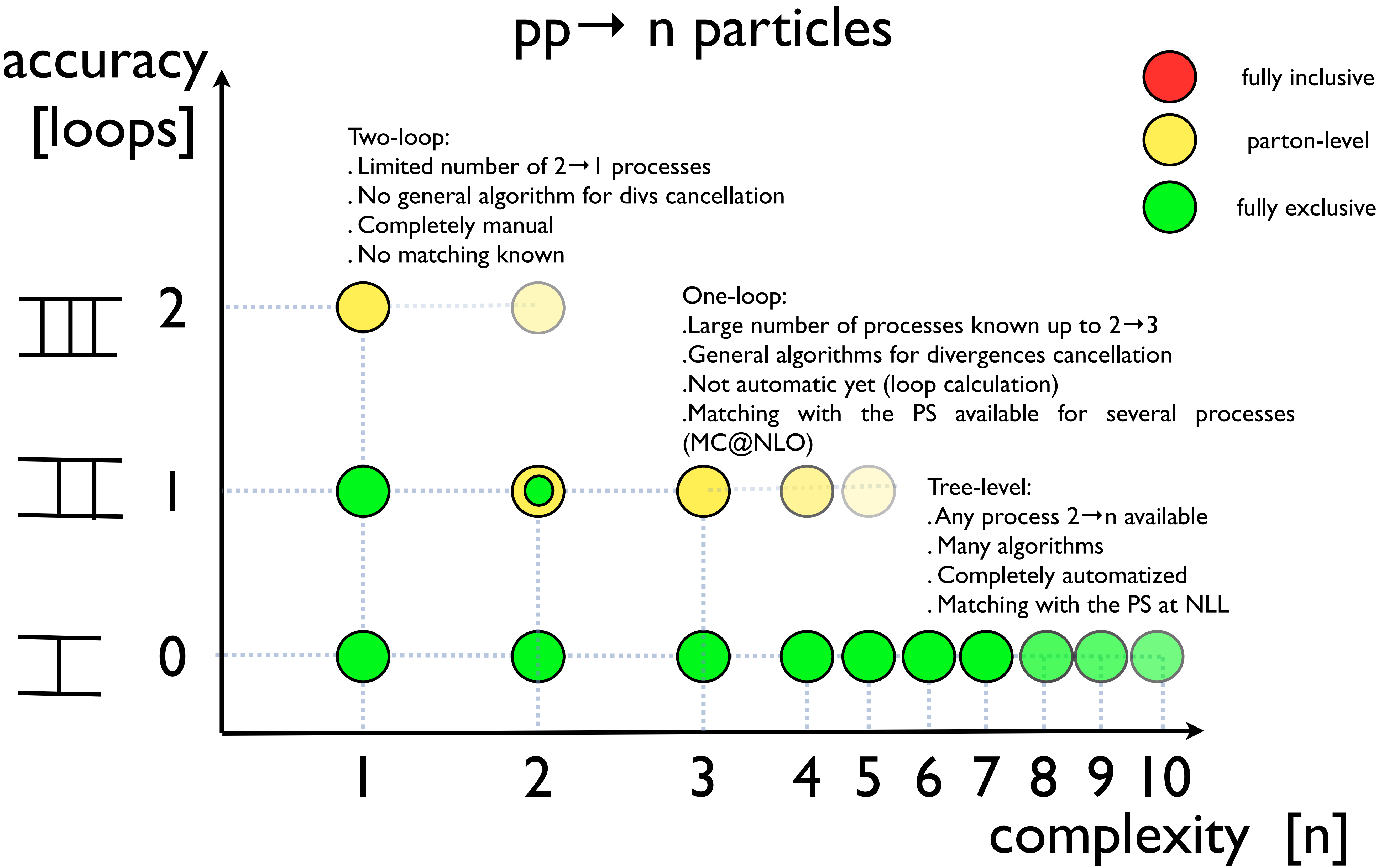
Status: SM



One-loop:
.Large number of processes known up to 2→3
.General algorithms for divergences cancellation
.Not automatic yet (loop calculation)
.Matching with the PS available for several processes (MC@NLO)

Tree-level:
.Any process 2→n available
. Many algorithms
. Completely automatized
. Matching with the PS at NLL

