Forward jets and saturation within high energy factorization

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PLAN

- Motivation
- Framework
  - “hybrid” high energy factorization
  - off-shell matrix elements
  - unintegrated gluon density
- Results: three jet production in p-p and p-Pb
  - forward-central rapidity region
  - purely forward jets
- Summary and future plans

Motivation

Studies of small x "unintegrated" gluon densities in more exclusive observables

Different evolution scenarios

- BFKL
- KMS (Kwieciński-Martin-Staśto) = BFKL + DGLAP unified framework
- BK (Balitsky-Kovchegov) $\Rightarrow$ saturation
- KS (Kutak-Staśto) = BK + DGLAP
- CCFM
- KGBJS (Kutak-Golec-Biernat-Jadach-Skrzypek) = CCFM + nonlinear term

Some of them may be applied to heavy ions.

- relevant observables $\Rightarrow$ forward jets
- three jets

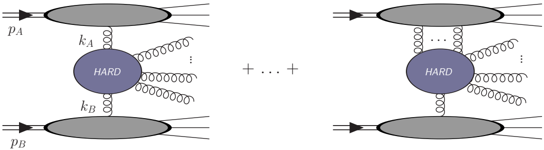
$\rightarrow$ very exclusive
$\rightarrow$ test high energy factorization for larger multiplicities
$\rightarrow$ test tools we have developed
$\rightarrow$ give (crude) predictions for LHC

Framework

Framework

"Hybrid" high energy factorization formula[1,2]

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



$$k_A^\mu = x_A p_A^\mu + k_{T\,A}^\mu, \qquad k_B^\mu = x_B p_B^\mu + k_{T\,B}^\mu \sim x_B p_B, \quad x_A \ll x_B$$

- collinear PDFs $f_{b/B}(x_B,\mu)$
- unintegrated gluon PDF $\mathcal{F}(x_A, k_{T\,A})$
- off-shell gauge invariant tree-level matrix element resides in $d\sigma_{g^* b\to X}$

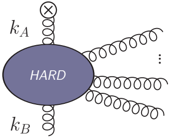
Implemented in MC codes: C++ code `LxJet` (dijets, trijets), `fortran` code of A. van Hameren (any process) – OSCARS (Off-shell Currents And Related Stuff))

★ in general TMD factorization does not hold for hadron-hadron collisions, but here just single TMD PDF $\Rightarrow$ needs more study

[1] S. Catani, M. Ciafaloni, F. Hautmann, Nucl.Phys. B366 (1991) 135-188
[2] M. Deak, F. Hautmann, H. Jung, K. Kutak, JHEP 0909 (2009) 121

Framework: off-shell amplitudes

One-leg off-shell high-energy amplitudes



$+$ terms needed to maintain gauge invariance

eikonal coupling:  $= |\vec{k}_{T\,A}|\, p_A^\mu$

- basic approach: Lipatov's effective action and resulting Feynman rules[1]
- one can also find the lacking contributions without extending QCD action (suitable for automatic calculation)

$\rightarrow$ by embedding in a larger non-physical process; also for two off-shell legs and off-shell quarks $\Rightarrow$ very general and powerful[2]

$\rightarrow$ using the Slavnov-Taylor identities (only one off-shell gluon)[3]

$\rightarrow$ using matrix elements of straight infinite Wilson lines (arbitrary number of off-shell gluons)

[1] E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135

[2] A. van Hameren, P. Kotko, K. Kutak, JHEP 1301 (2013) 078; A. van Hameren, K. Kutak, T. Salva, arXiv:1308.2861

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

Framework: unintegrated gluon densities

- in the high-energy factorization originally BFKL gluon evolution was used
  $\Rightarrow$ why not to try to include more subtle effects relevant to small x?
- nonlinear evolution with saturation[1,2] fitted to HERA data[3]

$$\mathcal{F}\left(x,k_T^2\right)=\mathcal{F}_0\left(x,k_T^2\right)+\frac{\alpha_s N_c}{\pi}\int_x^1\frac{dz}{z}\int_{k_{T0}^2}^{\infty}\frac{dq_T^2}{q_T^2}\left\{\frac{q_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)\theta\left(\frac{k_T^2}{z}-q_T^2\right)-k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\left|q_T^2-k_T^2\right|}+\frac{k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\sqrt{4q_T^4+k_T^4}}\right\}$$
$$+\frac{\alpha_s}{2\pi k_T^2}\int_x^1 dz\left\{\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_{T0}^2}^{k_T^2}dq_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)+zP_{gq}(z)\,\Sigma\left(\frac{x}{z},k_T^2\right)\right\}$$
$$-\frac{2\alpha_s^2}{R^2}\left\{\left[\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\mathcal{F}\left(x,q_T^2\right)\right]^2+\mathcal{F}\left(x,k_T^2\right)\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\ln\left(\frac{q_T^2}{k_T^2}\right)\mathcal{F}\left(x,q_T^2\right)\right\}$$

