On the use of $k_\perp$ dependent PDFs in studies of hadronic data

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Why $k_\perp$ dependent PDFs? (TMD PDFs)

In DIS at HERA use of collinear fact. with integrated parton densities has been rather successful in describing data.

Factorization for different processes well established and DGLAP evolution equations derived to impressive accuracy.

Yet there are good reasons to try go beyond collinear approach:

$\exists$ many observables for which parton kinematics must be treated better than in collinear approach

e.g di-hadron with low $q_\perp$

Treating kinematics better at LO
reduces size of NLO effects (Collins, Jung 2005)

And as cms energy increases, high energy evolution important even for inclusive data.

At LHC we study many exclusive hadronic observables at very high energy. Thus crucial to understand TMD PDFs and associated TMD factorization theorems.

Phenomenology of TMD PDFs

$k_\perp$ dependent PDFs used for many observables, and have implied reasonable description of data and also improvements

Dijet events in DIS

W,Z boson production

prompt photon production

Exclusive VM production

diffractive Higgs production

$E_\perp$ spectrum and $\frac{dN}{d\eta}$

angular correlations in dijets and multijets

Forward jets

Forward jets+dijets

And lately many approaches using ideas of small-x evolution of TMD PDFs.

In these cases $k_\perp$ factorization formula used to make predictions in pp and AA collisions.

Careful here! We need better understanding of both the PDFs and factorization.

One major concern we should have at small-x: Lack of proofs of factorization and careful definitions of the TMD PDFs.

Small x applications using gluon TMD

Many different approaches in small-x physics used in order to describe semi-inclusive data:

Applications based on ideas from dipole and CGC formalisms and BK equation:

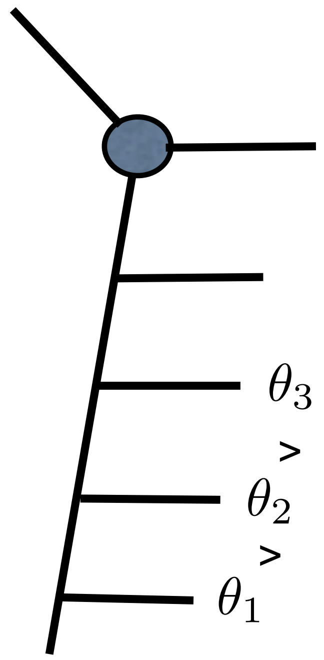
No proofs of formulas

Applied to $\frac{dN}{d\eta}$ and $p_\perp$ spectrum. Some different factorization formulas used, mostly based on parton model analogy

Catani, Ciafaloni, Fiorani and Marchesini (CCFM) formalism.

Implemented in CASCADE MC (Jung)

Ideas of coherence and angular ordering



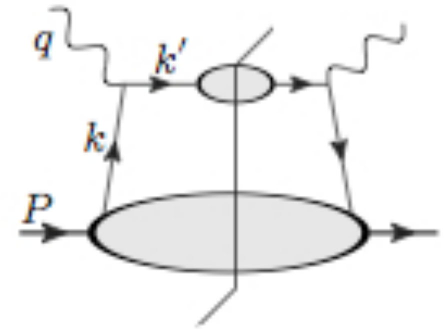
Uses factorization formula by Catani, Ciafaloni, Hautmann (CCH)

Lack of explicit operator definitions of TMD PDFs in CCH and CCFM...

What is a parton density? A model case

Intuitive ideas about parton densities can be made exact in a model field theory.

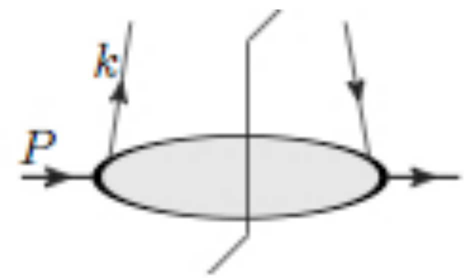
Super-renormalizable and non-gauge



Intuitive definition of TMD PDF is that it is a number density:

$$f_\alpha(z, k_\perp) = \frac{1}{2z(2\pi)^3} \frac{\langle P | a^\dagger_{k,i,\alpha} a_{k,i,\alpha} | P \rangle}{\langle P | P \rangle}$$

$$k^+ = zP^+$$



Integrated PDF:

$$f_\alpha(z) = \frac{1}{2z} \int \frac{d^2 k_\perp}{(2\pi)^3} \frac{\langle P | a^\dagger_{k,i,\alpha} a_{k,i,\alpha} | P \rangle}{\langle P | P \rangle}$$

