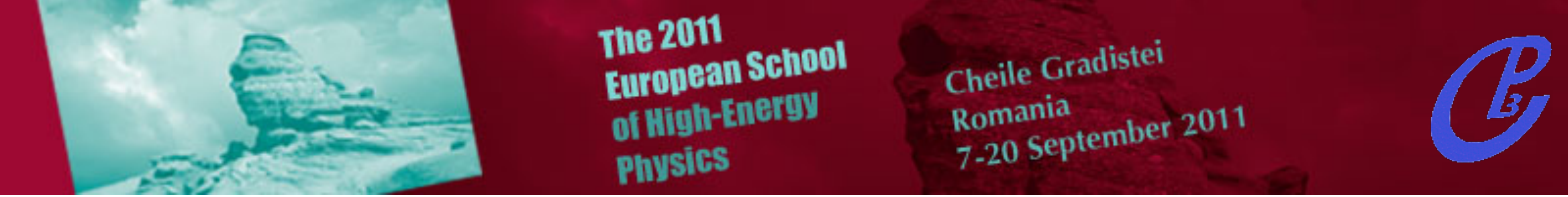

Basics of QCD for the LHC

Lecture V

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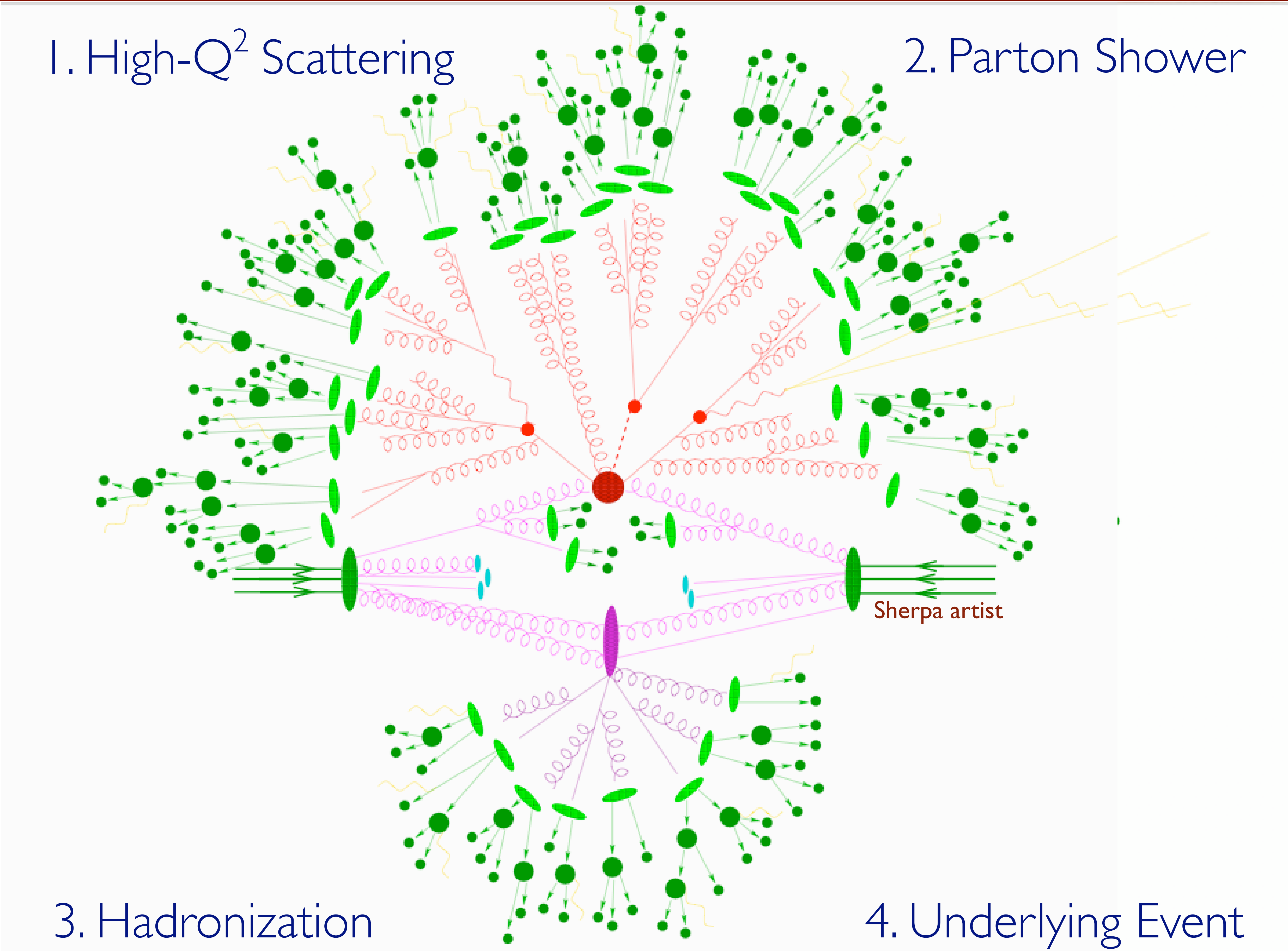
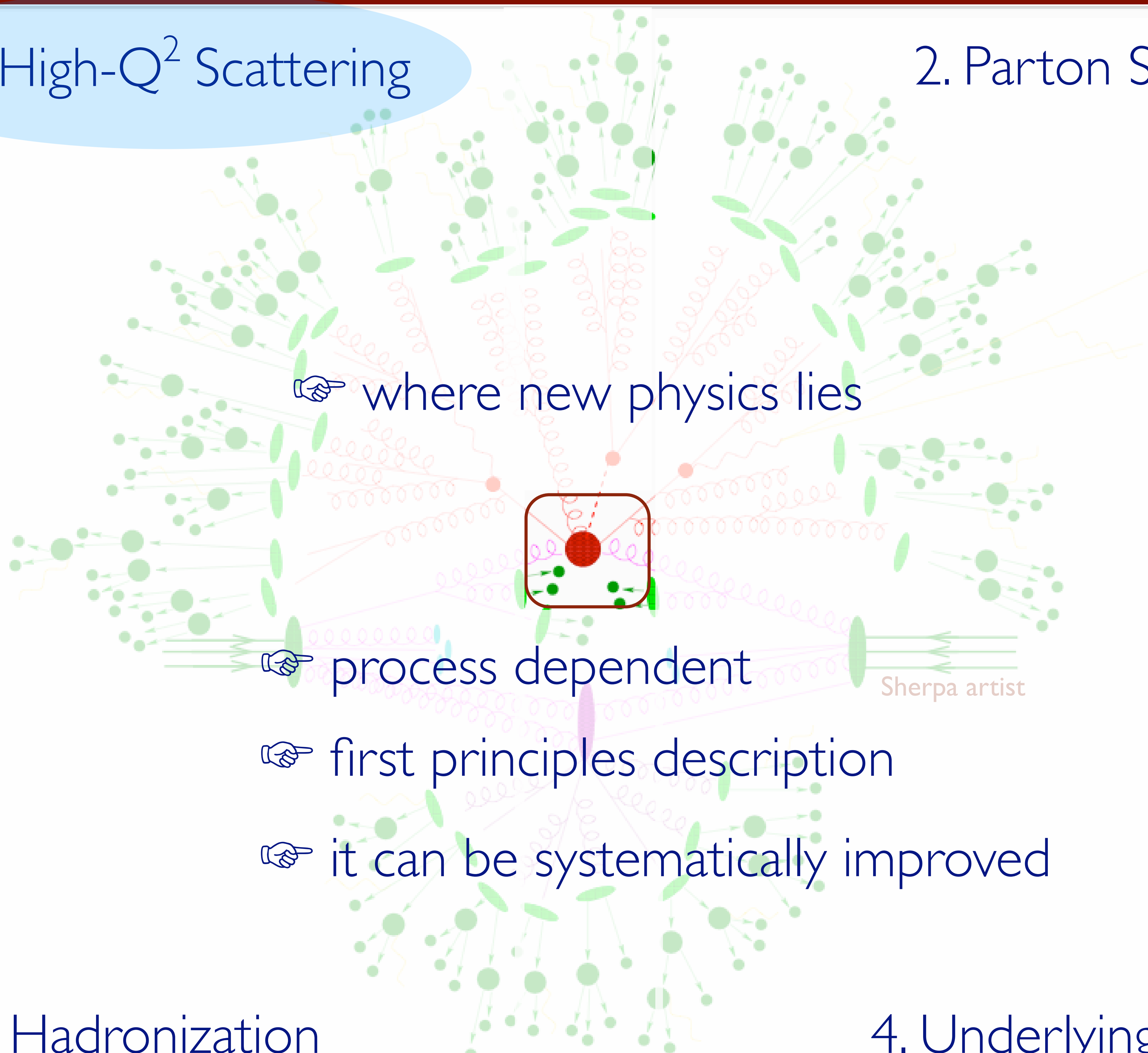
How do we make predictions?

1. Fixed order computations: from LO to NNLO — TH-Accurate
2. Parton showers and fully exclusive simulations — EXP-Useful

In other words we enter here the realm of the proper Monte Carlo Event generators!

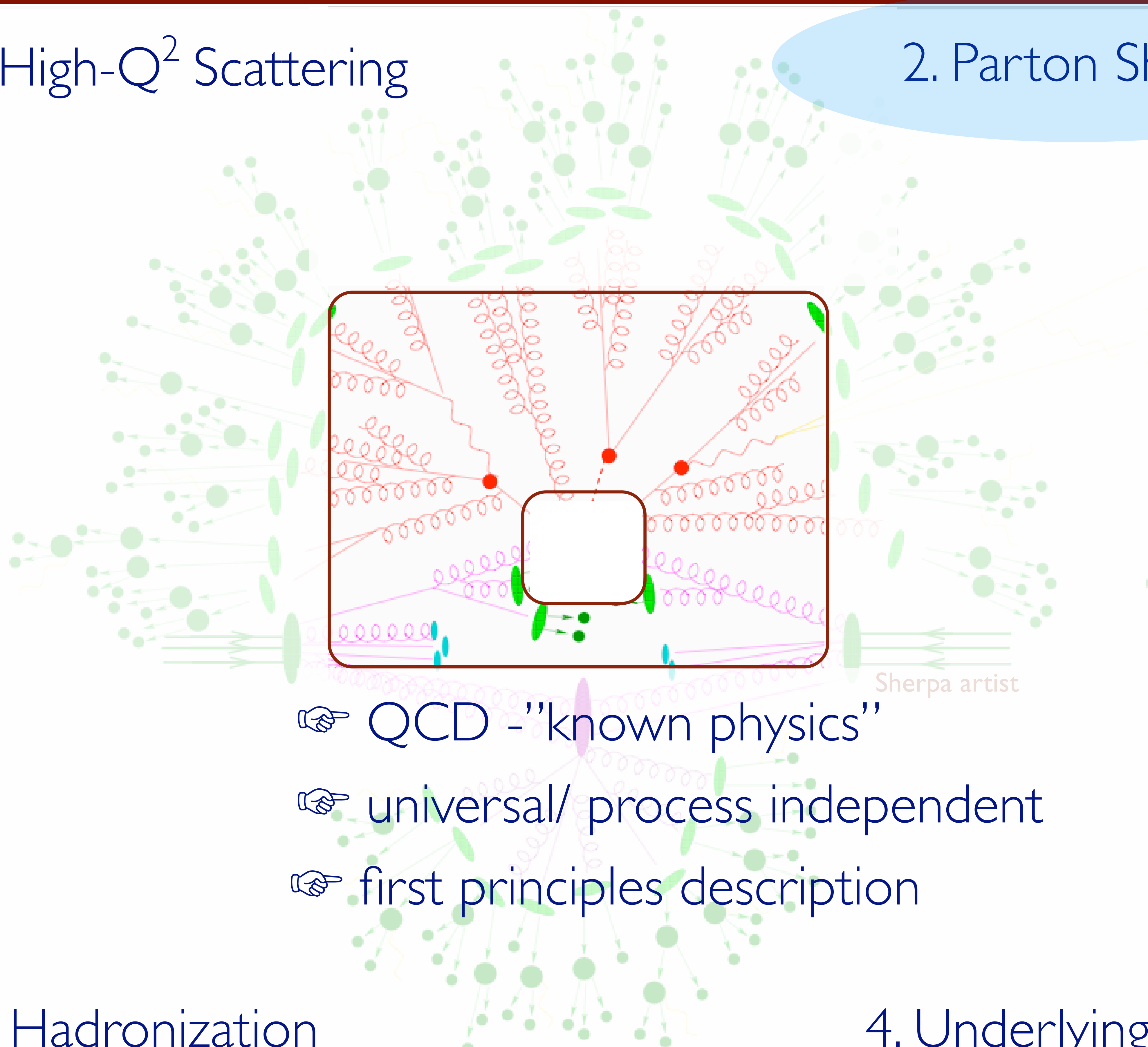

1. High-Q^2 Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event
Sherpa artist



- ☞ where new physics lies
- ☞ process dependent
- ☞ first principles description
- ☞ it can be systematically improved

1. High-Q^2 Scattering

2. Parton Shower



☞ QCD -"known physics"

☞ universal/ process independent

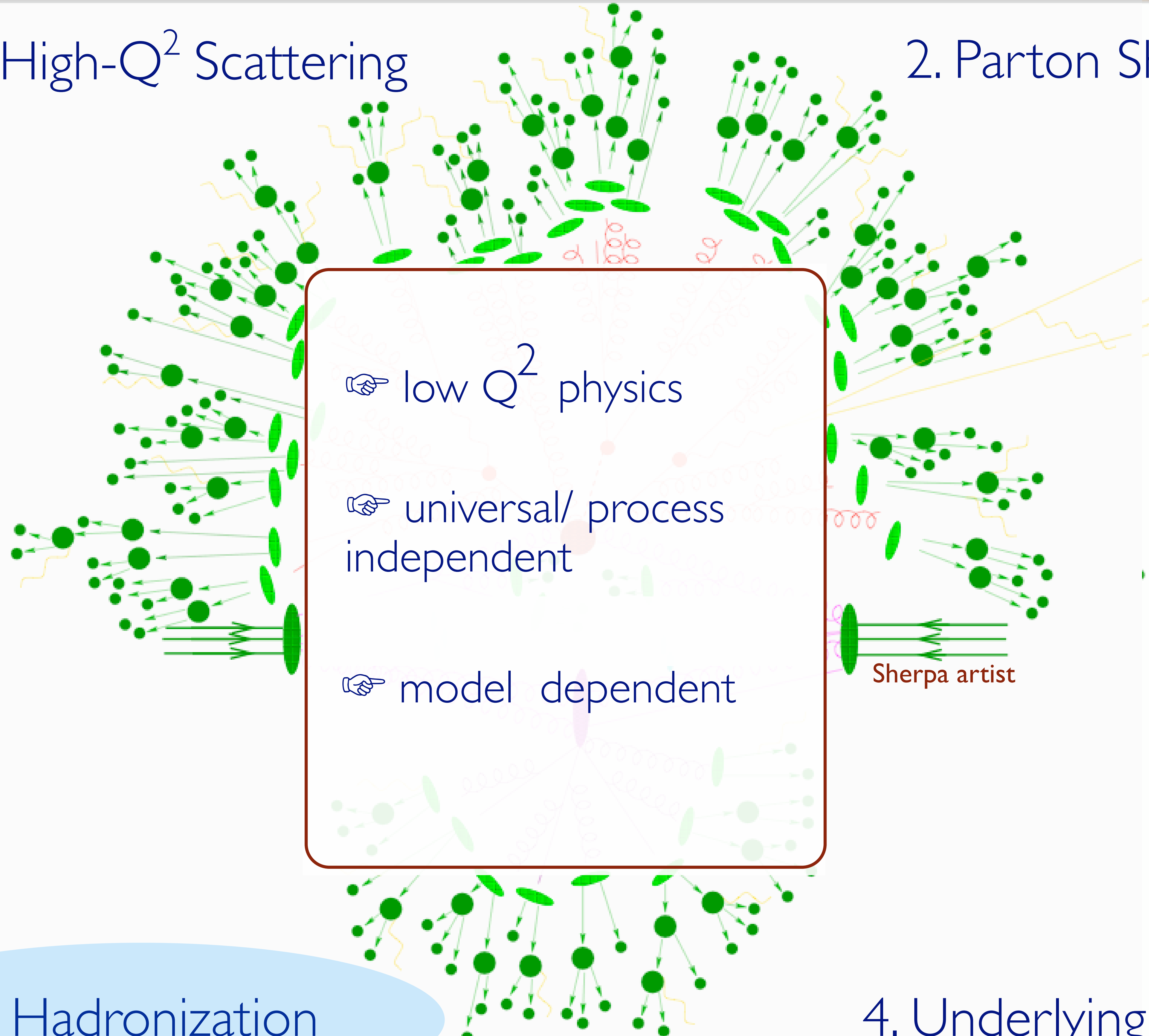
☞ first principles description

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



Sherpa artist

☞ low Q^2 physics

☞ universal/ process independent

☞ model dependent

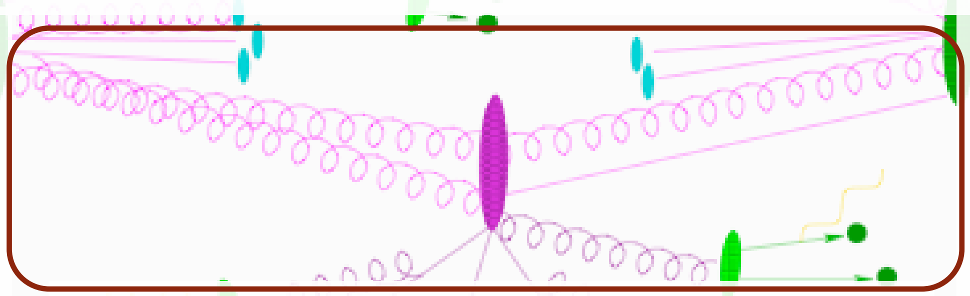
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

