LU TP 13-34
MCnet-13-13
September 2013

Challenges for QCD theory – some personal reflections –

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Abstract

At the LHC *all* processes are QCD ones, whether "signal" or "background". In this review the frontiers of current QCD research are addressed, towards increased understanding, improved calculational precision, and role in potential future discoveries. Issues raised include
the limits of perturbative QCD calculations and parton distribution usage,
the nature of multiparton interactions,
the impact of colour reconnection on physical observables,
the need for progress on hadronization modelling,
the improvements of parton showers and their combination with the matrix-element description,
the use of QCD concepts in Beyond-the-Standard-Model scenarios, and
the key position of event generators and other software in the successful exploration of LHC physics.
On the way, several questions are posed, where further studies are needed.

To appear in the proceedings of the Nobel Symposium on LHC results, Uppsala, Sweden, 13 – 17 May 2013

1 Introduction

Given that LHC collides hadrons, it follows that *all* processes are QCD ones. The calculation of even the most exotic process is done within a perturbative QCD framework, with parton distributions and higher-order QCD corrections as important ingredients, and with other QCD-calculated processes as background, often with normal QCD jets production on top of the list.

Today the QCD Lagrangian is well tested, and is not an issue. Nevertheless challenges abound, and here we collect them into three partly overlapping frontiers, as always with the proviso that ultimately everything hangs together.

- Understanding: many established phenomena still lack a proper theoretical description, such as confinement, the quark–gluon plasma, the hadronization process, the behaviour of interactions in the small-x limit, multiparton interactions, and colour reconnection.
- Precision: higher-order matrix elements and parton distributions allow for higher precision, but loop calculations are demanding and progress takes time. Parton showers offers a complementary approach that is convenient in collinear and soft regions, but the matching between the two descriptions is nontrivial.
- Discovery: characterizing signal and background properties is essential for searches, notably when jets are produced. In addition, several scenarios for BSM physics involve new aspects where QCD offers a template.

Examples from overlapping regions is that jet properties and the proton spin involve both understanding and precision, that the higher-order calculation of BSM involve both precision and discovery, and that the mass definition of coloured particles (like the top) involve both understanding and discovery.

In the following I will touch on several of these topics. It is beyond the scope of this brief presentation to cover all interesting issues, so what follows is a subjective selection, with subjective opinions. Some of the topics not discussed here are covered in the experimental QCD presentation of A. De Roeck [1]. Another useful reference is the recent minireview by G. Salam [2].

2 Perturbative QCD and parton distributions

There is a steady stream of new calculations being presented, and previous wish lists of NLO calculations have been checked off. All this is thanks to a healthy, strong community of calculators, even with an influx from the superstring side, that also increasingly make new results available in the form of public codes. More specifically

- LO calculations are fully automatized up to the order of six to eight final-state particles, the limit being set by computer resources more than anything else.
- NLO calculations are also in the process of being automatized. Currently the limit is somewhere around four final-state particles.
- NNLO is the current calculational frontier, with only one-particle processes fully under control, but two-body final states are now in the process of being mastered.
- Quite apart from the matrix elements themselves, the phase-space sampling can be a bottleneck, and efficient methods are needed to speed up calculations.

Among all the many calculations, maybe the gg $\to$H^0 NNLO one [3] deserves special attention. It showed that the convergence of the cross section is slow, going from LO to NLO to NNLO, and also in terms of the width of the scale variation band. This is interesting to understand, and also is highly relevant for tests of the Standard-Model nature of the Higgs. The results of several other calculations are used in other presentations at this symposium.

Also when it comes to parton distributions there exists a healthy competition/collaboration between a few different groups, regularly providing new tunes to available data [4]. High precision has been obtained with NLO fits, and there are some first NNLO fits. Needless to say, these sets are to be combined with the above NLO/NNLO calculations.

