Quantum Chromodynamics
at Modern High-Energy Facilities

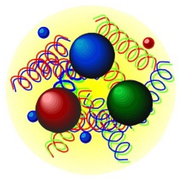
I.O. Cherednikov, M. Pieters, P. Taels

QCD Theory Group@UAntwerpen

Large Hadron Collider

LHC collides hadrons: particles bound by the strong interaction

strong interaction dominates what happens in the LHC!



strong interaction is theoretically described by *Quantum Chromodynamics (QCD)*

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i[\gamma^\mu D_\mu]_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Confinement: fundamental building blocks of QCD [quarks and gluons] do not exist as free particles

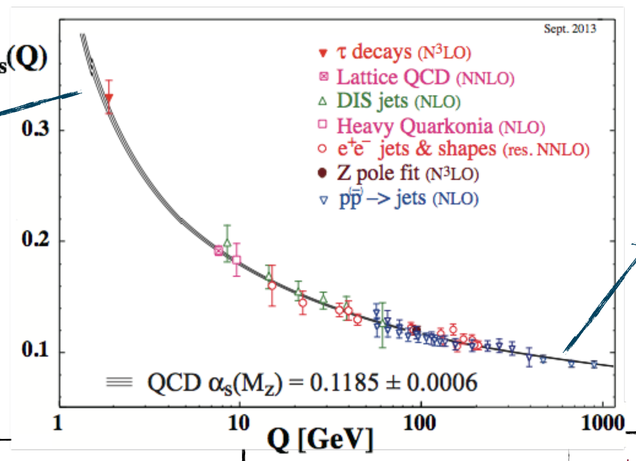
Running coupling: the strong coupling changes with the characteristic energy

Asymptotic freedom: at small distance the quarks and gluons are (almost) free particles and the perturbative approach is applicable

Factorisation: enables the separation of large- [essentially nonperturbative] and small-distance [perturbative hard scattering matrix elements] contributions

Parton distribution functions [pdfs]: accumulate information about intrinsic structure of hadrons

confinement region: color objects cannot be observed outside of hadrons



asymptotic freedom region: quarks and gluons behave as free particles

nonperturbative contributions: ***soft physics***

perturbation theory: ***hard physics***

3D- and Spin- Structure of the Nucleon in Modern and Planned Experiments

***COMPASS@CERN, HERMES@DESY*:** a richness of data on *polarized* hadronic processes

***RHIC@BNL*:** reactions with *polarized* protons and nuclei

***LHC@CERN*:** *unpolarized* processes with sensitivity to some *polarized* gluon distributions; testing resummation algorithms; *Higgs, jet and heavy flavor production*

***CEBAF@Jefferson Lab*:** one third of approved experiments for the *12 GeV Upgrade* are devoted to the *3D structure of the nucleon* (TMD and GPD)

***Electron-Ion Collider@BNL[?]*:** large-x regime, high luminosity, broad TMD program; spin effects

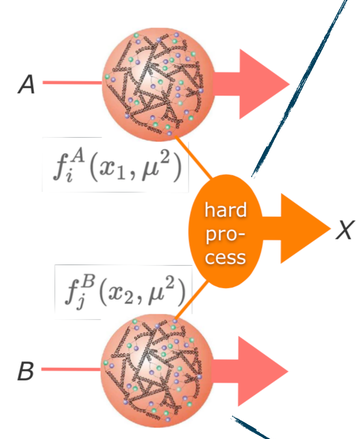
Fundamental understanding of the nucleon structure

- spin structure
- high-density QCD
- confinement
- nuclear matter

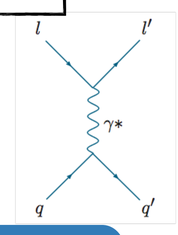
Idea of Factorization:

separate the *short distance/large momentum transfer* (perturbatively calculable) part from the *large distance/small momentum transfer* (essentially nonperturbative) part of the cross section

Hard part:



hard scattering matrix elements are in principle calculable in perturbative QCD



matrix element @ LO, NLO, ...

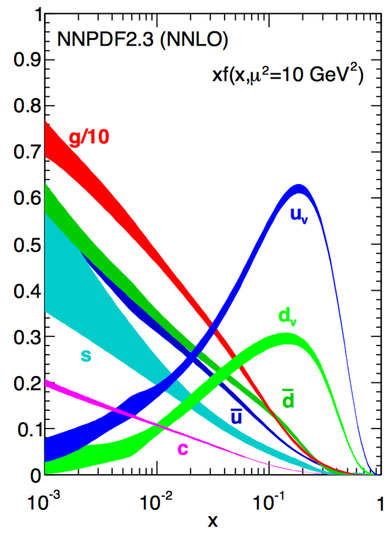
$$\sigma_{pp} = f_i^A(x_1,\mu^2) \otimes \hat{\sigma}(i+j \to X) \otimes f_j^B(x_2,\mu^2)$$

parton density functions (PDFs) with evolution driven by DGLAP equations: $f(x,\mu^2)$ determined by $f(x_0>x,\ \mu_0^2<\mu^2)$

Soft part:

- x is the *longitudinal momentum fraction* carried by a parton
- μ^2 is the energy scale

non-perturbative information about the longitudinal proton structure is encoded in the universal **parton density functions** that need to be measured experimentally



transverse degrees of freedom are integrated out

collinear factorization

Problems of Theoretical Description of Hadronic Processes at High Energy

Inclusive processes [collinear factorization]: one or less hadron detected, e.g., DIS, electron-positrion annihilation to hadrons

***Semi-inclusive processes* [TMD or k_T factorization]**: two or more hadrons in the initial or the final state detected; e.g., Drell-Yan, SIDIS, hadron-hadron to jets, Higgs and heavy-flavor production

***Collinear factorization*:** longitudinal momenta of the patrons are intrinsic, transverse momenta can be created by perturbative radiation effects (parton showers)

***TMD factorization*:** a unifying QCD-based framework which suggests both intrinsic (essentially non-perturbative) and perturbative radiation mechanisms of the transverse-momentum creation

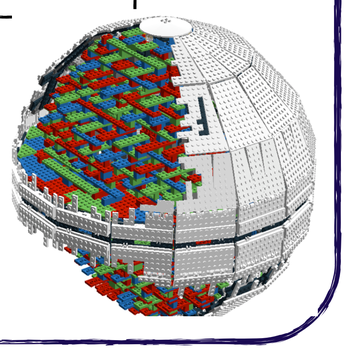
Transverse Momentum Dependent pdfs

parton showers in initial- and final-state radiation

multiple parton interactions

need to go beyond the *collinear* limit
add *transverse* degrees of freedom

factorization with ***transverse momentum dependent pdfs*** (TMDs) provides a unifying theoretical framework



- R. Angeles-Martinez et al., *Transverse Momentum Dependent parton distribution functions: status and prospects*, **Acta Phys. Pol. B46 (2015) 2501**
- I.O. Cherednikov, T. Mertens and F.F. Van der Veken, *Wilson lines in quantum field theory,* **De Gruyter Studies in Mathematical Physics**, Berlin, 2014

Particle Physics Group
University of Antwerp