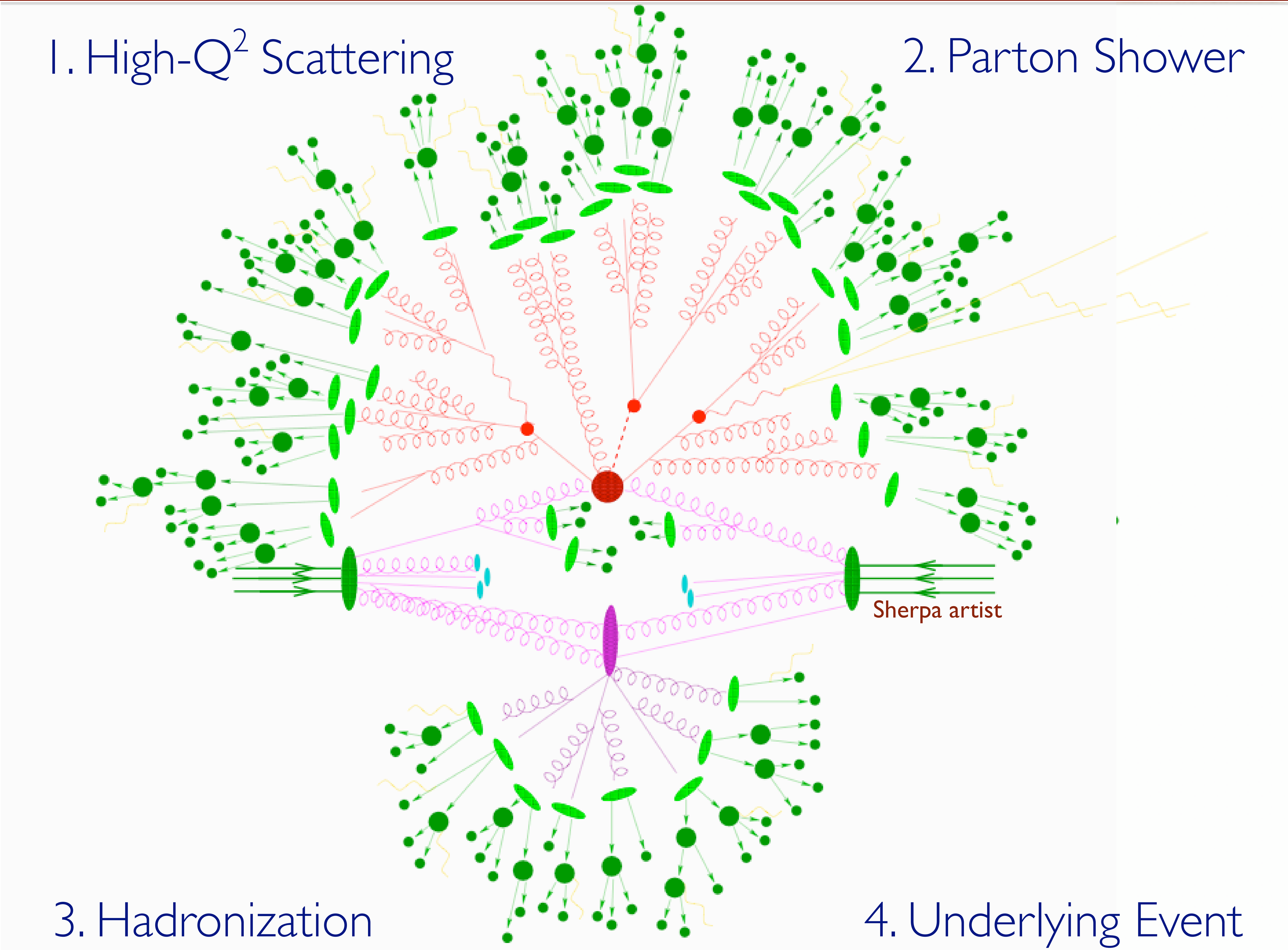
- low Q^2 physics
- energy and process dependent
- model dependent



Sherpa artist

3. Hadronization

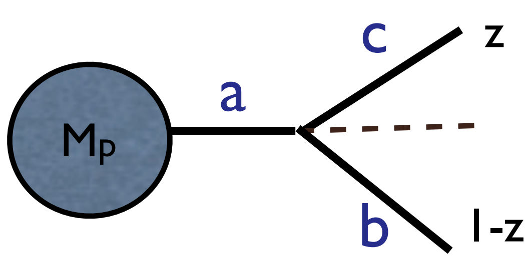
4. Underlying Event



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

Parton showers

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



$$z = E_b/E_a\,, t = k_a^2$$

$$\begin{aligned}\theta &= \theta_b + \theta_c \\ &= \frac{\theta_b}{1-z} = \frac{\theta_c}{z} \\ &= \frac{1}{E_a}\sqrt{\frac{t}{z(1-z)}}\end{aligned}$$

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

$$\begin{aligned} d\sigma_{N+1} &= d\sigma_N \frac{dt}{t}\frac{d\phi}{2\pi} dz \frac{\alpha_S}{2\pi} \left|K_{ba}(z)\right|^2 \\ d\bar\sigma_{N+1} &= d\bar\sigma_N \frac{dt}{t} dz \frac{\alpha_S}{2\pi} P_{ba}(z) \end{aligned}$$

In the collinear limit the cross section factorizes. The splitting can be iterated.

Parton showers

It is easy to iterate the branching process:

$$a(t) \longrightarrow b(z) + c\,, \quad b(t') \longrightarrow d(z') + e$$

$$d\bar{\sigma}_{N+2} = d\bar{\sigma}_N \frac{dt}{t} dz \frac{dt'}{t'} dz' \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ba}(z) P_{db}(z')$$

This is a generalized Markov process (in the continuum), where the probability of the system to change (discontinuosly) to another state, depends only on present state and not how it got there:

$$\tau_1 < \ldots < \tau_n \quad \Longrightarrow$$

$$P\Big(x(\tau_n) < x_n | x(\tau_{n-1}), \ldots, x(\tau_1)\Big) = P(x(\tau_n) < x_n | x(\tau_{n-1}))$$

No memory!

Parton showers

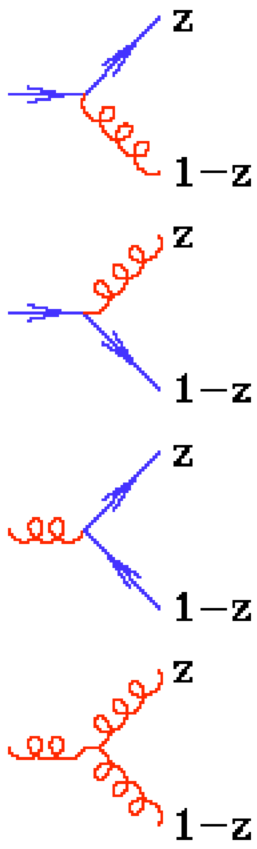
The spin averaged (unregulated) splitting functions for the various types of branching ar

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

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

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

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



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

Comments:
* Gluons radiate the most
* There are soft divergences in z=1 and z=0.
* Pqg has no soft divergences.

Parton showers

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

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

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

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

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

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

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

Parton showers

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

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

Simple interpretation. First term describes the evolution to Q_0, where no branching has occurred. The second term is the contribution coming from evolving with no branching up to a given t and then branching there. Now conservation of probability imposes that:

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

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

Parton showers

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

Which gives an explicit expression for the Sudakov form factor, i.e. la probability that a parton will not branch in going from the virtuality Q^2 to Q^2_0 .

Proof:

derive the conservation of probability equation

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

and impose the initial condition

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

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

Parton showers

Formulation in terms of Sudakov form factor is well suited to computer implementation, and is the basis of parton shower Monte Carlo programs. Let's rewrite the formula using p_T and a parton-level event at the Born level:

$$d\sigma^{\mathrm{PS}} = d\Phi_B B(\Phi_B)\left[\Delta(p_\perp^{\mathrm{min}}) + d\Phi_{R|B}\Delta(p_T(\Phi_{R|B}))\frac{R^{\mathrm{PS}}(\Phi_R)}{B(\Phi_B)}\right]$$

$$\Delta(p_T) = \exp\left[-\int d\Phi_{R|B}\frac{R^{\mathrm{PS}}(\Phi_R)}{B(\Phi_B)}\Theta(p_T(\Phi_R)-p_T)\right] \quad . \quad R^{\mathrm{PS}}(\Phi) = P(\Phi_{R|B})\,B(\Phi_B).$$

Monte Carlo branching algorithm operates as follows. Given an initial configuration (parton-level event at the Born level), a parton is chosen, a rnd value of p_T is chosen accordingly to the probability of non-emission down to p_T. If it is larger than a p_T^{min}, than a branching occurs at p_T, and x is generated according to the splitting function $P(\Phi_{R|B})$ (as well as a flat azimuthal angle). An extra parton is now included and the process starts from there.

Due to successive branching, a parton cascade or shower develops. Each outgoing line is source of a new cascade, until all lines have stopped branching. At this stage, which depends on p_T^{min}, outgoing partons have to be converted into hadrons.

Parton showers

What happens for the initial state?

In that case we operate an explicit deconstruction of the DGLAP evolution of the pdf "backward evolution" from high space-like Q^2 to lower Q^2, from smaller x fractions to larger ones.

The corresponding Sudakov therefore includes information on the pdf's:

$$\Delta_a^{\mathrm{ISR}}(Q^2, Q_0^2, x) = \exp\left[-\int_{Q_0^2}^{Q^2} \frac{dt}{t} \sum_b \int \frac{dz}{z} \frac{\alpha_S}{2\pi} P_{ab}(z) \frac{f(x/z,t)}{f(x,t)}\right]$$

The backward evolution can be thought as a way to solve the DGLAP evolution equations and find the t dependence of the pdf's. The pdf's guide the evolution towards the most probable regions of (t,x)-space.

Parton showers

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

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

and obtain

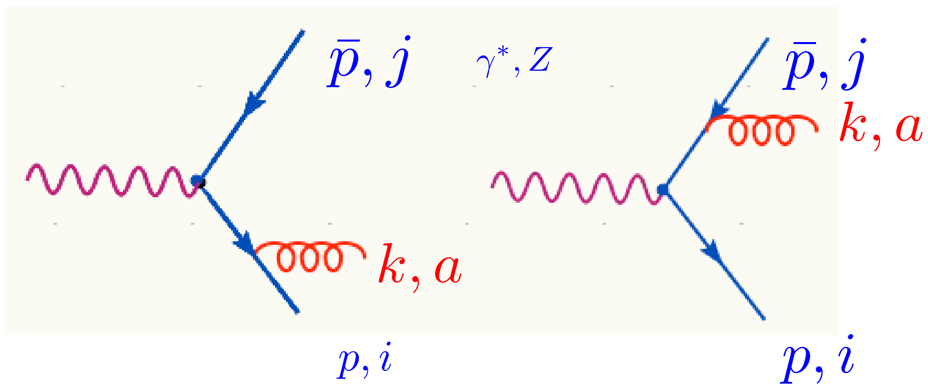
$$\frac{d\theta^2}{\theta^2} = \frac{dQ^2}{Q^2} = \frac{dp_T^2}{p_T^2} = \frac{d\tilde{t}}{\tilde{t}}$$

Different MC programs make different choices for the variable. HERWIG uses θ, while Pythia uses p_T.

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

Differences stem from the SOFT region. It is therefore necessary to study what happens for soft emissions to find the optimal choice.

Angular ordering



$$d\sigma_{qqg} = C_F \frac{\alpha_S}{2\pi} \sigma^{\rm Born} d\cos\theta \frac{dk^0}{k^0} \frac{d\phi}{2\pi} \frac{1-\cos\theta_{ij}}{(1-\cos\theta_{ik})(1-\cos\theta_{jk})} d\cos\theta$$

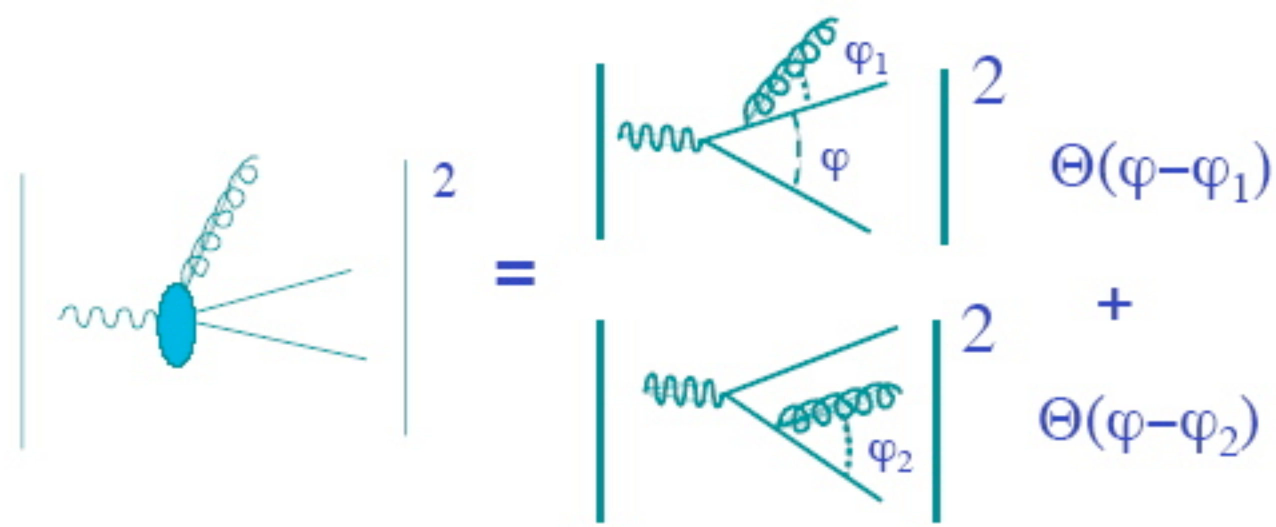
You can easily prove that:

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

The probabilistic interpretation of W_i and W_j is achieved simply by azimuthal averaging:

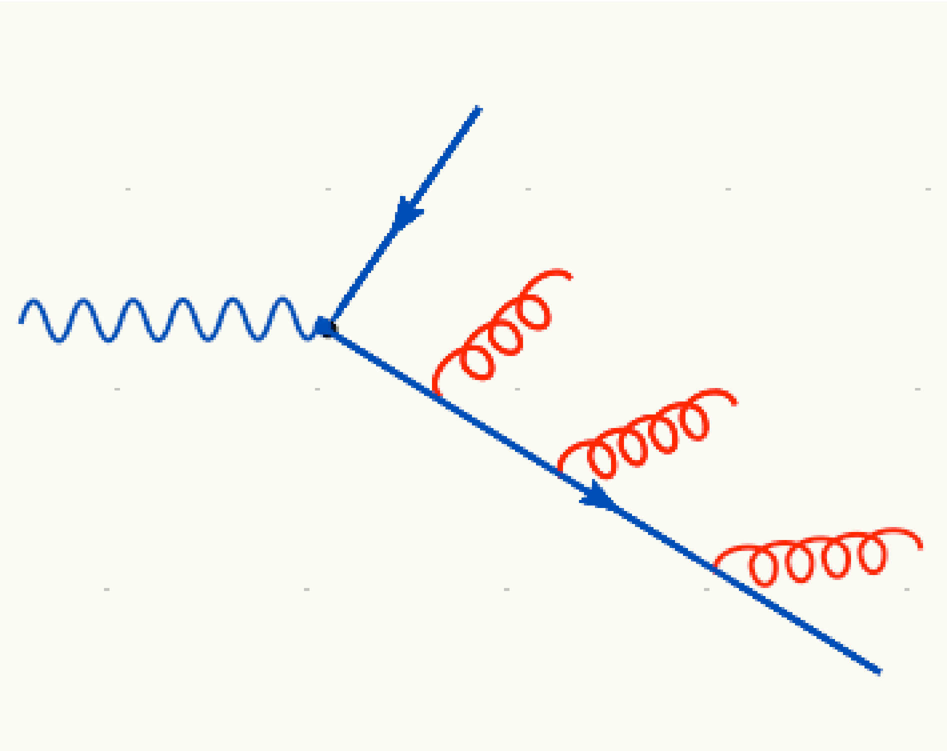
$$\int \frac{d\phi}{2\pi} W_i = \frac{1}{1-\cos\theta_{ik}} \quad \text{if} \quad \theta_{ik} < \theta_{ij}\,, 0\,\text{otherwise}$$

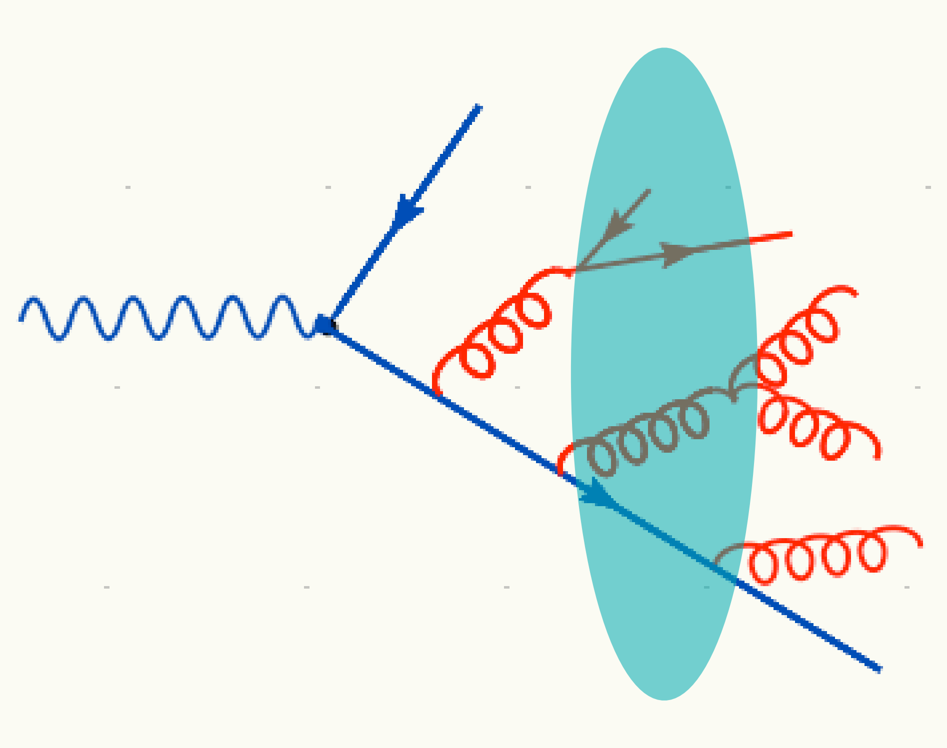
And the same for W_j



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

Angular ordering





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

One can generalize it to a generic parton of color charge Qk splitting into two partons i and j , Qk=Qi +Qj. 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 Qk.

KEY POINT FOR THE MC!

Angular ordering is automatically satisfied in p_T and θ ordered showers!

Angular ordering

Angular ordering is:

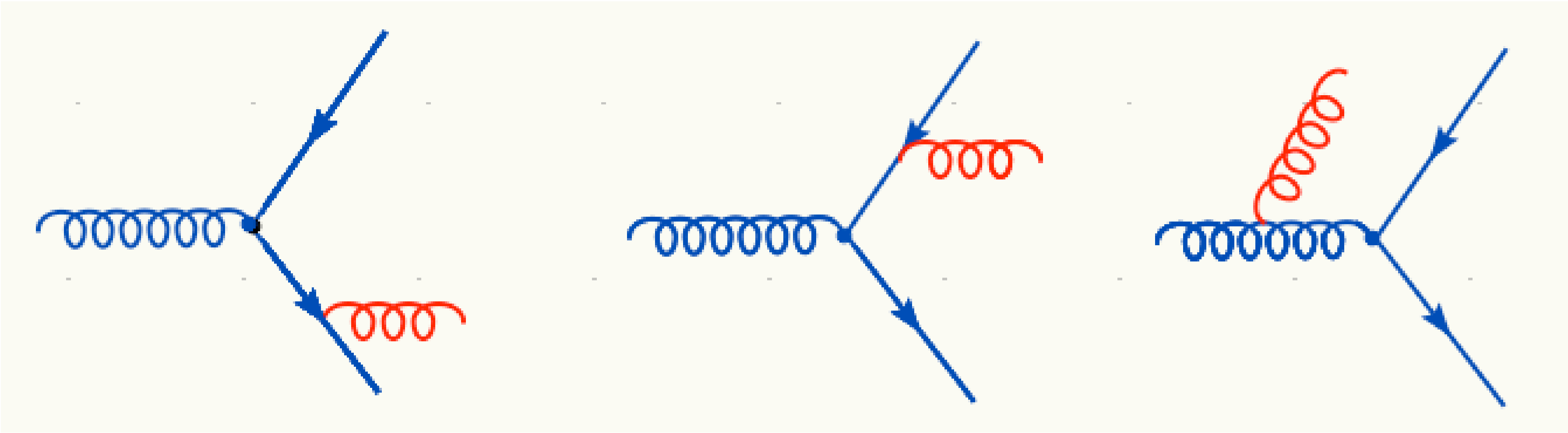
1. A quantum effect coming from the interference of different Feynman diagrams.

2. Nevertheless it can be expressed in "a classical fashion" (square of a amplitude is equal to the sum of the squares of two special "amplitudes"). The classical limit is the dipole-radiation.

3. It is not an exclusive property of QCD (i.e., it is also present in QED) but in QCD produces very non-trivial effects, depending on how particles are color connected.

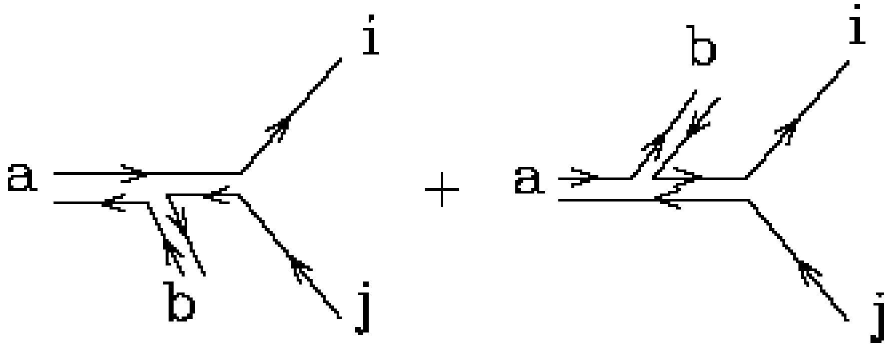
Angular ordering

How does look the amplitude for a soft-emission in a qqg system? (Virtual photon not shown, coming out of the screen)



$$A_{soft} = -g_s \left\{ (t^a t^b)_{ij} \left[\frac{Q\cdot\epsilon}{Q\cdot k} - \frac{\bar{p}\cdot\epsilon}{\bar{p}\cdot k} \right] - (t^b t^a)_{ij} \left[\frac{p\cdot\epsilon}{p\cdot k} - \frac{Q\cdot\epsilon}{Q\cdot k} \right] \right\} A_{Born}$$

The two terms correspond to the two possible ways colour can flow in these diagrams:



The interference between the two color structures is suppressed by 1/Nc2:

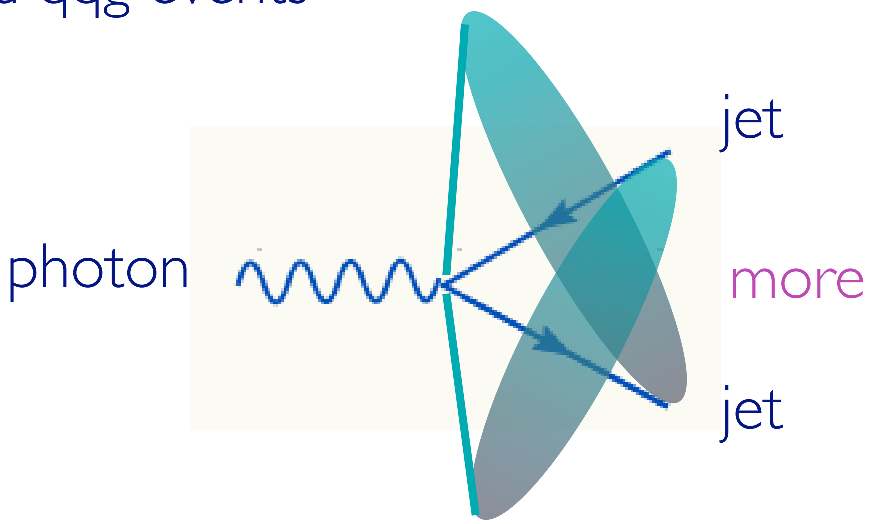
$$\sum_{a,b,i,j} |(t^a t^b)|^2 = \frac{N_c^2-1}{2}\frac{N_c^2-1}{2N_c} = O(N_c^3) \qquad \sum_{a,b,i,j} (t^a t^b)(t^b t^a)^\dagger = \frac{N_c^2-1}{2}\left(-\frac{1}{2N_c}\right) = O(N_c)$$

In the large Nc limit, this is equivalent to the incoherent sum of the emission from the two currents.

Angular ordering

(a) amount of radiation between two quark-jets in qqγ and qqg events

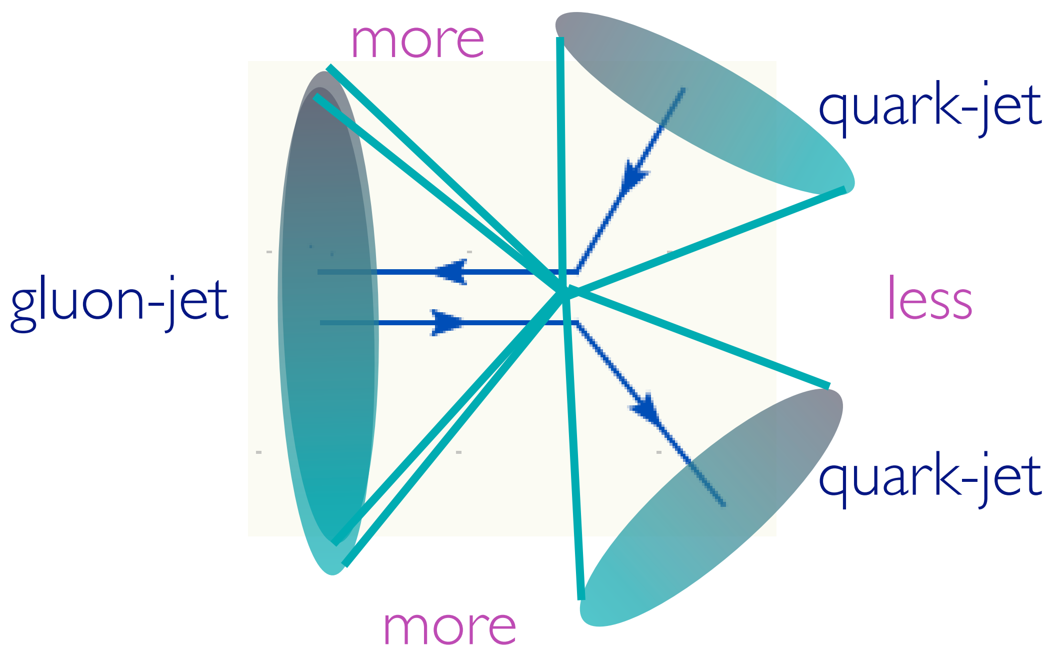
$$\frac{dN_{q\bar{q}}^{(q\bar{q}\gamma)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{2(N_c^2-1)}{N_c^2-2} = \frac{16}{7}$$



$$(\text{experiment} : 2.3 \pm 0.2)$$

(b) radiation between the qg and qq

$$\frac{dN_{qg}^{(q\bar{q}g)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{5(N_c^2-1)}{2N_c^2-4} = \frac{22}{7}$$



Parton Shower MC event generators

A parton shower program associates one of the possible histories (and pre-histories in case of pp) of an hard event in an explicit and fully detailed way, such that the sum of the probabilities of all possible histories is unity.

- 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.

Complete MC Generators: PYTHIA, HERWIG, SHERPA

Lectures

1. Intro and QCD fundamentals
2. QCD in the final state
3. QCD in the initial state
4. From accurate QCD to useful QCD
5. Advanced QCD with applications at the LHC

CAN WE MAKE ACCURATE AND REALISTIC PREDICTIONS?

Accurate:

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

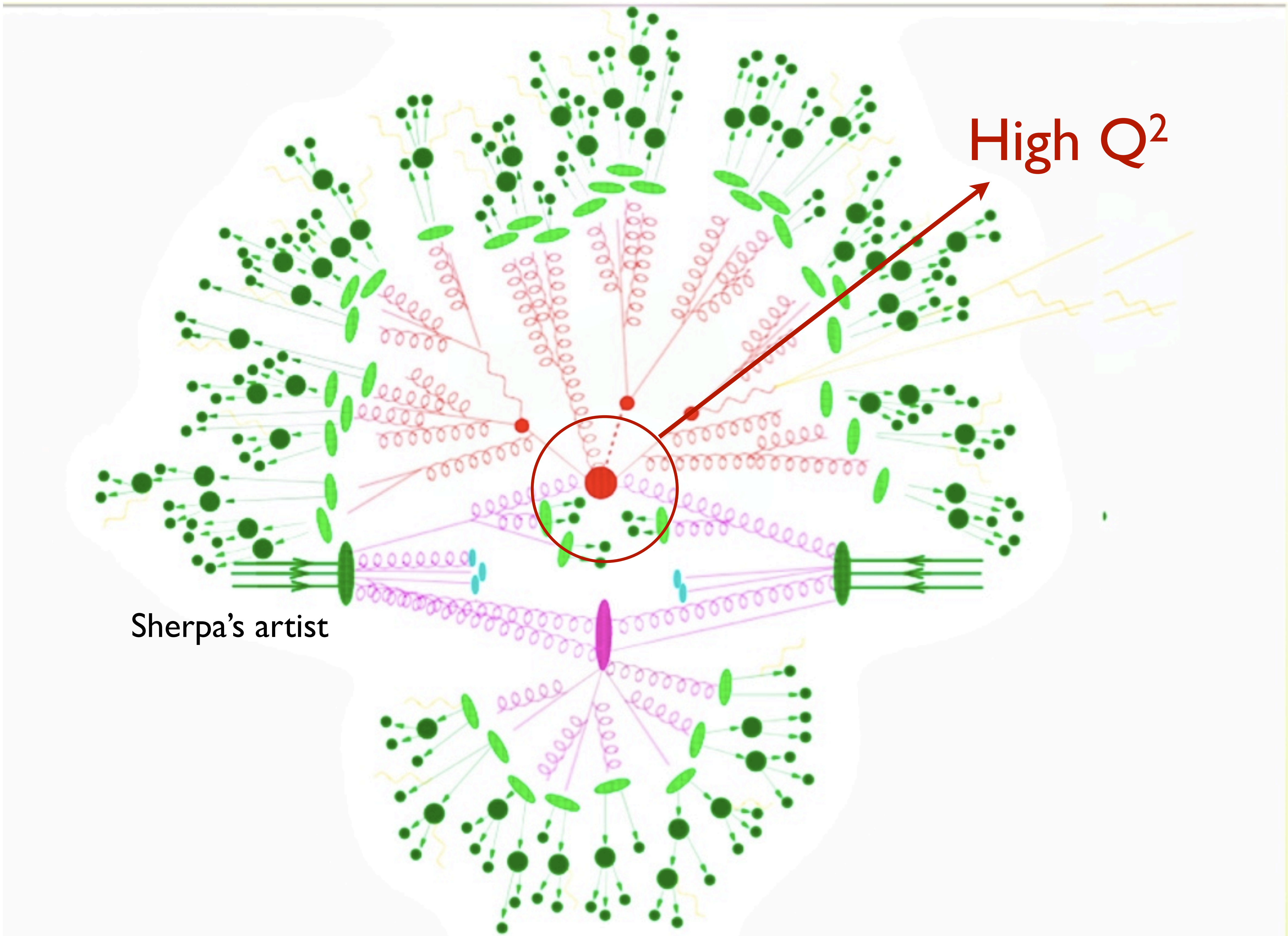
$$\Rightarrow \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

- We use the corresponding evolution in the PDF's

Comments:

1. The theoretical errors systematically decrease.
2. A lot of new techniques and universal algorithms have been developed.
3. The frontier is now NNLO!
4. Final description only in terms of partons

and calculation of IR safe observables ⇒ not directly useful for exp simulations.