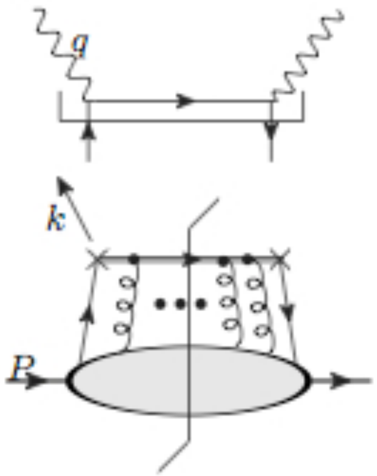
Note that integral is over *all* momenta

Then in parton model, exactly true that: $f_\alpha(z) = \int d^2 k_\perp f_\alpha(z, k_\perp)$

Many ideas and applications of TMD PDFs in QCD based on this picture. Relations above frequently assumed even in QCD. However assumptions here not true for QCD! Thus relations above and some intuition must be changed in full QCD. This is important for understanding data...

Complications in QCD

Factorization much more tricky because gauge interactions



TMDs: Operator definitions with Wilson lines ensuring gauge invariance.

For definitions to make sense one must remove divergences appearing Feynman graph calculations.

UV divergences removed by renormalization: ⟶ μ dependence of PDFs

DGLAP

For TMDs additional "rapidity divergence": ⟶ Rapidity/energy evolution of TMDs

↑

Important how this is treated

CSS evolution in TMD factorization approach

At small x BFKL, CCFM, BK-JIMWLK...

Number density interpretation no longer valid

Inclusive particle production at small-x

Seen as ideal test ground for looking for small-x effects in energy dependence

On theoretical side computation of single inclusive gluon production using

$$\frac{d\sigma}{d^2k_\perp dy} = \frac{2\alpha_s}{C_F k_\perp^2} \int d^2q_\perp \frac{f_1(x_1, q_\perp^2)\, f_2(x_2, |k_\perp - q_\perp|^2)}{q_\perp^2 (k_\perp - q_\perp)^2}$$

← Obvious and intuitive looking result, easy to write down

Originally in GLR. In this case f was "defined" by $f(x, q_\perp^2) = \frac{dxG(x, q_\perp^2)}{d\ln q_\perp^2}$

Problematic in QCD!

In recent applications using "dipole" picture, f identified with

$$f(x, k_\perp) = \mathcal{C}\, k_\perp^2 \int d^2r_\perp e^{-ik_\perp \cdot r_\perp} \mathcal{N}(x, r_\perp)$$

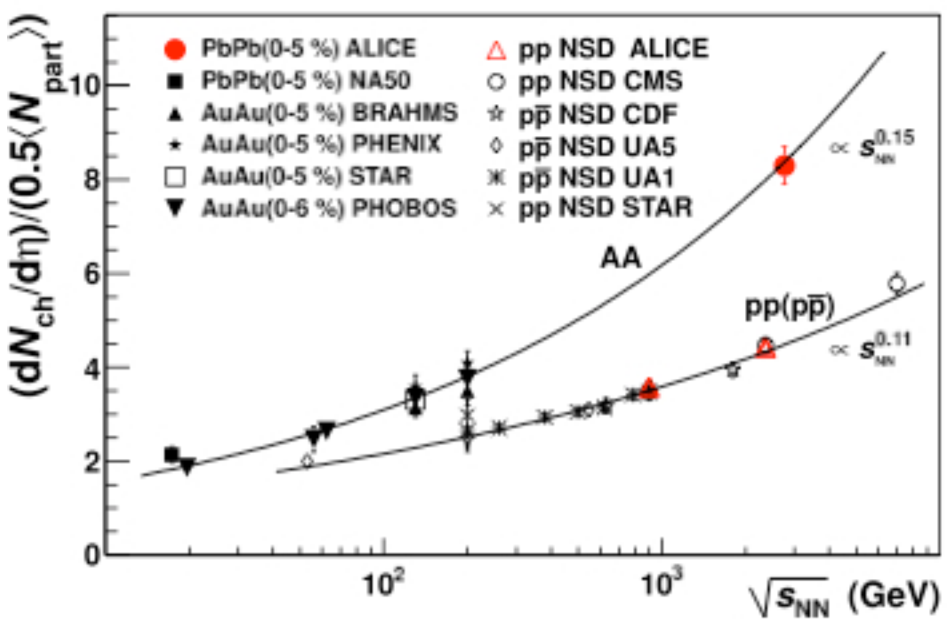
← Dipole "scattering amplitude"
Satisfies BK

However, this f not really an "unintegrated gluon distribution"!

