Multiparton interactions: from RHIC to LHC

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Based on several recent papers with B.Blok, Yu.Dokshitzer, L.Frankfurt, W.Vogelsang, C.Weiss

Jlab 10/22/10
Studies of generalized parton distributions in nucleons

→ information about transverse distribution of partons in nucleons

Information on properties of high energy pp collisions with hard triggers

High energy multiparton interactions

Correlation of partons in nucleons
Important characteristic of high energy collisions is the impact parameter of collision. Well defined since angular momentum is conserved and $L = bp$

Different intensity of interactions for small and large impact parameters

**Small $b$ ➔ large overlap of parton densities**

Large probability of multiparton, soft/hard interactions
Geometry of pp collision with production of dijet in the transverse plane

\[ f_j(x_1, \rho_1) \rightarrow f_j'(x_2, \rho_2) \]

Diagonal Generalized Parton distribution

For hard collision

\[ \rho_1 + b - \rho_2 \propto 1/p_{t\text{jet}} \sim 0 \]

\[ \sigma_h \propto \int d^2 b d^2 \rho_1 d^2 \rho_2 \delta(\rho_1 + b - \rho_2) f_1(x_1, \rho_1) f_2(x_2, \rho_2) \sigma_{2 \rightarrow 2} \]

\[ = \int d^2 \rho_1 d^2 \rho_2 f_1(x_1, \rho_1) f_2(x_2, \rho_2) \sigma_{2 \rightarrow 2} = f_1(x_1) f_2(x_2) \sigma_{2 \rightarrow 2} \]

For inclusive cross section at high virtuality transverse structure does not matter - convolution of parton densities

\[ \downarrow \]

Ignored by many pQCD people
Goals for colliders - realistic account of the transverse structure of the nucleon, the global structure of the events with Higgs, SUSY, ...

Critical for interpretation of structure of the events with dijets at the colliders, multiple collisions. Multiparton interactions have significant probability at Tevatron and large probability at LHC - rates scale as $1/(\text{transverse area occupied by partons})$, depend on the shape of the transverse distribution and on the degree of the overlap.

First quantitative analysis including information on the transverse structure from HERA - Frankfurt, MS, Weiss, 2003

Goals for nucleon structure - probing correlations between quarks, gluons, ....; Distinguish

MIT bag
Constituent quark model with localized gluon fields
quark - diquark
String models
Can nucleon look as a pancake?

Does it make a difference?

or a cucumber?

Very different fluctuations of final states - can easily explain CMS ridge
A tool to learn about transverse parton distributions:

QCD factorization theorem for DIS exclusive meson production
(Brodsky, Frankfurt, Gunion, Mueller, MS 94 - vector mesons, small x; general case Collins, Frankfurt, MS 97)
Universal t-slope: 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, 

$$F_g(x,t) \cdot \frac{d\sigma}{dt} \propto F_g^2(x,t).$$

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

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.

\[ \Rightarrow \text{Transverse distribution of gluons can be extracted from } \gamma + p \rightarrow J/\psi + N \]
γ + p \rightarrow J/\Psi + p, \langle E_\gamma \rangle = 100 \text{ GeV}

Binkley et al 82

Theoretical analysis of $J/\Psi$ photoproduction at $100 \text{ GeV} \geq E_\gamma \geq 10 \text{ GeV}$ corresponds to the two-gluon form factor of the nucleon for $0.03 \leq x \leq 0.2$, $Q_0^2 \sim 3 \text{ GeV}^2$, $-t \leq 2 \text{ GeV}^2$

$$F_g(x, Q^2, t) = (1 - t/m_g^2)^{-2}. m_g^2 = 1.1 \text{ GeV}^2$$

which is larger than e.m. dipole mass

$$m_{e.m.}^2 = 0.7 \text{ GeV}^2. \quad (FS02)$$

A part of the difference is due to the chiral dynamics - lack of scattering off the pion field at $x > 0.05$ (Weiss &MS 03)

*Enters into calculation of the gap survival probability in the double Pomeron exclusive Higgs production in a very sensitive way*
In LT limit $x_1 - x \ll x_1$