High Q^2
Sherpa's artist

CAN WE MAKE ACCURATE AND REALISTIC PREDICTIONS?

Realistic:

- Describe final states with high multiplicities starting from $2 \to 1$ or $2 \to 2$ procs, using parton showers

$$d\sigma^{\mathrm{PS}} = d\Phi_B B(\Phi_B) \left[\Delta(p_\perp^{\mathrm{min}}) + d\Phi_{R|B} \Delta(p_T(\Phi_{R|B})) \frac{R^{\mathrm{PS}}(\Phi_R)}{B(\Phi_B)} \right]$$

$$\Delta(p_T) = \exp\left[- \int d\Phi_{R|B} \frac{R^{\mathrm{PS}}(\Phi_R)}{B(\Phi_B)} \Theta(p_T(\Phi_R) - p_T) \right] \quad \cdot \quad R^{\mathrm{PS}}(\Phi) = P(\Phi_{R|B})\, B(\Phi_B).$$

(no or first emisssion) and then a hadronization model.

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.

CAN WE MAKE ACCURATE AND REALISTIC PREDICTIONS?

Fixed order prediction

1. parton-level description
2. fixed order calculation
3. quantum interference exact
4. valid for few partons
4. NLO results available

Shower MC

1. hadron-level description
2. resums large logs
3. quantum interference through angular ordering
4. valid when partons are collinear and/or soft
5. nedeed for realistic studies

Approaches are complementary: merge them!

Difficulty: avoid double counting

CAN WE MAKE ACCURATE AND REALISTIC PREDICTIONS?

New Trend:

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

Three directions:

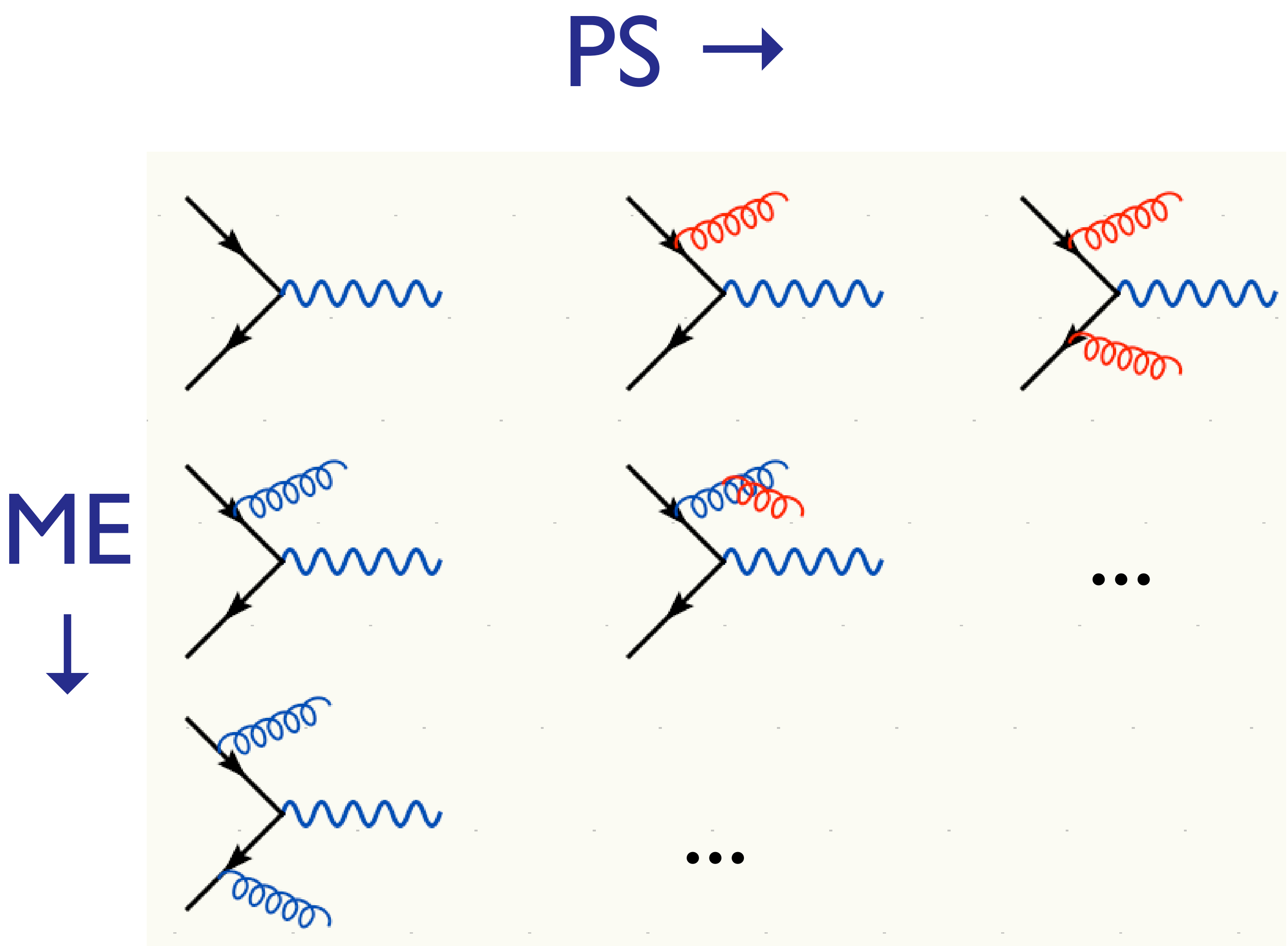
1. Get fully exclusive description of many parton events correct at LO (LL) in all the phase space. **MEPS**

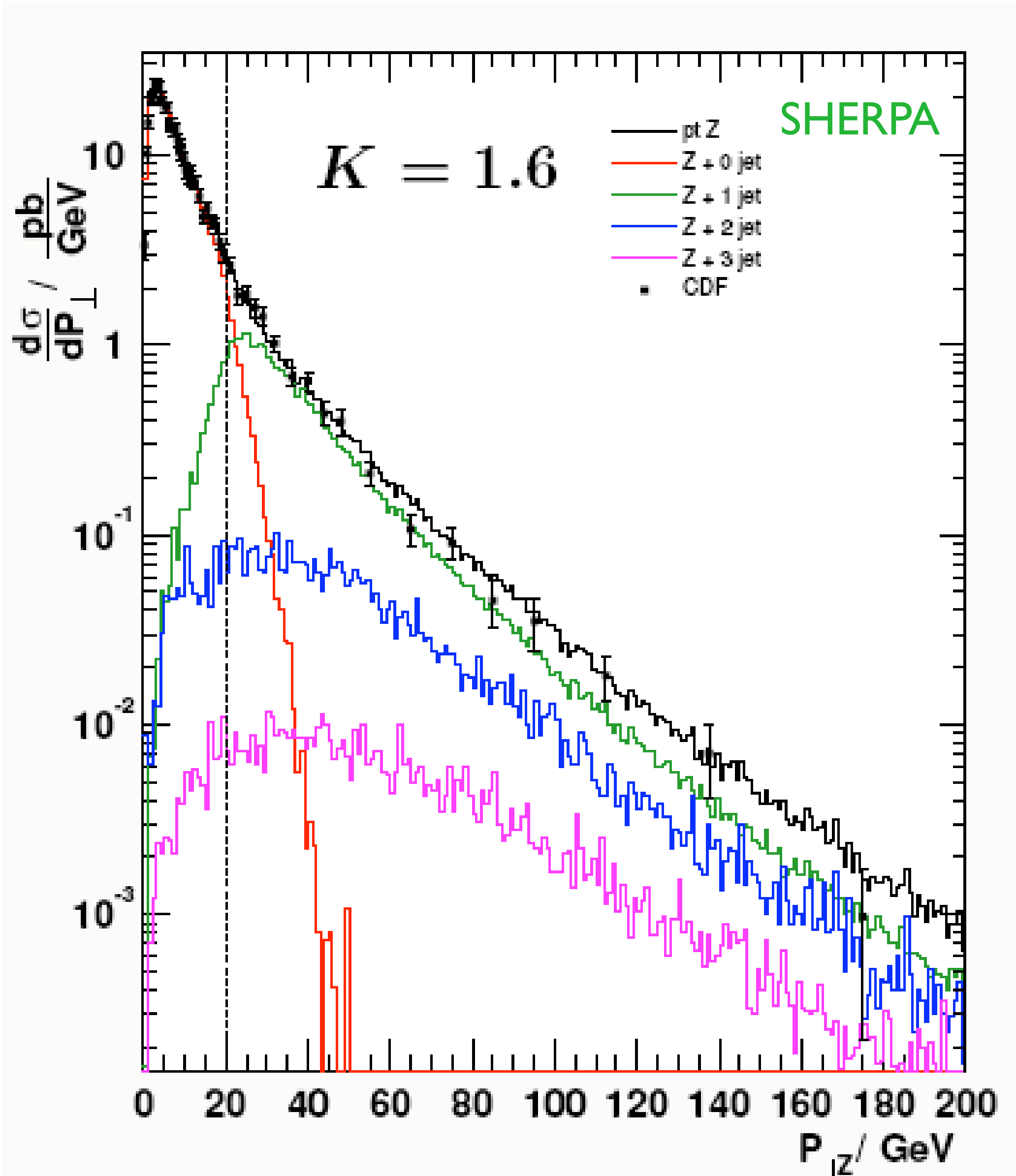
2. Get fully exclusive description of events correct at NLO in the normalization and distributions. **NLOwPS**

3. Get fully exclusive descriptions at NLO with multi-parton matching for higher multiplicities. **MENLOPS**

Merging fixed order with PS

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



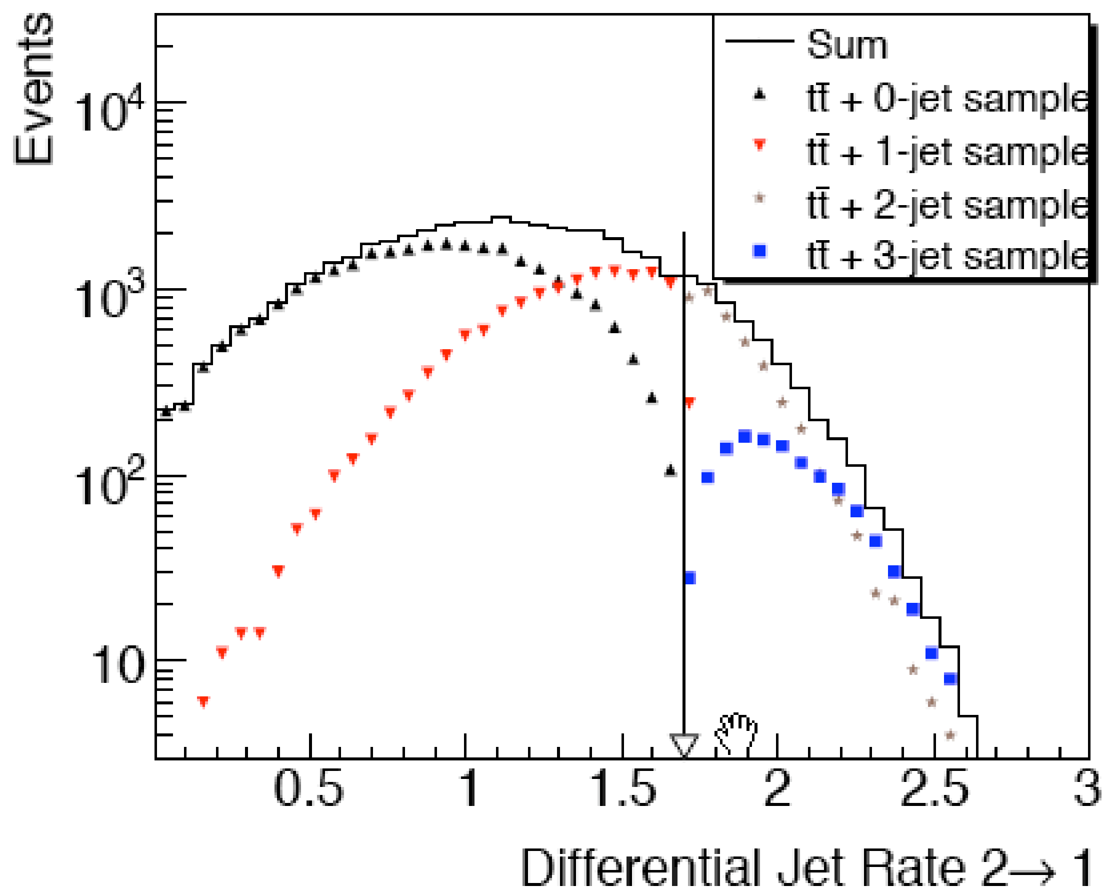


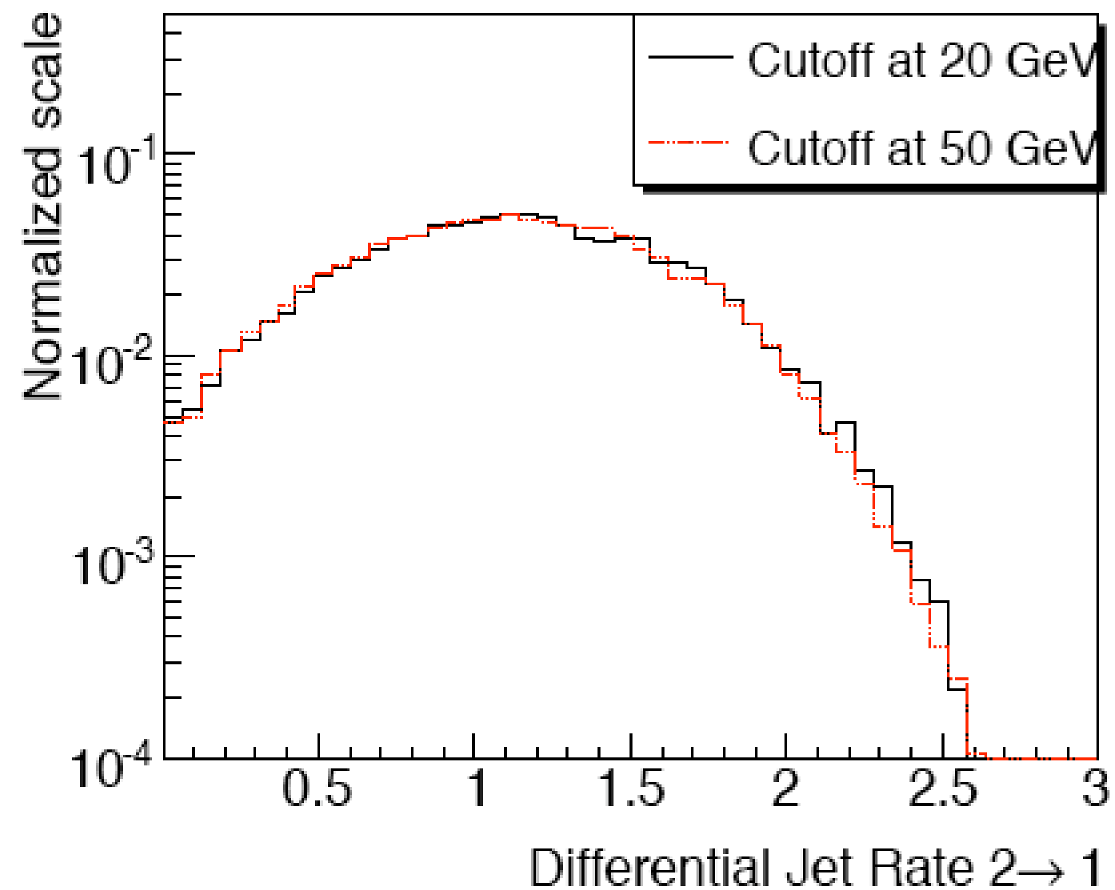
Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample.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