Status: SM



🔴 fully inclusive
🟡 parton-level
🟢 fully exclusive

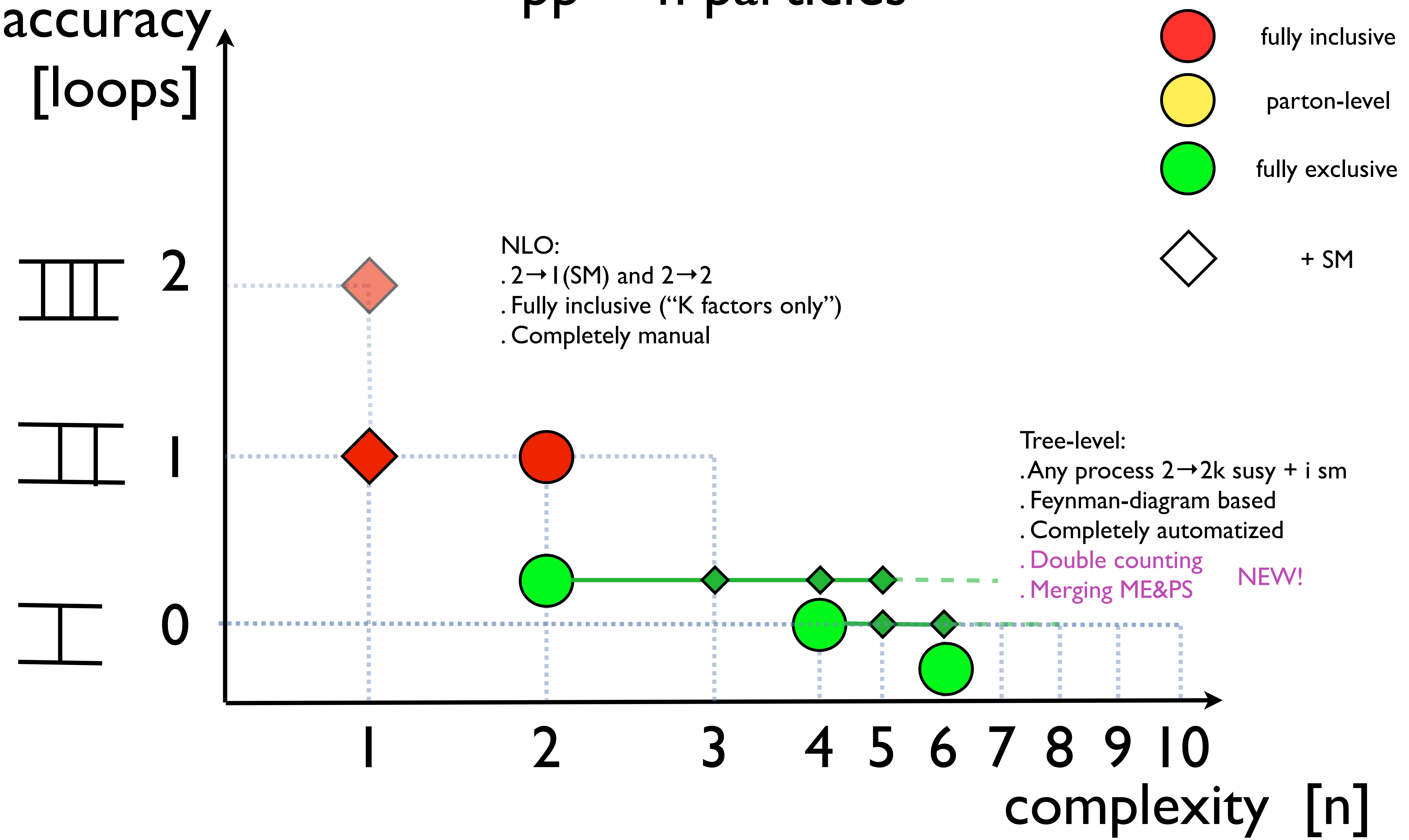
Two-loop:
. Limited number of 2→1 processes
. No general algorithm for divs cancellation
. Completely manual
. No matching known

One-loop:
.Large number of processes known up to 2→3
.General algorithms for divergences cancellation
.Not automatic yet (loop calculation)
.Matching with the PS available for several processes (MC@NLO)

Tree-level:
.Any process 2→n available
. Many algorithms
. Completely automatized
. Matching with the PS at NLL

Status: SUSY

pp→ n particles



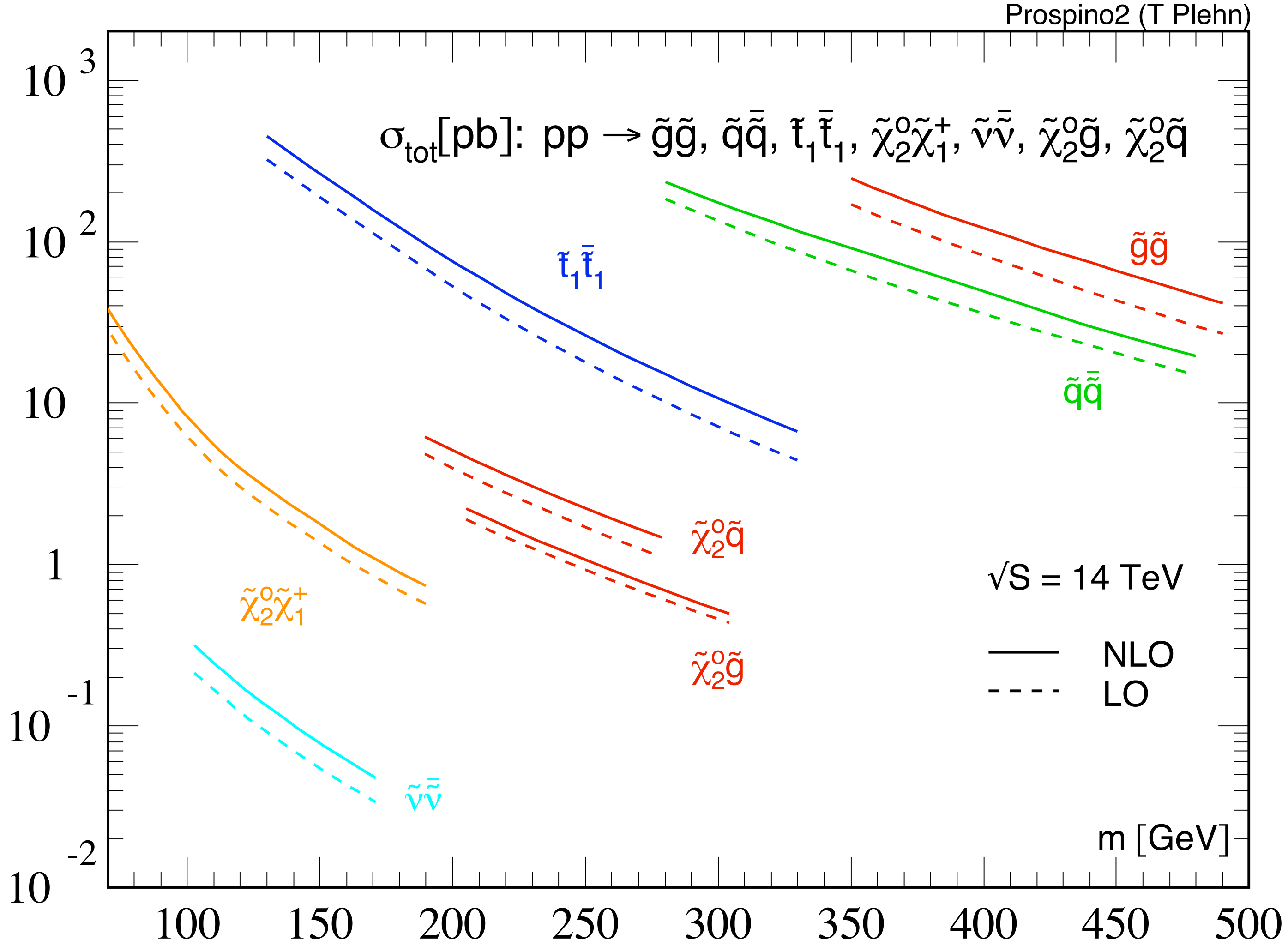
NLO:
. 2→1(SM) and 2→2
. Fully inclusive ("K factors only")
. Completely manual

