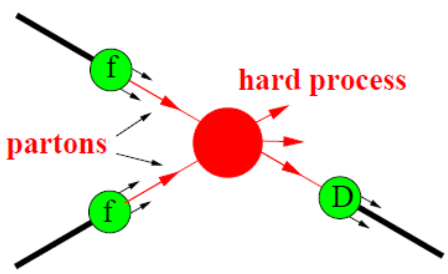
Section 1: Quantum Chromodynamics at WORK

Introduction to partons and Parton Distribution Functions

Quantum Chromodynamics (QCD) plays a central role in this proposal. It is the well-established theoretical framework for the strong nuclear force, which binds together quarks and gluons into protons and neutrons, which in turn constitute the building blocks of the atomic nuclei. The theory of QCD describes the interactions among the quarks, anti-quarks and gluons carrying colour charges, collectively referred to as partons. Because energy grows with separation between colour charges, quarks and gluons cannot exist in isolation, but only in colour neutral combinations. This is known as confinement. The simplest nontrivial combinations are quark–anti-quark bound states (mesons) and three-quark bound states (baryons). The collective name for strongly interacting particles made up of quarks and gluons is hadrons. Even if the quarks and anti-quarks have only tiny masses that are of the order of twenty times that of the electron, the bound states become very massive in comparison. The proton is almost two thousand times heavier than the electron. This is the consequence of the strong binding. The size of hadrons is the confinement scale, about 1 fm or 10^{-15} m. At distances smaller than the confinement scale, quarks and gluons in essence start behaving as free particles (known as asymptotic freedom, Nobel Prize 2004).

Basic keywords:
Hadrons: strongly interacting particles like protons and neutrons, built from partons.
Partons: quarks and gluons, the fundamental particles interacting via their colour charges.

In collisions between particles at high energies one probes distances of the order of the corresponding quantum mechanical wavelength, which in colliders with energies considerably above the GeV-scale is much shorter than the confinement scale and one can describe the scattering directly in terms of collisions between the (quasi-free) quarks and gluons. This description uses established perturbative quantum field theoretical methods and allows comparison of cross sections (counting rates) for various scattering processes at various energies. To account for the initial and final state hadrons, for example in proton-proton scattering at the Large Hadron Collider (LHC), one in essence needs to know the probability of finding quarks and gluons inside the protons. These probabilities are known as Parton Distribution Functions (PDF's), functions $f_{h\rightarrow i}(x)$ with x being the parton's momentum as fraction of the momentum of the original hadron (a fraction which must lie between 0 and 1). There are such functions for any hadron h and any kind of parton i (i can be a quark or anti-quark of any flavour or a gluon). In a similar way one needs to know how many and which hadrons h a particular parton i can produce in the final state. This is described by Parton Fragmentation Functions (PFF's), functions $D_{i\rightarrow h}(z)$; here z is the hadron's momentum fraction.



Pictorial description of a high-energy collision with (consider figure from left to right) two colliding hadrons (thick lines on left) producing partons with probabilities described by **Parton Distribution Functions** (PDF's *f*). These partons collide with each other, a hard process that can be calculated in QCD and finally they fragment into jets of hadrons in the final state (black lines on right) described by **Parton Fragmentation Functions** (PFF's *D*).

The intuitive confirmation for the above picture of the scattering process is the appearance of jets – bunches of hadrons all moving roughly parallel to each other. In a worldwide effort over the last few decennia, this intuitive description of PDFs and PFFs has rigorously been incorporated in the QCD framework with impressive precision results. The functions have been shown to be *universal*, appearing in *factorized* expressions. They can be extended to include additional degrees of freedom, namely the spins of the partons as well as the spins of the hadrons, describing the transfer of polarization between hadrons and partons (*spin-spin correlations*).

Breakthrough – from integrated PDF's to transverse momentum dependent (TMD) PDF's

A breakthrough, in which my group played the initiating role (during the second half of the nineties [1]) and to which my students and myself have made seminal contributions since then is the consideration of the role of the transverse momenta in the PDF's and PFF's, which means looking at $f_i(x,k_T)$ where x and k_T characterize the parton's momentum in a hadron with momentum P (the parton momentum is written as $k = x\ P + k_T$), x being the fraction of the hadron's momentum, k_T the (transverse momentum) component orthogonal to this momentum. This may at first sight seem very trivial, but the problem is that the transverse momentum is small (hundreds of MeV scale), quantum mechanically (through $k \sim h/\lambda$) corresponding to wavelengths around the confinement scale. In that domain the forces between quarks and gluons are large, prohibiting the use of (perturbative) QCD. Perturbative methods in QCD can only deal with the functions $f_i(x)$, integrated over k_T, or they can be and have been used in calculations that study the limit in which the transverse momentum becomes very large. In order to incorporate small transverse momenta, one needs the transverse momentum dependent (TMD) functions $f_i(x,k_T)$. These are a set of new functions which constitute part of the complex structure of hadrons and which have specific intrinsic k_T-dependence. Our breakthrough in introducing these new TMD functions, however, came when we found that they can incorporate specific angular correlations between the (transverse) momentum and the spin of quarks. Some of these correlations had been studied before, others were new. Setting up a systematic treatment, we introduced the true correlations that disappear upon integration and are absent at high k_T. Moreover, it turned out to be very important to characterize the nature of the correlation functions according to their behaviour under time-reversal symmetry (T) with special focus on the T-odd correlation functions. Because QCD respects time reversal symmetry, there is a unique experimental signature for these T-odd correlations. They show up in *single spin asymmetries* (SSA), non-vanishing differences between cross sections of processes in which the spin of only *one* hadron is reversed. This single spin effect is also reflected in the T-odd correlation functions. Instead of the usual spin transfer between hadrons and partons, they correlate the transverse spin with a particular transverse momentum configuration (*momentum-spin correlations*).

The impact of the concept of transverse momentum dependent PDFs on particle physics

Two special (T-odd) transverse momentum dependent (TMD) PDFs have had major impact: one function correlates transverse momentum of quarks with the transverse spin of the hadron it belongs to (*Sivers function*) and a second function describes a specific correlation between the transverse polarization and momentum of quarks in an unpolarized hadron (*Boer-Mulders function*). Both of these TMD functions have generated tremendous theoretical and experimental activity in the last ten years. On the theoretical side, they shed new light on spin structure of hadrons. Our group among several other groups in the world are working on theoretical aspects of these new functions. On the experimental side, our initiatives have given an enormous boost to the field of transverse spin physics, for example the RHIC Spin Physics program at Brookhaven National Laboratory (U.S.A.). Also at DESY (Hamburg) and CERN (Geneva) experiments on SSA have been and are being performed.

If one searches using for instance *Google* with the combination *Boer-Mulders*, one gets of the order of ten thousand hits, indicating that this work has a wide impact.

The next step forward – ambition of this ERC proposal

Having established the potential of the TMD PDFs, the time has come to take this concept a crucial step forward. I want to break with the restrictions of the collinear approximation for partons in high-energy processes and develop the full QCD dynamics underlying the novel correlations and make them into workable tools. These tools will enable a full manipulation of spins and momenta of the partons for understanding experimental results at all frontiers, energy and precision. If successful, the results of the project proposed here will create a new level of understanding in high-energy physics and nuclear physics, providing unifying links between models and computational tools that are currently disjoint. The timely development of this next-generation theoretical toolset ideally coincides with the running of the LHC and feasibility studies of future dedicated experimental facilities such as Electron-Ion Collider (EIC) in the U.S. and the Large Hadron Electron Collider (LHeC) in Europe, so that they can be combined towards effectively revealing the interplay of mechanisms in and beyond the standard model. It is beyond question that the issues in our proposal will need to be addressed in evaluating the experimental results expected from these facilities.