THE MLM MATCHING ALGORITHM

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

Sanity checks: differential jet rates

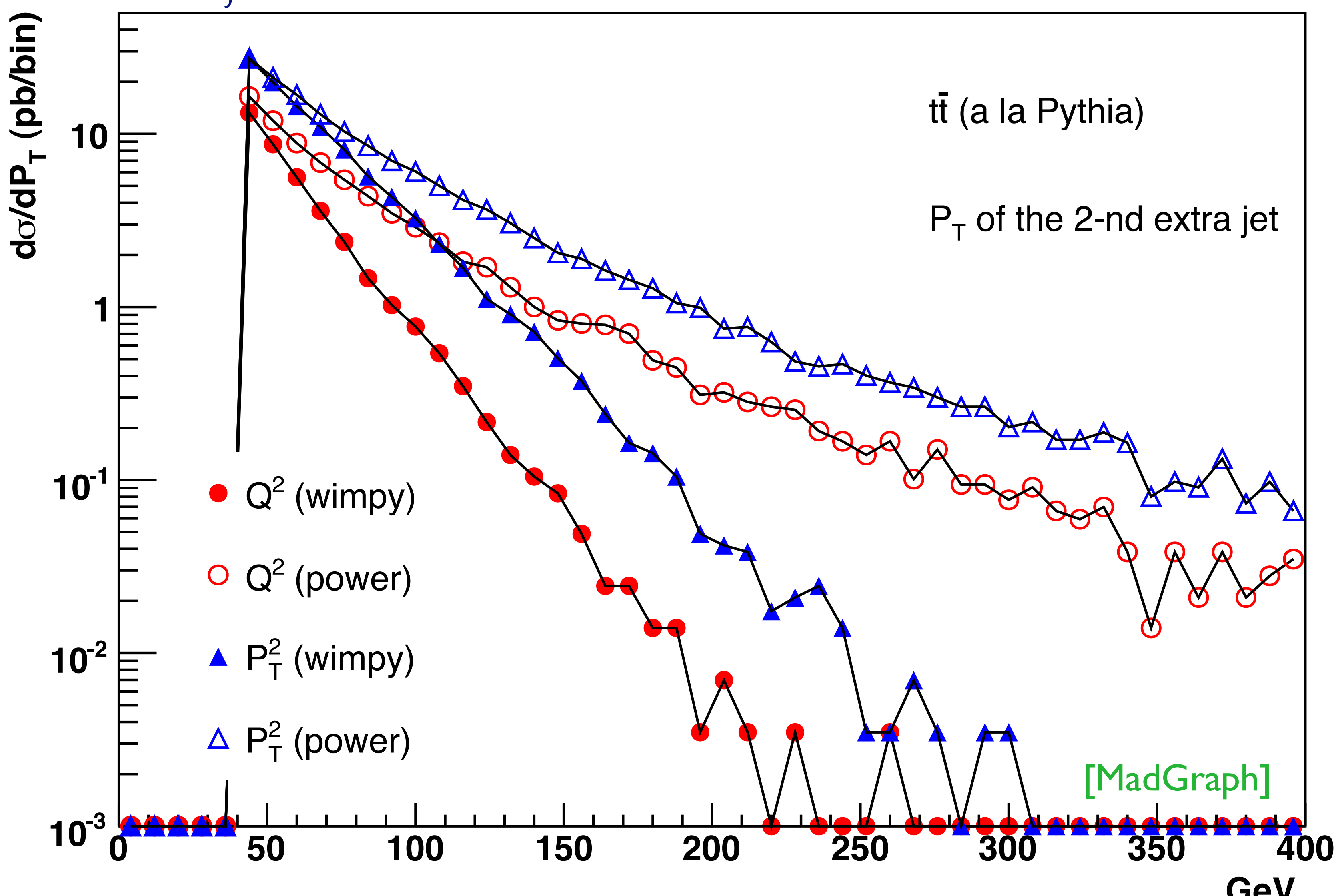




Jet rates are independent of and smooth at the cutoff scale

PS alone vs matched samples

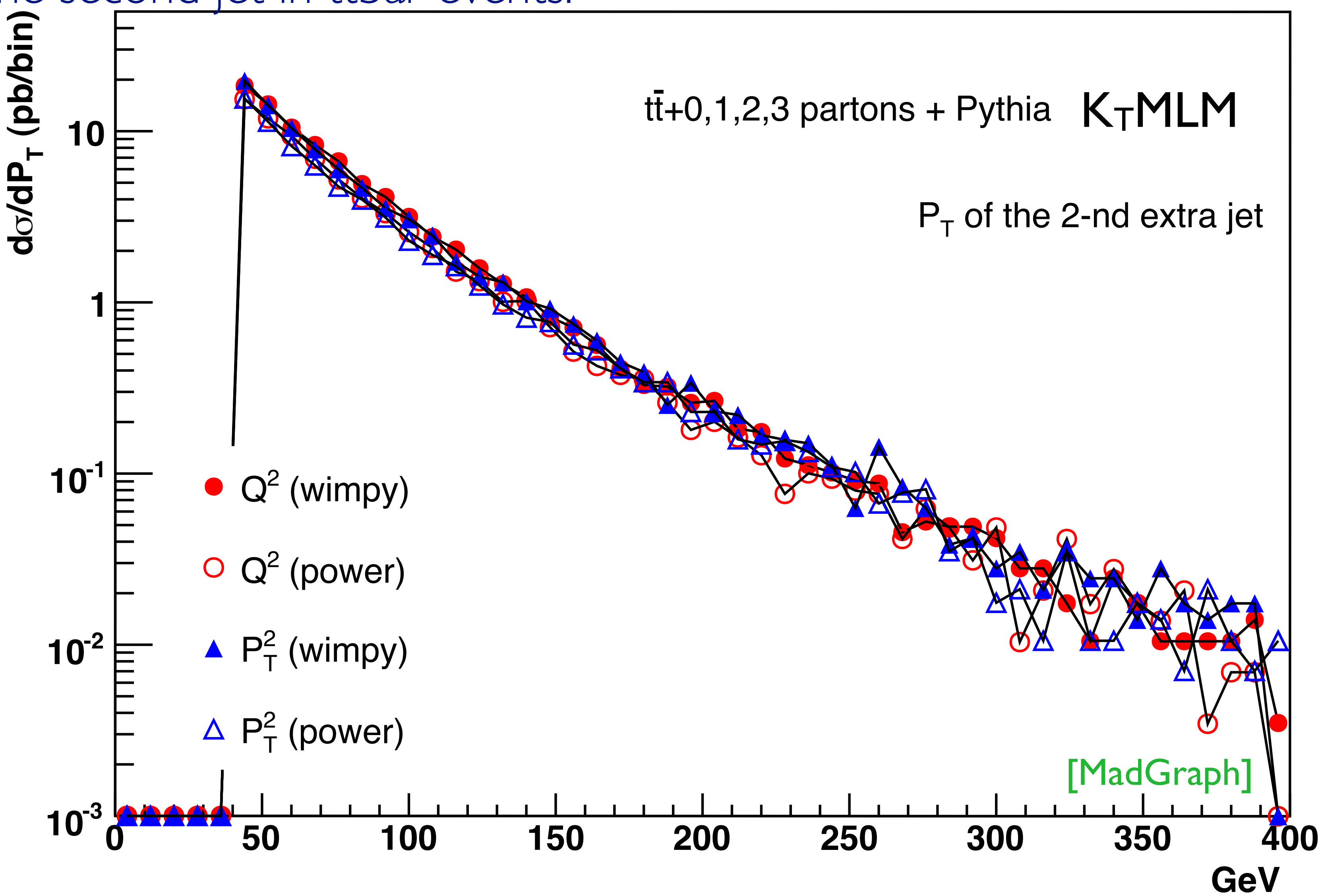
A MC Shower like Pythia produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution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



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

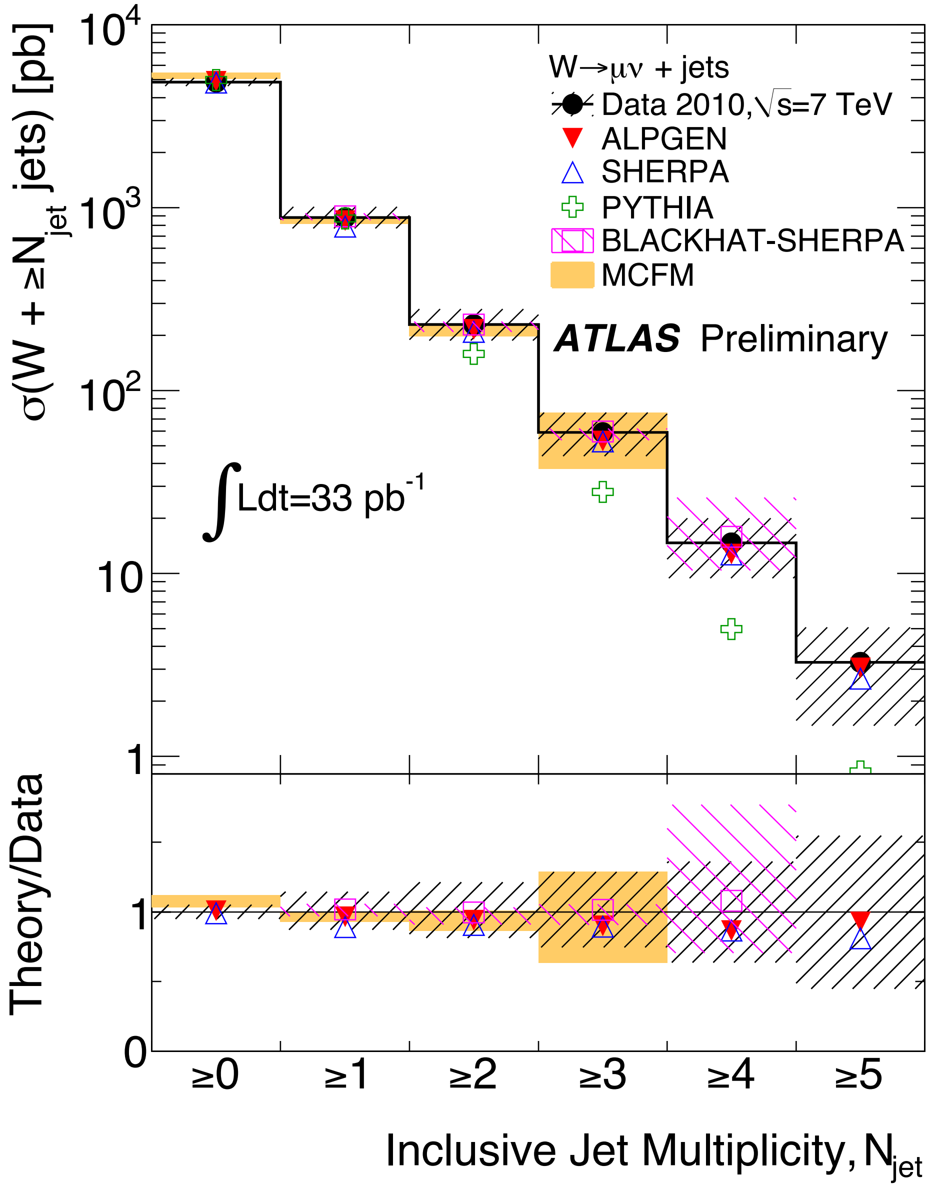
PS alone vs matched samples

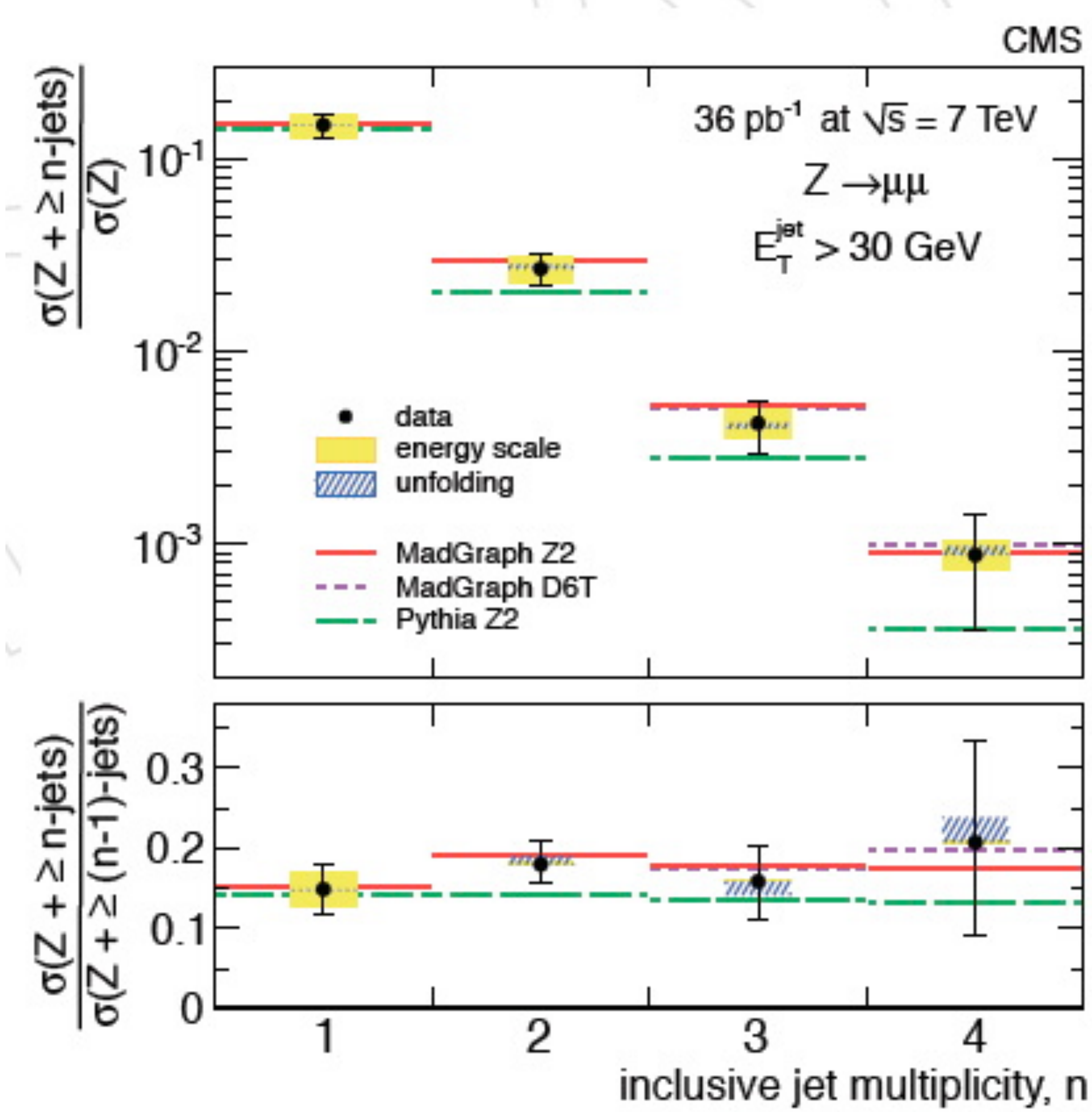
A MC Shower like Pythia produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution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



