3D Parton Distributions and the LHC

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Executive Summary

The study of the quark-gluon structure of nucleons and nuclei is one of the main goals of nuclear physics. Transverse space distributions of partons, encoded in Generalized Parton Distributions (GPDs), and transverse momentum dependent distributions, encoded in Transverse Momentum Distributions (TMDs), have been widely recognized as key objectives of the JLab 12 GeV upgrade and a driving force behind construction of the Electron Ion Collider. The knowledge of the structure of the proton, and in particular of TMDs, can be relevant for studies in proton colliders, even at the LHC energies. The transverse momentum dynamics may be very important at low x. It is manifested in very high energy hadronic collisions and is described by Unintegrated Gluon Distribution Functions. For example, the transverse-momentum spectrum of vector bosons produced in Drell-Yan-like processes at the LHC is influenced by the contribution of intrinsic partonic transverse momentum. Higgs production is influenced by gluon TMDs and is also sensitive to linear gluon polarization. LHC data can offer unique insights to improve the knowledge of TMDs and, on the contrary, the knowledge of TMDs can be necessary to achieve high-precision results demanded by the search for new physics. TMDs can also be affected by the nuclear environment in heavy-ion collisions, leading to the concept of Nuclear TMDs.

In recent years the measurements of single spin asymmetries (SSAs) in final state hadrons and photons in semi-inclusive and exclusive processes have been widely used to access the underlying GPDs and TMDs. Although the interest to TMD/PDF has grown enormously, we are still in need of fresh theoretical and phenomenological ideas. The 2016 marks the 20 years since first measurements of SSAs were performed by HERMES collaboration and one of the main challenges still remaining is the extraction of actual 3D PDFs (GPDs and TMDs) from different spin and azimuthal asymmetries in a reliable and model independent way. We specifically focus on the GPD and TMD programs in particular the question how to extract underlying 3D parton distribution and fragmentation functions from the wealth of data expected from semi-inclusive deep inelastic scattering (SIDIS), pp and e^+e^- experiments including the future electron-ion collider (EIC), outlining what measurements with present and future facilities are crucial to establish the underlying dynamics defining the nucleon structure across the wide range in Bjorken-x.

The Science Motivation

Flavor decomposition of 3D PDFs requires reliable and model independent technique for the extraction of transverse momentum dependent distribution and fragmentation functions from the experimental observables. Various assumptions involved in preliminary extraction of TMDs from available data, have yet to allow credible estimates of systematic errors associated with those assumptions, preventing also useful projections for the statistics needed for extraction of relevant 3D PDFs. A similar situation exists for hadron-hadron collision experiments looking to extract TMDs from their anticipated data.

We intend the proposed workshop to be an important opportunity to efficiently address unresolved issues of the physics of the transverse structure of the nucleon and also, to identify directions for further development of this quickly developing field. The following list represents current key questions of the field of the transverse parton structure of hadrons to be addressed by proposed workshop.

1) QCD issues associated with 3D structure

- **Factorization issues in hadron production.** Factorization, operator definitions and gauge invariance of parton densities are important ingredients of the 3D PDF extraction framework. Despite enormous efforts in the past years it is still unclear how various spin-azimuthal asymmetries observed in pp-scattering can be described in terms of QCD factorization using TMDs. The recently proposed process $ep \to hX$ in DIS is on similar footing. It is important to settle this points in order to push forward a common global analysis of TMDs obtained from hadron-hadron and from lepton-nucleon scattering.

- **Study of the QCD evolution properties of 3D PDFs.** The TMD-experiments are performed at rather different energies. Therefore, in order to get a quantitative relation between the experiments, the energy dependence of the TMD observables, as predicted by perturbative QCD, has to be studied. Understanding of QCD evolution properties of TMDs in different x_B regimes will allow reliable extraction of TMDs from data. First extractions of PDFs are already available using different TMD evolution schemes.

- **Unintegrated and Generalized Transverse Momentum Distributions.** Defining the correct quark and gluon operators in non-perturbative approaches to nucleon structure is a challenging problem. Several definitions have been proposed, motivated by different ideas about their most natural form. Extraction of quantitative information on partonic orbital angular momenta from experimental data is one of the central issues of QCD.

2) Essential observables, which will direct the future experimental effort. The global analysis of 3D PDFs require coordination of efforts from different experiments world wide including SIDIS, pp, πp, $\bar{p}p$, pN, NN, and e^+e^- facilities.