The NLO framework tends to break down if the description is extended to low Q^2 scales, say below 4 GeV^2. Data in combination with the NLO splitting kernels tends to drive the gluon negative (or at least very close to zero) in the low-x region, a behaviour that becomes even more marked at NNLO. More generally, the NLO and NNLO frameworks are unstable at low Q^2. Interestingly, it appears that resummed PDFs recover the physical LO behaviour. Thus

Open question 1: would it be possible to develop a new calculational scheme, wherein both MEs and PDFs are systematically resummed to increasing order, in such a way that both retain a cleaner physical interpretation than the traditional $\overline{\mathrm{MS}}$ *route offers?*

3 Multiparton interactions and colour reconnection

Given the composite nature of the incoming protons, it is inevitable that multiparton interactions (MPIs) play an important role. Indeed, in most models they are the driving force for the structure both of minimum-bias and underlying events. The most direct manifestation of MPIs is the very long tail out to high multiplicities in minimum-bias events, where most of the particles have no apparent association with hard jets. At the other end, studies that involve correlations between four hard jets (or three jet and a photons, or two jets and a weak gauge boson) corroborate the MPI picture, but only probe a tiny fraction of its total cross section [5].

The dominant QCD processes involve t-channel gluon exchange, which leads to a $\mathrm{d}p_\perp^2/p_\perp^4$ divergence for $p_\perp \to 0$. This behaviour must be regularized, e.g. by a dampening to $\mathrm{d}p_\perp^2/(p_{\perp 0}^2+p_\perp^2)^2$. The obvious scale would have been $p_{\perp 0} \sim \Lambda_{\mathrm{QCD}} \sim 0.3$ GeV, but empirically a value like $p_{\perp 0} \sim 2 - 3$ GeV is called for [6]. This raises

Open question 2: is the size of $p_{\perp 0}$ *set by colour screening effects inside the proton and, if so, how could it be calculated rather than fitted?*

While MPIs produce outgoing partons, these need to hadronize. As will be discussed later, in the Lund string model quarks and antiquarks sits at the ends of strings while gluons form kinks on the string, and it is these strings that fragment to produce the primary hadrons. The way the strings are stretched is based on the colour assignment. The issue is then the reliability of the naive perturbative assignments, specifically whether colours could be rearranged before the hadronization stage. One early example of this is J/ψ production in B meson decay [7], where the colour singlet nature of the W puts the c and $\overline{\mathrm{c}}$ in separate singlets in b$\to$cW$\to$c$\overline{\mathrm{c}}$s decays.

W pair production at LEP 2 offered a interesting test bed for such concepts, i.e. whether the q$\overline{\mathrm{q}}$ pair produced in each W decay would hadronize separately or whether e.g. the q from one W could hadronize together with the $\overline{q}$ of the other. Notably, this could mess up W mass determinations. Unfortunately, results were not conclusive.

- Perturbative effects are suppressed for a number of reasons, notably that hard-gluon exchanges would force the W propagators off-shell, giving a negligible uncertainty $\langle \delta M_{\mathrm{W}} \rangle \leq 5$ MeV [8].
- Several nonperturbative colour reconnection models predicted large effects and could promptly be ruled out. The more conservative ones [8] could not be excluded, although they were not favoured [9], and gave $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV.
- Additionally Bose-Einstein effects, i.e. that the wave function of identical integer-spin hadrons should be symmetrized, could affect the separate identities of the W^+ and W^- decay products. Effects on $\langle \delta M_{\mathrm{W}} \rangle$ could be as large as 100 MeV, but again more likely around 40 MeV [10]. An effect of the latter magnitude is disfavoured by data, but again not fully ruled out [11].

Hadron collisions offers a much more busy environment that did LEP 2, however. A typical LHC collision may involve five MPIs. The dominant gg→gg processes each pulls out a colour octet from the two incoming beams, thereby naively leading to two (triplet) strings being stretched between the two beam remnants. Since the transverse size of these strings is the same as that of proton this leads to ten string almost on top of each other over much of the rapidity range. It would be surprising indeed if this did not have consequences.

The most direct probe of such effects is how the average transverse momentum of charged particles varies with the charged multiplicity. In cases where each subcollision system fragments independently one would expect $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$ to be essentially flat — the variation in multiplicity mainly reflects the variation in the number of MPIs, but a higher multiplicity just means more of the same.

