Azimuthal and rapidity correlations of forward-central dijets in heavy ion collisions and TMD PDFs

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First attempt: hybrid factorization and dijets

High energy factorization and forward jets

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

**Conjecture**

Deak, Jung, Kutak, Hautmann '09

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**Obtained from CGC after neglecting all nonlinearities**

\[ g^*g \to gg \text{ Iancu, Laidet} \]

\[ qg^* \to qg \text{ Van Hameren, Kotko, Kutak, Marquet, Petreska, Sapeta} \]

**Resummation of logs of x**

**Logs of hard scale**

**Knowing well parton densities at large x** one can get information about low x physics

\[
\begin{align*}
  x_1 &= \frac{1}{\sqrt{s}} \left( |p_{1t} e^{y_1} + p_{2t} e^{y_2}| \right) \\
  x_2 &= \frac{1}{\sqrt{s}} \left( |p_{1t} e^{-y_1} + p_{2t} e^{-y_2}| \right)
\end{align*}
\]

**Inbalance momentum:**

\[ |k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}| \cos \Delta \phi \]

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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

\[ p_1 + p_2 = q_1 + q_2 + k \]
High Energy Factorization (HEF)

- Hybrid HEF formula for Pb-Pb collision:

\[
\frac{d\sigma_{acd}}{dy_1 dy_2 dp_{t1} dp_{t2} d\phi} = \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} |\mathcal{M}_{ag^* \rightarrow cd}|^2 \times 1 \frac{f_{a/A}^{Pb}(x_1, \mu^2) \mathcal{F}_{g/B}^{Pb}(x_2, k_t^2, \mu^2)}{1 + \delta_{cd}}
\]

- Exact kinematics at leading order in \( \alpha_s \)
  - Jets not necessarily back to back

- Transversal momentum dependent (TMD) nuclear parton density function (nPDF)

\[
\mathcal{F}_{g/B}^{Pb}(x_2, k_t^2, \mu^2)
\]

- Collinear nPDF

\[
x_1 f_{a/A}^{Pb}(x_1, \mu^2)
\]

- Implemented in the Monte Carlo program Katie (used in this analysis)

A. van Hameren, arXiv:1611.00680
Jets passing through the medium

Azimuthal cross section of the medium

Longitudinal cross section of the medium

- Kinematics:
  
  \[ k_t^2 = p_{t1}^2 + p_{t2}^2 + 2p_{t1}p_{t2} \cos \Delta \phi, \text{ and} \]

  \[ x_1 = \frac{1}{\sqrt{S}} (p_{t1}e^{y_1} + p_{t2}e^{y_2}), \quad x_2 = \frac{1}{\sqrt{S}} (p_{t1}e^{-y_1} + p_{t2}e^{-y_2}) \]
Multiple Soft Scattering (MSS)

- Emission spectrum of medium induced bremsstrahlung in MSS:

\[
\omega \frac{dI_R(\chi)}{d\omega} = \frac{\alpha_s C_F}{\omega^2} 2 \text{Re} \int_0^{\chi \omega} \frac{d^2 q}{(2\pi)^2} \int_0^\infty dt' \int_0^{t'} dt \int d^2 z \exp \left[ -i q \cdot z - \frac{1}{2} \int_{t'}^\infty ds \, n(s) \sigma(z) \right] \times \frac{\partial_z}{\partial_y} \left[ \mathcal{K}(z,t';y,t|\omega) - \mathcal{K}_0(z,t';y,t|\omega) \right]_{y=0},
\]

with

\[
\mathcal{K}(z,t';y,t|\omega) = \int_{r(t)=y}^{r(t')=z} D\mathbf{r} \exp \left\{ \int_t^{t'} ds \left[ \frac{i \omega}{2} \mathbf{r}^2 - \frac{1}{2} n(s) \sigma(r) \right] \right\}
\]

- Describes propagation of a quark through nuclear medium
- Gluon emission spectrum in MSS:

\[
P_R(\epsilon) = \Delta(L) \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^n \int_0^L dt \int d\omega_i \frac{dI_R(\chi)}{d\omega_i dt} \delta \left( \epsilon - \sum_{i=1}^n \omega_i \right)
\]

- Probability resulting from resummation of in medium emissions
- "Drag" in the longitudinal direction – transversal momentum “kicks” neglected

HEF in Heavy Ion Collisions

- Cross section formula with medium effects included:

\[
\frac{d\sigma}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta \phi} = \sum_{a,c,d} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 P_a(\epsilon_1) P_g(\epsilon_2) \quad \frac{d\sigma_{acd}}{dy_1 dy_2 dp_{t1}' dp_{t2}' d\Delta \phi} \bigg|_{p_{1t}'=p_{1t}+\epsilon_1}^{p_{2t}=p_{2t}+\epsilon_2}
\]

\[
P(\xi, r) = C_1 \delta(\xi) + C_2 D(\xi, r)
\]

- Probability density has 2 components:
  - discrete – no-suppression $\leftrightarrow$ coefficient $C_1$
  - continuous $\leftrightarrow$ coefficient $C_2$