- **Electroproduction with fixed target facilities and EIC.** Ongoing studies of 3D PDFs indicate that extraction of spin-dependent cross sections may be important for future precision studies of underlying PDFs. Experimental tests to check factorization in the semi-inclusive deep inelastic scattering are also required to understand the applicability and limitations of the leading twist picture.

- **Drell-Yan lepton pair production and Drell-Yan plus jets.** Both the low-q_T part and the high-q_T part of vector boson spectra can be sensitive to 3D structure effects. Multi-differential measurements are especially important as one can access azimuthal correlations in the lepton + jet final states which constitute distinctive TMD predictions. Comparison of Z + jet final states at small transverse momentum imbalance with di-boson ZZ final states may shed light on color flow patterns which are eventually responsible for factorization breaking phenomena in hard processes sensitive to very low transverse momentum scales.

- **Higgs boson production and Higgs boson plus jets**. Differential cross sections, are relevant for gluon 3D PDFs and QCD studies of polarized gluons and color correlations, once sufficient statistics is reached. Measurements of Higgs versus Drell-Yan at the same invariant mass may be used to reduce the influence of pile-up in the high-luminosity LHC runs. The Higgs boson q_T spectrum, Higgs-jet angular correlations and underlying event observables in Higgs production all constitute useful probes of different aspects of the Higgs coupling to gluons in the heavy top limit.

- **Heavy flavor production**. Measurements of heavy quark pair production spectra can provide comparable information to the previous two cases but with additional complexity due to the presence of color charges in the final state. The associated initial-state / final-state color correlations at small q_T could be studied to examine factorization-breaking contributions in the region of very small transverse momenta, provided sufficient resolution can be reached. It will also be interesting to investigate kinematic effects of longitudinal momentum reshuffling in parton showers at heavy flavor scales. All such studies are interesting at top quark scales as well as at lower mass scales with bottom and charm quarks. In particular, despite the complexity of the bound state, the $c\bar{c}$ and $b\bar{b}$ quarkonia production is a useful probe of TMD gluon effects at low mass scales. Measurements of the spectra and especially of the polarization for J/ψ, Υ and all quarkonium states at the LHC Run II will be particularly interesting for studying polarized gluon effects.

- **Soft particle production and multi-parton interactions**. It is relevant to investigate to what extent 3D proton structure may be important not only for factorization of hard processes but also for the understanding of soft particle production and, in particular, of the multi-parton interactions which are found to be needed at low to moderate transverse momenta for Monte Carlo simulations to describe experimental data on underlying events, particle multiplicities and spectra. Double parton interactions including parton's transverse momentum dependence are starting to be investigated, as is the role of parton's transverse momentum in the interpretation of energy flow measurements, charged particle multiplicities, and underlying events at the LHC Run II.

3) Framework for the extraction of 3D PDFs

- **Evolution of TMDs and fits to physical cross sections**. Most of the current approaches to TMD determinations from low-q_T data employ, in practice, either approximate analytic (or semi-analytic) solutions of the evolution equations or perturbative expansions of the TMDs in terms of collinear pdfs, or a combination of both. TMDlib is a new proposal, based on global fits to experimental data to obtain TMD parton distributions at different evolution scales, and on using these to make predictions for physical quantities. This is similar in spirit (but different in its realization) to what is done in the case of collinear parton distributions. Theoretical predictions for physical cross sections which obey TMD factorization formulas could then be obtained by applying these formulas, using perturbatively calculable coefficients and appropriately evolved TMDs determined from fits to experimental data. In this approach, unlike most current implementations of TMD formalisms, the nonperturbative dependence on longitudinal and transverse degrees of freedom is fully coupled, and can be entangled with the dependence on the evolution scale. For phenomenological applications this can be important when for instance comparing theory with experimental measurements over a wide range in x and evolution scales.

- **MC generators for global analysis of 3D PDFs.** A crucial prerequisite for a global analysis is the development of a Monte Carlo event generators including transverse degrees of freedom in a systematic way that is applicable in a wide range of energies. Several programs have been developed covering different aspects of TMD and GPD analysis and using different sets of models for TMDs and GPDs. Development of Monte Carlo programs, which includes spin-dependent effects in parton showering and hadronization, will be crucial for proper simulations of complex orbital structure of outgoing final states. The effective TMDs and Fracture Functions could be extracted from existing MC event generators like PYTHIA etc..