$\rightarrow$ includes kinematic constraints
$\rightarrow$ includes non-singular pieces of the splitting functions
$\rightarrow$ the coupling is running
$\rightarrow$ the parameter R has an interpretation of a target radius
  $\Rightarrow$ one may attempt to use it for nuclei[3]

[1] K. Kutak, J. Kwiecinski, Eur.Phys.J. C29, 521 (2003)
[2] K. Kutak, A. Stasto, Eur.Phys.J. C41, 343 (2005)
[3] K. Kutak, S. Sapeta, Phys.Rev. D86, 094043 (2012)

Results

Results: process definition and cuts

Basic setup:

- p-p and p-Pb collisions
- CM energy $5\,\mathrm{TeV}$ and $7\,\mathrm{TeV}$
- $p_{T\,1} > p_{T\,2} > p_{T\,3} > p_{T\,\mathrm{cut}}$
- anti-k_T clustering with $R = 0.5$
- collinear PDF $\Rightarrow$ CTEQ10 NLO set, scale choice $\mu = a\,(E_1 + E_2 + E_3)$, where the variation of a gives the (large) theoretical uncertainty
- calculations are made and cross-checked using `LxJet` and `OSCARS`

Two scenarios:

1. central-forward jets

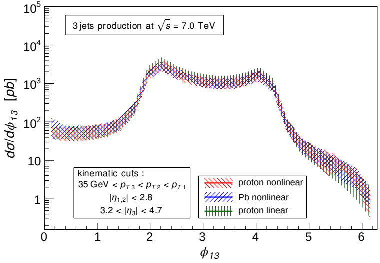
   $\rightarrow$ two leading jets are in the central region with $\left|\eta_{1,2}\right| < 2.8$
   $\rightarrow$ the softest jet is in the forward region $3.2 < \eta_3 < 4.7$
   $\rightarrow$ $p_{T\,\mathrm{cut}} = 35\,\mathrm{GeV}$
   $\rightarrow$ we may restrict additional cuts on the central jets, e.g. $\left|\vec{p}_{T\,1} + \vec{p}_{T\,2}\right| < D_{\mathrm{cut}}$

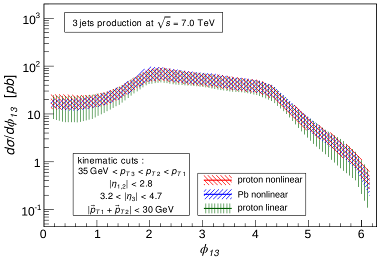
2. purely forward jets

   $\rightarrow$ all the jets are in the forward region $3.2 < \eta_{1,2,3} < 4.9$
   $\rightarrow$ $p_{T\,\mathrm{cut}} = 20\,\mathrm{GeV}$

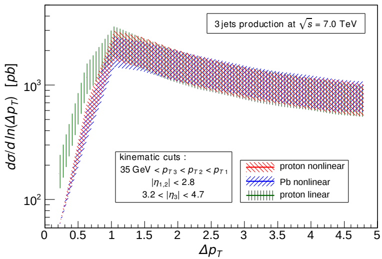
Results: forward-central three jet production

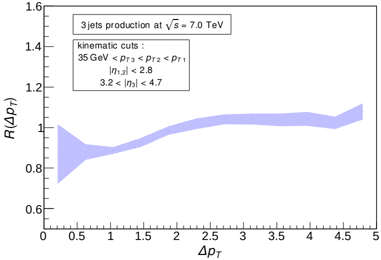
- decorrelations ($\phi_{13} = |\phi_1 - \phi_3|$)





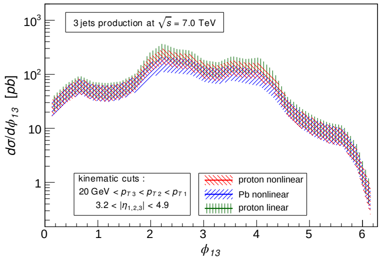
- unbalanced p_T of the jets

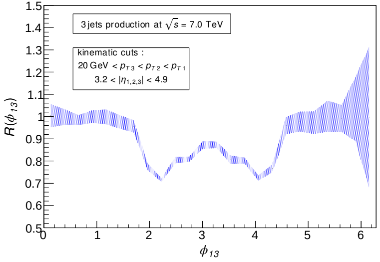




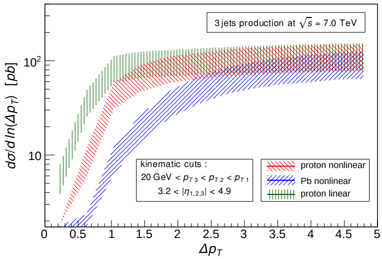
Applications: forward three jet production