- Algorithm:
  1. generate random $0 < R < 1$
     - if $R < C_1$ no suppression occurs $\xi = 0$; go to next event
     - else
  2. generate $\xi$ according to $D(\xi, r)$; go to next event

\[
\xi = \epsilon/\omega_c \text{ with } \omega_c = \hat{q}L^2/2
\]

\[
r = \hat{q}L^3/2
\]

Model of rapidity dependence and other parameters

- A model of the rapidity dependence of the nuclear medium:

\[ \hat{q} = 2K\varepsilon^{3/4} \]

\[ \varepsilon = \varepsilon_{\text{tot}} W(x, y; b) H(\eta) \]

- We neglect the dependence on in impact parameter \( \rightarrow W(x, y; b) = 1 \)
- \( K=1 \) (not fitted)
- \( \varepsilon_{\text{tot}} = 143 \text{ GeV/fm}^3 \) total energy density corresponding to \( \hat{q} = 1 \text{ GeV/fm} \) at mid rapidities (not fitted)
- \( L = 5 \text{ fm} \) constant

A fit to ALICE (0 - 5% centrality) data:

\[ H(\eta) = \frac{1}{\sqrt{2\pi}(a_1 b_1 - a_2 b_2)} \left[ a_1 e^{-|\eta|^2/(2b_1^2)} - a_2 e^{-|\eta|^2/(2b_2^2)} \right] \]

\[ a_1 = 2108.05, \quad b_1 = 3.66935, \quad a_2 = 486.368, \quad b_2 = 1.19377 \]

Transversal momenta of jets

\[ p_{t_c} > 100 \text{ GeV} \quad p_{t_f} > 30 \text{ GeV} \]
\[-1 < \eta_c < 1 \quad 2 < \eta_f < 3 \]

- back-to-back peak in the plot on the right
Relative transversal momentum difference

\[ p_{tC} > 100 \text{ GeV} \quad p_{tf} > 30 \text{ GeV} \]
\[-1 < \eta_c < 1 \quad 2p_{tC} > 100 \text{ GeV} \]

- Nuclear medium is shuffling dijets from back-to-back configuration to less balanced configuration – effect increases with bigger constant \( K \) (bigger \( \hat{q} \))

\[ A_j = \frac{(p_{tc} - p_{tf})}{(p_{tc} + p_{tf})} \]
Rapidity and azimuthal angle distance

\[ p_{tc} > 100 \text{ GeV} \quad p_{tf} > 30 \text{ GeV} \]
\[ -1 < \eta_c < 1 \quad 2 < \eta_f < 3 \]

- Slow increase of medium suppression with \( \Delta \eta \)
- “re”-emergence of \( \Delta \phi \) dependence for low \( \Delta \phi \)
Summary and Outlook

- Implementation of nuclear medium effects into a HEF Monte Carlo program

Planned:
- More precise description for nucleus-nucleus collision (impact parameter dependence, event by event treatment, variable medium length)
- Inclusion of saturation effects
  - Complicates the factorization formula
- More precise treatment of the medium jet interactions
$R_{AA}(|y|) / R_{AA}(|y|<0.3)$, measured out to $|y| = \pm 2.7$

- visible $y$-dependence for $p_T > 300$ GeV jets

- interplay of (1) path length, (2) spectral shape, (3) flavor?
Improved TMD for dijets

High energy factorization and forward jets

\[
\frac{d\sigma_{SPS}^{P_1 P_2 \rightarrow dijets + X}}{dy_1 dy_2 dp_1 dp_2 d\Delta \phi} = \frac{p_{1t} p_{2t}}{8\pi^2 (x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/P_1}(x_1, \mu^2) |M_{a g \rightarrow cd}|^2 F_{g/P_2}(x_2, k_t^2) \frac{1}{1 + \delta_{cd}}
\]

can be used for estimates of saturation effects.

can be derived but no nonlinearities

Generalization but no possibility to calculate decorrelations since no kt in ME

Dominguez, Marquet, Xiao, Yuan '11

Application to differential distributions in d+Au
Stasto, Xiao, Yuan '11

\[
\frac{d\sigma^{pA \rightarrow cd X}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} x_1 f_{q/P}(x_1, \mu^2) \sum_{i=1}^{n} F^{(i)}_{ag} H^{(i)}_{ag \rightarrow cd} \frac{1}{1 + \delta_{cd}}
\]
Improved TMD for dijets
High energy factorization and forward jets

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

$$\frac{d\sigma}{d^2 P_t d^2 k_t d y_1 d y_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1, \mu^2) \sum_{i=1}^{2} K_{ag^* \rightarrow cd}^{(i)} \Phi_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}$$
Decorelations inclusive scenario forward-central

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

In DGLAP approach i.e 2 →2 + pdf one would get delta function

 Observable suggested to study BFKL effects  
Sabio-Vera, Schwensen '06

Studied also context of RHIC  
Albacete, Marquet '10

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

$3.2 < |y_2| < 4.7$

$|y_1| < 2.8$

Leading jets, no further requirement