In reality, it is not realistic to assume that the beam remnants acquire an arbitrarily large colour charge. This will naturally connect several interactions, such that strings are not pulled all the way out to the remnants. The $p_{\perp}$ kicks from the MPIs themselves thus gets to be shared between fewer hadrons, and $\langle p_{\perp} \rangle (n_{\mathrm{ch}})$ obtains a rising trend. This is nowhere near, however, and models require a significant amount of reconnections, wherein partons from different MPIs get their colours dramatically exchanged, in such a way that the total string length is reduced [6]. Then the hadronic multiplicity increases slower-than-linear with the number of MPIs. That way, it is possible to obtain a good description of data, but

Open question 3: what physics mechanisms are at play when several colour fields overlap and how should they be modelled correctly?

Recently it has also been noted that colour reconnection in pp can give some of the observed effects similar to the collective flow of heavy-ion collisions [12].

4 The mass of coloured unstable particles

The top quark, as well as the W and Z gauge bosons, travel a distance $c\tau \approx 0.1$ fm before they decay, i.e. significantly less than a proton radius. Therefore their decay takes place right in the middle of the hadronization region, and so quarks (and gluons) produced in the decays are subject to the reconnection issues already discussed above. (By contrast the Higgs is so long-lived, $c\tau \approx 50$ fm, that there is no problem.)

Current top mass measurements at the Tevatron and the LHC now have statistical errors of the order 0.5 GeV, and quote systematic errors below 1 GeV [13]. These measurements heavily rely on comparisons with event generators. What is quoted as the top mass is actually the mass parameter used in the generators, which is close to the pole mass, but not necessarily identical. It is also to be assumed that the handling of higher-order matrix-element and parton-shower corrections is under control. Colour reconnection uncertainties then come on top of that. Model studies have suggested a total (perturbative + nonperturbative) uncertainty approaching 1 GeV [14], almost saturating the current systematic-error budget.

Clearly this issue needs to be studied further, to try to constrain the possible magnitude of effects from data itself. Effects of colour reconnection should have a dependence on the event kinematics, which would allow to test and constrain models. Such studies have already begun in CMS [15], although statistics does not yet allow any conclusions to be drawn. In view of the long and winding path ahead of us, one may look for alternatives:
Open question 4: is it possible to find better (theoretical + experimental) mass definitions for coloured unstable particles?

5 Hadronization

The oldest hadronization model still in common use is the Lund string one [16]. When a colour-singlet $\mathrm{q\overline{q}}$ pair is pulled apart, it is assumed that the colour field lines are pulled together to a tube-like region, giving a transverse radius ∼0.7 fm comparable with the proton one, and a linear confinement potential $V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm.

The string does not get very long, however, since it breaks by the production of new $\mathrm{q\overline{q}}$ pairs inside the string, that screen the colour charges of the endpoint. Repeated such breaks give rise to the primary hadrons, which are distributed approximately flat in rapidity space, but with short-range anticorrelations from local energy (and flavour) conservation in the string, and longer-range effects from global conservation. The required tunneling of quarks with nonzero transverse mass gives a Gaussian transverse momentum spectrum and a suppression of heavier quarks (and hadrons). While generally supported by LEP data, its weak point is that it relies on a number of parameters for the flavour production properties.

Multiparton configurations are considered in the $N_c \to \infty$ limit, so that all colours are unique and gluons carry a separate colour and anticolour index. This means that a string is stretched from a quark end via a number of gluons to an antiquark end (or in a closed gluon loop). Diquarks are treated like antiquarks, to first approximation. LEP $\mathrm{q\overline{q}g}$ events thus contain two string pieces, one from q to g and another from g to $\overline{\mathrm{q}}$. Each of those two pieces can be viewed as boosted copies of the simple $\mathrm{q\overline{q}}$ string, tied together at the gluon corner. No new parameters are needed. The model predicts a depletion of particle production in the angular region between the q and $\overline{\mathrm{q}}$ where there is no string, well verified in data.

The main alternative is cluster models [17], wherein the parton shower to a low cutoff scale is complemented by final $\mathrm{g \to q\overline{q}}$ branchings that splits the system into smaller singlets. Originally these were assumed to decay isotropically, but for larger singlets a preferred decay direction is introduced along string ideas.