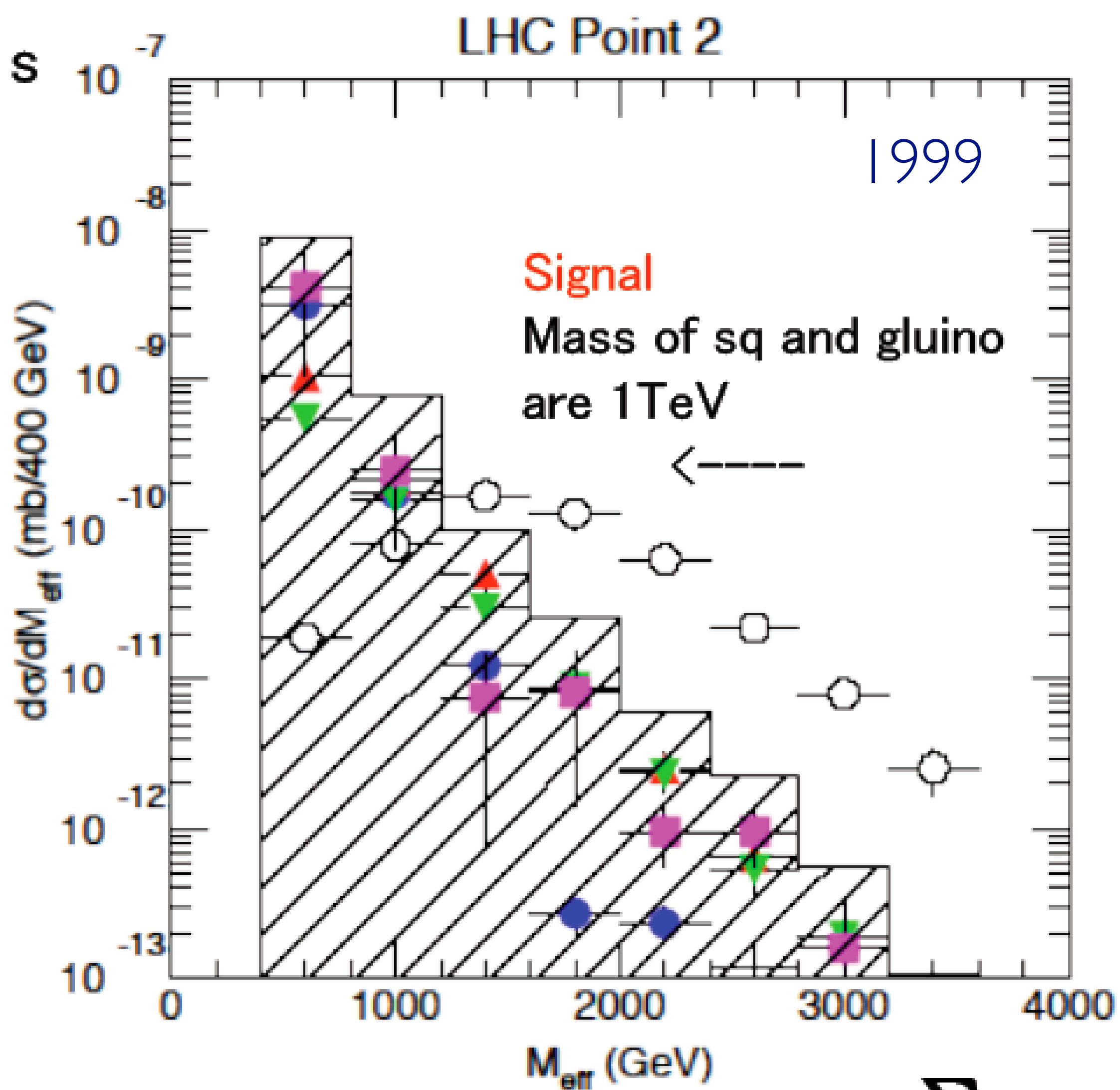
In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

TH/EXP comparison at the LHC

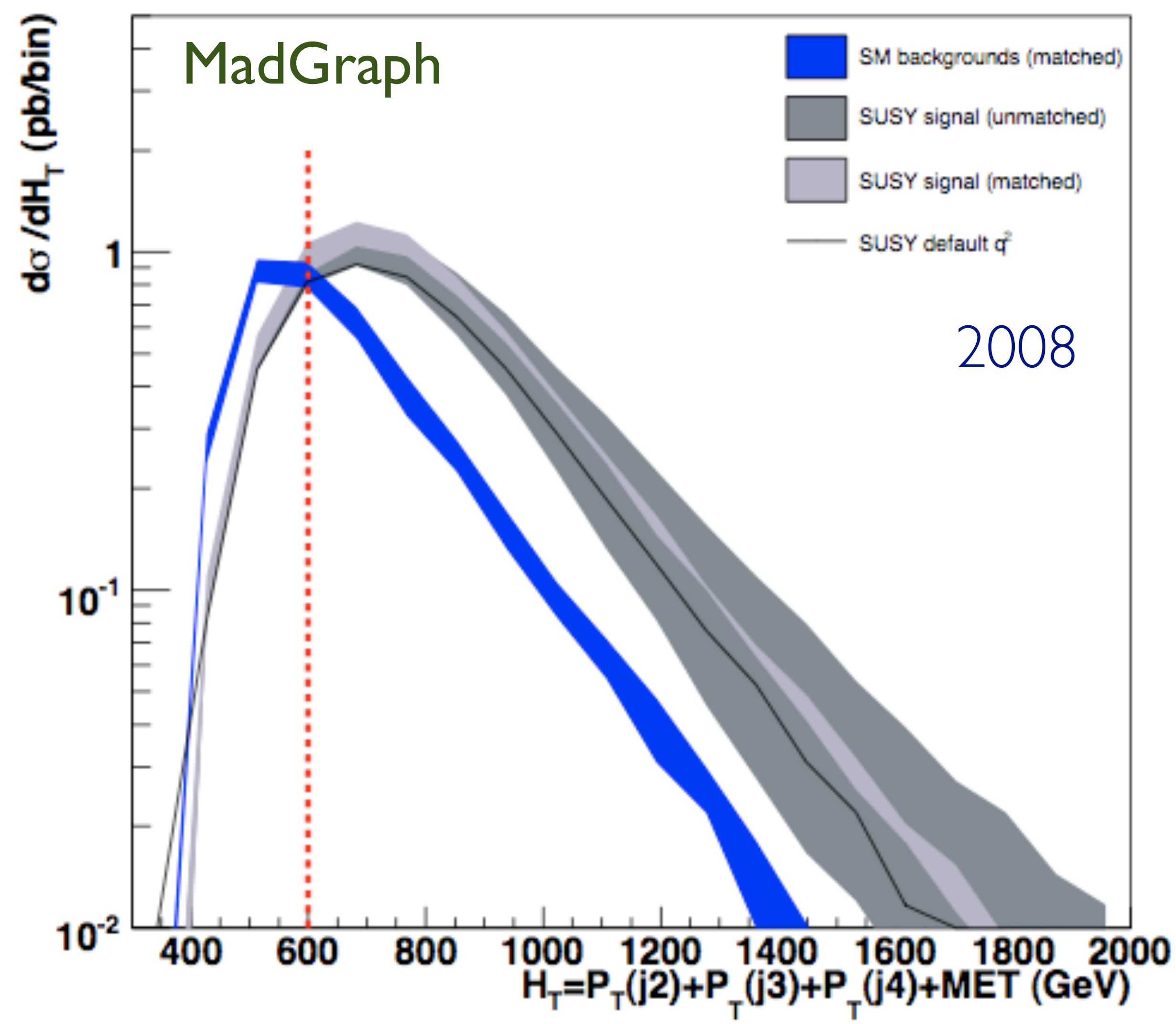




SUSY MATCHED SAMPLES



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



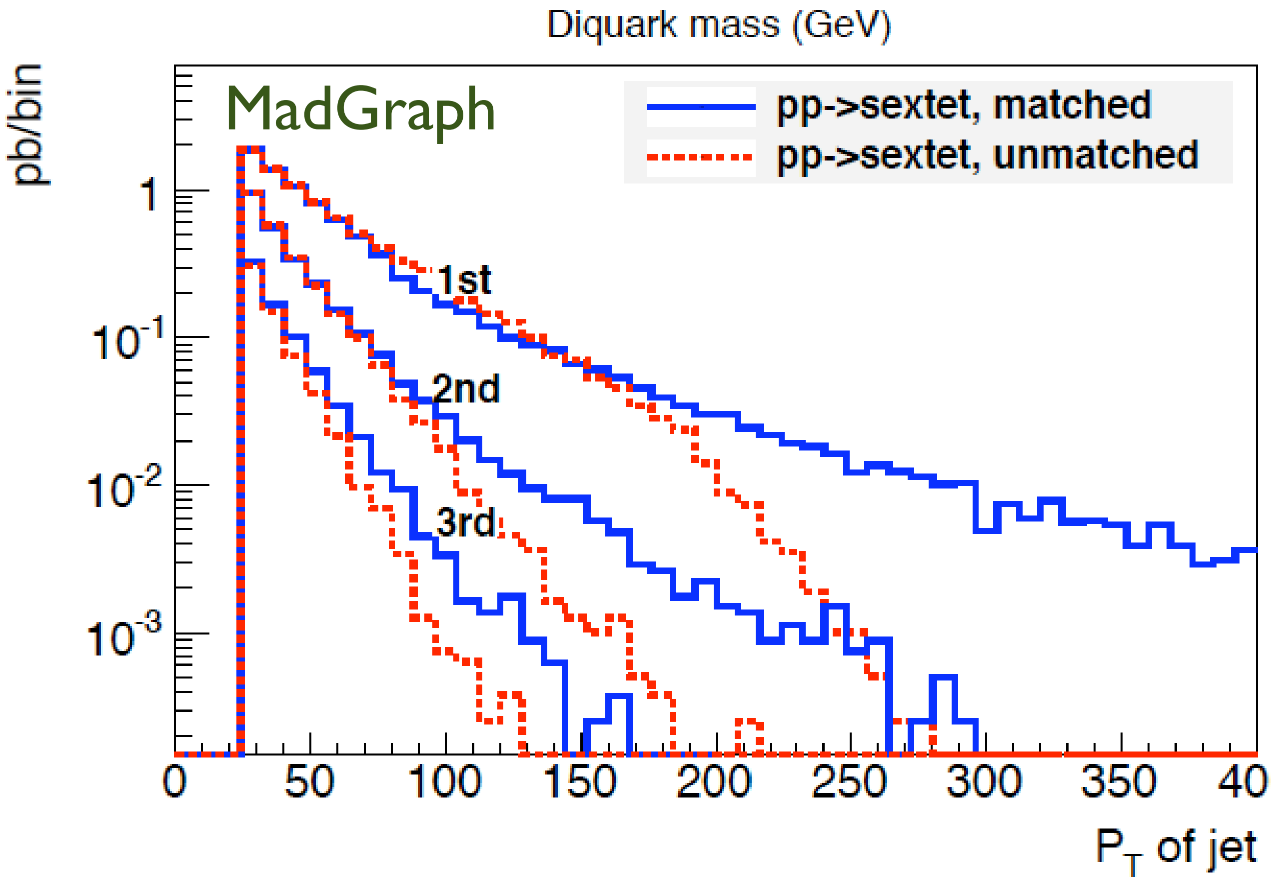
Both signal and background matched!

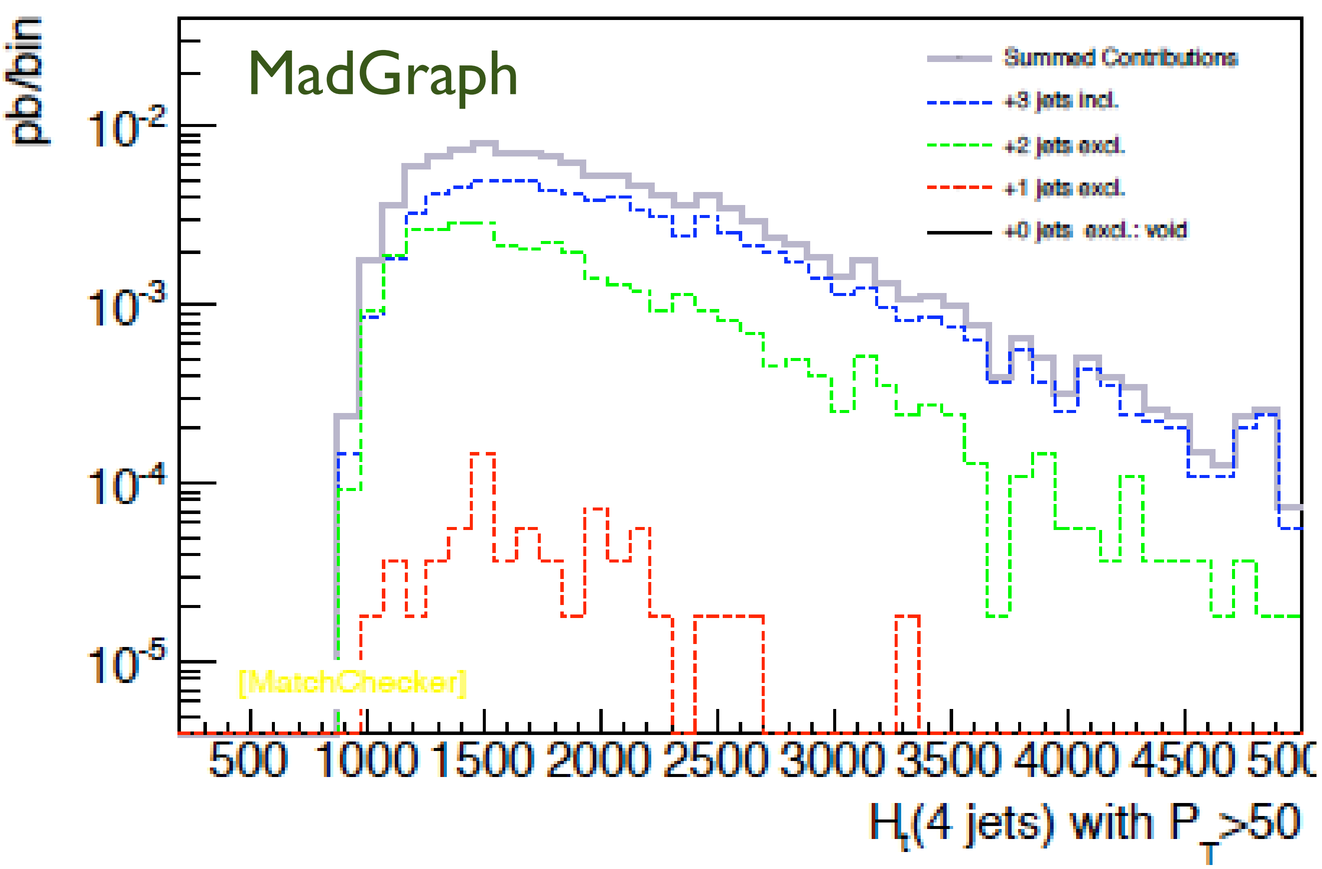
Sizable reduction of the uncertainties and simulation consistency .

Example: BSM multijet final states

pp→X6 +jets

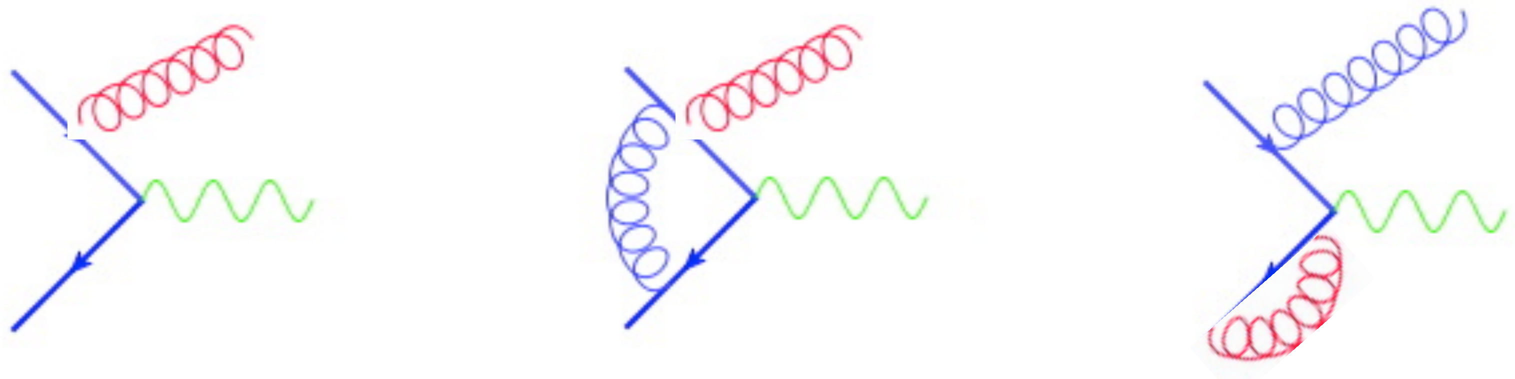
pp→Graviton (ADD&RS) +jets





New Physics models can be easily included in Matrix Element generators via FeynRules and results automatically for multi-jet inclusive final state obtained at the same level of accuracy that for the SM.

What about NLO?



$$d\sigma^{\mathrm{NLOwPS}}_{\mathrm{NAIVE}} = \left[d\Phi_B(B(\Phi_B) + V + S^{\mathrm{int}}_{\mathrm{ct}})\right] I^n_{\mathrm{MC}} + \left[d\Phi_B d\Phi_{R|B}(R - S_{ct})\right] I^{n+1}_{\mathrm{MC}}$$

This simple approach does not work:

- Instability: weights associated to I^n_{MC} and I^{n+1}_{MC} are divergent pointwise (infinite weights).

