Forward jets and saturation within High Energy Factorization

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Motivation & Plan

Motivation

One of the approaches to small x physics is High Energy Factorization (HEF) which relies on Unintegrated Gluon Densities (UGD).
Various configurations of forward jets are good tools to scan UGDs.

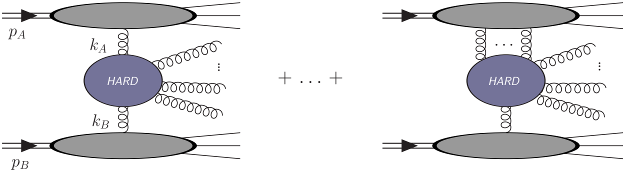
Plan

- High Energy Factorization
- Off-shell matrix elements (new tools)
- Saturation in forward dijets and trijets for p+p and p+Pb
- Scans of UGD for large off-shellnes
  - central-forward dijets $\Rightarrow$ good description of new CMS data!
    (see P. Cipriano and K. Kutak's devoted talk)
  - forward-central trijets and very forward jets using possible extension of CASTOR
- Outlook

High Energy Factorization

"Hybrid" high energy factorization formula relevant for forward jets

[e.g. M. Deak, F. Hautmann, H. Jung, K. Kutak, JHEP 0909 (2009) 121]



$$k_A = x_A p_A + k_{T\,A},\ k_A^2 = k_{T\,A}^2, \quad k_B = x_B p_B,\ k_B^2 = 0, \quad x_A \ll x_B$$

$$d\sigma_{AB\to X} = \int \frac{d^2 k_{T\,A}}{\pi} \int \frac{dx_A}{x_A} \int dx_B\, \mathcal{F}\left(x_A, k_{T\,A}, \mu\right) f_{b/B}\left(x_B, \mu\right) d\sigma_{g^* b\to X}\left(x_A, x_B, k_{T\,A}, \mu\right)$$

- collinear PDFs $f_{b/B}\left(x_B, \mu\right)$
- unintegrated gluon PDF $\mathcal{F}\left(x_A, k_{T\,A}, \mu\right)$
  the hard scale dependence is crucial to describe forward-central data
- off-shell gauge invariant tree-level matrix elements reside in $d\sigma_{g^* b\to X}$

★ In general k_T-factorization does not hold for hadron-hadron collisions.

Off-shell amplitudes

"Hybrid" HEF

Tree-level processes $g^* a \to X$, $a = g, q, \bar{q} \Rightarrow$ one off-shell leg

- not gauge invariant when calculated from ordinary Feynman rules (for arbitrary gauge and polarization vectors)
- the gauge invariant “extension” for arbitrary number of external on-shell gluons with arbitrary polarization vectors can be calculated recursively (suitable for helicity method)

  [A. van Hameren, P.K., K. Kutak, JHEP 1212 (2012) 029]

More off-shell legs

- Lipatov’s effective action and resulting Feynman rules (off-shell gluons ≡ reggeons R, in “hybrid” HEF we need $Rg \to X$)

  [E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135]
- embedding off-shell ampl. in a larger gauge invariant unphysical process (`fortran` codes by A. van Hameren for arbitrary particles; not public yet)

  [A. van Hameren, P.K., K. Kutak, JHEP 1301 (2013) 078]

  [A. van Hameren, K. Kutak, T. Salwa, Phys.Lett. B727 (2013) 226-233]
- matrix elements of straight infinite Wilson lines (automatic analytic calculation using `FORM` program `OGIME` – see next slide) [P.K., arXiv:1403.4824]

Off-shell amplitudes and Wilson lines

Off-shell gauge invariant amplitude $\tilde{\mathcal{M}}_{e_1\ldots e_n}(k_1,\ldots,k_n;X)$ for

$$g^*(k_1,e_1)\ldots g^*(k_n,e_n)\to X$$

where k_i, e_i are momentum and "polarization" vector of an off-shell gluon can be defined as [P.K. arXiv:1403.4824]

$$\langle 0|\,\mathfrak{R}^{c_1}_{e_1}(k_1)\ldots\mathfrak{R}^{c_n}_{e_n}(k_n)\,|X\rangle \overset{*}{=} \delta(k_1\cdot e_1)\ldots\delta(k_n\cdot e_n)$$
$$\delta^4(k_1+\ldots+k_n-X)\,\tilde{\mathcal{M}}_{e_1\ldots e_n}(k_1,\ldots,k_n;X)$$

