Aspects of forward di-jet production at the LHC

Krzysztof Kutak
Why jets?

• Jets are direct manifestation of partonic structure of hadrons

• Jets are challenging to get good description of their properties and especially to find saturation

• Tomography of QGP

• One can test different types of PDFS

• γ A → 2 jets is sensitive to the Weizsacker-Williams (WW) unintegrated gluon distribution (UGD), whereas other processes like J/ψ or inclusive jets are sensitive to the dipole UGD

• pA → 2 jets is sensitive to both UGDs (directly to the dipole UGD and indirectly to WW)

• Dipole UGD for proton is relatively well constrained from HERA; this not the case for the WW UGD
LHC and tomography of partons → di-jet example

From Cyrille Marquet
hybrid High Energy Factorization

Strongly decreasing transversal momentum of DGLAP-like partons

\[ p_1 + p_2 = q_1 + q_2 \]

Strongly decreasing longitudinal momentum fractions of off-shell partons

\[ p_1 + p_2 = q_1 + q_2 + k \]
First attempt: hybrid factorization and dijets

\[
\frac{d\sigma_{\text{SPS}}^{P_1 P_2 \rightarrow \text{dijets} + X}}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta \phi} = \frac{p_{1t} p_{2t}}{8\pi^2 (x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/P_1}(x_1, \mu^2) |M_{ag^* \rightarrow cd}|^2 F_{g/P_2}(x_2, k_t^2) \frac{1}{1 + \delta_{cd}}
\]

conjecture
Deak, Jung, Kutak, Hautmann '09

obtained from CGC after neglecting all nonlinearities
\[g^* g \rightarrow gg\] Iancu, Laidet
\[qg^* \rightarrow qg\] Van Hameren, Kotko, Kutak, Marquet, Petreska, Sapeta

resummation of logs of \(x\)
logs of hard scale
knowing well parton densities at large \(x\) one can get information about low \(x\) physics

\[x_1 = \frac{1}{\sqrt{s}} (|\vec{p}_{1t}| e^{y_1} + |\vec{p}_{2t}| e^{y_2})\]
\[\rightarrow \quad y_1, y_2 \gg 0 \quad \Rightarrow \quad x_1 \sim 1\]
\[x_2 = \frac{1}{\sqrt{s}} (|\vec{p}_{1t}| e^{-y_1} + |\vec{p}_{2t}| e^{-y_2})\]
\[x_2 \ll 1\]

Inbalance momentum:
\[|\vec{k}_t|^2 = |\vec{p}_{1t} + \vec{p}_{2t}|^2 = |\vec{p}_{1t}|^2 + |\vec{p}_{2t}|^2 + 2|\vec{p}_{1t}| |\vec{p}_{2t}| \cos \Delta \phi\]
Relevant scales and factorization

\[ P_t \sim k_t \]  
High Energy Factorization → partons carry some \( k_t \)

\[ k_t \ll P_t \]  
Collinear Factorization → partons in one of hadrons are just collinear with hadron \( k_t \) is neglected

\[ Q_s \sim k_t \ll P_t \]  
generalized Transverse Momentum Dependent Factorization → rescatterings formal treatment of nonlinearities but does not allow for calculation of decorrelations

\( Q_s, k_t, P_t \) Improved Transverse Momentum Dependent Factorization

average transverse momentum of dijets

target gluon's transverse momentum

scale at which gluon recombination nonlinear effects at the target start to be relevant
The saturation problem: sensitivity to gluons at small $k_t$

Solution of BFKL equation

\[ \mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} \]
High energy factorization and saturation

Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

On microscopic level it means that gluon apart splitting recombine

Linear evolution equation

Nonlinear evolution equations

splitting splitting recombination
High energy factorization and saturation

Saturation – state where number of gluons stops growing due to high occupation number. Way to fulfill unitarity requirements in high energy limit of QCD.