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

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

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

$$G(x, x, t) \equiv G(x, t) = \int d^2 \rho e^{-i\Delta_\perp \rho} G(x, \rho)$$

integral of GPD transverse spatial distribution of gluons

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

total gluon density
J/ψ elastic photo and electro production

\[ B = B(W_0) + 2\alpha' \ln(\frac{W^2}{W_0^2}) \]

\( \alpha' \) is consistent with zero!!!

\[ t\text{-slope for } J/\psi \text{ especially at } Q^2=9 \text{ GeV}^2 \text{ is systematically lower than for DVCS and for } \rho \text{ - production} \]
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

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

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

Two scale picture

Can be measured in ultraperipheral collisions at LHC
The change of the normalized $\rho$–profile of the gluon distribution, $F_g(x, \rho; Q^2)$, with $Q^2$, as due to DGLAP evolution, for $x = 10^{-3}$. The input gluon distribution is the GRV 98 parameterization at $Q_0^2 = 3 \, \text{GeV}^2$, with a dipole–type $b$–profile.
Implication - hard processes correspond to collisions where nucleons overlap stronger & more partons hit each other - use hard collision trigger to study central collisions/ all new physics LHC craves to discover corresponds to central pp collisions.

\[ x_{1,2} = 2q_T/W \sim 10^{-2} \]

"peripheral" (dominate total cross section)

"central"
**Impact parameter distribution for a hard multijet trigger.**

For simplicity take $x_1 = x_2$ for colliding partons producing two jets with $x_1 x_2 = 4q^2_\perp/s$. Answer is not sensitive to a significant variation of $x_i$ for fixed $q_\perp$.

The overlap integral of parton distributions in the transverse plane, defining the $b$–distribution for binary parton collisions producing a dijet follows from the figure:
Hence the distribution of interactions over $b$ for events with dijet trigger (Higgs production,...) is given by

$$P_2(b) = \int d^2 \rho_1 \int d^2 \rho_2 \delta^{(2)}(\vec{b} - \vec{\rho}_1 + \vec{\rho}_2) F_g(x_1, \rho_1) F_g(x_2, \rho_2),$$

$$F_g(x, \rho) = \frac{m_g^2}{2\pi} \left( \frac{m_g \rho}{2} \right) K_1(m_g \rho)$$

for

$$F_g(x, t) = 1/(1 - t/m_g(x)^2)$$

$$P_2(b) = \frac{m_g^2}{12\pi} \left( \frac{m_g b}{2} \right)^3 K_3(m_g b)$$
Need to compare with b-distribution for minimal bias (generic) inelastic pp scattering

\[ P_{in}(s, b) = \frac{2 \text{Re} \Gamma^{pp}(s, b) - |\Gamma^{pp}(s, b)|^2}{\sigma_{in}(s)} \]

where

\[ \Gamma_h(s, b) = \frac{1}{2is(2\pi)^2} \int d^2 \vec{q} e^{i\vec{q}\vec{b}} A_{hN}(s, t) \]

\[ \Gamma(b) = 1 \equiv \sigma_{inel} = \sigma_{el} \quad \text{- black disk regime (BDR)}. \]
Impact parameter distributions of inelastic pp collisions at $\sqrt{s} = 7$ TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2} = 0$, c, for $p_T = 100$ (10) GeV. Dotted line: Distribution of minimum–bias inelastic events.

Median impact parameter $b$ (median) of events with a dijet trigger, as a function of the transverse momentum $p_T$, cf. left plot. Solid line: Dijet at zero rapidity $y_{1,2} = 0$. Dashed line: Dijet with rapidities $y_{1,2} = \pm 2.5$. The arrow indicates the median $b$ for minimum–bias inelastic events.
Much smaller impact parameters for hard dijet trigger

Impact parameters for hard dijet triggers with different rapidities, $p_T$'s are practically the same

Universal underlying event for dijet triggers which is much higher than for minimal bias events

Schematic illustration of the expected dependence of the transverse multiplicity, $N(p_T)$, on the $p_T$ of the trigger.
UE distributions

\[
\frac{d^2N_{\text{chg}}}{dp_T^2}\quad \text{(leading charged particle)} \quad [\text{GeV}]
\]