where (almost-)infinite (almost-)straight Wilson lines are defined as

$$\mathfrak{R}^{c_i}_{e_i}(k_i)=\int d^4y\, e^{iy\cdot k_i}\,\mathrm{Tr}\left\{\frac{1}{\pi g}\,t^{c_i}\,\mathcal{P}\exp\left[ig\int_{-\infty}^{\infty}ds\,\frac{dz_\mu(s)}{ds}\,A^\mu_b(z)\,t^b\right]\right\}$$

where t^a are color generators and the path is parametrized as

$$z^\mu(s)=y^\mu+\frac{2}{\epsilon}\tanh\left(\frac{\epsilon s}{2}\right)e^\mu_X,\quad s\in(-\infty,\infty)$$

In the matrix element definition the limit $\epsilon\to 0$ is taken and only connected contributions are retained.

⋆ Used in `OGIME` = Off-shell Gauge Invariant Matrix Elements

Saturation in forward dijets (i)

We consider p+p and p+Pb collisions with two jets with $p_T > 20\,\mathtt{GeV}$ in the forward rapidity region $3.2 < y_1, y_2 < 4.9$.

[A. van Hameren, P.K., K. Kutak, C. Marquet, S. Sapeta, arXiv:1402.5065]

- highly asymmetric kinematics $x_A \ll x_B$, $x_A \sim 10^{-4} \div 10^{-5}$
- two UGDs incorporating saturation effects are used

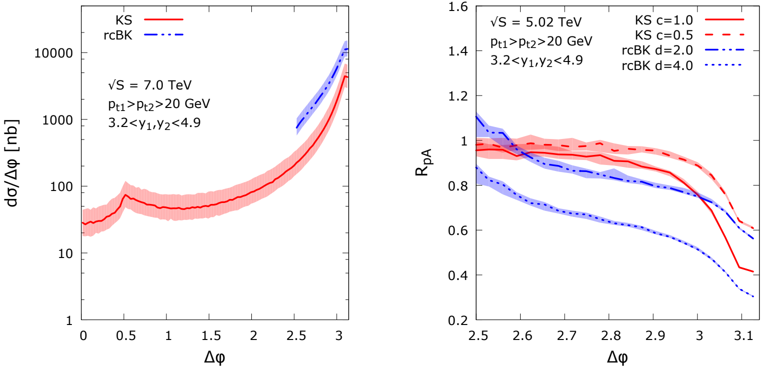
1. rcBK [J. L. Albacete, N. Armesto, J.G. Milhano, P. Quiroga-Arias, C.A. Salgado, Eur. Phys. J. C 71 (2011) 1705]
   Balitsky-Kovchegov (BK) equation in the momentum space with running coupling [I. Balitsky, G.A. Chirilli, Phys.Rev. D77, 014019 (2008)]
2. KS [K. Kutak, S. Sapeta, Phys.Rev. D86, 094043 (2012)]
   Kwieciński-Martin-Staśto (unified BFKL+DGLAP) with nonlinear BK term [K. Kutak, A. Stasto, Eur.Phys.J. C41, 343 (2005)]

- fitted to HERA data (for proton)
- for Pb either saturation scale is increased (rcBK) or nonlinear term is enhanced (KS)
- no hard scale dependence in UGD

★ See more on evolution equations in K. Kutak's talk

Saturation in forward dijets (ii)

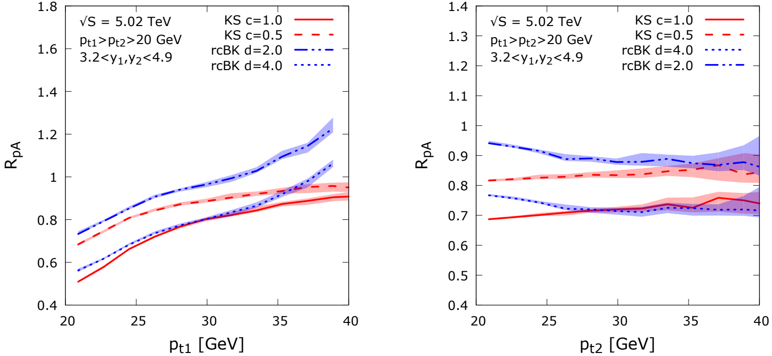
Azimuthal decorrelations



★ nuclear modification ratio (right), i.e. $d\sigma_{p\mathrm{Pb}}/d\sigma_{pp}$ shows strong suppression due to the saturation near back-to-back region