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Splitting

Linear evolution equation

Nonlinear evolution equations

Recombination
The saturation problem: suppressing gluons at small $k_t$

Originally formulated in coordinate space
Balitsky '96, Kovchegov '99
first solved
Golec-Biernat, Motyka, Stasto '01
(momentum space, WW density)
Now at NLO accuracy
Balitsky, Chirilli '07
and solved
Lappi, Mantysaari '15
More general approach
Jalian-Mariani, Iancum McLerran
Weigert Leonidov, Kovner '01

The BK equation for dipole gluon density

$$F = F_0 + K \otimes F - \frac{1}{R^2} V \otimes F^2$$

hadron's radius

Solution of the equation

$x = 10^{-5}, ..., 10^{-7}$

Momentum space

Kwiecinski, Kutak '02
Nikolaev, Schafer '06
Glue in $p$ vs. glue in $Pb$ vs. linear - $kt$ dependence

\[ \mathcal{F}(x, k^2) \]

\[ x = 10^{-4} \]
Numerical calculations

Parton densities

KS (Kutak-Sapeta) nonlinear → gluon density from extension of momentum space version of BK equation to include:
• kinematical constraint
• complete splitting function,
• running coupling
• quarks

KK, Kwiecinski '03 fitted to '10 HERA data KK, Sapeta '12, nonlinear extension of unified BFKL+DGLAP Kwiecinski, Martin, Staśto framework '97.

KMRW (Kimber, Martin Ryskin, Watt) → full set of pdfs obtained from unfolding collinear pdfs and imposing angular ordering. LO and NLO formulation available

Monte Carlo KaTie by Andreas van Hameren, arXiv:1611.00680
• complete Monte Carlo program for tree-level calculations in HEF (at present)
• any process within the Standard Model
• any initial-state partons on-shell or off-shell
• employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes
• automatic phase space optimization
Central-forward di-jets
Decorelations inclusive scenario forward-central

In DGLAP approach i.e. $2 \to 2 + \text{pdf}$ one would get delta function

Kotko, K.K, Sapeta, van Hameren '14

$p_{t1}, p_{t2} > 35 \text{GeV}$

$3.2 < |y_2| < 4.7$

$|y_1| < 2.8$

Leading jets, no further requirement

Observable suggested to study BFKL effects

Sabio-Vera, Schwensen '06

Studied also context of RHIC

Albacete, Marquet '10
Predictions for $p$-$Pb$ for forward-central jets

$\sqrt{s} = 5.0$ TeV
$p_{t1}, p_{t2} > 35$ GeV
$|y_1| < 2.8$, $3.2 < |y_2| < 4.7$

Saturation effects are rather weak for forward-central jets
Forward-forward di-jets
Dipole gluon density

In dipole picture

Following talk by Stephan Munier QCD@LHC 2014
Dipole gluon density

We factor out wave function.

We multiply the amplitude by its hermitian conjugate.

\[ F(x, k_t^2) \propto k_t^2 \int \frac{d^2x}{(2\pi)^2} e^{-ik_t \cdot x} S(x, x) \]
Dipole gluon density

- Enters directly into DIS structure function and DY cross section
- Can be expressed in terms of the expectation value of the S–matrix for scattering of a qq dipole off a dense target, $SF$
- One can write BK equation in the momentum space which as a solution gives dipole gluon density

$$\mathcal{F}(x, k_t^2) \propto k_t^2 \int \frac{d^2x}{(2\pi)^2} e^{-ik_t \cdot x} S(x, x)$$

$$xG^{(1)}(x, k_t^2) \equiv \mathcal{F}(x, k_t^2)$$
Weizacker-Williams gluon density

Double inclusive production

\[ q + g \rightarrow gq \]
Weizacker-Williams gluon density

Large number of color limit

\[ S \propto \langle Tr(U^\dagger(x_2)U(x_3)) \rangle \]
\[ Q \propto \langle Tr(U^\dagger(x_1)U(x_2)U^\dagger(x_3)U(x_4)) \rangle \]
Weizacker-Williams gluon density

- Can be determined from dijet production in DIS
- In general can be obtained from a quadrupole operator
- For Gaussian distribution of sources one can express it through the expectation value of the S – matrix for scattering of a gg dipole

\[
xG^{(1)}(x, k_t^2) \propto \int \frac{d^2 \mathbf{x}}{(2\pi)^2} e^{-i \mathbf{k}_t \cdot \mathbf{x}} \left(1 - \frac{S_A(x, \mathbf{x})}{x^2}\right)
\]