Objectives

(I) The first objective is to reach the same level of sophistication for TMD distribution and fragmentation functions as that for the collinear approach, in which no TMD correlations are considered. This requires proper identification of the relevant quantum fields of QCD, for instance through identification of k_T-weighted observables as expectation values of specific combinations of quark and gluon fields. It is essential that we clearly distinguish the treatment within the rigorous QCD framework, the proper identification of gauge-invariant matrix elements and the relevant quark and gluon operators from other, often intuitively appealing, approaches that are based on model assumptions for nonperturbative (confining) aspects of QCD. This first objective goes far beyond a mere extension of work that has been done so far [2]. It requires a new research line aiming for a full understanding of the quark-gluon dynamics that needs to be accounted for. In the treatment all aspects of QCD being a non-abelian gauge field theory play a role and one needs to combine perturbative and nonperturbative aspects.

(II) The second objective is the exploitation of the correlations as tools in high-energy scattering processes. Following the ground-breaking work outlined in the previous paragraph, studies on TMD correlations are now included worldwide in the research programmes of many existing or future facilities that have programmes on hadron physics (the RHIC-Spin programme at Brookhaven National Laboratory and the upgrade of Jefferson Laboratory in the U.S.A., the COMPAS experiment at CERN, plans for FAIR at GSI in Darmstadt, the J-PARC programme at KEK in Japan). Ongoing experiments confirm the appearance of novel phenomena such as specific single spin asymmetries. Although polarization is useful, the TMD correlations also could be employed in dedicated LHC experiments. They may be useful to investigate the Higgs sector through specific effects in the final state. Furthermore, TMD functions are going to play a role in other long-term plans, among them ambitious new large scale facilities such as the proposed LHeC in Europe or the EIC project in the US (we will give details below). Using the results of the investigations that are part of the first objective, it is possible to critically assess which novel aspects of hadron structure can be addressed in such future facilities.

Highlighting the objectives:

I I want to grasp the fundamental novel aspects of quark and gluon dynamics that are needed for TMD correlations, in particular the T-odd ones, and give a new meaning to the concept of *parton* in high energy collisions.

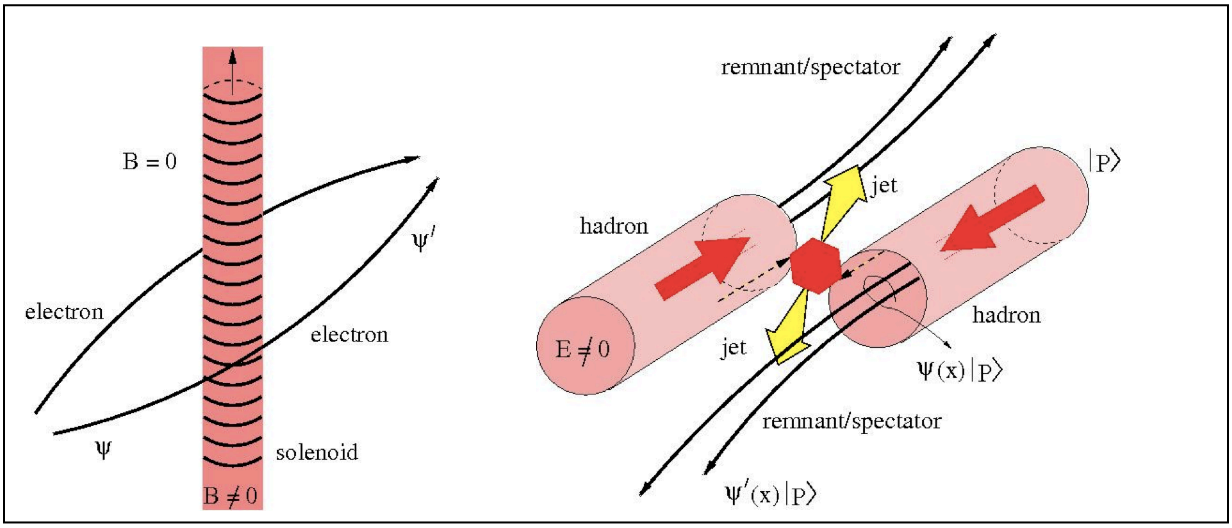
II I want to critically assess which TMD correlations can reliably be used in the tagging of very specific partonic initial states or in analysing specific asymmetries in partonic final states.

Knowing the effort that over decades went into establishing the collinear approach, these objectives are certainly very ambitious. Incorporating small k_T from the start avoids problems (collinear singularities) but doesn't come for free. I am confident that by a combination of the existing worldwide knowledge base for the collinear treatment and our expertise and knowledge base on TMD functions, I can develop a successful new research line with a team of dedicated Ph.D. students, postdocs and visitors. I am in a unique position here, not only because of expertise but also because of excellent connections with physicists active in the field of perturbative QCD as well as with physicist working in QCD phenomenology. And even if we do not solve all issues, the initiative will generate new, most probably unexpected, breakthroughs and will lead to new ways of rigorously employing QCD in hard scattering processes beyond the collinear approach.

Methodology and resources

The scale, ambition and impact of the project proposed here is larger than national individual programmes allow and in line with the high-risk/high-impact character of the ERC Advanced Grant scheme. The chosen methodology is such that it, in a natural way, is divided into parts that by themselves may yield important results. The overall strength and the chances of producing ground-breaking results, however, lie in the coherence of the different aspects in the full proposal, which will run for five years, as the major project in my group. Within the proposal, I envision the following interrelated **topics**:

(A) Fundamental studies of TMD functions (towards objective I): When one integrates over transverse momenta (the collinear approach), the transition hadron-to-parton and parton-to-hadron involves gluon dynamics, but accounting for these effects is relatively straightforward in the form of quantum mechanical phases. In the collinear case, only one direction is probed and the phases do not affect observables, i.e. they do not lead to interference; one can interpret the distribution and fragmentation functions as probabilities and decay functions, respectively. Including transverse momenta the gluon dynamics produces phases that do affect observables. To be precise, they track the flow of colour charge in the high-energy process and can have observable consequences. Technically one encounters basic non-local contributions that go beyond the usual standard *operator product expansion*. In the last year, T.C. Rogers and M. Aybat (postdocs in Amsterdam) have obtained some interesting new results [3] that constitute a first step to calculate the scale dependence (evolution equations) for TMD functions, combining aspects of TMD physics and collinear approaches (the Collins-Soper-Sterman formalism).



The dependence on colour flow can be compared with the famous Aharonov-Bohm phase in quantum electrodynamics (QED). The phase of the electron becomes visible in interference experiments. If an electron can travel to a screen via two different paths passing two sides of a current-carrying long solenoid (see left half of figure above), an interference pattern emerges even if it only passes through space where there are no electromagnetic fields. Similarly, a high-energy scattering process is a sudden process (see right half of figure above) in which a parton is removed from a hadron. If two hadrons are involved, the phases in the 'wave functions of the coloured remnants' produce physical effects, which are characterized as T-odd (odd under time reversal). They show up as non-vanishing single spin asymmetries combined with azimuthal asymmetries of the produced particles. It is one of the effects encoded in TMD distribution and fragmentation functions. As emphasized already, it is the rigorous embedding of the potentially very rich TMD phenomenology as portable effects in the QCD framework (establish factorisation) that is being pursued. I am confident that such a description can be formulated, but it constitutes a new research line, requiring combination of our strength with that of experts on the evolution of PDFs.

(B) Phenomenology of TMD's (towards objective II): High-energy scattering processes have been and are being studied at many accelerators around the world. Higher energies allow to probe ever smaller distances. Detection of specific particles allows focus on gluons or on the various flavours of quarks (up, down, strange, charm, bottom and top). Polarization of beams and targets and polarimetry in the final state allows to compare different quantum states of the particles involved, hence increasing our understanding of the dynamics of the scattering processes and enhancing our knowledge of the detailed inner structure of the proton. As such TMD's clearly play a dual role. Firstly, the functions themselves encode many aspects of the structure of the proton, which will be challenging input for lattice gauge calculations. Secondly, their understanding within the QCD framework makes them into tools for detection of physics beyond the Standard Model. In particular the signs of asymmetries in various processes depend on the colour flow in the hard part of the process. This makes it possible to focus on particular final states containing gluon jets or heavy quark pairs or no colour at all. In particular the study of TMD's for gluon distributions is far less developed as compared to that for quark distributions, while gluon distributions are much more important for applications at the highest energies.