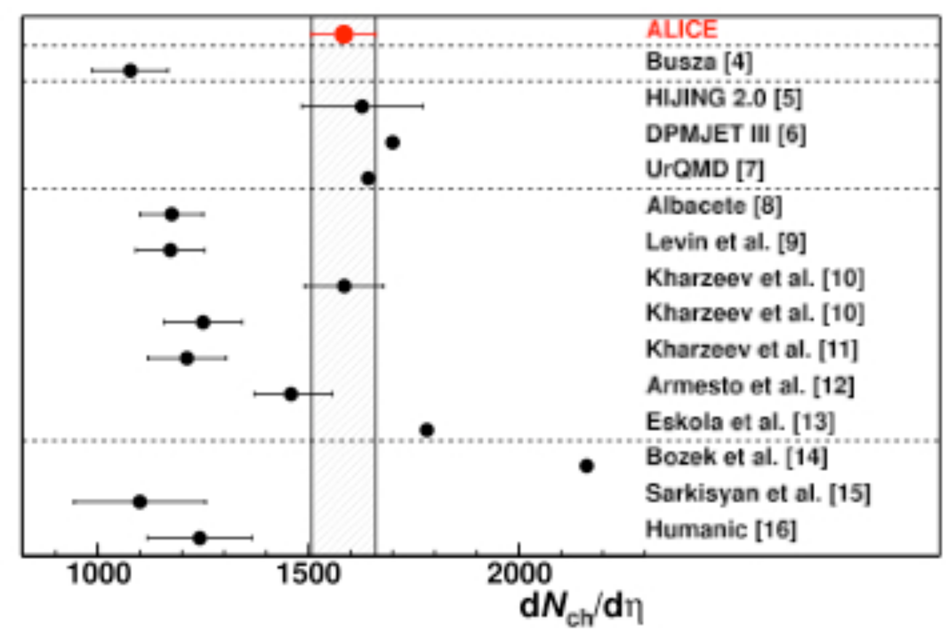
Moreover, dipole formula studied for DIS on classical nucleus, application to pp non-trivial...

$dN/d\eta$ at the LHC

pp data + AA from ALICE:



Pb-Pb from ALICE



Many predictions failed in this case. Of course really tough to know what happens in AA!

However, without proper factorization theorem even harder...

Is failure because lack of factorization, not correct evolution, ...?

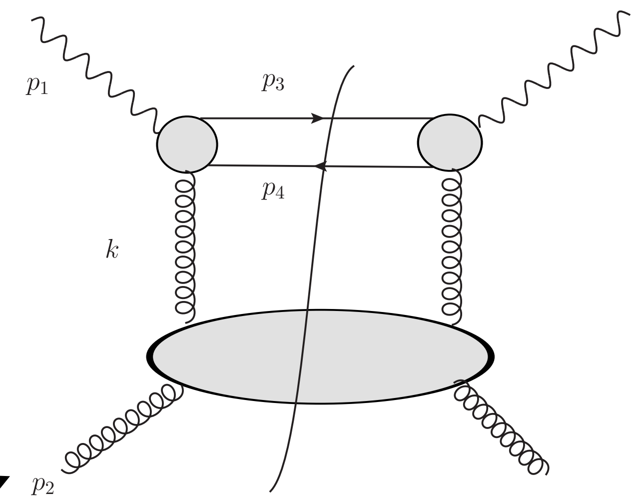
Not only initial but also final state evolution extremely non-trivial

Big warning here for directly relating ideas of small-x evolution to data without proper factorization and well defined TMDs

A note on CCH and CCFM

Both uses axial gauge $n \cdot A = 0$. Simplifies contributing graphs but troubles with singular propagator

Formulation such that connection to collinear case can be made



Without operator def. hard to see gauge invariant structure.
Generic gauge invariant formulation?

"Partonic" DIS studied, *assuming* a factorization of initial parton

For collinear fact. that may be ok, but for TMD extremely non-trivial and subtle

Especially for pp

Breakdown of TMD fact. in pp: Collins, Qiu 0705.2141
Rogers, Mulders 1001.2977

How about small-x?

Final comments/Summary

At LHC many processes in need of TMD PDFs, clear motivation for use.

not only small-x!

Semi-inclusive ones

Additionally small x physics to be discovered/probed: small-x evolution and saturation

Anticipating factorization formula not difficult. Intuition based on parton model + "common sense". Yet nature (QCD) complex...

pp collisions especially complicated. No TMD factorization.

AA even more so!

Much of small-x physics based on ideas about $k_\perp$/TMD factorization. Clarify implications.

Before trying to interpret implications of small-x evolution on observables, establish factorization and associated PDFs!