- Double counting: $d\sigma^{naive}_{NLOwPS}$ expanded at NLO does not coincide with NLO rate. Some configurations are dealt with by both the NLO and the PSMC.

Two solutions available

NLO with PS in a nutshell

$$d\sigma^{\mathrm{NLO+PS}} = d\Phi_B \bar{B}^s(\Phi_B)\left[\Delta^s(p_\perp^{\mathrm{min}}) + d\Phi_{R|B}\frac{R^s(\Phi_R)}{B(\Phi_B)}\Delta^s(p_T(\Phi))\right] + d\Phi_R R^f(\Phi_R)$$

integrates to 1 (unitarity)

with

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B})\right]$$

Full cross section at fixed Born kinematics (If F=1).

$$R(\Phi_R) = R^s(\Phi_R) + R^f(\Phi_R)$$

This formula is valid both for both MC@NLO and POWHEG

MC@NLO: $R^{\mathrm{s}}(\Phi) = P(\Phi_{R|B})\, B(\Phi_B)$

Needs exact mapping (ΦB,ΦR) →Φ

POWHEG: $R^{\mathrm{s}}(\Phi) = F R(\Phi)\,,\, R^{\mathrm{f}}(\Phi) = (1-F)R(\Phi)$

F=1 = Exponentiates the Real. It can be damped by hand.

MC@NLO AND POWHEG

MC@NLO

[Frixione, Webber, 2003;

- Matches NLO to HERWIG and HERWIG++ angular-ordered PS.
- Some events have negative weights.
- Large and well tested library of processes.

- Now available also for Pythia (Q^2) [Torrielli, Frixione, 1002.4293]
- Now automatized [Frederix, Frixione, Torrielli]
- Now available in aMC@NLO (see later)

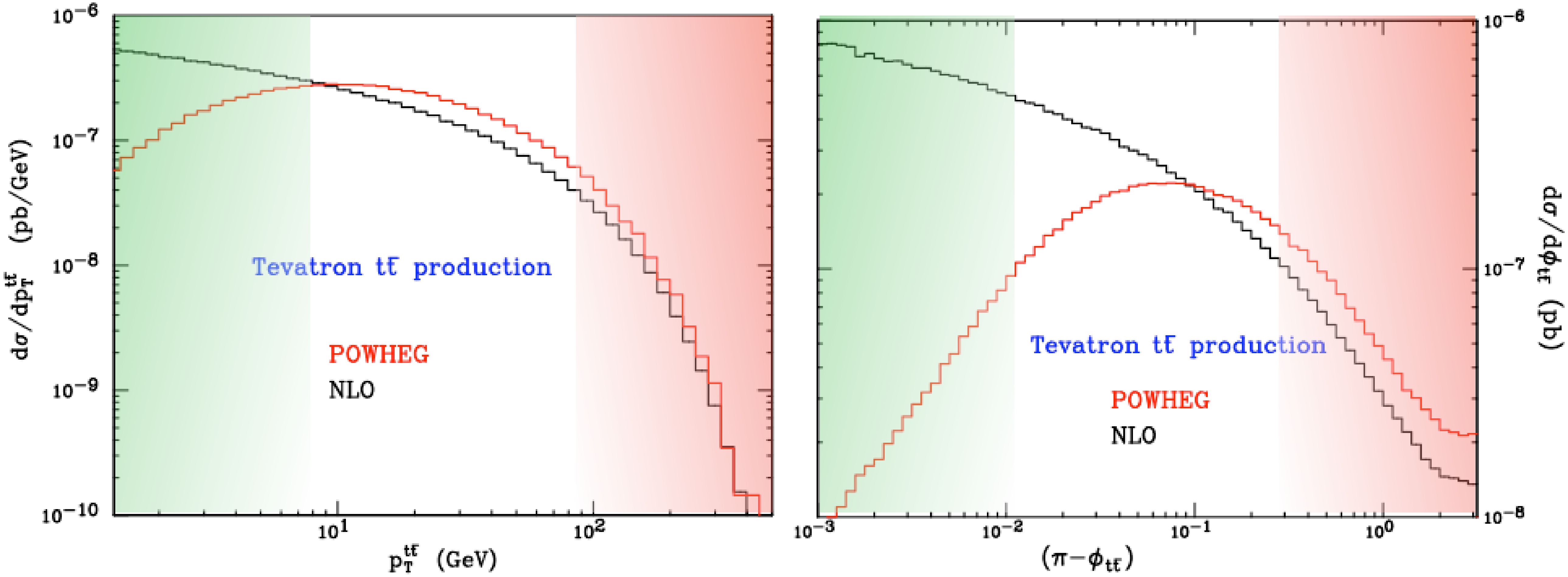
POWHEG

[Nason 2004;
Frixione, Nason, Oleari, 2007]

- Is independent* of the PS. It can be interfaced to PYTHIA, HERWIG or SHERPA.
- Generates only* positive unit weights.

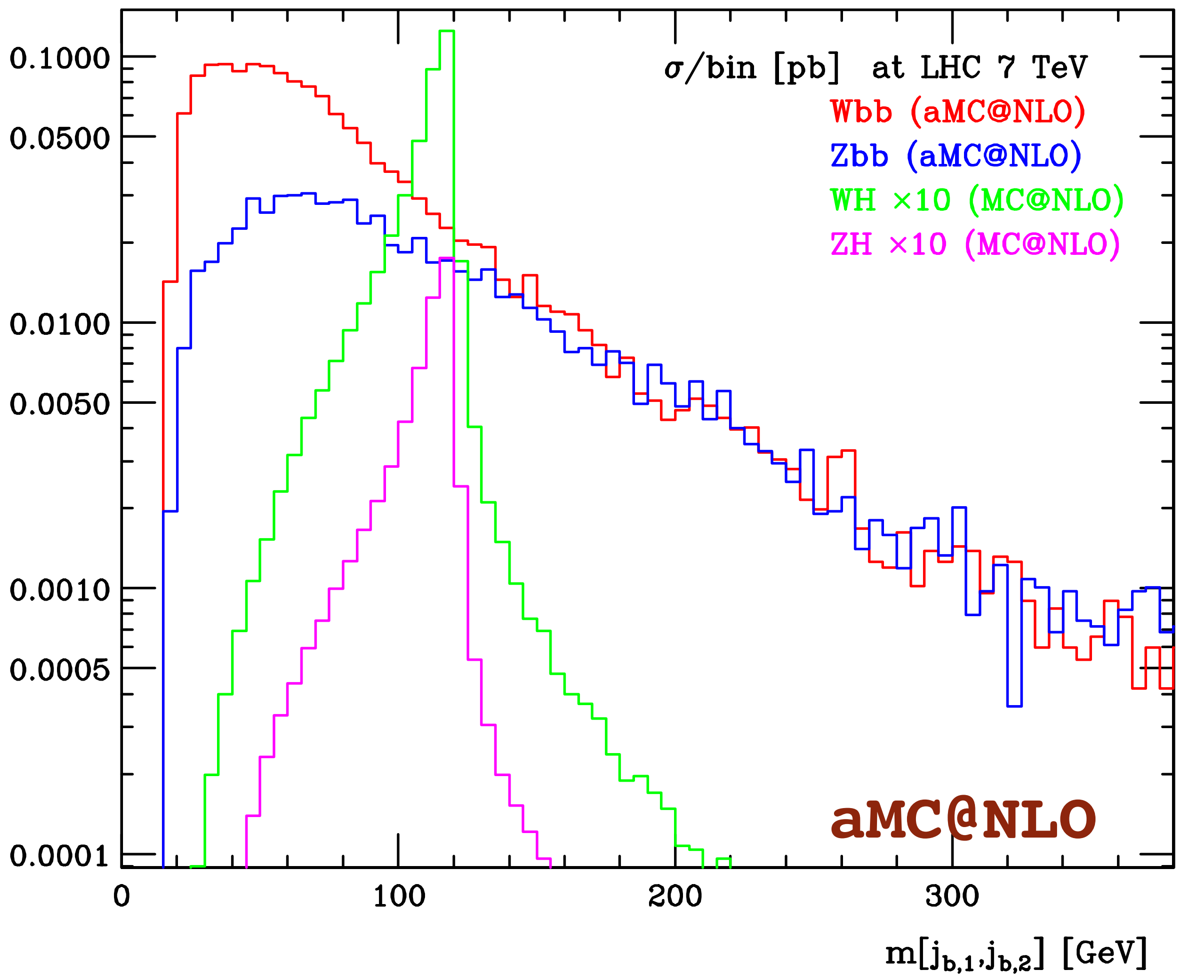
- Can use existing NLO results via the POWHEG-Box [Aioli, Nason, Oleari, Re et al. 2009]
- Method used by HELAC, HERWIG++ and SHERPA [Kardos, Papadopoulos, Trocsanyi 1101.2672], [Hoeche,Krauss, Schooenner, Siegert, 1008.5399]

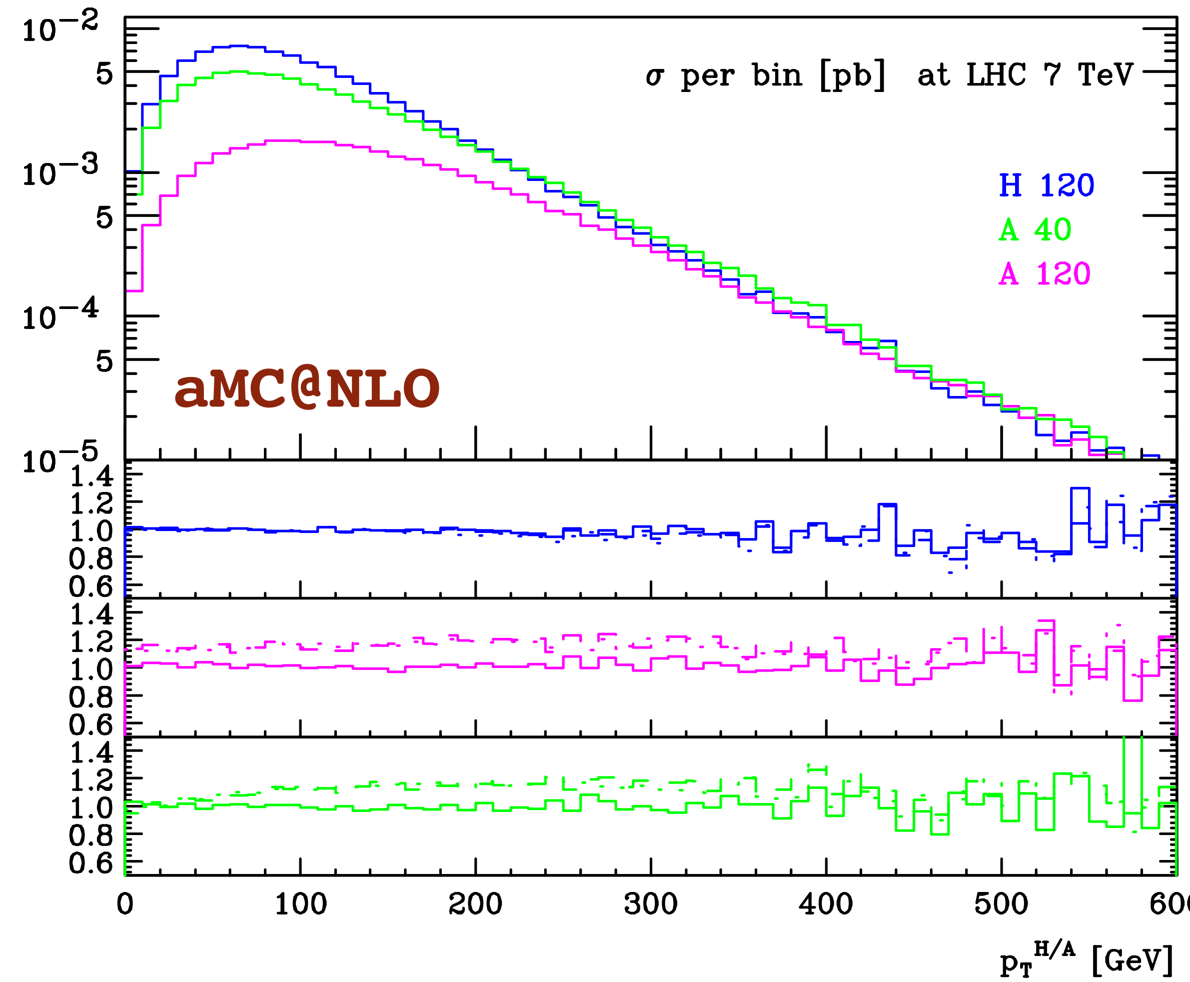
TTBAR : NLOwPS vs NLO



- 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!!

Examples via aMC@NLO

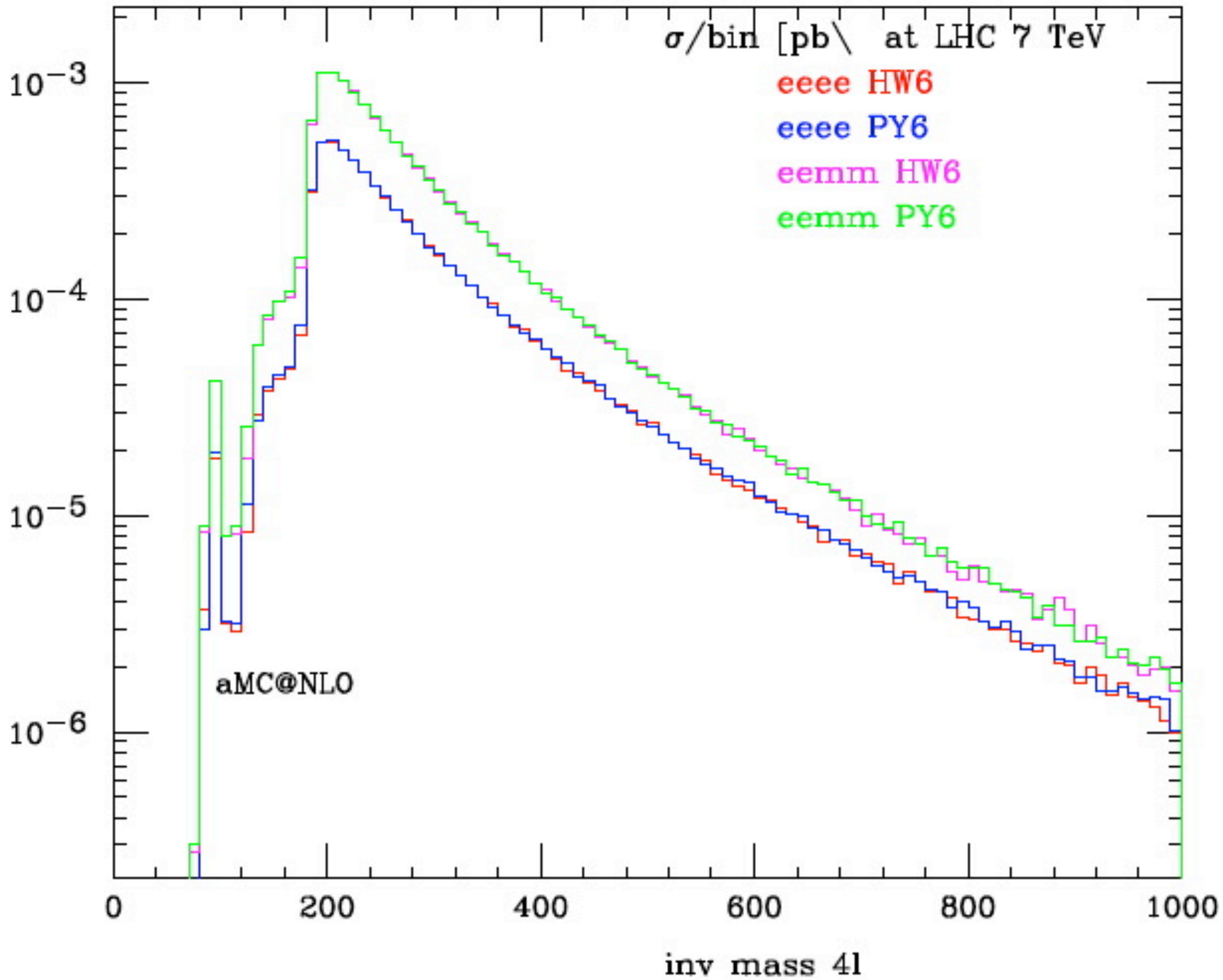




- NLO results obtained in a fully automatic way
- Interface to the shower programs also fully automatic and process independent.
- Results for signal and backgrounds at an unprecedented level of accuracy and experimental-friendliness achieved.

