Executive Summary of the MITP Topical Workshop/Scientific Program: "Factorization Violation and Glauber Gluons"

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Goals of the Topical Workshop/Scientific Program

Glauber gluons are low-energy gluons with transverse components parametrically larger than the longitudinal ones. Such gluons mediate the low-angle scattering of partons, and thus are intimately related to 'forward scattering' (or BFKL) physics. Glauber interactions are prevalent in proton-proton scattering events. Even if one considers the production of some hard final state, there will generically be many forward parton-parton collisions mediated by Glauber gluons that accompany the hard scattering. Furthermore, the products of any of these collisions can rescatter via Glauber exchanges with each other, or with 'spectator' partons in the beam remnant, with large probability. Glauber exchanges are extremely difficult to treat theoretically, and it is currently not known how to incorporate the effect of arbitrarily many such exchanges in the factorisation frameworks used to make predictions for proton-proton collisions. It has been proven that the effects of the Glauber gluons cancel if one considers colourless particle production, and measures properties only of the colourless particle(s). The argument here uses unitarity considerations [1, 2, 3]. However, this is the only case in which we can be sure that the Glauber effects cancel. In recent years, it has been shown that for several observables in proton-proton collisions the Glauber effects do not cancel, and factorisation is said to be violated. There are two important situations where factorisation violation is known to occur. The first is coloured particle production where the transverse momentum of the coloured system is measured [4] and the second is measurement of event shape variables accompanying colourless particle production [5, 6, 7]. In the latter case, estimates using Monte Carlo event generators and experimental measurements indicate that the Glauber effects are very significant [8, 9]. The types of Glauber exchanges leading to factorisation violation for the two processes are illustrated schematically in figure 1.

Glauber effects are relevant in non-global observables where we sharply veto jets in certain regions of phase space ('gaps between jets'). In e^+e^- collisions, the asso-

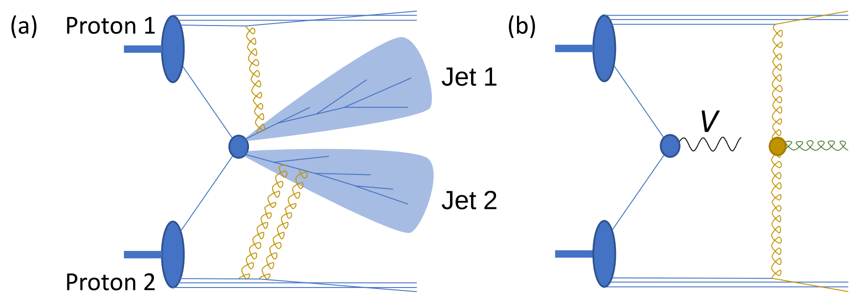

Figure 1: Examples of processes resulting in factorisation violation in (a) coloured particle (here, dijet) production with total transverse momentum of the coloured system being measured (b) measurement of a hadronic event shape accompanying the production of a colourless particle V. The blue lines represent generic partons, the green spiral is a 'normal' soft gluon, and the yellow spirals represent Glauber gluons.

ciated tower of large non-global logarithms is single logarithmic, whilst in proton-proton collisions Glauber effects give rise to terms that are 'superleading' compared to this single logarithmic tower [10]. They are also known to break the factorisation of amplitudes for hadron-hadron collisions into matrix elements and splitting functions when partons become collinear to each other [11, 12]. The Glauber effects causing these two phenomena are of identical structure [12].

Given that Glauber exchanges contribute to such a wide variety of theoretically and phenomenologically relevant processes, a better understanding of these effects, and new theoretical frameworks to predict their impact in a variety of situations, are urgently needed. The goal of this workshop was to bring together experts working on Glauber effects in different contexts, using different methodologies, and discuss latest progress in this emerging field. Through an exchange of ideas and methodologies, and by identifying common challenges and opportunities, this first workshop of its kind left the participants better equipped to face the task of developing tools to predict the effect of Glauber exchanges in these different contexts.

Scientific Highlights of the Topical Workshop/Scientific Program

Talks were organised covering all areas mentioned above. The workshop began with talks by J. Collins and I. Stewart, who introduced basic properties of Glauber exchanges and discussed the treatment of these modes in the traditional QCD and effective-field theory approaches respectively. The talk by J. Collins summarised the proofs of Glauber gluon cancellation for inclusive Drell-Yan [1, 2, 3]. An intuitive explanation for why this cancellation happens was given using a co-ordinate space picture. I. Stewart discussed his work with I. Rothstein [13], where soft-collinear effective theory has been extended to include Glauber modes. Work in progress to re-derive the factorisation of inclusive Drell-Yan using this framework was also mentioned. One interesting point regarding this is that this work uses a version of time-ordered perturbation theory (referred to here as 'Glauber ordered perturbation theory'). This is somewhat similar to the original proofs, where light-cone ordered perturbation theory was used. Such methods appear to be very convenient to show Glauber cancellation to all orders in QCD; there is currently no all-order proof using 'modern' Feynman perturbation theory.