Tree-level:
. Any process 2→2k susy + i sm
. Feynman-diagram based
. Completely automatized
. Double counting
. Merging ME&PS

NEW!

Example: SUSY Predictions at NLO

[Beenakker, Höpker, Krämer, Spira, Plehn, Zerwas]



Prospino

Example of an inclusive "MC integrator".

Total cross sections at NLO. Also available for LeptoQuark production. Useful for normalization and error estimates (scales, PDF's).

Necessary for precise SUSY parameter extraction from cross section measurements.

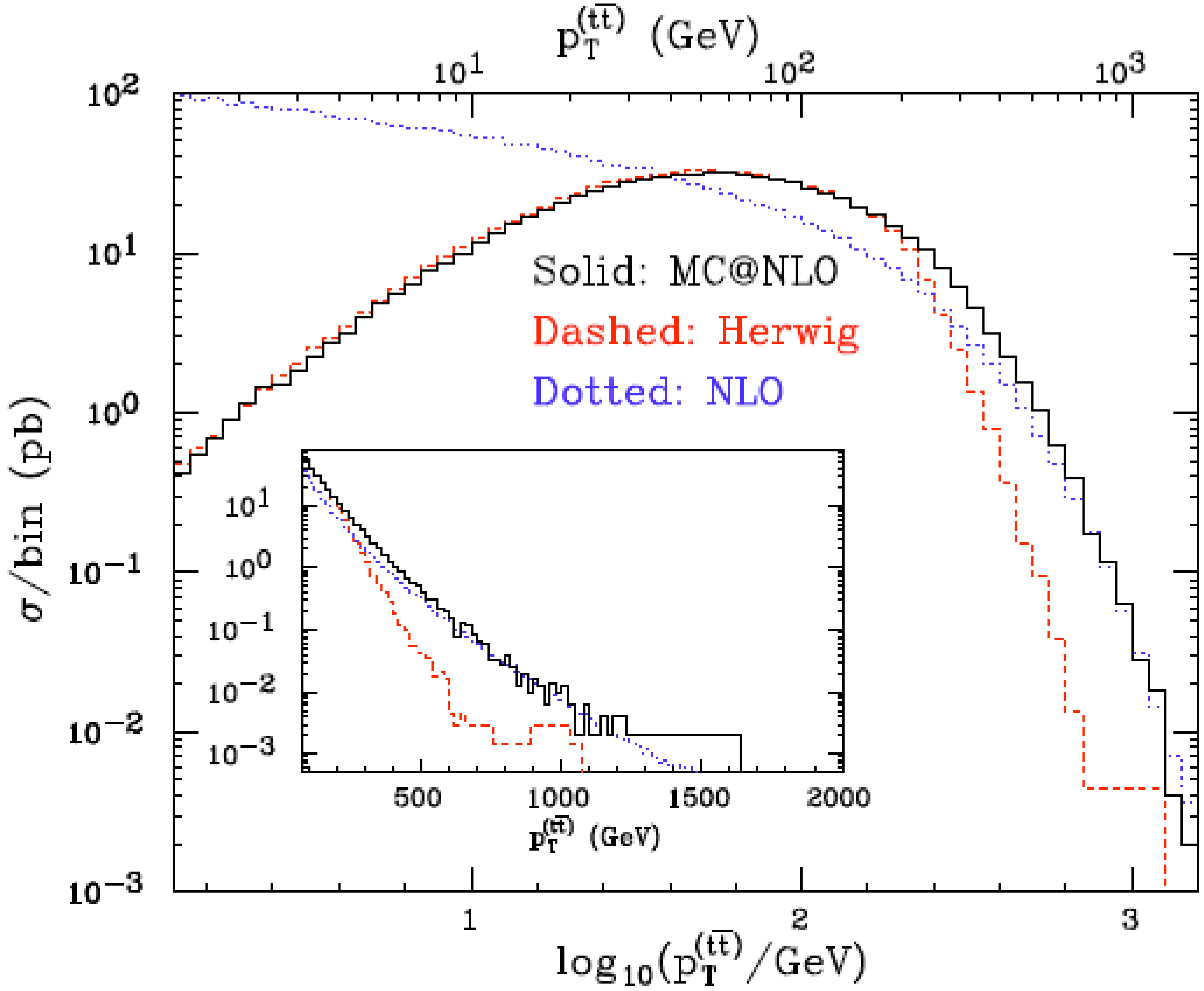
However, neither events nor distributions produced. Need to rely on tree-level based simulations.

Outlook for MC's at NLO

An independent new trend is to combine NLO accuracy in normalization and shapes of hard radiation with parton shower.

MC@NLO [Frixione, Nason, Webber, 2003] is the standard code. Quick progress and many developments in this field. For instance POWHEG [Frixione, Nason, Oleari, 2007].

