"Correlations between partons and high energy phenomena"

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Introduction

Investigation of structure functions measured structure functions of proton i.e. single parton distribution.

This knowledge is certainly insufficient for deciphering structure of hadrons - one need many parton distributions.

This problem come into center of attention recently due to important role of multiparton hard collisions in QCD physics at LHC, onset of new QCD regime of hard processes with different from pQCD continuous symmetry, necessity to separate new particles production from QCD physics.
Content

1. Impact parameter dependence of hard processes.

2. Multiparton hard collisions (mpi) and discovery of correlations between partons.

3. Mpi in Monte-Carlo modelling and puzzles.

4. Relationship between pdfs of a hadron and hard exclusive processes. Combination of QCD factorization theorem allows to measure correlations between partons. (TJNF, Compass...)

5. Puzzles of small x pQCD.

6. QCD regime of strong interactions with small coupling constant - second order phase transition in kinetic phenomena

7. Conclusions
Important variable for describing dynamics of pp collisions is the impact parameter, $b$:

Peripheral pp collisions

Central pp collisions

Proton momenta are perpendicular to the plane

$L$ - angular momentum is conserved - $L = b p_{\text{inc}}$

$b$ is conserved in the collision

Knowledge of the distribution of partons in nucleon in the transverse plane is crucial for a correct modeling of the NN collisions
QCD factorization theorem for DIS exclusive processes
(Brodsky, Frankfurt, Gunion, Mueller, MS 94 - vector mesons, small $x$; general case Collins, Frankfurt, MS 97)

\[ H \]

\[ \gamma^*_L \]

\[ x_1 \]

\[ x_1 - x \]

\[ M \]

Meson distribution amplitude

Hard scattering process

Generalized parton distribution (GPD)
In LT limit \( x_1 - x \ll x_1 \)

\[
x = \frac{Q^2 + m_V^2}{W^2}
\]

however due to DGLAP evolution skewed GPD kinematics for large \( Q \) probes diagonal GPD at \( Q_0 \) scale

\[
A(\gamma^* + p \rightarrow "Onium" + p) \propto G(x_1, x_1 - x, t)
\]

\[
G(x, x, t) \equiv G(x, t) = \int d^2 \rho e^{-i\vec{\Delta}_\perp \rho} G(x, \rho)
\]

transverse spatial distribution of gluons

\[
\int d^2 \rho G(x, \rho) = G(x)
\]

total gluon density
Universal $t$-slope: hard exclusive process is dominated by the scattering of quark-antiquark pair in a small size configuration - $t$-dependence is predominantly due to the transverse spread of the gluons in the nucleon - two gluon nucleon form factor $F_g(x,t). \quad d\sigma/dt \propto F_g^2(x,t)$.

Onset of universal regime FKS[Frankfurt,Koepf, MS] 97.

$\gamma^* \rightarrow q \bar{q}$

$d_T \propto \frac{1}{Q} \left( \frac{1}{m_c} \right) \ll r_N$

Convergence of the $t$-slopes, $B - \frac{d\sigma}{dt} = A \exp(Bt)$, of $\rho$-meson electroproduction to the slope of $J/\psi$ photo(electro)production.

$\Rightarrow$ Transverse distribution of gluons can be extracted from $\gamma + p \rightarrow J/\psi + N$. 
Gluonic transverse size - x dependence

Gluon transverse size decreases with increase of x

Pion cloud contributes for $x < M_\pi/M_N$ [MS & C. Weiss 03]

Transverse size of large x partons is much smaller than the transverse range of soft strong interactions

$$\langle \rho^2 \rangle_g = \frac{\partial}{\partial t} \frac{G(x,t)}{G(x,0)}$$

$$\langle \rho^2 (x > 10^{-2}) \rangle \ll R_{soft}^2$$

Two scale picture

Can be measured in ultraperipheral collisions at LHC
Interplay of hard and soft interactions in pp collisions, rate of multiple hard collisions is determined by the value of $<\rho^2_g>$ as compared to much larger radius of soft interactions. Note PYTHIA assumes $<\rho^2_g> = <\rho^2_q>$ which is a factor $\sim 2$ smaller than given by analysis of GPDs from $J/\psi$ production. They also assume it to be $x$-independent. Evidence from deeply virtual Compton scattering data that $<\rho^2_g>$ somewhat smaller than $<\rho^2_q>$ [perhaps due to the pion fields, MS & C. Weiss 09]

The form of gluon distribution within proton is similar to that extracted by G. Miller from e.m form factor but more narrow.
Are transverse positions of partons in nucleon correlated? To answer the question one has to study multijet production in pp scattering and combine this information with information about GPDs from HERA, from TJNF.