***(C) Involvement in long-range planning*:** The dual role of TMD's in enhancing our understanding of QCD as a fundamental cornerstone of the Standard Model and providing tools in the study of high energy scattering processes gives them a wide applicability in QCD-related investigations. For instance, I expect them to have impact in defining and clarifying the physics cases for, for instance, the Electron-Ion Collider (EIC) in the U.S. or the Large Hadron Electron Collider (LHeC) in Europe. I intend to actively participate in such studies.

Large Hadron Electron Collider (LHeC)

The LHeC is a proposed colliding beam facility at CERN, which will exploit the new world of energy and intensity provided by the LHC for lepton-nucleon scattering. An existing 7 TeV LHC proton or heavy ion beam will collide with a new electron beam, running simultaneously with proton-proton or heavy ion collisions at the LHC. It will push the frontier reached at the HERA accelerator at DESY. Access to very low-x values, which are linked to the study of transverse momenta, may make it the ideal laboratory to study strong interactions in an environment of very high parton densities, but with small enough strong coupling to apply perturbative methods.

Electron-Ion Collider (EIC)

In the U.S. Nuclear Physics Long-Range Plan, the EIC has been proposed as a next-generation high luminosity electron-ion collider facility addressing compelling physics questions essential for understanding the fundamental structure of matter. Polarized beams in the EIC will give unprecedented access to the spatial (3-dimensional) and spin structure of gluons in the proton.

Organization and personnel

As PI, I plan to spend **60% of my time** on the proposal. I have previously pioneered the breakthrough that is underlying the current proposal, so I am well positioned to achieve its objectives. I plan to be working at VU University and the Nikhef Institute with a group of about 10 theoretical particle physicists, of which on average 5-6 persons are funded from this proposal. This group will involve three senior physicists. The PI at the full professor level will lead the project; senior researchers with experience in the same field are available in the immediate environment in Amsterdam. This assures an excellent core group of physicists working together and guiding the postdocs and graduate students. I plan to hire two Ph.D. students and three or four postdocs (in total 12 postdoc years) and I will have frequently visitors as part of the programme.

I expect to profit greatly from my extensive network of physicists in Europe, built over the years among others in previous EU Framework Programmes. This network involves theorists *and* experimentalists, which is an essential ingredient for making progress on the lines set out in this proposal. Also within the Netherlands there is an excellent embedding of my group. The group is located at a University with on campus many facilities and possibilities to attract students. Furthermore, my group is part of the Network for Theoretical High Energy Physics with theorists covering a broad range of fields, as well as the Nikhef collaboration, providing a stimulating environment for lively interactions with experimentalists.

References

1 Breakthrough papers from our group include two renowned papers (500 citations), P.J. Mulders and R.D. Tangerman, *The complete tree level result up to order 1/Q for polarized deep inelastic electroproduction,* Nucl. Phys. B 461:197-237, 1996 and Daniel Boer and P.J. Mulders, *Time-reversal odd distribution functions in leptoproduction*, Phys. Rev. D 57:5780-5786, 1998.

2 An excellent overview of the use of QCD methods in high-energy scattering processes including the collinear approach and the status of transverse momentum dependent functions is found in the book of J.C. Collins, *Foundations of Perturbative QCD*, Cambridge University Press 2011.

3 Following methods outlined in Ref. [2] and building on the formalism of J.C. Collins, D.E. Soper and G. Sterman, Nucl. Phys. B250 (1985) 199, interesting progress has been reported in S.M. Aybat and T.C. Rogers, *TMD Parton Distribution and Fragmentation Functions with QCD Evolution,* Phys. Rev. D83 (2011) 114042 including the availability of evolution programmes via http://projects.hepforge.org/tmd/.

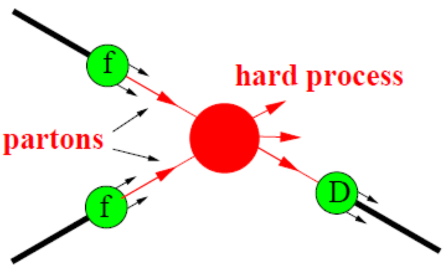
Section 2: ***Quantum Chromodynamics at Work***

a. State-of-the-art and objectives

Introduction

Quantum Chromodynamics (QCD) plays a central role in this proposal. It is the well-established theoretical framework for the strong nuclear force, which binds together quarks and gluons into protons and neutrons, which in turn constitute the building blocks of the atomic nuclei. The theory of QCD describes the interactions among the quarks, anti-quarks and gluons carrying colour charges, collectively referred to as *partons*. These partons do not exist in isolation, but only confined in colour neutral combinations, known as *hadrons*. The size of hadrons is the confinement scale, about 1 fm or 10^{-15} m. At distances smaller than the confinement scale, quarks and gluons in essence start behaving as free particles (known as asymptotic freedom).

In collisions between particles at high energies one probes distances of the order of the corresponding quantum mechanical wavelength, which in colliders with energies considerably above the GeV-scale is much shorter than the confinement scale and one can describe the scattering directly in terms of collisions between the (quasi-free) quarks and gluons. This description uses established perturbative quantum field theoretical methods and allows comparison of cross sections (counting rates) for various scattering processes at various energies. To account for the initial and final state hadrons, for example in proton-proton scattering at the Large Hadron Collider (LHC), one in essence needs to know the probability of finding quarks and gluons inside the protons. These probabilities are known as Parton Distribution Functions (PDF's), functions $f_{h\to i}(x)$ with x being the parton's momentum as fraction of the momentum of the original hadron (a fraction which must lie between 0 and 1). There are such functions for any hadron h and any kind of parton i (i can be a quark or anti-quark of any flavour or a gluon). In a similar way one needs to know how many and which hadrons h a particular parton i can produce in the final state. This is described by Parton Fragmentation Functions (PFF's), functions $D_{i\to h}(z)$; here z is the hadron's momentum fraction.



Pictorial description of a high-energy collision with (consider figure from left to right) two colliding hadrons (thick lines on left) producing partons with probabilities described by **Parton Distribution Functions** (PDF's f). These partons collide with each other, a hard process that can be calculated in QCD and finally they fragment into jets of hadrons in the final state (black lines on right) described by **Parton Fragmentation Functions** (PFF's D).

The intuitive confirmation for the above picture of the scattering process is the appearance of jets – bunches of hadrons all moving roughly parallel to each other. In a worldwide effort over the last few decennia, this intuitive description of PDFs and PFFs has rigorously been incorporated in the QCD framework with impressive precision results. The functions have been shown to be *universal*, appearing in *factorized* expressions. They can be extended to include additional degrees of freedom, namely the spin carried by partons as well as hadrons, then describing the transfer of polarization between hadrons and partons (*spin-spin correlations*).

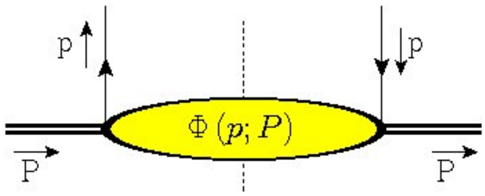
The field theoretical language for the PDF's and PFF's involves matrix elements of quark and gluon operators. In particular for PDFs one needs forward matrix elements like

$$\Phi^q_{ij} = \left\langle P \middle| \bar{\psi}_j(0)\,\psi_i(0) \middle| P \right\rangle$$

involving for the quark distribution functions quark fields. Local matrix elements can be incorporated into a field theoretical framework. The description of a PDF, however requires a tower of local operators including also (covariant) derivatives Dμ, which can be recast as a Fourier transform

$$\Phi^q_{ij}(x) = \int \frac{d(\xi.P)}{(2\pi)} e^{i\,p.\xi} \left\langle P \left| \bar{\psi}_j(0)\,\psi_i(\xi) \right| P \right\rangle_{\xi.n=\xi_T=0}$$

which only depends on the momentum fraction x (which in a full expansion of the momentum of a quark is the so-called light-cone component x = p.n). Involving only one component one has a non-local matrix element with a light-like separation ξ between the fields. This *collinear* treatment is useful at high energies, where the other components of the quark momenta are often irrelevant. The correlator above can be represented in a diagrammatic way as



'connecting' hadrons with partons (in this case quarks). Since time-ordering is not important in the high-energy limit (equal light-cone time) the diagram can be considered as a forward anti-parton – hadron amplitude. This diagram is then in the next step combined with the diagrams representing the squared hard amplitude of the scattering process involving quarks, gluons or other particles for which one uses the theory of the Standard Model of particle physics, in this way incorporating hadron confinement into a powerful field theoretical description of high-energy scattering processes.