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

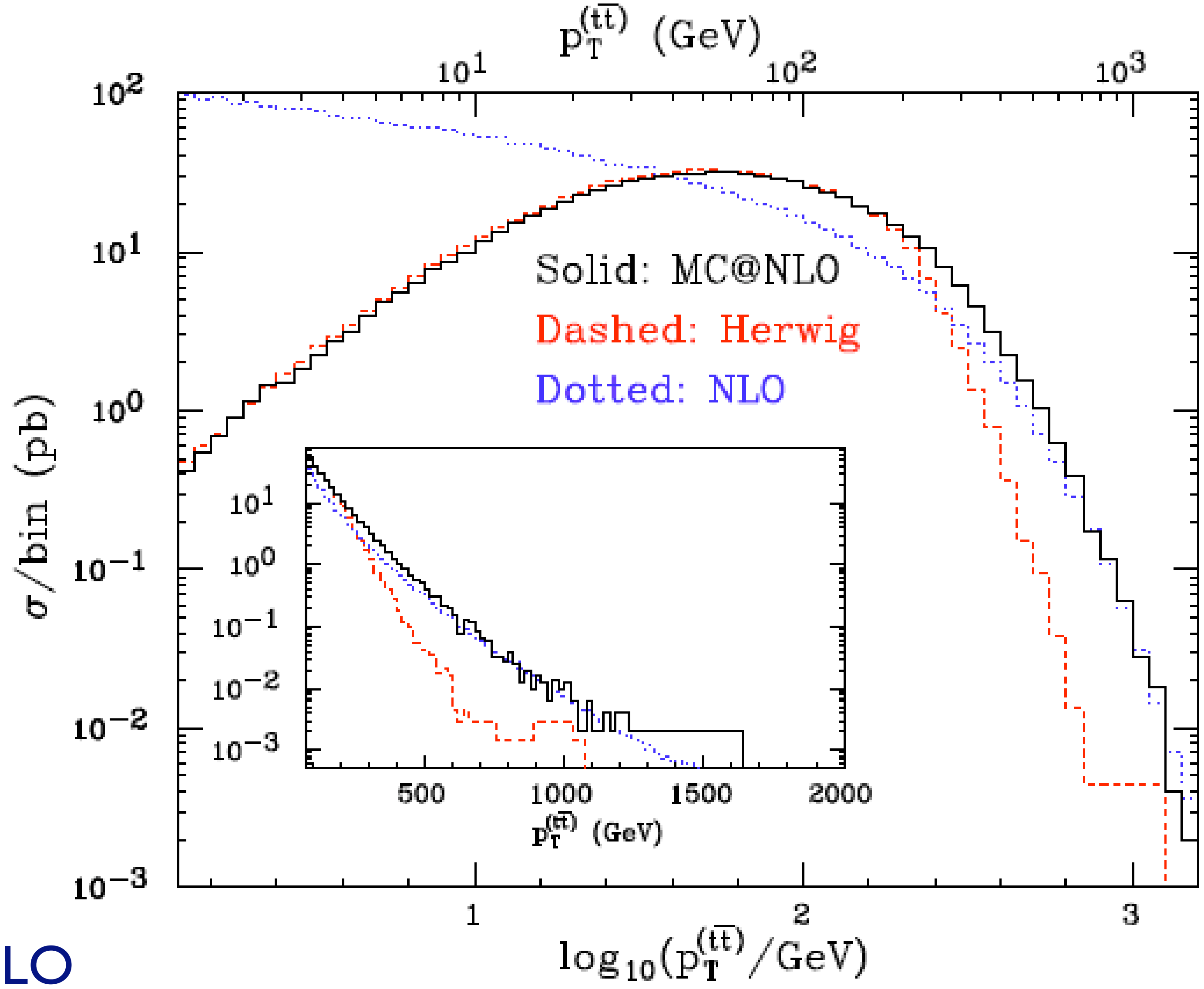


Outlook for MC’s at NLO

An independent new trend is to combine NLO accuracy in normalization and shapes of hard radiation with parton shower.

MC@NLO [Frixione, Nason, Webber, 2003] is the standard code. Quick progress and many developments in this field. For instance POWHEG [Frixione, Nason, Oleari, 2007].

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



Current limitations are:

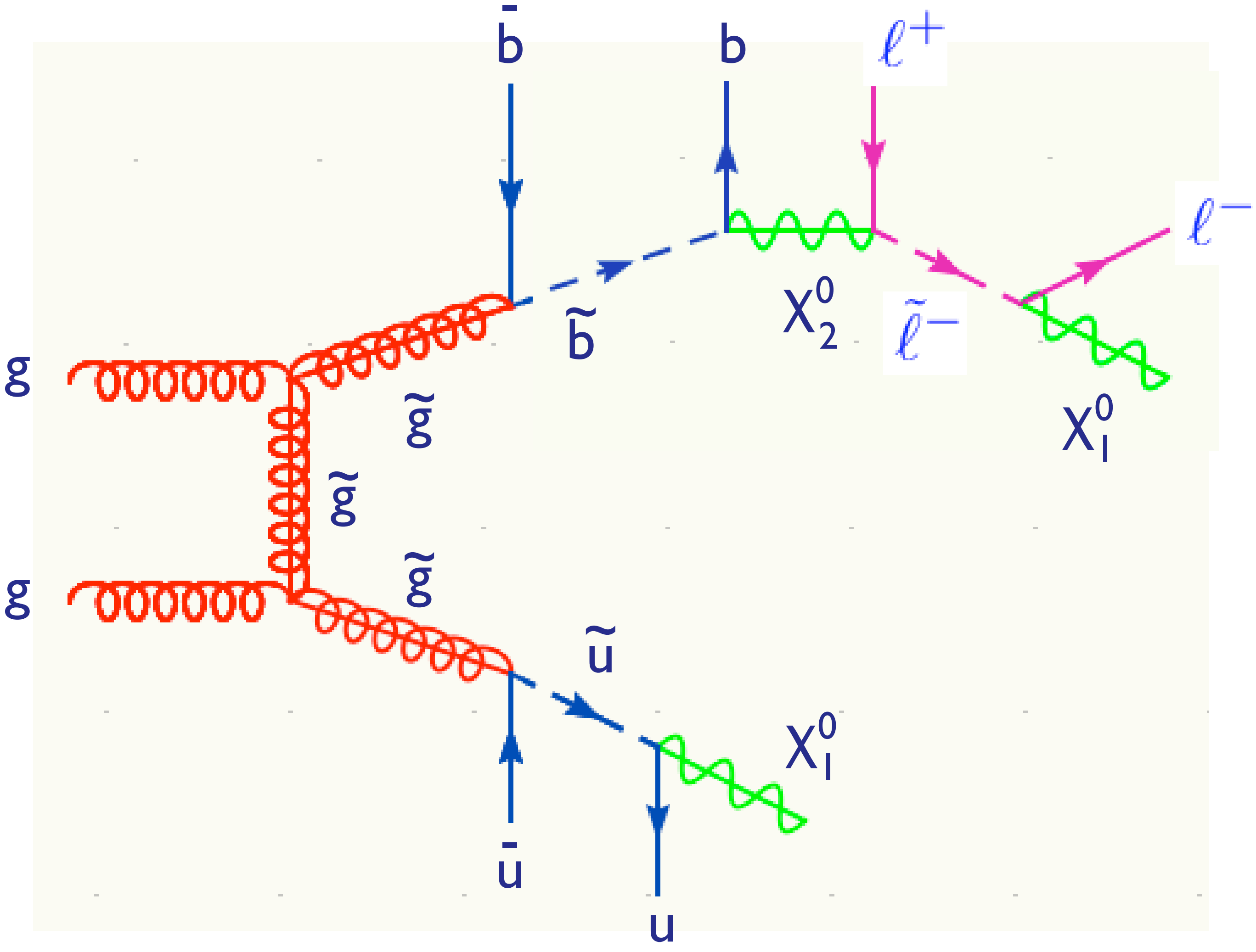
1. Considerable manual work for the implementation of a new process.
2. Only SM.
3. Only Herwig.

Outlook:

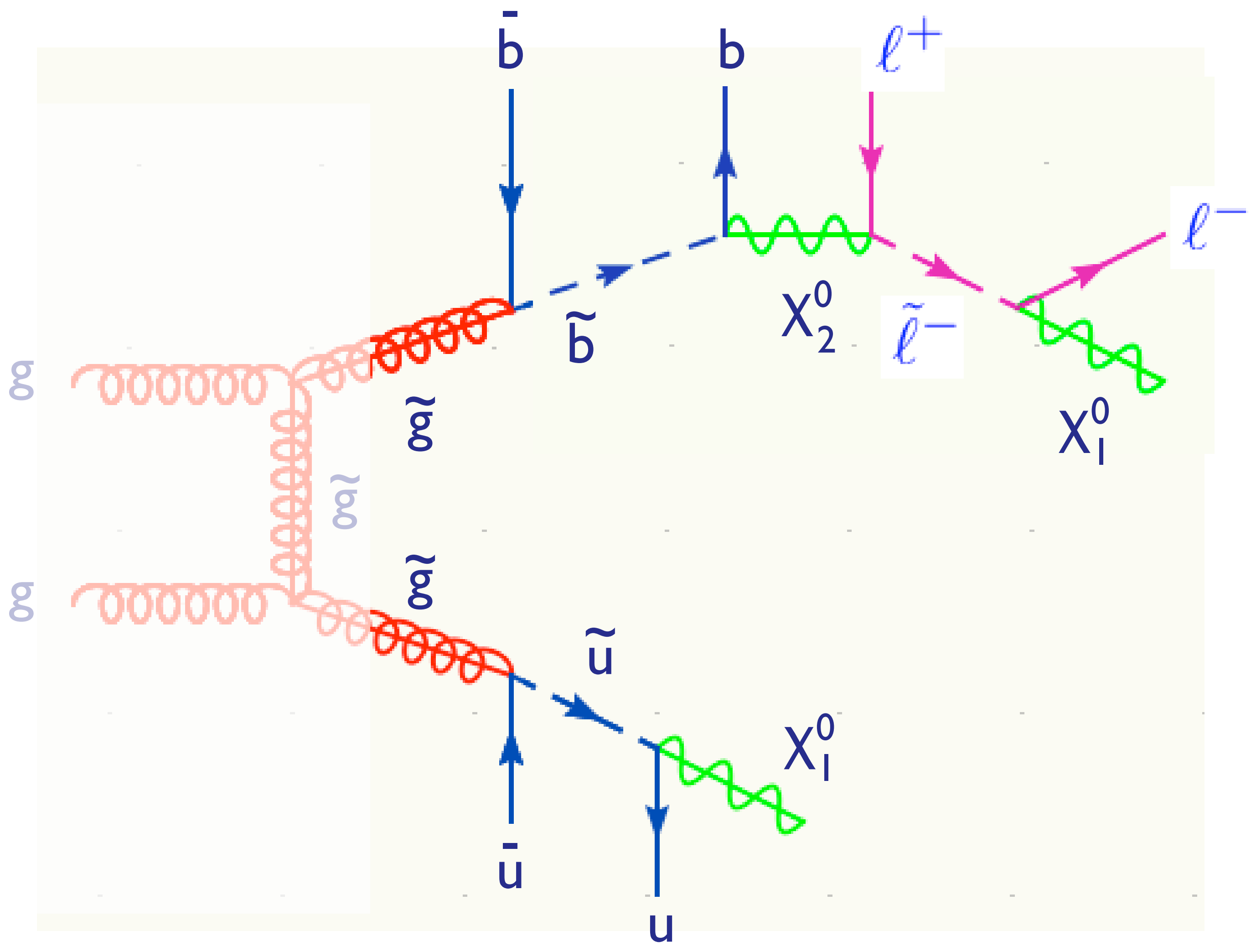
1. Automatization for the real contributions proven feasible
2. Automatization for 2→2 virtuals in sight.
3. General matching procedure available and shower indepedent.