Where is the infinite number of primordial 'sea' partons in the infinite momentum state of the proton: inside the constituent quarks (a) or outside (b)?

At high energies, two (three ...) pairs of partons can collide to produce multi-jet events which have distinctive kinematics from the process two partons → four partons.

A view of double scattering in the transverse plane.

Note - collisions at the points separated in b by ~ 0.5 fm ⇒ independent fragmentations.
Parton distributions within a hadron give information on the single parton distribution in the infinite momentum frame- IMF wave function of a hadron(nucleus). IMF description arises when residues in the Feynman diagrams are taken over fractions of photon momentum carried by a parton.

The same Feynman diagrams but with the residues carried over fractions of proton momentum give rest frame description of hard exclusive processes.

Thus hard exclusive processes give information on the correlations in impact parameter space between partons in the plane transverse to photon and target momenta.
Interparton correlations reveal itself in the hard exclusive processes.

Probability and properties of small seize $|q\bar{q}>$ configurations in the IMF w.f. of proton are measured in the process:

$$\gamma^* + p \rightarrow \text{Meson} + p$$

Probability and properties of small seize $|3q>$ configuration within proton IMF w.f. will be probed in the backward angle scattering:

$$\gamma^* + p \rightarrow p + \text{meson}$$

Variety of exclusive processes is so large so they allow sufficiently detailed investigation of interparton correlations.

Caution: applicability of QCD factorization theorem should be checked independently by observing CT.
Why multiparton collisions are worth of investigation

Multiparton collisions (mpi) are defined in the talk as the hard collision of several partons from projectile with several partons of target. For certainty we will discuss mostly production of 4 jets in pp scattering (double hard collision):

\[ pp \rightarrow 4\text{jet} + X \]

- Cross sections of such processes are rapidly increasing with energy and produces significant yield of minijets with \( x=0.1-0.001 \) at LHC. Problems for Monte Carlo approaches.

- Mpi produce significant background for new particles production like b, \( \overline{b} \)

Example (G. Salam):

\[ p + p \rightarrow Z^0 + Z^0 + X \]

where Z boson decay contains b quark. Imitates Higgs boson:

\[ H \rightarrow b \overline{b} \]

- Strongly sensitive to correlations between partons in transverse plane. New information on wave functions of hadrons.

- Sensitive probe of new phase of QCD-strong interaction of spatially small wave package with small coupling constant.
Multi-jet production - probe of parton correlations in nucleons

Where is the infinite number of primordial ‘sea’ partons in the infinite momentum state of the proton: inside the constituent quarks (a) or outside (b)?

At high energies, two (three ...) pairs of partons can collide to produce multi-jet events which have distinctive kinematics from the process two partons $\rightarrow$ four partons.

Note - collisions at the points separated in b by $\sim 0.5$ fm $\Rightarrow$ independent fragmentations

A view of double scattering in the transverse plane.
What would be interesting to study

What partons are more strongly correlated transversely:

a) quark - quark
b) quark - gluon
c) gluon - gluon

Need to consider samples of four jet events in the double scattering kinematics enriched with quark- (anti)quark (Z, W), gluon-gluon (charm...) , etc collisions

Explore dependence on x's - can one push to $x_g=0.05$ at Tevatron? Huge x range at LHC
QCD at LHC

- Study of multiparton interactions is one of the prime aims of pQCD at the LHC - first workshop MPI 08, next one MPI110

Several LHC detectors have much better acceptance in rapidity than CDF and D0 at the Tevatron collider. They are also sensitive to a broader range of channels - study of qg, qq, gg correlations, etc. New algorithms for jet determination (G.Salam et al) - possibility to study dynamics close to cutoff \( p_t \)

Major question is on the fluctuations of QCD state-smooth background can be subtracted from new particles production
Experimentally one measures the ratio

\[
\frac{d\sigma(p+\bar{p}\to jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}} \cdot \frac{d\sigma(p+\bar{p}\to jet_3+\gamma)}{d\Omega_{3,4}} = \frac{f(x_1,x_3)f(x_2,x_4)}{\sigma_{eff}f(x_1)f(x_2)f(x_3)f(x_4)}
\]

where \(f(x_1,x_3), f(x_2,x_4)\) longitudinal light-cone double parton densities and \(\sigma_{eff}\) is "transverse correlation area".