Similar for \(\Sigma p_T\) density

Emily Nurse

ATLAS: MB, UE and MC tuning
Conclusion from analysis of the ATLAS and CMS data

**pQCD starts to dominate charged particle production at relatively large and growing with** $s$ **$p_T$:**

\[
p_{T,\text{crit}}(\sqrt{s} = .9 \text{ TeV}) \sim 4 \text{ GeV}/c, \\
p_{T,\text{crit}}(\sqrt{s} = 1.8 \text{ TeV}) \sim 5 \text{ GeV}/c, \\
p_{T,\text{crit}}(\sqrt{s} = 7.0 \text{ TeV}) \sim 6 - 8 \text{ GeV}/c
\]

**Flattening of dependence on** $p_T$ **for** $p_T > p_{T,\text{crit}}$

Data confirm difference of the impact parameter scales of hard and soft interactions in pp collisions which is determined by the value of $<\rho_g^2>$ as compared to much larger radius of soft interactions. Note that MCs like PYTHIA, HERWIG assume $<\rho_g^2> = <\rho_q^2>$ a factor $\sim 2$ smaller than given by analysis of GPDs and neglect also their $x$-independence. Note also that from analysis DVCS there is evidence that $<\rho_g^2>$ somewhat smaller than $<\rho_q^2>$
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 → four partons.

Note - collisions at the points separated in b by ~ 0.5 fm ⇒ independent fragmentations
Experimentally one measures the ratio

\[
\frac{d\sigma(p+\bar{p}\rightarrow jet_1+jet_2+jet_3+\gamma)}{d\Omega_{1,2,3,4}} \cdot \frac{d\sigma(p+\bar{p}\rightarrow jet_3+\gamma)}{d\Omega_{3,4}} = \frac{f(x_1,x_3) f(x_2,x_4)}{\pi R^2_{int} f(x_1) f(x_2) f(x_3) f(x_4)}
\]

where \( f(x_1,x_3), f(x_2,x_4) \) longitudinal light-cone double parton densities and

\( \pi R^2_{int} \) is "transverse correlation area". One selects kinematics where \( 2 \rightarrow 4 \) contribution is small.

CDF observed the effect in a restricted x-range: two balanced jets, and jet + photon and found

\[ \pi R^2_{int} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb} \]

No dependence of \( \pi R^2_{int} \) on \( x_i \) was observed.

A naive expectation (based on \( r_N=0.8 \text{ fm} \)) is \( \pi R^2_{int} \sim 60 \text{ mb} \) indicating high degree of correlations between partons in the nucleon in the transverse plane - next 2 slides.
Here D's are GPD in the impact parameter space representation.

\[ \sigma_4 = \int d^2 B d^2 \rho d^2 \rho_1 d^2 \rho_2 d^2 \rho_3 d^2 \rho_4 D(x_1, x_2, \rho_1, \rho_2) \times D(x_3, x_4, \rho_3, \rho_4) \]

\[ = \int d^2 B d^2 \rho_1 d^2 \rho_2 D(x_1, x_2, \rho_1, \rho_2) \times D(x_3, x_4, \vec{B} + \rho_1, -\vec{B} + \rho_2) \]

Here D's are GPD in the impact parameter space representation.

\[ D(x_1, x_2, \rho_1, \rho_2) = \sum_{n=1}^{\infty} \int \prod_{i=1}^{i=n} [dx_i d^2 \rho_i] \]

\[ \psi_n(x_1, \rho_1, x_2, \rho_2, ... x_i, \rho_i, ) \times \psi_n^+(x_1, \bar{\rho}_1, x_2, \bar{\rho}_2, ..., x_i, \bar{\rho}_i, ...) \delta(\sum_{i=1}^{i=n} \bar{\rho}_i). \]

\[ \psi(x_1, \rho_1, x_2, \rho_2, ...) = \int \prod_{i=1}^{i=n} \frac{d^2 k_i}{(2\pi)^2} \times \exp(i \sum_{i=1}^{i=n} \bar{k}_i \rho_i) \psi_n(x_1, \bar{k}_1, x_2, \bar{k}_2, ...)(2\pi)^2 \times \delta(\sum_{i=1}^{i=n} \bar{k}_i). \]
Assuming no correlations between partons in transverse plane distribution of $4 \rightarrow 4$ in $b$ plane, $P_4(b)$ is

$$P_4(b) = \frac{P_2^2(b)}{\int d^2b \ P_2^2(b)} ; P_4(b) = \frac{7 m_g^2}{36\pi} \left( \frac{m_g b}{2} \right)^6 [K_3(m_g b)]^2$$

$$\pi R_{\text{int}}^2 = \frac{28\pi}{m_g^2} \sim 34 \text{ mb.}$$

FSW03

For $m^2 = 0.7 \text{ GeV}^2 \sim 54 \text{ mb}$
Possible sources of small $\pi R_{\text{int}}^2$ for CDF kinematics of $x \sim 0.03-0.3$ include:

- Small transverse area of the gluon field --accounts for 50% of the enhancement $\pi R_{\text{int}}^2 \sim 34 \text{ mb}$ (F&S & Weiss 03)

- Constituent quarks - quark -gluon correlations (F&S&W)

If most of gluons at low $Q \sim 1\text{ GeV}$ scale are in constituent quarks of radius $r_q/r_N \sim 1/3$ found in the instanton liquid based chiral mean field model (Diakonov & Petrov), the enhancement as compared to uncorrelated parton approximation is

$$\frac{8}{9} + \frac{1}{9} \frac{r_N^2}{r_q^2} \sim 2$$

Hence, combined these two effects are sufficient to explain CDF data for $x > 0.1$. (F&S&W)

- Fluctuations of the transverse size of nucleons (Treliani, &F&S & W) - effect works in right direction but only 15 -- 20% effect.

- 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 not to be relevant in the CDF kinematics as $x$’s of colliding partons are relatively large ($>0.01$). Also it leads to a different structure of the final state.
Can we derive geometric results from the first principles?

\[ d\sigma_4 = \int \frac{d^2 \Delta}{(2\pi)^2} \int dx_1 \int dx_2 \int dx_3 \int dx_4 \]
\[ \times D_a(x_1, x_2, p_1^2, p_2^2, \Delta) D_b(x_3, x_4, p_1^2, p_2^2, -\Delta) \]
\[ \times \frac{d\sigma^{13} d\sigma^{24}}{dt_1 dt_2} d\hat{t}_1 d\hat{t}_2. \]

Here we introduced double GPD

\[ D(x_1, x_2, p_1^2, p_2^2, \Delta) = \sum_{n=3}^{\infty} \int \frac{d^2 k_1}{(2\pi)^2} \frac{d^2 k_2}{(2\pi)^2} \theta(p_1^2 - k_1^2) \times \theta(p_2^2 - k_2^2) \]
\[ \times \prod_{i \neq 1,2} \int_0^1 \frac{d^2 k_i}{(2\pi)^2} \prod_{i \neq 1,2} dx_i \times \left[ \psi_n(x_1, \bar{k}_1, x_2, \bar{k}_2, .., \bar{k}_i, x_i..) \times \psi^+_n(x_1, \bar{k}_1 + \Delta, x_2, \bar{k}_2 - \Delta, x_3, \bar{k}_3, ..) + h.c. \right] \]
\[ \times (2\pi)^3 \delta(\sum_{i=1} x_i - 1) \delta(\sum_{i=1} \bar{k}_i). \]

D is diagonal in the space of all partons except the two partons involved in the collision. No recoil as total momentum transfer is zero.

After several Fourier transforms one can derive from these equation the geometric representation I started with.
**General expression for collision of particles a and b**

\[
\frac{1}{\pi R_{\text{int}}^2} = \int \frac{d^2 \Delta}{(2\pi)^2} D_a(x_1, x_2, -\Delta) D_b(x_1, x_2, \Delta)
\]

**Independent particle approximation which could be reasonable for small \(x_1, x_2\)**

\[
D(x_1, x_2, p_1^2, p_2^2, \Delta) = G(x_1, p_1^2, \Delta) G(x_2, p_2^2, \Delta)
\]

\[
\frac{1}{\pi R_{\text{int}}^2} = \int \frac{d^2 \Delta}{(2\pi)^2} F_{2g}^4(\Delta) = \frac{m_g^2}{28\pi}.
\]

**Original result we obtained in FSW03 - now we see it is pretty stable**

- as \(F_{2g}^2(\Delta)\) is measured directly.