Both the string and cluster models were developed in an $\mathrm{e^+e^-}$ environment and then

applied to pp/p$\overline{\text{p}}$ events with moderate extensions. Notably the large string (or cluster) overlaps at the LHC, already described above, are tackled by mechanisms like colour reconnection that do not put in question the relevance of the string model as such. There have been some studies of fields in higher colour representations ("colour ropes") [18], but rather little else that attempts to bridge the gap between the simple e^+e^- picture and a full-blown quark–gluon plasma. Thus
Open question 5: can one develop new hadronization models more relevant for the busy LHC environment, while still not clashing with established e^+e^- *phenomenology in that limit?*

6 Parton showers

Traditional showers are constructed by combining repeated $1 \to 2$ branchings, $a \to bc$. Partons originally assumed massless may need to be assigned virtualities in the process, and thus local or global correction procedures need to be introduced to handle energy–momentum conservation. Emissions can be ordered in angle, virtuality or $p_{\perp}$, with restrictions from colour coherence phenomena [19, 20].

An alternative is the dipole shower [21], inspired by the Lund string and the St. Petersburg dipole [22]. In it branchings are instead of the $2 \to 3$ character, $ab \to cde$. When a, c and d are close to collinear (and flavours match) the a can be viewed as the radiator and the b as a recoiler, there to ensure local energy–momentum conservation, $p_c + p_d + p_e = p_a + p_b$. Again relying on the $N_C \to \infty$ limit, consecutive emissions give rise to an increasing number of separate dipoles, e.g. an original q$\overline{\text{q}}$ dipole after a gluon emission turns into two dipoles, qg and g$\overline{\text{q}}$, essentially smaller replicas in their respective rest frames. When emissions are ordered in $p_{\perp}$ also coherence conditions are fulfilled.

Nowadays the dipole-style showers are the ones most commonly used. From their origin in final-state radiation they have been extended to initial-state radiation, and in the form of Catani–Seymour dipoles [23] found a use also in NLO calculations.

A crucial ingredient of the shower approach is the Sudakov form factor $\Delta(p_{\perp 1}^2, p_{\perp 2}^2)$, which expresses the no-emission probability between the $p_{\perp 1}$ and $p_{\perp 2}$ evolution scales. It can be obtained by an appropriate exponentiation of the real-emission probability over that range, and thus ensures that emission probabilities never exceed unity.

The universal nature of showers makes them very convenient to add onto a fixed-order calculation, to construct more realistic final states. Still the shower approach faces challenges, and work is ongoing in different directions [24], e.g. the following ones.

- The accuracy is formally only to LL, even if the many beyond-LL aspects added to the showers should include the bulk of NLL effects (energy–momentum conservation, $\alpha_{\mathrm{s}}(p_{\perp}^2)$, full z dependence of splitting kernels, coherence, ...).
- Most showers do not cover the full phase space, but leave some gaps.
- Nonleading colour terms are neglected when defining the colour flow (but not in the splitting kernels).
- It may become relevant to include weak gauge boson emission, notably for high-$p_{\perp}$ jets at the LHC.
- Most importantly, showers should attach as well as possible to the matrix elements that they are combined with, which is the topic of the next section.

7 Matching/merging of matrix elements and parton showers

In some respects the improved calculational capability for matrix elements has reduced the need for parton showers. Today it would be possible to describe an 8-jet final state purely by matrix elements, which would have been infeasible ten years ago. In other respects, however, parton showers are as needed now as ever. One first point is that the perturbative description must go down to scales of the order of 1 GeV, where nonperturbative hadronization can take over, and at such low scales the effective number of partons can exceed any matrix-elements capacity. Other points will be raised as we go along.

Given the need both for the more precise ME description and the more flexible PS one, quite some work has gone into the best ways to combine the two. Such efforts go under the name of matching or merging; with a distinction that largely is author-dependent. For many years this work has either been for multiple legs, i.e. final-state partons, or more loops, i.e. NLO. Currently the emphasis has shifted to combining the two, i.e. to have multileg at NLO.