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found \(\sigma_{eff} = 14.5 \pm 1.7\pm 1.7 \text{ mb}\) rather small - a naive expectation is \(\sigma_{eff} \sim 60 \text{ mb}\) indicating high degree of correlations between partons in the nucleon in the transverse plane. No dependence of \(\sigma_{eff}\) on \(x_i\) was observed.

Recently new Tevatron data appeared. They agree with the earlier CDF data. Actually, \(\sigma_{eff}\) is probably smaller \(\sim 11 \text{ mb}\) (D.Treliani) due correction for six jet events.
Possible sources of small $\sigma_{\text{eff}}$ for CDF kinematics of $x \sim 0.1-0.3$ include:

- Small transverse area of the gluon field --accounts for 50% of the enhancement $\sigma_{\text{eff}} \sim 30\text{mb}$ (F&S & Weiss 03)

- Fluctuations of the transverse size of nucleons (Treliani, &F&S & Weiss 08) - works in right direction but too small ($\sim 20\%$).

- QCD evolution leads to “Hot spots” in transverse plane (A.Mueller). One observes that such hot spots do enhance multijet production as well. However, this effect is likely to be small in the CDF kinematics as $x$’s of colliding partons are relatively large ($>0.01$).
MC models on mpi. Will use PYTHIA as the example.

Transverse parton distribution is x independent and fixed from multijet production $\Rightarrow \rho_{2g}^2$ two - three times smaller than measured by HERA

Problem with $p_t$ cut for dijet production

Hard Scattering

jet multiplicity $= \frac{\sigma^{\text{inel}}_{2\text{jets}}}{\sigma^{\text{inel}}_{\text{pp}}}$

large hadron multiplicity at $y=0$

energy dependent cutoff

$p_{t \text{ min}}$ (Tevatron) $\sim$ 3 GeV/c
$p_{t \text{ min}}$ (LHC) $\sim$ 5 GeV/c
$p_{t \text{ min}}$ (GZK) $\sim$ 10 GeV/c
Problem with $p_t$ cut.

Hard Scattering

Jet multiplicity = $\frac{\sigma_{2\text{jets}}^{\text{inel}}}{\sigma_{\text{inel}}(pp)}$

It is this growth which leads to a MC fixes:

- $p_t^{\text{min}}$ (Tevatron) $\sim$ 3 GeV/c,
- $p_t^{\text{min}}$ (LHC) $\sim$ 5 GeV/c,
- $p_t^{\text{min}}$ (GZK) $\sim$ 10 GeV/c
Current studies of the perturbative QCD lead to expectation that the growth of the parton densities predicted by LO DGLAP is weakly modified when NLO is included and the attempt to sum various extra terms does not modify result noticeably down to smallest $x$ relevant for GZK.

Can we trust pQCD prediction that the growth persists down to very small $x$?

Depends on transverse size of the system. As we argued above - in practical situation answer is that pQCD description becomes inapplicable already in the region where log $x$ effects are moderate and could be accounted for by NLO.
Smaller colorless wave package of quarks and gluons more rapid increase of interaction with energy. Evident within pQCD within the double logarithmic approximation:

\[ \alpha_s \ll 1 \quad \text{but} \quad \alpha_s \ln(x_0/x) \ln(Q^2/Q^2) \geq 1 \]

which dominates within DGLAP, BFKL, resummation approximations. Increase of structure functions with \( x \) decrease starts for \( x \leq x_0 \approx 0.1 - 0.05 \)

\[ \ln(Q^2/Q^2_0) \]

accounts dependence on the size of wave package. So

\[ F_2(x, Q^2) \propto (1/x)^n(Q^2) \]

where \( n \) is increasing with \( Q \). This numerical fit to the pQCD formulae agrees well with FNAL and H1, ZEUS data on structure functions of proton.