Transverse momentum dependent (TMD) PDF's

Next, I want to explain the breakthrough in which my group played the initiating role, starting with the now classic work of Mulders and Tangerman [1]. We considered the role of the transverse momentum dependence in the PDF's and PFF's, which means looking at $f_i(x,p_T)$ where x and p_T characterize the parton's momentum in a hadron with momentum P (the parton momentum is written as $p = x\,P + p_T$), x being the fraction of the hadron's momentum, p_T the (transverse momentum) component orthogonal to this momentum. The field theoretical matrix elements involving the Fourier transform

$$\Phi^q_{ij}(x,p_T) = \int \frac{d(\xi.P)d^2\xi_T}{(2\pi)^3} e^{i\,p.\xi} \left\langle P \left| \bar{\psi}_j(0)\,\psi_i(\xi) \right| P \right\rangle_{\xi.n=0}$$

now include non-local combinations of parton fields where the separation ξ is no longer light-like, but also involves a transverse separation. This may at first sight seem very trivial, but the problem is that the transverse momentum is small (hundreds of MeV), quantum mechanically corresponding to wavelength of the order of the confinement scale. In that domain the forces between quarks and gluons are large, prohibiting the use of (perturbative) QCD. Perturbative methods in QCD can only deal with the functions $f_i(x)$, integrated over p_T, or with the behaviour when the transverse momentum becomes very large, a limit which indeed has been studied in detail. The latter can be done using perturbation theory within the QCD framework. For example, a quark, can acquire a large momentum by splitting off a gluon, which can be calculated and leads to a $1/p_T^2$ behaviour. The non-integrability at large p_T leads to a logarithmic energy dependence, that is experimentally verified with great precision. For small-p_T one finds in the calculation unphysical collinear divergences, which have to (and can) be carefully dealt with in perturbation theory. In order to incorporate small transverse momenta, one can also turn to the transverse momentum dependent (TMD) functions $f_i(x,p_T)$, in which case one doesn't have to worry about the collinear problems. Instead, one obtains a number of new functions which constitute part of the complex structure of hadrons and which have specific intrinsic p_T-dependence. All of them have very natural interpretations as momentum distributions (see box below). Our breakthrough in introducing these new TMD functions, however, came when we found that they can incorporate specific angular correlations between the (transverse) momentum and the spin of quarks. Some of these correlations had been studied before, others were new. Setting up a systematic treatment, we introduced the true correlations that disappear upon integration and are absent at high p_T. Moreover, it turned out to be very important to characterize the nature of the correlation functions according to their behaviour under time-reversal symmetry (T) with special focus on the T-odd ones in the work of

Boer and Mulders [2]. Because QCD respects time reversal symmetry, there is a unique experimental signature of such T-odd correlations. They show up in *single spin asymmetries* (SSA), non-vanishing differences between cross sections of processes in which the spin of only *one* hadron is reversed. This single spin effect is also reflected in the T-odd correlation functions. Instead of the usual spin transfer between hadrons and partons, they correlate the transverse spin with a particular transverse momentum configuration (*momentum-spin correlations*). Two special transverse momentum dependent (TMD) PDFs are the one that correlates transverse momentum of quarks with the transverse spin of the hadron it belongs to (*Sivers function*) or the one that describes a specific correlation between the transverse polarization and momentum of quarks in an unpolarized hadron (*Boer-Mulders function*). Both of these TMD functions have generated tremendous theoretical and experimental activity in the last ten years. On the theoretical side they shed new light on spin structure of hadrons. Our group among several other groups in the world are working on theoretical aspects of these new functions. On the experimental side the developments have given an enormous boost to the field of transverse spin physics, for example the RHIC Spin Physics program at Brookhaven National Lab. (U.S.A.). Also at DESY (Hamburg) and CERN (Geneva) experiments on SSA have been and are being performed.

A useful review on phenomenology of TMD's is given in Ref. [3]. An excellent overview of field theoretical methods for QCD in high-energy physics can be found in the recently published book of Collins [4].

The quark production matrix in a polarized nucleon

The interpretation as probability distributions of the correlator Φ is nicely illustrated by translating it into a quark production matrix. As basis states one can use left- and right-handed quarks in nucleon helicity eigenstates (pictorially given above the matrix). One finds a production matrix of the form

$$\begin{pmatrix} f_1 + g_{1L} & \frac{|p_T|}{M}\, e^{i\phi}\, g_{1T} & \frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp} & 2\, h_1 \\ \frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T}^{*} & f_1 - g_{1L} & \frac{|p_T|^2}{M^2}\, e^{-2i\phi}\, h_{1T}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, h_{1L}^{\perp *} \\ \frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp *} & \frac{|p_T|^2}{M^2}\, e^{2i\phi}\, h_{1T}^{\perp} & f_1 - g_{1L} & -\frac{|p_T|}{M}\, e^{i\phi}\, g_{1T}^{*} \\ 2\, h_1 & -\frac{|p_T|}{M}\, e^{i\phi}\, h_{1L}^{\perp} & -\frac{|p_T|}{M}\, e^{-i\phi}\, g_{1T} & f_1 + g_{1L} \end{pmatrix} .$$

The p_T-integrated function $f_1^q(x,p_T)$ for any quark of flavour q gives the collinear quark distribution, usually denoted q(x). For polarized nucleons one has 'longitudinal spin' distributions $g_{1L}^q(x,p_T)$, integrated usually denoted as Δq(x) and 'transverse spin' distributions $h_{1T}^q(x,p_T)$, integrated usually denoted as δq(x). Including transverse momentum dependence, these distributions fill the full spin-spin correlation matrix but each with a characteristic azimuthal behaviour. The T-odd functions show up as imaginary parts of the off-diagonal entries.

Objectives of the proposal

(I) The first objective is to reach the same level of sophistication for TMD distribution and fragmentation functions as that for the collinear approach, in which no TMD correlations are considered. This requires proper identification of the relevant quantum fields of QCD, for instance through identification of p_T-weighted observables as expectation values of specific combinations of quark and gluon fields. It is essential that we clearly distinguish the treatment within the rigorous QCD framework (factorization), the study of gauge-invariant matrix elements and other, often intuitively appealing, approaches that are based on model assumptions for nonperturbative (confining) aspects of QCD. This first objective goes far beyond a mere extension of work that has been done sofar. It requires a new research line aiming for a full understanding of the quark-gluon dynamics that needs to be accounted for, using all aspects of QCD being a non-abelian gauge field theory and combining perturbative and nonperturbative aspects.

(II) The second objective is the exploitation of the correlations as tools in high-energy scattering processes. Following the ground-breaking work outlined in the previous paragraph, studies on TMD correlations are now included worldwide in the research programmes of many existing or future facilities that have programmes on hadron physics (upgrade of Jefferson Laboratory in the U.S.A., plans for FAIR at GSI in Darmstadt, RHIC programme at Brookhaven National Laboratory, J-PARC programme at KEK in Japan). Early experiments confirm the appearance of novel phenomena. The TMD correlations, however, also offer possibilities for dedicated LHC experiments that may be useful to investigate the Higgs sector. Furthermore, TMD's are often mentioned in other long-term plans, among them ambitious new large scale facilities such as the proposed LHeC in Europe or the EIC project in the US (we will give details below). Using the findings of the study mentioned under the first objective, I want to critically assess which novel aspects of hadron structure can be addressed in these facilities.

Highlighting the objectives:

I I want to grasp the fundamental novel aspects of quark and gluon dynamics for TMD correlations, in particular the T-odd ones, and give a new meaning to the concept of *parton* in high energy collisions.

II I want to critically assess which TMD correlations can reliably be used in the tagging of very specific partonic initial states or in analysing specific asymmetries in partonic final states.