The key point about LO MEs is that they are inclusive: a $2 \to n$ calculation gives the rate of having at least n partons, but with no upper limit. This means that the observable exclusive n-parton rate is not directly related to the LO ME calculation. It is here the Sudakov form factor enters: by encoding the no-emission probability it can be used to turn an inclusive calculation into an exclusive one.

This is the basic idea of the CKKW approach [25]: use MEs for real emissions and Sudakovs for the virtual corrections needed to obtain an exclusive picture. To calculate those Sudakovs, it is necessary to construct a fictitious shower history, such that no-emission probabilities can be calculated also for intermediate propagators. When several histories are possible, their relative probabilities are used to pick one. With a shower history at hand, it also becomes possible to reweight events originally picked with a fixed α_s (necessary to preserve gauge invariance) to have a running $\alpha_s(p_\perp^2)$ at the $p_\perp$ scale of each branching.

The original CKKW scheme was based on analytic Sudakovs, which are rather crude, and this is no longer used. Instead the CKKW–L approach is based on using trial showers to provide the Sudakov factors [26]. For instance, given a $p_\perp$-ordered shower algorithm, a $p_\perp$-ordered history is constructed from the ME information. Then, for each step from n to $n+1$ partons, a trial shower is started up from the n-parton topology at scale $p_{\perp n}$, and if a branching occurs above $p_{\perp n+1}$ the event is rejected. This way the Sudakov suppression includes exact kinematics, running α_s, coherence effects, and so on. The more accurate the shower algorithm, the more trustworthy the Sudakov factors, so the incentive for improved showers remains high.

An alternative to CKKW–L is the MLM algorithm [27]. Also here showers are used as a means to go from inclusive to exclusive event samples. Without going into the details, the difference is that MLM does not micromanage the shower, but only considers whether the final jet state after showers matches the original parton state.

At the other frontier, matching with NLO calculations, there are two well established approaches, MC@NLO [28] and POWHEG [29, 30]. In retrospect these can be combined into one master formula, in simplified form (for a fixed Born-level topology)

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{R,\mathrm{hard}} + (\sigma_B + \sigma_{R,\mathrm{soft}} + \sigma_V) \left[\frac{\mathrm{d}\sigma_{R,\mathrm{soft}}}{\sigma_B} \exp\left(- \int \frac{\mathrm{d}\sigma_{R,\mathrm{soft}}}{\sigma_B} \right) \right]$$

where σ_B is the n-body Born term, $\mathrm{d}\sigma_R = \mathrm{d}\sigma_{R,\mathrm{hard}} + \mathrm{d}\sigma_{R,\mathrm{soft}}$ are the real-emission terms to $n+1$-body states, and σ_V are all virtual corrections (including PDF counterterms) for the n-body states. The expression in square brackets is normalized to unity, and can be viewed as a parton-shower-like downwards evolution in an emission hardness variable like $p_\perp$, with the exponential providing the Sudakov factor for not having a harder emission than the currently considered one. (For a nonzero lower $p_{\perp\mathrm{min}}$ cutoff there also appears an additional term inside the square bracket, to represent that this lower cutoff sometimes can be reached without an emission, and thereby unitarity is preserved.) The prefactor $(\sigma_B + \sigma_{R,\mathrm{soft}} + \sigma_V)$, with $\sigma_{R,\mathrm{soft}} = \int \mathrm{d}\sigma_{R,\mathrm{soft}}$, gives the cross section for this exponentiated part, whereas $\int \mathrm{d}\sigma_{R,\mathrm{hard}}$ gives the cross section for the non-exponentiated part. Thus all events contain an emission (apart from those falling below the $p_{\perp\mathrm{min}}$ cutoff). A normal shower can take over below the $p_\perp$ scale of the one and only ME "emission" (or below $p_{\perp\mathrm{min}}$).

In this formula, POWHEG corresponds to the special case $\mathrm{d}\sigma_{R,\mathrm{hard}} = 0$, i.e. the whole cross section is exponentiated. Specifically, the $n+1$-body high-$p_\perp$ tail is multiplied by a $K = (\sigma_B + \int \mathrm{d}\sigma_R + \sigma_V)/\sigma_B$ factor typically above unity. This is formally a NNLO ambiguity and so allowed in an NLO approach, but is not appreciated by all.