Following this, several talks were given that were linked by the theme of summing logarithms, incorporating also the effects of Glauber gluons, using amplitude-level parton branching-type algorithms. Such algorithms, where the factorisation principle is from the hard process 'outwards' (rather than organising the dynamics into distinct soft, collinear, and hard functions), offer significant promise for incorporating Glauber effects. T. Becher gave a talk on work in progress together with M. Neubert and D. Shao to sum up super-leading logarithms using their framework for summing non-global logarithms [14, 15], which in practice has a parton-shower-style structure. A summation of the leading tower of super-leading logarithms has been achieved. S. Plätzer discussed the ongoing development of an amplitude-level parton branching algorithm [16], where the intention is to develop a general-purpose resummation algorithm including the effect of Glauber exchanges (see also [17, 18] for work along similar lines). J. Forshaw summarised the original derivations [10] of super-leading logarithms, as well as more recent work [19] in which it was shown that the natural ordering variable for a parton branching algorithm including Glauber effects is the transverse momentum k_T.

G. Rodrigo summarised work done together with S. Catani and D. de Florian [11] in which strict collinear factorisation of amplitudes for hadron-hadron colliders was shown to be violated. Following this, K. Yan gave a talk describing ongoing work in which this factorisation violation has been observed in the context of an explicit three-loop soft function calculation.

The connection between Glauber gluons and small-x/BFKL physics, mentioned briefly in the talk by I. Stewart, was covered in more depth during a talk by G. Vita. Here an overview of the use of the effective-field theory framework of [13] to achieve small-x resummation was given, including also a discussion of subleading power effects such as the inclusion of Glauber quarks [20].

Two further talks were given on subjects linked to the general theme of factorisation. M. Diehl described how 'normal' soft gluon exchanges between colliding protons can be decoupled into a soft function via nonabelian Ward identities, for both single Drell-Yan and for multiple hard scattering processes producing colourless particles. This is an important step of the factorisation proof, and was achieved for the latter case by Diehl and Nagar in [21]. An interesting implication of recent work in which factorisation has been studied for multiple scattering [21, 22] is that some of the steps of the factorisation proof for single Drell-Yan in the classic papers [1, 2, 3] need to be refined and re-ordered. H. Hannesdottir discussed recent work performed together with M. Schwartz and others [23, 24] that aims at developing infrared finite formulations of cross sections and the S-matrix for theories involving massless particles. An important component of this work is a careful consideration of unitarity cancellations between cuts of a Feynman graph, where such unitarity cancellations also play a vital role in factorisation proofs.

Aside from the organised talks, there was also considerable time available for discussions; many of these were informal small-group discussions, but also a few large-scale discussions were organised. Of particular importance was a discussion of the role played by the rapidity regulator in methodologies where an explicit contribution from the Glauber region is computed. It was noted, through various examples, that when the regulator is changed the contributions of certain Glauber graphs can be altered or even be set to zero, although the final physical result summing over graphs and leading regions is unchanged. Using different regulators, the allowed structure of the Glauber graphs, and/or the pattern of cancellations between graphs, can be made more or less simple or complex. An open question is what the optimal choice of rapidity regulator(s) is to derive factorisation proofs or compute factorisation violating effects. It may also be possible to develop a technique to compute factorisation violating effects that does not rely on explicit computations of the Glauber region, adapting approaches used by Collins, Soper and Sterman [2, 3]; this would avoid the issue of the rapidity regulator.

Finally, two of the workshop organisers (J. Gaunt and T. Kasemets) put together two interactive 'examples classes' designed for the student participants. The aim here was to go through some basic concepts of Glauber physics in detail, such that the students could more easily understand and contribute to the rest of the workshop programme. The first class involved looking at a number of one-Glauber exchange processes in a toy Drell-Yan model calculation, to illustrate where Glauber exchanges are cancelled, or absorbed into conventional collinear or soft functions. The second class covered the derivation of the so-called Lipatov vertex, an important ingredient in small-x resummation. These classes seemed to be very much appreciated by the participants.

Open problems and Conclusions

Despite much recent progress in this field, many challenges remain. One important goal is to develop frameworks to compute the numerical impact of the Glauber-related effects in the scenarios where factorisation is known to be violated. Some of the ideas presented and discussed at the workshop, summarised above, should be useful in this direction. Given that much of the physical intuition seems to be based on a co-ordinate space picture, a rigorous co-ordinate space formulation of hadron-hadron scattering may also be useful.

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