Knowing the effort that went into establishing the collinear approach, the first objective is certainly very ambitious. Incorporating small p_T from the start avoids problems (collinear singularities) but doesn't come for free. I am confident that given the existing worldwide knowledge base for the collinear treatment and our expertise on TMD functions, I can develop a successful new research line with a team of dedicated Ph.D. students, postdocs and visitors. And even if we do not solve all issues, the initiative will generate new breakthroughs and may lead to new ways of rigorously employing QCD in hard scattering processes beyond the collinear approach.

b. Methodology

In general I have been quite successful in obtaining funds for Ph.D. and/or postdoc position. An ERC Advanced Grant, however, will offer me the possibility to start this ambitious enterprise, of which the scale is larger than national individual programmes allow. Even if it is a large scale enterprise, the chosen methodology is such that it, in a natural way, is divided into parts that by themselves will yield important results. The overall strength and the chances of producing ground-breaking results, however, lie in the coherence of the full proposal, which will run for five years, starting on **January 1, 2013** and which will be the major project in my group in those years. Within the proposal, I envision the following interrelated **topics**:

(I) Fundamental studies of TMD's (towards objective I): starting point and projects

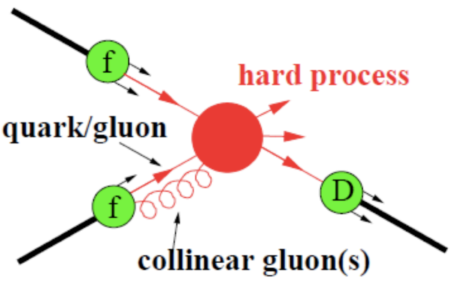
It has become clear that taking the partonic description of nucleons beyond the collinear approach would be extremely nice to deepen our understanding of QCD and because it helps us in the understanding of experiments. A systematic formalism using perturbation theory known as the Collins–Soper–Sterman (CSS) formalism [5] has been set up already in 1985 and has been used in a number of high-energy scattering processes. As compared to this formalism, the introduction of the TMD functions is still in its infancy. Nevertheless, the promise of these TMD functions is great because of their intuitive simplicity and their ability to provide, in a natural way, candidates for T-odd functions that can explain single spin asymmetries appearing at leading order, rather than at subleading (higher twist) order. A first step towards a full incorporation of TMD functions into the field theoretical framework of QCD has been the study of the matrix elements and the role of gluon fields therein. When one integrates over transverse momenta (the collinear approach), the transition hadron-to-parton and parton-to-hadron involves gluon dynamics, but accounting for these effects is relatively straightforward in the form of quantum mechanical phases. In the collinear case, only one direction is probed and the phases do not affect observables, i.e. they do not lead to interference; one can easily interpret the distribution and fragmentation functions as probabilities and decay functions, respectively. Including transverse momenta the gluon dynamics produces phases that do track the flow of colour charge in the high-energy process and can have observable consequences. Technically one encounters basic non-local contributions that go beyond the usual standard *operator product expansion*.

In B1 we compared the situation with the famous Aharonov-Bohm phase in quantum electrodynamics (QED). The phase of the electron becomes visible in interference experiments. In a high energy scattering process one has a sudden process in which a parton is removed from a hadron. If two hadrons are involved, the phases in the 'wave functions of the remnants' produce physical effects, which are characterized as T-odd (odd under time reversal). They show up as non-vanishing single spin asymmetries, but only in combination with azimuthal asymmetries of produced particles. It is the rigorous embedding of such TMD effects as portable effects in the QCD framework (establish factorisation) that is being pursued. At that point a number of problems have been encountered that hamper TMD-factorization.

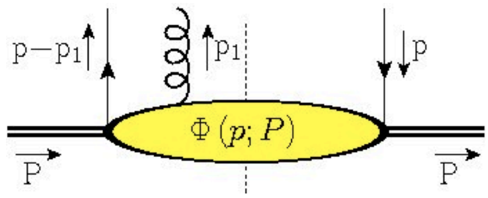
Next, I want to outline specific studies, emphasizing the novel aspects and discussing the feasibility.

(I.a) Proper field theoretical treatment of TMD's

The proper field theoretical definitions of PDFs, both in collinear as well as in the TMD case is a highly non-trivial issue [6]. In Feynman diagram language, one may have additional partons participating in the hard process. These are mostly suppressed at high energies, but gluons with polarizations parallel to the quark momentum must be resummed, modifying the most naive definition of PDFs. Two partons originating from one hadron (the line-with-arrow representing a quark and the curled-up line representing a gluon) participate in the hard scattering process. The addition of gluons is what opens Pandora's box!



The inclusion of gluons with polarization parallel to the parton momentum gives rise to correlators including appropriate future/past pointing gauge links (see box on next page).



For TMD's one obtains correlators with different gauge links in particular the future- or past-pointing links discussed in some detail in the box below (possibilities a and b for quarks, respectively). The sum of these is T-even, the difference T-odd. Since it depends on the hard scattering process (which absorbs the additional gluons) which correlator to use. As a consequence one gets differences for azimuthal asymmetries associated with the T-odd TMD's. The simplest cases are deep inelastic scattering (DIS), electron-positron annihilation and lepton-pair production (Drell-Yan or DY). In these cases the flow of colour charge is unique, being either a simple annihilation or creation of colour charges or a simple flow of colour from initial to final state. The fact that in DIS the hadron correlator contains a future-pointing gauge link, while in DY one needs a past-pointing gauge link produces a crucial sign change in the asymmetries expected for DIS versus DY (for experts known as Collins and Sivers asymmetries, respectively).

We want to understand what happens beyond these simplest processes as well as what happens for gluons. The extension to gluons involves a more complex gauge link structure (see box on gauge links) and is actually discussed in more detail as the second project (I.b). Although the process dependence coming from the gauge invariance requirements points to a factorization breaking, there are situations in which the full effect can be cast in the form of modified cross sections (see under II). *But the full solution is as yet unknown*, requiring inclusion of the full QCD dynamics, which includes besides appropriate gauge links the study of the evolution of distribution functions. A number of problems has been encountered hampering TMD-factorization with recently some promising steps towards implementing QCD-evolution [7]. I am confident that a full description can be formulated, but it requires combining our strength with that of several experts on the evolution of PDFs. This project deals with the basic theoretical issues and is central to the proposal. It is naturally linked and completed by the other theoretical parts in I and the phenomenological studies in II and III.

For this part (I.a), I plan to attract at least two experienced postdoc with complementary expertise to myself and with relevant (different) backgrounds. They work together with two Ph.D's, one of them being a Ph.D in this proposal. I intend to spend around 20% of my time (one third of my commitment of 60%) on this part.

Gauge links for quark and gluon TMD's

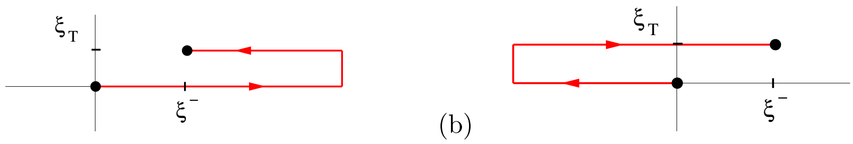
For quark distribution functions the field theoretical expression in terms of a non-local product of quark fields ψ is given by

$$\Phi_{\rm quark}(x,p_T;n,C) = \int \frac{d(\xi{\cdot}P)\,d^2\xi_T}{(2\pi)^3}\;e^{i\,p\cdot\xi}\;\langle P|\overline{\psi}_j(0)\,U_{[0,\xi]}^{[n,C]}\,\psi_i(\xi)|P\rangle\Big|_{\xi\cdot n=0},$$

where the gauge link U,

$$U_{[0,\xi]}^{[n]} = \mathscr{P}\,\exp\left(-i\int_0^\xi d(\eta{\cdot}P)\,n{\cdot}A(\eta)\right),$$

is a path-ordered exponential, which depends on the process through the path C running from the point 0 to ξ. The simplest possibilities are