The rival MC@NLO is based on having a shower that attaches well to the $\mathrm{d}\sigma_R$ behaviour in the $p_\perp \to 0$ limit, Sudakov factor uncounted, as a shower should. It is this shower-without-Sudakov rate that is associated with $\mathrm{d}\sigma_{R,\mathrm{soft}}$. Furthermore, by picking a "bad" shower algorithm, that falls off faster than $\mathrm{d}\sigma_R$ at large $p_\perp$, one ensures that the unexponentiated $\mathrm{d}\sigma_{R,\mathrm{hard}}$ dominates in this region. This term is not multiplied by a K factor, which some people prefer. The price to pay is a stronger bond to a specific shower, and the possibility of negative-weight events in regions where the shower overestimates the matrix elements.

In the few cases where the NNLO answer is available, such as Higgs production, it turns out that the K-factor rescaling of POWHEG gives a more accurate $p_\perp$ spectrum than MC@NLO [31]. That it, whatever physics causes the large K factor of gg→H also seems to give a correspondingly large correction to gg→Hg.

As already mentioned, the current frontline is to combine the multileg matching technique with NLO input. Taking the Higgs case as example, there are two reasons for this. Firstly the multileg matching does not offer a total Higgs cross section more accurate than LO. Secondly, the basic NLO scheme only offers NLO for the total Higgs rate; it is LO for H + 1 jet, and gives nothing beyond that. Or, alternatively, NLO for H + 1 jet and LO for for H + 2 jet, if one starts one order up. Current technology now can handle both H and H + 1 jet to NLO, and more jets to LO [32, 33, 34]. It does not come without a price, however, either of allowing spurious NNLO terms, or of having quite complicated formulae, with negative-weight events needed to preserve the normalizations. Recently there has even been a first implementation that preserves the NNLO total cross section for Higgs production [35], again at the price of significant complexity. So
Open question 6: is it possible to construct a generic, transparent, robust and reliable approach to matching beyond LO?

(Note that Sudakov factors and resummation are related to each other, so progress on open question 1 could go a long way in this direction, but we should not wait for that to happen.)

8 Event generators

LHC events are of daunting complexity, if one starts to consider all the different physics mechanisms that are at play in them. In this article we have mentioned matrix elements and parton distributions, multiple partonic interactions, initial- and final-state showers, beam remnants, colour reconnection, hadronization, decays and Bose-Einstein effects. Further mechanisms and aspects have been proposed, and new ideas may still come along.

Currently the only known way to address this complexity is through event generators [20], where the overall task is broken into more manageable subtasks, along the lines of the above list. Monte Carlo methods are used to represent quantum mechanical choices at all steps along the way. Given all the limitations, it is fair to ask

Open question 7: can one find better alternatives to event generators, that have a corresponding breadth of applicability?

The three workhorses for LHC pp physics are Herwig [36], Pythia [37] and Sherpa [38]. Since they set out to describe the same physical reality, they do share many common traits.Nevertheless there are distinguishing features, and different historical roots, reflecting the topics of interest at the time.

- Pythia has it roots in the Lund string code begun in 1978, and has retained a high profile in soft physics, such as multiparton interactions.
- Herwig originated in 1984 from the introduction of coherent shower evolution through angular ordering, and this has remained the hallmark of the program.
- Sherpa dates back to 2000 and has in particular been developed to handle CKKW and related kinds of ME/PS matching procedures.

The (EU-funded) MCnet [39] offers common activities of these collaborations, and other related projects, such as summer schools on event generator physics.

Since the generators involve many parameters, mostly related to nonperturbative physics, there is a need to tune them to data. Once tuned, they can then be applied to make predictions for observables not yet studied. The key assumption is that the generators contain the correct physics, and that therefore good tunes can be found. Counterexamples may already be at hand, e.g. in terms of a somewhat different flavour composition at LEP and LHC. The tuning effort is shared between the generator authors, the experimental collaborations, and some separate efforts [42]. Much data, but far from all that would have been useful, is made available in such a form that it can be compared with the output from generators [43], so there is room for improvement.