In approximation

\[
S_A(x, \mathbf{x}) = [S(x, \mathbf{x})]^2
\]
**Improved TMD for dijets**

\[
\frac{d\sigma_{SPS}^{P_1P_2 \rightarrow \text{dijets} + X}}{dy_1dy_2dP_{1t}dP_{2t}d\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1, \mu^2) \left| \mathcal{M}_{ag^{+cd}} \right|^2 F_{g/P_2}(x_2, k_t^2) \frac{1}{1 + \delta_{cd}}
\]

Generalization but **no possibility to calculate decorelations** since no \( k_t \) in ME so called correlation limit

Dominguez, Marquet, Xiao, Yuan '11

Application to differential distributions in \( d+Au \)

Stasto, Xiao, Yuan '11

\[
\frac{d\sigma_{P^A \rightarrow cdX}}{d^2P_t d^2k_t dy_1dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2} x_1 f_{q/p}(x_1, \mu^2) \sum_{i=1}^{n} F_{ag}^{(i)} H_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}
\]
Improved TMD for dijets

We found a method to include $k_t$ in ME and express the factorization formula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density.

Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15

\[
\frac{d\sigma^{pA\rightarrow \text{dijets} + X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1, \mu^2) \sum_{i=1}^{2} K_{ag^*\rightarrow cd}^{(i)} \Phi_{ag\rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}
\]
Glimpse on the first results – HEF vs. ITMD

Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren '16

HEF gluon density i.e. dipole UGD

WW gluon density

In large $N_c$ one can express WW UGD in terms of dipole UGD. We use this approximation
UPC collision of Pb-Pb

\[ \gamma + g \rightarrow \bar{q}q \]

\[
d\sigma_{AA\rightarrow 2jet+X} = \int d\gamma x \frac{dN_{\gamma}}{dx_{\gamma}} d\sigma_{\gamma A\rightarrow 2jet+X}
\]

\[
\frac{d\sigma_{\gamma A\rightarrow 2j}}{dy_1 d^2 p_{T_1} dy_2 d^2 p_{T_2}} \sim x_A G_1(x_A, k_T^2) \otimes K_{\gamma_g^*\rightarrow q\bar{q}}(k_T)
\]
Longitudinal momentum fraction distributions
– different cuts scenario

Kotko, Kutak, Sapeta, Stasto, Strikman '16
**WW vs. dipole gluon density**

![Graphs showing WW vs. dipole gluon density](image)
Nuclear modification factor - azimuthal decorrelations

\[ R_{γA} = \frac{dσ^{UPC}_{AA}}{Adσ^{UPC}_{Ap}} \]

\( pT_0 = 10 \text{ GeV} \)
\( pT_0 = 6 \text{ GeV} \)

UPC with A=Pb
ITMD+Sudakov with KS

\( √S = 5.1 \text{ TeV} \)
\( pT_1 > pT_2 > pT_0 \)
\( 0<γ_1,γ_2<5.0 \)
Other relevant effects – Final State Radiation

Final state emissions and hadronization.

Work in progress with IFJ PAN team: Bury, Jung, van Hameren, Sapeta, Serino
Jets in Pb-Pb using HEF

Deak, Kutak, Tywoniuk 1706.08434

\[
\frac{d\sigma}{dy_1 dy_2 d\eta_1 d\eta_2 d\phi} = \sum_{a,c,d} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 P_a(\epsilon_1) P_g(\epsilon_2) \frac{d\sigma_{acd}}{dy_1 dy_2 d\eta_1' d\eta_2' d\phi} \left| \begin{array}{c} p_{1t}' = p_{1t} + \epsilon_1 \\ p_{2t}' = p_{2t} + \epsilon_2 \end{array} \right|
\]

quenching weights vacuum Pb-Pb scattering
Conclusions and outlook

- New framework ITMD for calculations of forward dijets has been developed
- The framework is applicable for UPC collisions too
- It seems that saturation effects are relevant for forward-forward jet configuration
- New Monte Carlo tool has been developed KaTie. It allows for calculation of any process in SM with exact kinematics and low x resummation.

- Update the pdfs used.
- Include FSR, hadronization
- NLO effects