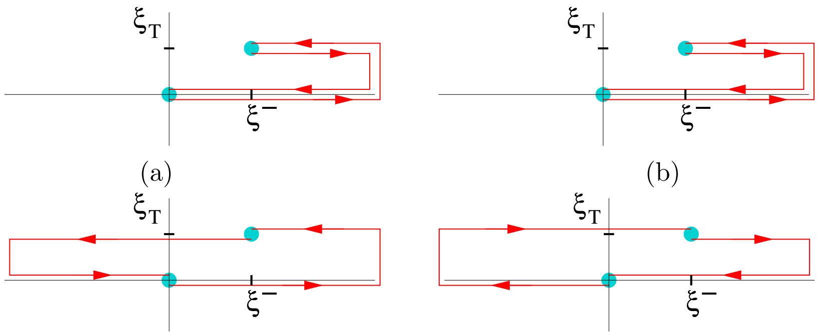


(a) (b)

which are relevant for semi-inclusive deep inelastic scattering (a) or the Drell-Yan process (b),respectively. For gluons the field theoretical expression in terms of a non-local product of gluon field strengths Gis given by

$$\Phi^{\alpha\beta}_{\rm gluon}(x,p_T;n,C,C') = \int \frac{d(\xi{\cdot}P)\,d^2\xi_T}{(2\pi)^3}\;e^{i\,p\cdot\xi}\;\langle P|{\rm Tr}\left(G^{n\beta}(0)\,U_{[0,\xi]}^{[n,C]}\,G^{n\alpha}(\xi)\,U_{[\xi,0]}^{[n,C']}\right)|P\rangle\Big|_{\xi\cdot n=0},$$

with already as simplest possibilities four different gauge link connections (possibilities a – d in the figure below), since one needs for TMD's two gauge links U[C] and U[C'] to deal with the colour of gluons,



(a) (b) (c) (d)

(I.b) Gluon TMD's

The emphasis in many discussions is on transverse momentum dependence of quark distributions, but at high energies the role of quarks is less prominent than that of gluons. For many of the issues of universality and evolution it is natural and also simpler to start with the quarks, as they have the smallest possible nonzero colour charge. Putting emphasis on gluons, however, brings in new subtleties, e.g. the colour flow can be quite different. Depending on the hard process, the gluon charge can split into a colour – anti-colour charge, which requires for TMD's even at the simplest level, the consideration of four different gauge links (see box on gauge links on previous page). Like for the quarks, there are also several novel momentum-spin correlations for gluons (see production matrix below). The collinear functions naturally parameterize the circular gluon polarizations in nucleon helicity states. Including TMD's one has for instance the very interesting option of parameterizing longitudinally polarized gluons through characteristic azimuthal asymmetries (discussed under II). Such asymmetries can even show up in scattering processes with unpolarized protons. Another reason to consider gluon TMD's is my expectation that they can play an important role in diffractive phenomena, at this stage merely a conjecture. In these phenomena there is no colour exchange between the scattered hadron and the hard part (This could naturally occur when the two partons originating from a single hadron are both gluons). This project will start by extending the work on quarks related to non-trivial gauge links. Together with the incorporation of aspects of evolution (project I.a), it will provide the essential background for the phenomenology for LHC physics (see II) as well as for establishing the physics case for electron-hadron colliders (see III).

This project (I.b) is planned to be the focus of the second Ph.D. projects. I also want to attract a postdoc with expertise in this field.

The gluon production matrix in a polarized nucleon

The interpretation as probability distributions of the gluon correlator can also be translated into a production matrix similar as for quarks. As basis states one can use circularly polarized quarks in nucleon helicity eigenstates (pictorially given above the matrix). One finds a production matrix of the form

$$\begin{pmatrix} f_1 + g_{1L} & \frac{k_T e^{-i\phi}}{M}\left[g_{1T} + i f_{1T}^{\perp}\right] & e^{-2i\phi}\left[h_1^{\perp\prime} - i h_{1L}^{\perp\prime}\right] & i\frac{k_T e^{-3i\phi}}{M} h_{1T}^{\perp\prime} \\ \frac{k_T e^{+i\phi}}{M}\left[g_{1T} - i f_{1T}^{\perp}\right] & f_1 - g_{1L} & \frac{i k_T e^{-i\phi}}{M}\left[h_{1T} + h_{1T}^{\perp\prime}\right] & e^{-2i\phi}\left[h_1^{\perp\prime} + i h_{1L}^{\perp\prime}\right] \\ e^{+2i\phi}\left[h_1^{\perp\prime} + i h_{1L}^{\perp\prime}\right] & \frac{-i k_T e^{+i\phi}}{M}\left[h_{1T} + h_{1T}^{\perp\prime}\right] & f_1 - g_{1L} & \frac{k_T e^{-i\phi}}{M}\left[g_{1T} + i f_{1T}^{\perp}\right] \\ -i\frac{k_T e^{+3i\phi}}{M} h_{1T}^{\perp\prime} & e^{+2i\phi}\left[h_1^{\perp\prime} - i h_{1L}^{\perp\prime}\right] & \frac{k_T e^{+i\phi}}{M}\left[g_{1T} - i f_{1T}^{\perp}\right] & f_1 + g_{1L} \end{pmatrix}$$

The imaginary (T-odd) functions are explicitly shown in the matrix. The function $f_1^g(x,p_T)$ is the unpolarized gluon distribution, in the p_T-integrated (collinear) case usually denoted g(x). For a polarized nucleon one has 'longitudinal spin' distributions $g_{1L}^g(x,p_T)$, in the collinear case usually denoted as $\Delta g(x)$. These are the only functions that survive in the collinear limit. The TMD's are different with transverse momenta naturally correlated with linear gluon polarizations.

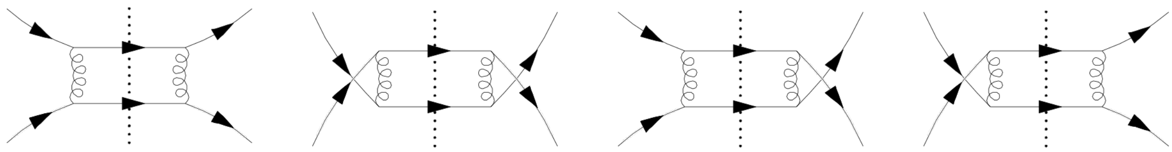
(I.c) Model calculations

With appropriate field theoretical definitions for the TMD's, one can turn to lattice gauge theories [8], effective field theories or other models. These model approaches offer interesting possibilities when one wants to study the matrix elements, e.g. their dependence on the gauge link structure. This is being pursued by some of the lattice gauge collaborations. I consider the model calculations as useful, but they are not the main purpose. Model calculations certainly will provide guidance when one turns to phenomenology. We plan to do such calculations in many cases in collaboration with other groups.

I do not plan to attract postdocs specifically for model calculations, but in the process of attracting postdocs during the runtime of the project the need for expertise in specific areas under (I.c) may have come up.

An intermezzo: QCD-entanglement in the lab

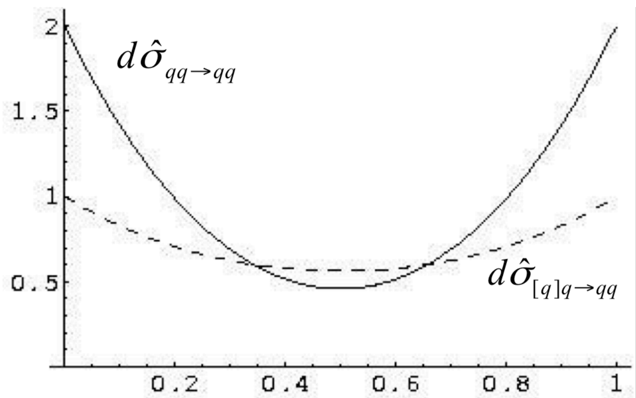
In proton-proton scattering a possible subprocess is quark-quark scattering, two quarks in, two quarks out, described by a quantum mechanical amplitude. This amplitude can be calculated with the help of Feynman diagrams. In lowest order one has the exchange of a colour force particle (gluon) between the two quarks. One has two contributions in the amplitude (A_1 and A_2) and in the squared amplitude (which is the measured probability) one has four contributions, as Feynman diagrams pictorially represented as



$A_1 A_1^*$ $A_2 A_2^*$ $A_1 A_2^*$ $A_2 A_1^*$

Each of these diagrams also has two colour flow possibilities. The sum of these four (including colour flow eight) contributions gives the result of the hard process and is multiplied with corresponding PDF's representing quark probabilities in initial state and decay into final states. In the figure below this result is shown as the *qq→qq* contribution.