- **Phenomenology of 3D parton distribution and fragmentation functions.** A transition from parton-model to QCD-based global fits of TMDs and GPDs is under way, several extractions are already available. Extraction of TMDs and GPDs will require detailed understanding of evolution effects. Some existing approaches are being improved to make more realistic extraction of 3D PDFs, and several new methods are being developed based on Bessel weighting and other procedures.

- **Validation of extraction frameworks** Various assumptions used in different extraction frameworks require strict procedures for validation of the extracted 3D PDFs. Development of calcualtional tools, which would allow for easy comparison of results, also using libraries of PDFs like TMDlib in the extraction and validation stage, will be important to understand systematics due to different models and parametrizations. Defining benchmarks for calculations, such as benchmarks for the TMD QCD evolution programs as well as on the cross-section calculations, will be important for validation of different frameworks.

- **Extraction of PDFs from di-hadron production.** New methods have been proposed for extraction of different partonic distributions, based on di-hadron production in hard processes. In di-hadron framework the transverse momentum of hadrons is integrated, and the final asymmetries depend on the product of underlying distribution and fragmentation functions, thus providing model independent procedures for extraction of some relevant PDFs, including the transversity distribution.

- **Radiative corrections to hard scattering in exclusive and semi-inclusive processes.** Understanding of radiative corrections is crucial for precision studies of TMDs and GPDs from data on exclusive and semi-inclusive hadron production. It is essential to identify outstanding issues in calculations of radiative corrections and their integration into data analysis procedures. Examples include treatment of bremsstrahlung beyond peaking approximation, resummation of multiphoton emission, two-photon exchange effects for TMD and GPD measurements, and Coulomb corrections for SIDIS on heavy nuclei.

4) Medium modifications of multidimensional PDFs across the wide range in x_B

- **Medium modifications of distribution functions.** Understanding of medium modification of transverse momentum dependent distributions of quarks and gluons are crucial for the interpretation of polarized target measurements in SIDIS, as well as interpretation of heavy-ion collisions.

- **Medium modifications of fragmentation functions.** Consistent description of energy energy loss and the modification of the QCD evolution by the medium are important for understanding of hadron electroproduction and heavy-ion collisions.

5) Partonic Structure beyond Densities: Orbital motion, correlations, fluctuations

- **Target fragmentation and conditional probabilities**

  Due to lack of the analysis framework the current physics program of the EIC doesn't cover observables involving hadrons produced in the target fragmentation region, which can shed light on the non-perturbative structure of the nucleon. Extending the studies of the nucleon structure beyond the traditional current fragmentation, when a hadron in the target fragmentation region is observed in association with another hadron in the current fragmentation region (so called back-to-back or b2b SIDIS) will provide a new window to study the nucleon complex structure.

- **Higher twist asymmetries in SIDIS.** In spite of being now available for a decade and in spite of numerous dedicated theoretical and phenomenological studies, the underlying mechanisms for observables at 1/Q level remain not understood and the issue of factorization is not clarified. Twist-3 azimuthal asymmetries were the first experimentally established single spin phenomena in SIDIS, and are among the largest and clearest asymmetries. The detailed understanding of these data belongs to the most important and challenging goals.

- **New insights on 3D PDFs from non-perturbative models.** Predictions from non-perturbative methods like AdS/QCD, light-front holography, or light-front Hamiltonian methods as well as results from reliable QCD-inspired models are of great importance for the understanding of the hadron structure, and can be valuable in identification of suitable reactions and kinematical regions for future measurements. The light-front wavefunctions (LFWFs) of hadrons allow computations of 3D PDFs and provide a direct connection between observables and the QCD Lagrangian.

Workshop Outcomes

- **Develop a framework for extraction of 3D PDFs in a wide range of x and attract new collaborators for 3D structure studies.**

There exists data on spin-azimuthal distributions of hadrons in semi-inclusive DIS, providing access to TMDs and GPDs, accumulated in recent years by several collaborations, including HERMES, COMPASS, BELLE, BaBar, BESIII and Halls A, B and C at JLab, as well as the LHC experiments. The measure of the success of the workshop will be the development of a clear and specific plan for the extraction of 3D PDFs in nucleons and nuclei. We also contemplate the exchange of ideas between different physics communities leading to addition of new collaborators and the coordination of efforts on studies of the transverse structure of the nucleon worldwide, thereby supporting the JLab12 physics program as well as the development of a strong physics case for EIC using also wealth of data accumulated by the LHC experiments in the gluon sector.