In addition to the above three generators, a plethora of more specialized programs exist, and new ones are added all the time. These include complete generators for QCD physics (heavy ions, cosmic rays), separate shower programs, matrix-element generators and ditto libraries, Feynman rule generators, PDF libraries, specialized programs for BSM scenarios (mass spectra, decays, matrix elements, . . .), jet finders (including jet grooming techniques) and other analysis packages (including detector simulation and parameter constraints from data). Some are projects at the same scale as the three standard generators, such as MadGraph [40], and Geant [41] of course is orders of magnitude bigger. The most impressive point is that all of these different kinds of software can come together to produce meaningful simulations of LHC physics. One reason that this has been possible is that common standards have been developed for a number of interfacing tasks.

9 QCD and BSM physics

Many/most scenarios for BSM involve coloured particles, and so QCD is not only a matter of production processes but also of the consecutive fate. When the coloured particles are short-lived and decay to standard particles this description need not involve much more than the kind of framework already developed e.g. to handle showers in top decay. But there are cases that go beyond the simple scenarios, such as the following four.

- Baryon number violation is allowed in some SUSY scenarios. If a neutralino is the lightest supersymmetric particle it can decay to three quarks. On the shower level the standard radiator–recoiler picture has to be extended, and on the hadronization level the fragmenting string has a Y-shaped topology with a junction in the middle [44].
- Other SUSY scenarios allow for long-lived squarks or gluinos, that then have time to fragment into so-called R-hadrons. The squark will be at the end of a string, and so hadronization is not so different from that of a heavy quark, but the gluino will be a massive kink inside a string, which has no precedent in the SM. In addition to the possible formation of "mesons" $\tilde{\mathrm{g}}\mathrm{q}\overline{\mathrm{q}}$ and "baryons" $\tilde{\mathrm{g}}\mathrm{qqq}$, also "glueballs" $\tilde{\mathrm{g}}\mathrm{g}$ could be allowed [45].
- If black holes can be formed, notably in scenarios with extra dimensions, they will rapidly evaporate by the emission of all kinds of particles, but mainly by hadrons. The emission properties depends on the temperature of the black hole, which increases as its mass drops, requiring an evolution and hadronization approach quite different from the normal one [46].
- Hidden-valley scenarios could allow for a repetition of a strong-interaction framework in some secluded sector, with showers and hadronization. Seepage back into the normal sector would partly reveal the pattern, which therefore needs to be modelled. It is also possible to have particles with both SM and hidden charges, where thus radiation into the two sectors may be interleaved [47].

10 Summary and outlook

This (biased) selection of topics illustrates the breadth of current QCD-based research, both in its own right and in support of all other LHC physics studies.

There are many other topics that would deserve attention, such as

- Jet production rates, jet properties and jet algorithms.
- Production of other SM (and BSM) particles, such as photons, weak gauge bosons, quarkonia, top and the Higgs.
- Identified particle production, such as the $\pi/\mathrm{K}/\mathrm{p}$ composition.
- Heavy-flavour (c and b) production topologies, especially by shower evolution.

- Flavour production asymmetries, observed in baryon number transport or B hadron composition, reflecting the beam proton valence flavours.
- Relations between minimum-bias and underlying-event physics.
- Total, elastic and diffractive cross sections.
- Diffractive and forward physics.
- Tests of small-x evolution.
- The proton wave function and spin physics.
- The ridge effect, signs of collective flow and other connections between pp and heavy-ion physics.

Fortunately many of these topics are brought up in other presentations at this symposium.

The overall picture is that the QCD community has been quite successful in providing useful input to everybody working with LHC physics, from NLO/NNLO calculations to complete event generation. At the same time, less emphasis is put on QCD for its own sake, partly because nobody today would question the validity of QCD as such, partly because true progress in the understanding of QCD will be very tough. The old battle cry of "solving QCD" (be it by lattice or superstring methods) seems as remote as ever, but that does not mean we should not try to do better than we can today. The seven questions in this presentation are examples of issues that at least should be considered.

Acknowledgements

Work supported in part by the Swedish Research Council, contract number 621-2010-3326.

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