For the time-reversal odd PDF's (depending on transverse momenta) one gets a modified combination of these eight contributions, each with appropriate sign. This leads to calculable factors $C_G^{[U(D)]}$, where *D* refers to the diagrammatic contributions, each of which involves a specific gauge link structure *U(D)*, determined by the colour flow. In the figure this result is shown as the *[q]q→qq* contribution. There is a pronounced difference when the cross sections (summed contributions) are plotted (on a relative scale) as functiosn of the scattering angle in the center of mass frame of the hard scattering process.



$$y = \tfrac{1}{2}(1-\cos\vartheta)$$

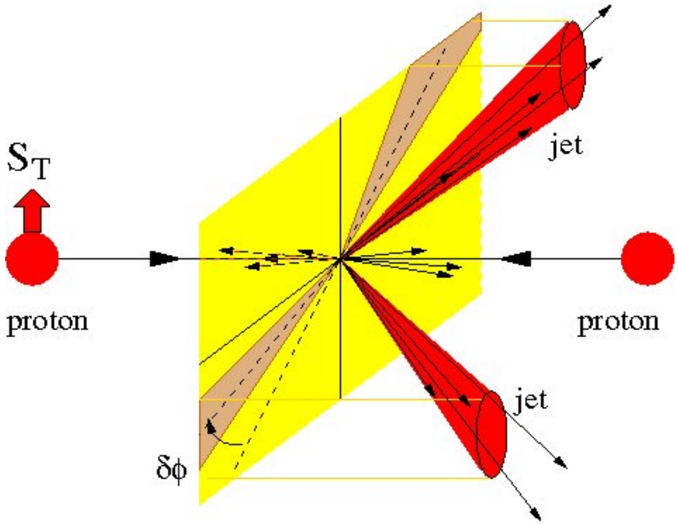
$$\hat{\sigma}_{qq\to qq} = \sum_{[D]} \hat{\sigma}^{[D]}$$

$$\hat{\sigma}_{[q]q\to qq} = \sum_{[D]} C_G^{[U(D)]} \hat{\sigma}^{[D]}$$

It should be noted that to single out the dependence on one of the quarks, one needs dedicated experiments (as will be pointed out under (II) when we discuss for proton-proton scattering the non-alignment of jets in the transverse plane). Theoretically interesting is the fact that there exists more than one colour gauge-invariant combination of squared amplitudes. The above example [taken from the paper: A. Bacchetta, C.J. Bomhof, P.J. Mulders and F. Pijlman, *Single spin asymmetries in hadron-hadron collisions*, Phys. Rev. D 72:034030, 2005] illustrates the possibilities to identify from the hard cross section specific (T-odd) momentum – spin correlations in initial (or final) state.

(II) Phenomenology of TMD's (towards objective II)

Consideration of the 'intrinsic transverse momentum' only makes sense if it can be properly measured. At high energies, that is not immediately obvious. Measurements of transverse momentum, indeed, are possible, but they often require that the colliding particles are polarized in a specific direction, or that one measures the polarization of produced particles (polarimetry), or that one measures angular distributions of produced particles (azimuthal asymmetries).



An example of the feasibility to access intrinsic transverse momentum in high energy processes is for proton-proton scattering shown in this figure. The non-collinearity (angle δφ) of the projections of two jets onto the transverse plane is a measure of transverse momentum. By taking specific weights and correlations with the azimuthal direction set by the polarized proton, one can isolate correlations due to intrinsic transverse momentum in those cases where perturbative calculations give zero as result in leading order [9]. Except the dependence on δϕ, the dependence on other variables like y = t/s follows the behaviour as expected for an entangled situation (see box on previous page).

The importance of symmetries as link between theory and experiment for TMD's has already been emphasized. The strong interactions are invariant under space inversion (P), charge conjugation (C) and time-reversal (T). Space inversion allows for a distinction of parity even and odd phenomena. In the same way, time-reversal invariance allows a distinction between time-reversal even (T-even) and time-reversal odd (T-odd) phenomena. This can be used as a powerful tool to identify specific parts in the interaction between quarks and gluons and relate them to suitable (experimentally accessible) observables as outlined above. In particular, the single spin asymmetries mentioned above are examples of T-odd observables.

For the phenomenology of TMD's, I distinguish three kinds of analyses, the first level would be assuming TMD-factorization, i.e. just working with the probabilities $f_i(x,p_T)$ and elementary hard cross sections, irrespective of this factorization has been established or not. It is clear that trying to describe data on azimuthal asymmetries in this most naive way is useful because if only to point out discrepancies. At a second level of analyses, one would take into account the fact that the naive factorization has to be replaced by a generalized factorization that accounts for the colour flow. For simple processes like the ones mentioned also in (I.a), deep inelastic scattering, electron-positron annihilation or lepton-pair production, the colour flow is unique and one expects predictable sign changes. More complex processes like proton-proton scattering imply more complex, but calculable effects (see box on QCD-entanglement). Some applications at this second level for quark and gluon TMD's have been worked out with collaborators worldwide [10], indicating interesting options for measurements at LHC or future high-luminosity electron-hadron colliders.

At the third level of analyses, we want to include the full gluon dynamics, using the results of the projects under (I), in particular (I.a). It requires the incorporation of beyond leading order (NLO, NNLO) results not only to deal with the regime of large p_T and study the evolution of TMD's. At the same time we want to use the regulating properties of TMD functions at small p_T and include the full set of TMD's including the T-odd ones. *Implementation of this third level is still unexplored territory.*

Next, I outline a few specific phenomenological studies.

(II.a) Analysis of observables

Transverse momenta of partons are by definition 'hidden' variables, that only show up by constructing the appropriate quantities (cf. the a-collinearity of jets discussed above). In particular situations hidden variables may give away their origin because they can only appear in combination with e.g. particular polarization directions (usually transverse polarization) or partons may give away their identity through a quark mass (c-or b-quarks) through characteristic decay patterns. For the analysis of final states, we will need to establish relations between jet observables and the transverse momenta in the fragmentation process. For the PFF's in the fragmentation process the use of time-reversal symmetry is very different from the PDF's and also the consequences of adding gluons differ. I want to make an exhaustive comparative study of observables, including the role of evolution, as part of the full project. Important guidance comes from the extensive investigations on effects beyond leading order that already exist for various jet observables.

Even if an analysis of observables may not be the most visible part of a project, it is for the phenomenology probably the most important part. It will be a natural focus point of a Ph.D. project.

(II.b) Actual phenomenology and comparison of processes

Experiments at existing and future hadron facilities play a role, because they provide testing ground for theoretical results, which often contain unproven conjectures (like conjectures on factorization). Such an interaction between theory and experiment has proven to be very fruitful in the study of the spin structure of the proton. A close interaction of theory and experiment is essential because the basic PDFs are parameterizations, both for the collinear functions as for the TMD functions. The gluon dynamics enters in the (usually logarithmic) scale dependence of processes and for TMD's in a specific non-universality such as the sign-flip for T-odd distribution functions depending on the colour-flow in a simple electroweak process (towards initial or final state for Drell-Yan versus deep inelastic leptoproduction, respectively). For hadron-hadron scattering a more complex result is expected as discussed above. The results of the investigations under (I) will be used to find the best processes to measure particular PDFs and include the full QCD dynamics. Presently, experiments are analysed at best at the second level (including sign flips and factors expected from gauge links). The aim is to extend this to the third level (including evolution), which would be essential if one wants to use TMD's as tools for LHC.