Future looks very bright for a BSM-MC@NLO

Decay Chains

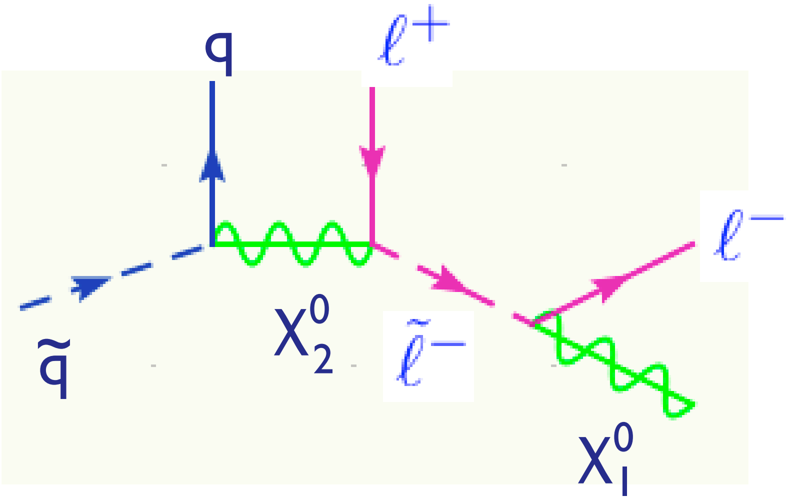


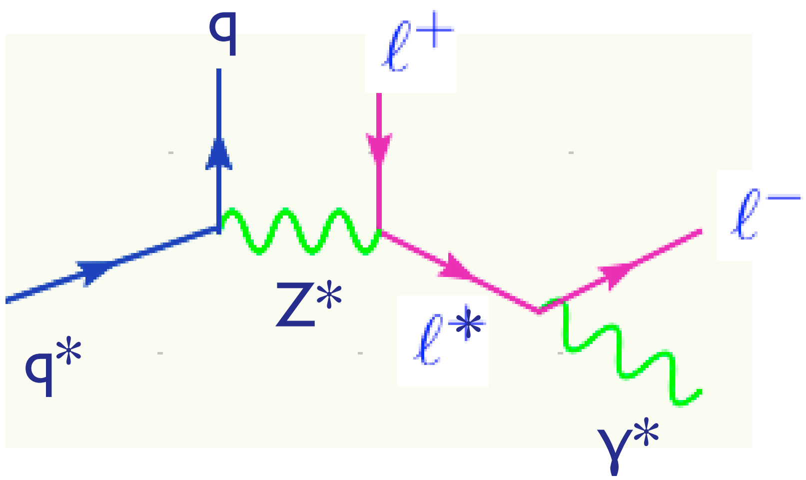
Decay Chains

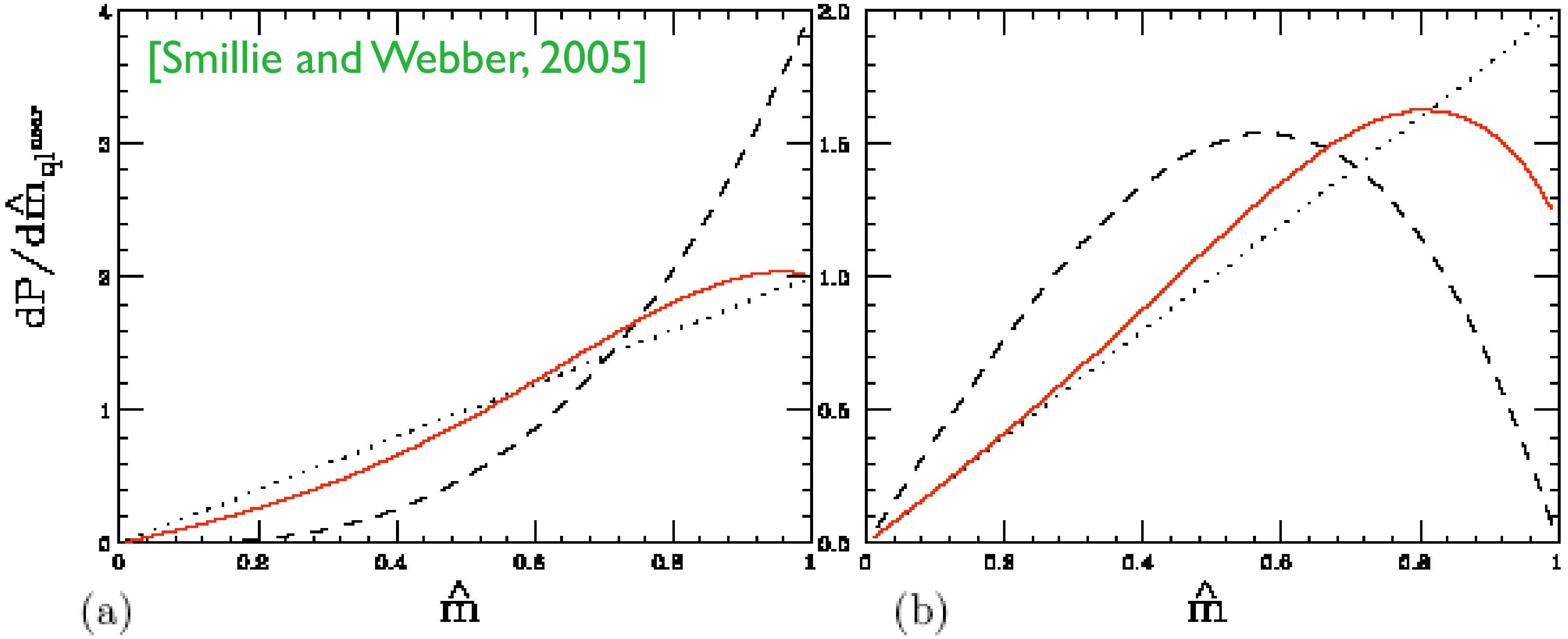


SUSY vs UED

New heavy states tend to decay into lower mass new states, leading to long decay chains, up to the lightest neutral particle (stable is R-parity like is conserved).
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:






[Smillie and Webber, 2005]

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

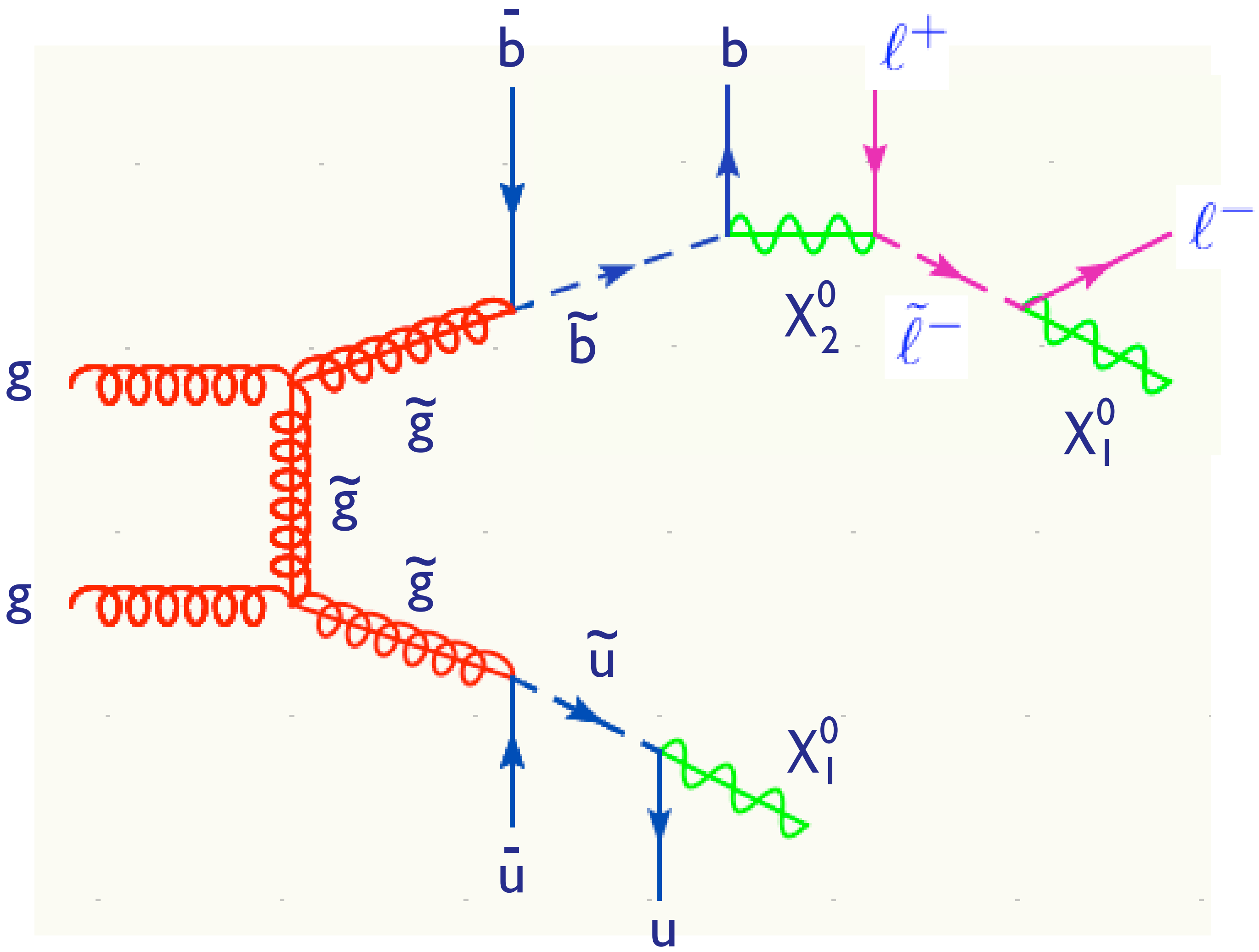
1. production and decay are factorized.
2. Spin is ignored.
3. Chains proceed only through 1→2 decays.
4. The narrow width approximation is employed.
5. Non-resonant diagrams are ignored.