**For N binary collisions**

\[
\sigma_{2N} \propto \int \prod_{i=1}^{i=N} \frac{d\Delta_i}{(2\pi)^2} D_a(\Delta_1, ... \Delta_N) \times D_b(\Delta_1, ... \Delta_N) \delta\left(\sum_{i=1}^{i=N} \Delta_i\right).
\]
LHC - plans to study various channels

What partons are more strongly correlated transversely:

a) quark - quark  
   diquark model

b) quark - gluon  
   constituent quark model

c) gluon - gluon  
   QCD evolution (?)

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 : huge \(x\) range at LHC. RHIC can do quark - quark for large \(x\) - longitudinal correlations - transverse more difficult
Comment - interaction at small impact parameters is very interesting / important from the QCD angle (on the top of understanding UE for Higgs, SUSY, ... searches)

- Amplification of the small x nonlinear effects: in proton - proton collisions a parton with given $x_R$ resolves partons in another nucleon with $x_2 = 4p_{\perp}^2 / x_R s$

At LHC $x_R = 0.01, p_{\perp} = 2\text{GeV/c} \Rightarrow x_2 \sim 8 \times 10^{-6}$
Evidence for double parton interaction mechanism in the forward production of two pions in pp and d-Au collisions at RHIC processes studied:

\[ \text{pp (d-Au)} \rightarrow \pi^0 + X \quad \eta \leq 4 \quad (x_F \leq 0.5), p_T > 1.5 \text{ GeV/c} \quad 2003-2006 \]

\[ \text{pp (d-Au)} \rightarrow \pi^0 + \pi^0 + X \quad \eta_{1,2} \leq 4 \quad (x_F \leq 0.5), p_T > 1.5 \text{ GeV/c} \quad 2009-2010 \]

pp data for single pion production described well by pQCD

d-Au data for single pion - large suppression as compared to the impulse approximation - suggested as an evidence for \( 2 \rightarrow 1 \) color glass condensate mechanism

dedicated run to measure forward \( \pi^0 + \pi^0 \) production
Trigger for two forward pions selects even larger $x_q$ than the single pion trigger

fraction of cross section due to given $x_a$ ($x$ of the quark of the proton)

Large enhancement of double parton interactions in pp and especially dAu
\[
\frac{d^4\sigma_{\text{double}}}{dp_{T,1} d\eta_1 dp_{T,2} d\eta_2} = \frac{1}{\pi R_{\text{int}}^2} \sum_{abc a'b'c'} \int dx_a dx_b dz_c dx_{a'} dx_{b'} dz_{c'} f^p_{aa'}(x_a, x_{a'}) f^p_b(x_b) f^p_{b'}(x_{b'}) \\
\times \left( \frac{d^2\hat{\sigma}^{ab\rightarrow cX}}{dp_{T,1} d\eta_1} \frac{d^2\hat{\sigma}^{a'b'\rightarrow c'X'}}{dp_{T,2} d\eta_2} \right) D_{c}^{\pi^0}(z_c) D_{c'}^{\pi^0}(z_{c'}). 
\]

\[
f^{p}_{qq'}(x_q, x_{q'}) = \frac{1}{2} \left[ f^p_q(x_q) \times \phi \left( \frac{x_{q'}}{1 - x_q} \right) + (q \leftrightarrow q') \right]
\]

\[
\phi(\xi) = \frac{c}{\sqrt{\xi}} (1 - \xi)^n
\]
We used experimental value of $\pi R_{\text{int}}^2 = 15 \text{ mb}$

Note that if the typical distances between large $x$ quarks are smaller than typical distance for small $x$ gluons we get

$$\pi R_{\text{int}}^2 = \left[ \int \frac{d^2 \Delta}{(2\pi)^2} F_{2g}^2(\Delta) \right]^{-1} = \frac{12\pi}{m_g^2} \approx 14 \text{ mb}$$
Comparison of the leading-twist cross section for $pp \rightarrow \pi^0 + \pi^0 + X$ (blue) and the double-interaction contribution (red) as functions of $p_{T,1}$ (left) and $\eta_1$. Insert the ratio of double and single cross sections.
Near side peaks unchanged in dAu peripheral to central. Azimuthal decorrelations show significant dependence on centrality. Away-side peaks evident in peripheral dAu and pp.

pp data

pedestal ?