Such a behaviour differs from Pomeron exchange where \( n \) should be independent on \( Q \)!
**HERA data confirm a fast increase of the cross sections of interaction small dipoles with energy predicted by pQCD due to**

\[ x G_N \propto x^{-n(Q)}, \quad n \in 0.2 \div 0.4 \]

The interaction cross-section, \( \hat{\sigma} \) for CTEQ4L, \( x = 0.01, 0.001, 0.0001, \lambda = 4, 10 \). Based on pQCD expression for \( \hat{\sigma} \) at small \( d_t \), soft dynamics at large \( b \), and smooth interpolation. Provides a good description of \( F_{2p} \) at HERA and \( J/\psi \) photoproduction. Provided a reasonable prediction for \( \sigma_L \)

Frankfurt, Guzey, McDermott, MS 2000-2001
Interaction of fast particles in QCD is expected to differ qualitatively from soft dynamics

Consider first “small dipole - hadron” cross section

\[ \sigma_{\text{inel}}^{\text{dipole-T}}(x, d) = \frac{\pi^2}{3} F^2 d^2 \alpha_s(\lambda/d^2)xG_T(x, \lambda/d^2) \]

\[ F^2 \quad \text{Casimir operator of color SU(3)} \quad \text{Baym, Blattel, F&S 93} \]

\[ F^2(\text{quark}) = 4/3 \quad F^2(\text{gluon}) = 3 \]

Comment: This simple picture is valid only in LO. NLO would require introducing mixing of different components. Also, in more accurate expression there is an integral over x, and an extra term due to quark exchanges. However the general pattern is now tested and works.
Transverse momenta of quarks in DIS, in the photon fragmentation region are increasing with energy.

\[ k_t^2 \propto s^{0.07} \]

Follows from the factorization theorem and rapid increase with energy of structure functions. Results from numerical calculations and evident within the double logarithmic approximation.

Thus hard pQCD interaction dominates in DIS, in exclusive hard processes at sufficiently large energies. Impact parameter distribution becomes more narrow.
Impact parameter distribution in “h”(dipole)p interaction

Study of the elastic scattering allows to determine how the strength of the interaction depends on the impact parameter, b:

\[ \Gamma_h(s, b) = \frac{1}{2is} \frac{1}{(2\pi)^2} \int d^2 \vec{q} e^{i\vec{q} \cdot \vec{b}} A_{hN}(s, t) ; \text{ Im}A = s \sigma_{tot} \exp(Bt/2) \]

\[ \sigma_{tot} = 2 \int d^2 b \text{Re} \Gamma(s, b) \]

\[ \sigma_{el} = \int d^2 b |\Gamma(s, b)|^2 \]

\[ \sigma_{inel} = \int d^2 b (1 - (1 - \text{Re} \Gamma(s, b))^2 - [\text{Im} \Gamma(s, b)]^2) \]

\[ \Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el} \]

- black disk regime -BDR

Note that elastic unitarity:

\[ \frac{1}{2} \text{Im}A = |A|^2 + \ldots \]

allows \( \Gamma(b) \leq 2 \)
Using information on the exclusive hard processes we can also estimate t-dependence of the elastic dipole-nucleon scattering and hence estimate $\Gamma_{q\bar{q}}$ from $\sigma(q\bar{q}N)$.

In the case gg-N scattering we assume pQCD relation

$$\Gamma_{gg} = \frac{9}{4} \Gamma_{q\bar{q}}$$

probability for $q\bar{q}$ not to interact with N at given $b$
Other evidences for onset of BDR for gluons at HERA

- Large ratio of diffraction/total for gluon channel

**gg -N interaction seems close to BDR for** \(Q^2 \sim 4\text{ GeV}^2, x \sim 10^{-4}\)

\[\text{gg - Pb interaction at } b=0 \text{ is deep in BDR (forward RHIC kinematics)}\]

\[\Rightarrow \text{Large probability of diffraction in gluon channel}\]

The probability of hard diffraction on the nucleon, \(P_{j\text{ diff}}\) as a function of \(x\) and \(Q^2\) for u quarks (left) and gluons (right).
**Propagation of ultrafast small dipoles through nuclear media**

Study of energy dependence of inelastic dipole - nucleus interactions in large

\[ q^2 = -(p_Y - p_V)^2 \] process \((Y, Y^*)A \rightarrow \) Vector Meson + rapidity gap + \(X\)

Fast track to observing the black disk regime of interaction with strong gluon fields  
F& L & Zhalov - PRL June 09

elementary reaction scattering of projectile off a parton of the target
at large \(t\) belongs to a class of reactions with hard white

exchange in \(t\)-channel

\[
\begin{align*}
\gamma^* & \rightarrow \text{VM} \\
\tilde{X} & \rightarrow N + X
\end{align*}
\]

\[
\begin{align*}
\tilde{s} & = \frac{q^2}{M_X^2 + q^2} \\
\tilde{x} & = \frac{q^2}{M_X^2 + q^2} \\
s' & = x W_{\gamma p}
\end{align*}
\]

best way to measure of the strength of inelastic interactions of small dipole in the processes
initiated by elastic small dipole - parton scattering at \([s']^{1/2} = 20 \text{ GeV} - 100 \text{ GeV}\) in AA at LHC