Examples via aMC@NLO

Kyle's example #3



Available in POWHEG and coming soon in aMC@NLO with the following features:

- pp→Z/γ* Z/γ* → 4 leptons
- Single and double resonant diagrams
- Spin correlations exact at NLO
- gg→4 leptons via quark loop
- Signal/background interference in gg channel
- Theoretical uncertainties (PDF and scale dependence) included at the event level.
- Interfaced to Pythia and Herwig

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!!!

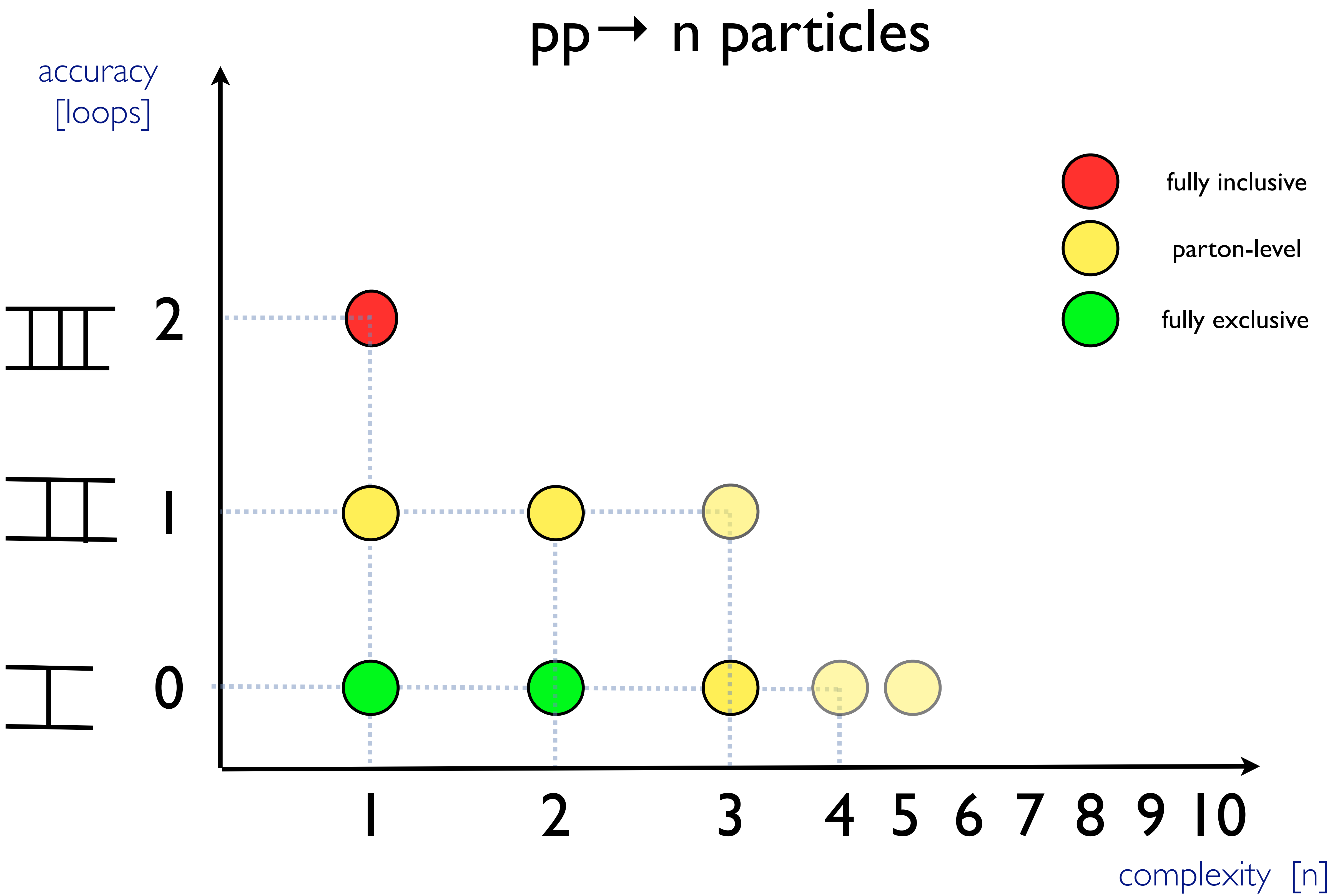
* Current developments:

    * Upgrading of all available NLO computations to MC's in progres
    * Extendable to BSM without hurdles.
    * Only available for low multiplicity: improvements possible.

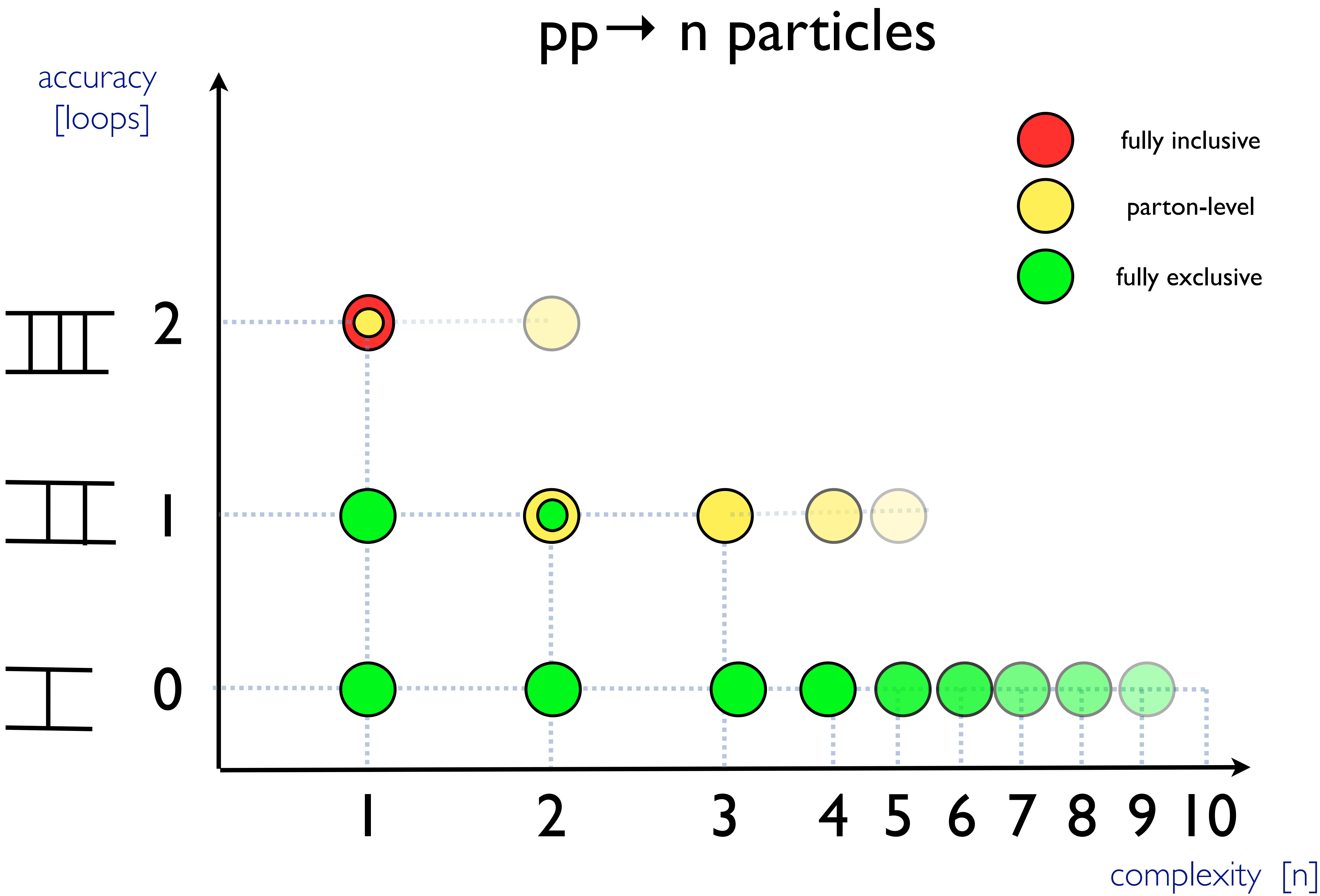
Conclusions

- 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 in the field of QCD and MC's.
- A complete set of NLO computations is available, even in fully automatic form. Several NNLO results are being used already now and will be extended in the future.
- New techniques and codes available for interfacing at LO and NLO computations at fixed order to parton-shower has been proven for the SM.
- Unprecedented accuracy and flexibility achieved.

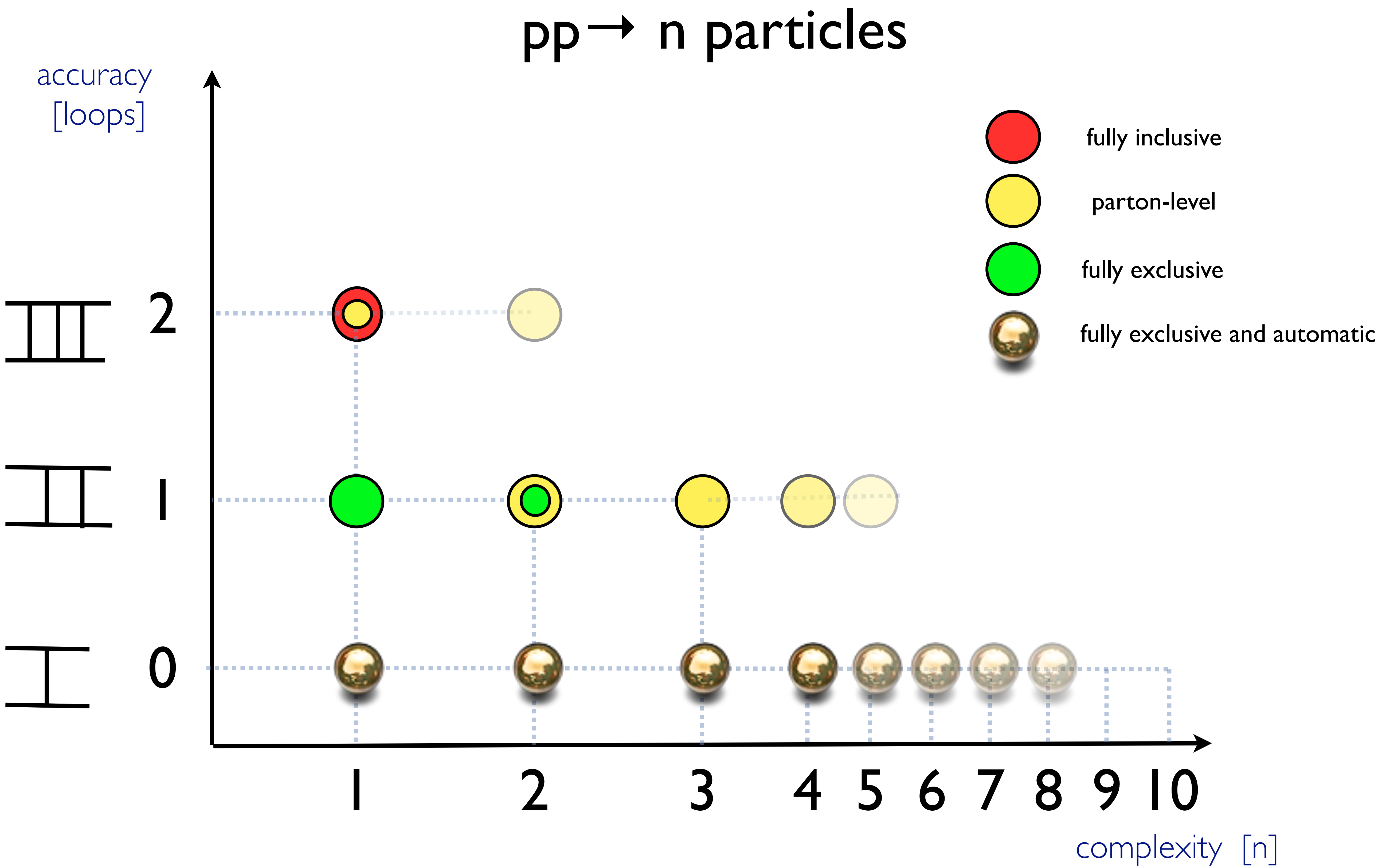
SM Status circa 2002



SM Status : since 2007

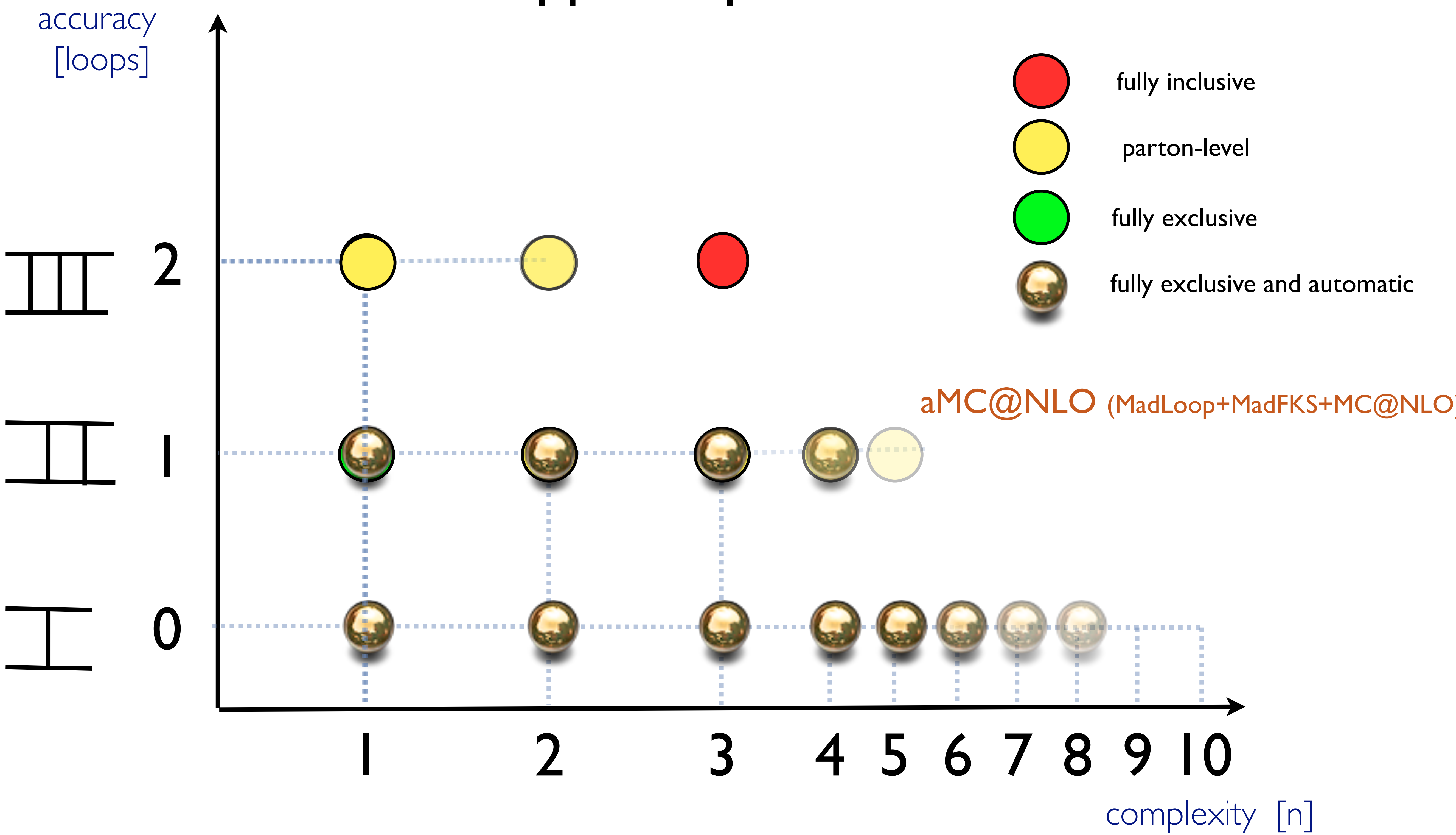


SM Status : since 2007



SM Status: now

pp→ n particles



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 in the field of QCD and MC's.
- A new generation of tools and techniques is now available.
- A complete set of NLO computations is available, even in fully automatic form. Several NNLO results are being used already now and will be extended in the future.
- New techniques and codes available for interfacing at LO and NLO computations at fixed order to parton-shower has been proven for the SM.
- Unprecedented accuracy and flexibility achieved.
- EXP/TH interactions enhanced by a new framework where exps and theos speak the same language.

The tera world is yours!

Enjoy and Mulţumesc