Saturation in forward dijets (iii)

Jet p_T spectra

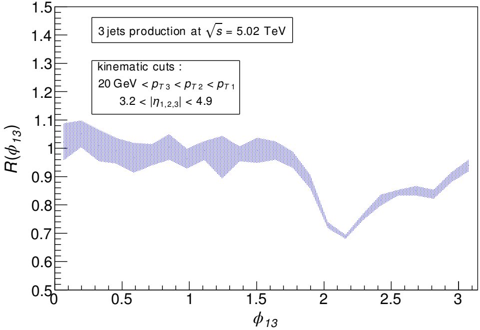


★ The subleading jet spectrum is more sensitive to saturation

Saturation in forward trijets

Azimuthal decorrelations between the leading and the softest jet

[A. van Hameren, P.K., K. Kutak, Phys.Rev. D88 (2013) 094001]



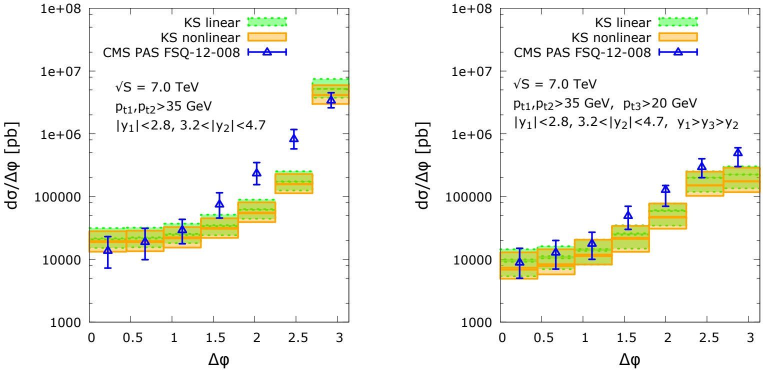
★ The suppression of the nuclear modification ratio remains strong

Scan of gluon densities for large k_T (i)

Saturation is important in the low-k_T region, but large-k_T is also very interesting.

Forward-central dijet decorrelations

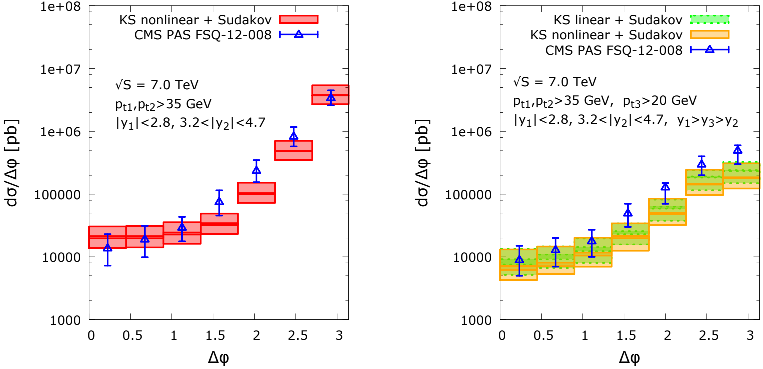
- new CMS data are available [CMS-PAS-FSQ-12-008] – see P. Cipriano's talk
- more events with k_T of the order of the hard scale is needed to describe the data within HEF [A. van Hameren, P.K., K. Kutak, S. Sapeta, arXiv:1404.6204]



Scan of gluon densities for large k_T (ii)

We enhance the large-k_T region using the "Sudakov resummation model"

- do not change the total cross section
- affect events with $k_T < \mu$ using the Sudakov form factor from the KMR [M. Kimber, A. D. Martin, and M. Ryskin, Phys.Rev. D63, 114027 (2001)], but do not affect events with $k_T > \mu$