STAR Preliminary

Uncorrected Coincidence Probability (radian^-1)

\[ p + p \rightarrow \pi^0 \pi^0 + X, \sqrt{s} = 200 \text{ GeV} \]

\[ p_T > 2 \text{ GeV/c}, 1 \text{ GeV/c} < p_{T,s} < p_{T,L} \]

\[ \langle \eta_L \rangle = 3.2, \langle \eta_s \rangle = 3.1 \]
Check - look at d-Au should see a large enhancement of the pedestal - two nucleons can hit many nucleons - (MS +Treleani 02)

![Diagram showing contributions to two-pion production in dA collisions through the double-interaction mechanism.](image)

**Figure 4:** Contributions to two-pion production in dA collisions through the double-interaction mechanism.

We may distinguish three contributions to the double-parton mechanism in dA scattering, as shown in Fig. 4:

(a) Two (valence) quarks from one of the nucleons in the deuteron participate in the hard-scattering, striking the same nucleon in the heavy nucleus (Fig. 4(a)).

(b) Independent scattering of the deuteron's proton and neutron off separate nucleons in the heavy nucleus. Each of the two collisions produces one of the observed pions (Fig. 4(b)).

(c) Same as (a), but with the double interaction occurring off two different nucleons in the heavy nucleus. Again each of the two collisions produces one of the observed pions (Fig. 4(c)).

We now proceed to make estimates for these contributions. For our more illustrative purposes, we neglect effects of nuclear (anti-)shadowing for the heavy nucleus. Also, we treat the heavy nucleus as roughly iso-scalar. For our estimates we need to take into account the distribution of nucleons in a heavy nucleus. Since the experiments are performed with a centrality trigger, it is useful to first write the double-inclusive cross section in a form where the integral over impact parameter is kept explicitly [12].

We write all expressions for N-nucleus scattering, where \( N = (p+n)/2 \) denotes an iso-scalar combination of proton and neutron. Since they are bound in a deuteron they propagate at similar impact parameters. We further assume that the impulse approximation is valid for the interaction with the nucleus. For any contribution that involves scattering off only one of the "target" nucleons, we then have the generic formula

\[
\frac{d^4\sigma}{d^2p_T,1 dp_T,2 d\eta_1} = \int d^2b_T(b) \frac{d^4\sigma_{NN}}{dp_T,1 dp_T,2 d\eta_1}(11)
\]

for the two-pion cross section. Here, \( T(b) \) is the nuclear thickness factor defined above in Eq. (10). Equation (11) holds for contribution (a), but evidently also for the leading-twist piece. Hence, if we consider a fixed impact parameter and take their ratio, the factor \( T(b) \) will...
We explained previously various regularities of single pion production as due to post-selection effect in proximity of the black disk regime (Frankfurt, Guzey, McDermott, MS 01) leading to fractional energy losses.

Accounting this effect, and LT gluon shadowing reduces $4\rightarrow 4/2\rightarrow 2$ ratio:

- $\Delta\phi$ independent pedestal in dA three times larger in pp
- Suppression of $\Delta\phi = 180^\circ$ peak by a factor $\sim 4$

Large nonlinear effects at the LHC in wide range of rapidities.
Small x physics is an unavoidable component of the new particle physics production at LHC. Significant effects already for Tevatron.

Centrality matters in pp: Minijet activity in events with heavy particles is much larger than in the minimum bias events or if it is modeled based on soft extrapolation from Tevatron.

Conclusions

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

Double hard processes at Tevatron provides evidence for transverse correlations between partons. Further studies of transverse correlations are underway at the LHC. RHIC opens new direction of studies of quark - quark correlations in nucleons.

Double (Triple,...) parton processes probe new multiparton GPDs.

Lattice QCD,... can calculate double GPDs relevant for multiparton processes.

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

Centrality matters in pp: Minijet activity in events with heavy particles is much larger than in the minimum bias events or if it is modeled based on soft extrapolation from Tevatron.

Challenge- understand dynamic mechanism which is modeled in the current MC by introducing ad hoc cutoff on $p_t > p_{min}$ of the jets (> 3GeV for LHC)

Already first QCD data bring surprises at LHC (as we predicted). More surprises to follow.