Application of the T-odd correlations at the LHC experiments mostly will focus on studies of final states. For example, all LHC detectors are able to detect polarized Lambda particles in the final state, at least in the mid-rapidity region. In many cases, however, our focus will be on final states with heavy quarks [11], which often are easier to identify. Furthermore, for the LHC the phenomenology of TMD functions for gluons is much more important than that for quarks, as gluons dominate the hard scattering. Most work up to now, however, has focussed on TMD functions for quarks (hence importance of project I.b). The role of the TMD functions is actually not the primary probing of the Higgs sector or whatever will be uncovered, but its role comes in when one wants to investigate the structure of particles and forces in this sector. We want to use our knowledge on how to treat degrees of freedom like transverse spin and transverse momentum to probe quantum numbers of new particles that show up in LHC experiments. For this project, we will interact intensively with experimentalists, profiting from the active participation of Nikhef in ATLAS, ALICE and LHC-B collaborations. All physicists involved in this research project will take part in such discussions.

It depends strongly on the projects under (I) if actual calculations, estimates or proposals will be part of a project at Ph.D., postdoc or staff level. In fact all results will be considered on their merits as tools in analysis or tests of QCD dynamics or both.

(III) Involvement in long-range planning

The dual role of TMD's in enhancing our understanding QCD as a fundamental cornerstone of the Standard Model and providing tools in the study of high energy scattering processes gives them a wide applicability in QCD-related investigations. For instance, I expect them to have impact in defining and clarifying the physics cases for, for instance, the Electron-Ion Collider (EIC) in the U.S. or the Large Hadron Electron Collider (LHeC) in Europe. I intend to actively participate in such studies, giving two *examples* below.

(III.a) LHeC

The LHeC is a proposed colliding beam facility at CERN, which will exploit the new world of energy and intensity provided by the LHC for lepton-nucleon scattering. An existing 7 TeV LHC proton or heavy ion beam will collide with a new electron beam simultaneously with proton-proton or heavy ion collisions taking place at the existing LHC experiments.

Two possibilities are being pursued for the electron beam. In the first, it circulates in the existing LHC tunnel with a nominal energy of 50 GeV, resulting in an unprecedented kinematic range for lepton-nucleon scattering: the centre of mass energy of 1.2 TeV is 4 times larger than the previous highest at HERA. The luminosity of over 10^{33} $cm^{-2}s^{-1}$ is two orders of magnitude larger than previous similar proposals. An alternative solution is an electron linac, resulting in reduced luminosities, but larger centre of mass energies (nominally 2 TeV).

The large energy and luminosity make the LHeC uniquely sensitive to the direct single production of massive new electron-quark bound states and to other new physics, such as supersymmetric particles. But it also allows the parton densities of the proton to be measured at previously unexplored momentum transfers (Q^2 beyond 100 GeV^2) and small fractional momenta (x below 10^{-6}). Access to the low x region may make it the ideal laboratory to search for novel strong interaction dynamics in an environment of extremely high parton densities, but with small enough strong coupling to apply perturbative methods.

As our role, I see a critical study that should clarify if any expected novel strong interaction dynamics issues are linked to partonic transverse momenta. In particular the gluon TMD's (see also I.b) would be a part of this novel strong interaction dynamics, going beyond the collinear treatment.

(III.b) EIC

In the U.S. Nuclear Physics Long-Range Plan, the EIC has been proposed as a facility that will address compelling physics questions essential for understanding the fundamental structure of matter. The EIC will focus on gluons in matter. Without gluons there are no protons, no neutrons, and no atomic nuclei. Interactions among gluons determine the unique features of strong interactions. However, gluon properties in matter remain largely unexplored. Recent theoretical breakthroughs and experimental results suggest that both nucleons and nuclei when viewed at high energies appear as dense systems of gluons, creating the strongest fields in nature. The emerging science of this universal gluonic matter drives the development of a next-generation high luminosity electron-ion collider. Polarized beams in the EIC will give unprecedented access to the spatial and spin structure of gluons in the proton. The EIC embodies the vision of the U.S. nuclear physics community for reaching the next QCD frontier. Realization of an EIC will require advancements in accelerator science and technology, detector R&D, and continued theoretical development. An EIC Collaboration has been formed with the goals to develop the most compelling science case.

Within this collaboration, I am actually involved in discussions on the physics case [12].

Structuring the work programme

As PI, I will spend at least 60% of my time on the proposal. To achieve the objectives, I plan to be working with a group of about 10 theoretical particle physicists, of which on average 5-6 people are funded within this proposal. This group is expected to consist of three senior physicists. The PI at the full professor level will lead the project; at present plans are being developed to hire a new staff member at the assistant or associate professor level to replace Dr. Daniel Boer, who recently accepted a position at the University of Groningen. This assures an excellent core group of physicists that will be able to work together and assist in guiding the postdocs and graduate students to be hired. I plan to hire two Ph.D. students, starting in first or second year of the project and three or four postdocs. As already mentioned under the description of projects, I expect to profit greatly from my extensive network of physicists in Europe, built over the years among others in previous EU Framework Programmes. My network involves theorists *and* experimentalists, which is in this proposal an essential ingredient for making progress on the lines set out. Also within the Netherlands there is an excellent embedding of my group. The group is located in a university environment with on campus many facilities and possibilities to attract students. Furthermore, my group is part of the Network for Theoretical High Energy Physics as well as the Nikhef collaboration. This facilitates involvement of theorists with different expertise and consultation of experimentalists in achieving our goals.

Our working strategy internally will be similar to other successful theory groups, namely self-education through intensive and frequent discussions to keep up to date with developments in the field and related areas, combined with other successful discussion meetings in the Netherlands which are being organized for instance in the context of the running national FOM programme 'Theoretical Physics in the Era of the LHC', which addresses a number of complementary issues. The self-education programme will be complemented by input from visitors. I anticipate about 5 visitors per year for periods of the order of a week and 5 visitors for shorter periods (few days), ensuring a stimulating atmosphere for postdocs and graduate students. Postdocs will be hired for periods of (two or) three years depending on their career development and their role in the full programme. Ph.D. students will be enrolled and employed for four years, the nominal duration of a Ph.D. in the Netherlands. They will participate in activities of the Dutch Research School for Theoretical Physics, which assures career-related development opportunities, monitored supervision and an excellent educational programme (two-week course programmes in the first two years). Postdocs and Ph.D. students will also attend relevant international schools.

Scientific output

The results of the project will be reported through publications in top peer-reviewed journals in our field as well as through presentations at international workshops and conferences and contributions to the proceedings thereof. Besides this, all participants including senior staff, postdocs and graduate students will be involved in interactions with experimental colleagues. They will be available as advisors in collaboration meetings and participate as experts in working groups and contribute to internal reports or working group documents (e.g. white papers). We will also disseminate the results via a webpage, including talks at informal meetings, workshops, schools or conferences.

Education

The main results of the proposal are scientific results, disseminated in journals. However, I also consider the education of the next generation of physicist to be an essential ingredient and a responsibility to society. Here several aspects are considered:

- Contributions to specialized courses in bachelors, masters and graduate programmes at universities. These provide the researchers with opportunities to attract and work with excellent students. An advantage at VU University is the collaboration with the UvA University in Amsterdam and several Research Institutes in the area (among them the Nikhef Institute) at the Bachelors and Masters level and a national setup for the graduate student educational programme.
- More directly linked to the scientific output of the research proposal, will be the development of lecture series that point out the important results to the scientific community. In my opinion many research topics require such dedicated efforts that soon a closed group of experts emerges which decouples from the outside world. The central aim is here that we put the results in a broader context. In a specialized field as this one related to QCD, this means, on the one hand, to address both experimentalists and theorists in the field, and, on the other hand, address different sub-disciplines such as nuclear physics, particle physics and astrophysics.

Outreach

Besides education, outreach is also extremely important and a responsibility to society. The relevant research fields for this proposal within science are nuclear physics, particle physics and increasingly also the field of astrophysics. In these fields there are many fascinating aspects that make people wonder, but also confuse them. It is important to provide a clear separation of facts and fiction. Directly relevant for society is the role of strong interactions in issues related to nuclear energy and fusion research. Interesting to many is also their role in astrophysical processes or as tools to study fundamental issues of particles and forces. The focus of this research proposal is central with respect to the three fields mentioned and we see it also as a responsibility to inform society. This will be done through general audience lectures but also by taking part in or setting up activities aimed at high schools and possibly even elementary schools.

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A more detailed schedule towards achieving the scientific goals, as described in section 2(b) is given in the following diagram, in which also the starting date, May 1, 2013 has been indicated.