FS 89, FS95,  
Mueller & Tung 91  
Forshaw & Ryskin 95
Structure function of a hadron increases with energy forever-taming exists but at energies unachievable in lab.

\[ F_2(x, Q^2) \propto Q^2 \ln(x_0/x)^3 \]

At large energies cross section behaves according to Froisart limit. Additional \( \ln(x_0/x) \) follows from ultraviolet divergencies and related behaviour of polarization operator of photon. This energy dependence is even faster than that within the pQCD approaches.

\( Q^2 \) term follows from the condition of complete absorption where memory on Bjorken scaling, on two dimensional conformal invariance is lost. Thus at the energies above BDR boundary phase transition with the change of continuous symmetry
For these $x$ nuclear gluon shadowing effect is rather small.

Suppression of the leading hadron production in pA scattering at large $p_t$ comparable to the scale of Black disk regime at given energy (FS 01-06).

-forward partons with $p_t$ less than BDR scale should loose energy and $p_t$ distribution should broaden

Natural explanation of the BRAHMS forward pion result at RHIC, and the forward - central STAR correlations data.

Gluon densities at small $x$ in heavy nuclei at $b=0$ and in the proton at $b=0$ are similar.

In high energy pp (p-A) collisions at small $b$ no partons with $p_t < \text{few GeV}$ can survive.
Implications for the searches of new heavy particles at LHC.

Background cannot be modeled based on study of minimal bias events and cannot be reliably extrapolated to LHC without understanding the origin of the effect.

Events with production of heavy particles should contain a significant fraction of hadrons with transverse momenta \( p_{\perp} \sim p_{\perp BDR} \) originating from fragmentation of partons which passed through by the strong gluon field. Transverse momenta of these hadrons are unrelated to the transverse momenta of the jets. Strong increase of multiplicity at central rapidities: a factor \( \sim 2 \) increase observed at FNAL, much larger at LHC.

Difficult to identify jets, isolated leptons,... unless \( p_{\perp jet} \gg p_{\perp BDR} \)

Significant corrections to the LT approximation results for small \( p_{\perp} < p_{\perp BDR} \) differential cross sections of new particle production.
Conclusions

- Understanding of the complexity of the nucleon structure is gradually emerging.

- Double hard processes at Tevatron provides evidence for transverse correlations between partons. Maybe due to lumpy structure of nucleon at low scale (constituent quarks) and size fluctuations. Further studies of transverse correlations are necessary at colliders.

- Small x physics is an unavoidable component of the new particle physics production at LHC. Significant effects already for Tevatron.

- Minijet activity in events with heavy particles should be much larger than in the minimum bias events or if it is modeled based on soft extrapolation from Tevatron.

- Significant corrections to the LT predictions especially for moderate transverse momenta.

- Challenge- understand dynamic mechanism which is modeled in the current MC by introducing ad hoc cutoff on $p_T > p_{\text{min}}$ of the jets (> 4GeV for LHC).

Prepare for QCD surprises at LHC -- highly desirable to have a sample of minimal bias and central trigger events which would allow among other things to adjust quickly MCs for high lumi runs.
What dynamics governs the BLACK DISK regime in hadron-hadron collisions?

In central pp collision at collider energies leading quarks get transverse momenta > 1 GeV/c

If a leading parton got a transverse momentum \( p_\perp \)

probability for a nucleon to remain intact is

\[ P_q \sim F_N^2(p_\perp^2) \]

If \( \langle p_\perp \rangle > 1 \text{GeV}/c \implies P_q \ll 1/2 \)

However there are three leading quarks (and also leading gluons) in each nucleon.

⇒ Probability not to interact \( \equiv |1 - \Gamma(b)|^2 \leq [P_q]^6 \sim 0 \)

\( \Gamma(b \sim 0) = 1 !!! \)

Explains the elastic pp data for small b, predicts an increase of b range, \( b < b_F \) where \( \Gamma = 0, \ b_F = c \ln s \) - Froissart-like regime but \( c \ll 1/m_{\Pi} \).