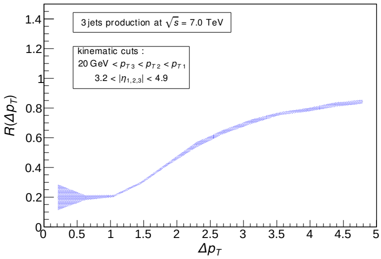
- decorrelations ($\phi_{13} = |\phi_1 - \phi_3|$)





- unbalanced p_T of the jets





Summary and outline

- three jets at the LHC using off-shell gauge invariant tree-level matrix elements and and gluon unintegrated densities relevant for larger p_T

  $\rightarrow$ the forward-central setup with $p_{T\,\mathrm{cut}} = 35\,\mathrm{GeV}$ does not discriminate between different evolutions, although additional restrictions on the central jets may do so

  $\rightarrow$ the purely forward jets with $p_{T\,\mathrm{cut}} = 20\,\mathrm{GeV}$ are sensitive to saturation; in particular there is a strong suppression of the nuclear modification ratio

- calculations were performed using new MC codes: `LxJet`[1] (C++, ROOT, FOAM) and `OSCARS` (`fortran` code similar to `HELAC`)

Future developments:

- final state parton shower (our programs – event generators)
- NLO jets within "hybrid" high energy factorization (possibility of use dipole subtraction method for massive Aivazis-Collins-Olness-Tung factorization[2])
- nonlinear extension of CCFM evolution equation[3]
- MPIs

[1] http://annapurna.ifj.edu.pl/~pkotko/LxJet.html
[2] P. Kotko, W. Slominski, Phys.Rev. D86 (2012) 094008
[3] K. Kutak JHEP 1212 (2012) 033, solution currently investigated by D. Toton

Backup

Small x and forward processes

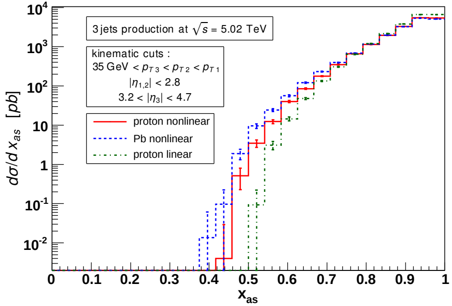
Forward processes (relevant for small x) correspond to asymmetric configurations

$$x_A = \sum_i \frac{|\vec{p}_{T\,i}|}{\sqrt{S}} \exp(\eta_i)$$

$$x_B = \sum_i \frac{|\vec{p}_{T\,i}|}{\sqrt{S}} \exp(-\eta_i)$$

$$x_{as} = |x_A - x_B| \,/\, (x_A + x_B)$$

central-forward three jet production



This accounts for a simplification:

- large fractions $x_B \rightarrow$ collinear approach (with on-shell partons)
- small fractions $x_A \rightarrow$ high energy factorization (with an off-shell gluon)

Framework: off-shell amplitudes

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

$$\widetilde{\mathcal{A}}(\varepsilon_1, \ldots, \varepsilon_N) = -\left|\vec{k}_{TA}\right| \left[k_{TA} \cdot J(\varepsilon_1, \ldots, \varepsilon_N) \right.$$

$$\left. + \left(\frac{-g}{\sqrt{2}}\right)^N \frac{\varepsilon_1 \cdot p_A \ldots \varepsilon_N \cdot p_A}{k_1 \cdot p_A \; (k_1 - k_2) \cdot p_A \ldots (k_1 - \ldots - k_{N-1}) \cdot p_A} \right]$$

where

$$J^\mu(\varepsilon_1, \ldots, \varepsilon_N) = \frac{-i}{k_{1N}^2} \left(g^\mu_\nu - \frac{k^\mu_{1N} p_{A,\nu} + k_{1N\,\nu} p^\mu_A}{k_{1N} \cdot p_A} \right)$$

$$\left\{ \sum_{i=1}^{N-1} V_3^{\nu\alpha\beta}\left(k_{1i}, k_{(i+1)N}\right) J_\alpha(\varepsilon_1, \ldots, \varepsilon_i) J_\beta(\varepsilon_{i+1}, \ldots, \varepsilon_N) \right.$$

$$\left. + \sum_{i=1}^{N-2} \sum_{j=i+1}^{N-1} V_4^{\nu\alpha\beta\gamma} J_\alpha(\varepsilon_1, \ldots, \varepsilon_i) J_\beta\left(\varepsilon_{i+1}, \ldots, \varepsilon_j\right) J_\gamma\left(\varepsilon_{j+1}, \ldots, \varepsilon_N\right) \right\}$$

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