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

Decay chains in madgraph

[J. Alwall, T. Stelzer]

```
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

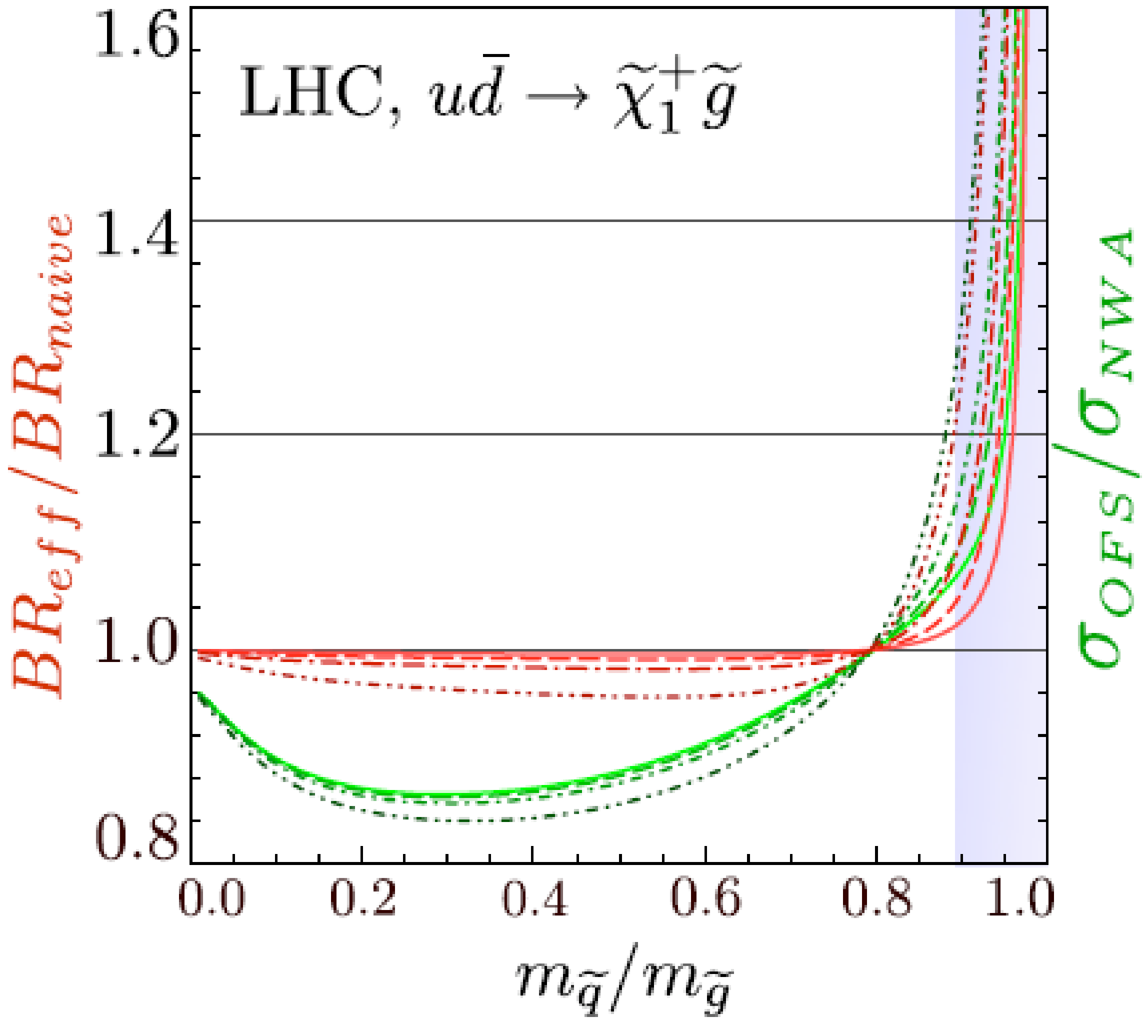
```
gg >(go>u~ul)(go>b~b1)
```

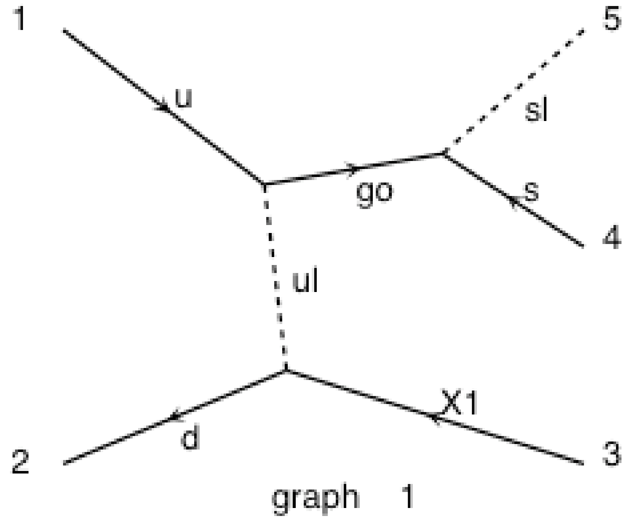
where the squarks can be decayed at the event level, for example by BRIDGE [Maede and Reece,2007]

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

Breakdown of the NW approximation

[Berdine, Kaur, Rainwater, PRL99, 2007]





$$u\bar{d} \to \tilde{\chi}_1^+ \bar{s}\tilde{s}_L$$

Non trivial behaviour which comes from the t-channel topology of the diagram.
Threshold effects when the gluino mass is close to the decay product mass (squark).

Conclusions

- Making discoveries at the LHC (most probably) won’t be easy.
- SM backgrounds and in particular those coming from QCD multi-jet processes are large and their detailed understanding will be needed.
- Remarkable progress in developing MC tools since the “2001 Revolution”. A new generation of codes to perform physics simulation is now available.
- These new tools can address basically all the needs from th and exp point of view (both top-down and bottom-up) for studying any Lagrangian based model at the LHC, including the good old SUSY.
- In my view, one of the most important outcomes of this effort is the emergence of a new framework where model builders, phenomenologists, MC developers and experimentalists collaborate in an effective way.

Conclusions

- Making discoveries at the LHC (most probably) won't be easy.
- SM backgrounds and in particular those coming from QCD multi-jet processes are large and their detailed understanding will be needed.
- Remarkable progress in developing MC tools since the "2001 Revolution". A new generation of codes to perform physics simulation is now available.
- These new tools can address basically all the needs from th and exp point of view (both top-down and bottom-up) for studying any Lagrangian based model at the LHC, including the good old SUSY.
- In my view, one of the most important outcomes of this effort is the emergence of a new framework where model builders, phenomenologists, MC developers and experimentalists collaborate in an effective way.

Eagerly waiting for data...