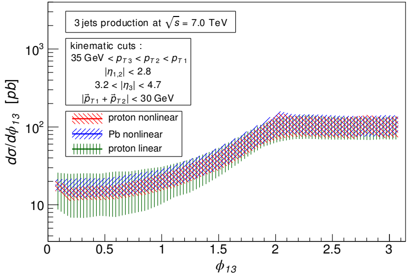


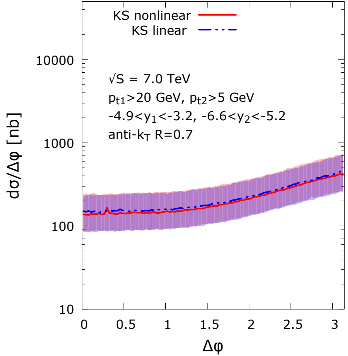
★ more theoretic study has to be done according to [A. Mueller, B.-W. Xiao, and F. Yuan, Phys.Rev.Lett. 110, 082301 (2013)]

Scan of gluon densities for large k_T (iii)

Other interesting observables sensitive to large-k_T region:

- forward-central trijet azimuthal decorrelations where two central jets are back-to-back-like
- forward-very forward dijet azimuthal decorrelations using possible upgrade of CASTOR





★ the more flat the distributions the more large-k_T emissions

Outlook

- usage of evolution equations with full hard scale dependence
  - CCFM (studied by M. Deak, K. Kutak, D. Toton; H. Jung, F. Hautmann)
  - KGBJS [K. Kutak, K. Golec-Biernat, S. Jadach, M. Skrzypek, JHEP 1202 (2012) 117]
    = CCFM + nonlinear term (studied by M. Deak, K. Kutak, D. Toton)
  - development of libraries for evolution equations (D. Toton)
- final state parton shower is still missing
- better understand factorization issues of the "hybrid" HEF
- NLO calculation for jets (possibly using dipole subtraction method for massive partons [P.K., W. Slominski, Phys.Rev. D86 (2012) 094008])
- calculations with off-shell quarks (A. van Hameren, K. Kutak)

My programs:

- `LxJet` [http://annapurna.ifj.edu.pl/~pkotko/LxJet.html] – Monte Carlo C++ program capable of doing presented calculations (the "Sudakov resummation model" is not public yet)
- `OGIME` [http://annapurna.ifj.edu.pl/~pkotko/OGIME.html] – FORM program for analytic calculation of gluonic matrix elements of straight infinite Wilson lines

Backup

Off-shell Multigluon Amplitude

Color ordered result for $g^* g \to g \ldots g$

$$\widetilde{\mathcal{A}}(\varepsilon_1, \ldots, \varepsilon_N) = -\left|\vec{k}_{TA}\right| \Bigg[k_{TA} \cdot J(\varepsilon_1, \ldots, \varepsilon_N) + \left(\frac{-g}{\sqrt{2}}\right)^N \frac{\varepsilon_1 \cdot p_A \ldots \varepsilon_N \cdot p_A}{k_1 \cdot p_A \; (k_1 - k_2) \cdot p_A \ldots (k_1 - \ldots - k_{N-1}) \cdot p_A} \Bigg]$$

where

$$J^\mu(\varepsilon_1, \ldots, \varepsilon_N) = \frac{-i}{k_{1N}^2} \left(g^\mu_\nu - \frac{k^\mu_{1N} p_{A,\nu} + k_{1N\nu} p^\mu_A}{k_{1N} \cdot p_A} \right) \Bigg\{ \sum_{i=1}^{N-1} V_3^{\nu\alpha\beta}\left(k_{1i}, k_{(i+1)N}\right) J_\alpha(\varepsilon_1, \ldots, \varepsilon_i) J_\beta(\varepsilon_{i+1}, \ldots, \varepsilon_N) + \sum_{i=1}^{N-2} \sum_{j=i+1}^{N-1} V_4^{\nu\alpha\beta\gamma} J_\alpha(\varepsilon_1, \ldots, \varepsilon_i) J_\beta\left(\varepsilon_{i+1}, \ldots, \varepsilon_j\right) J_\gamma\left(\varepsilon_{j+1}, \ldots, \varepsilon_N\right) \Bigg\}$$

where $k_{ij} = k_i + k_{i+1} + \ldots + k_j$, V_3 and V_4 are three and four-gluon vertices.

The red piece was obtained using the Slavnov-Taylor identities and correspond to bremsstrahlung from the straight infinite Wilson line along p_A (in axial gauge).

[1] A. van Hameren, P. Kotko, K. Kutak, JHEP 1212 (2012) 029