New results on forward jets within High Energy Factorization

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in collaboration with
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supported by:
LIDER/02/35/L-2/10/NCBiR/2011
DEC-2011/01/B/ST2/03643
DE-FG02-93ER40771

Outline

Summary of our activity in the subject of High Energy Factorization

Studies of gauge invariant off-shell matrix elements:
- [A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029]
- [A. van Hameren, PK, K. Kutak, JHEP 1301 (2013) 078]
- [A. van Hameren, K. Kutak, T. Salwa, Phys.Lett. B727 (2013) 226-233]
- [A. van Hameren, JHEP 1407 (2014) 138]
- [PK, JHEP 1407 (2014) 128]

Computer programs:
- A. van Hameren, `OSCARS` (Off-Shell Currents And Related Stuff) (MC `FORTRAN` code)
- PK, LxJet (MC C++ code)
- S. Sapeta, `forward` (MC C++ code)
- PK, `OGIME` (Off-Shell Gauge Invariant Matrix Elements), (`FORM` code for analytic off-shell MEs)

Applications:
- [A. van Hameren, PK, K. Kutak, Phys.Rev. D88, 094001 (2013)] (three-jet production)
- [A. van Hameren, PK, K. Kutak, C. Marquet, S. Sapeta, Phys.Rev. D89, 094014 (2014)] (saturation in forward-forward dijets)
- [K. Kutak, arXiv:1409.3822] (forward-forward dijets with new unintegrated gluon densities)
- [A. van Hameren, PK, K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340] (forward-central dijets, comparison with data)
- [A. van Hameren, PK, K. Kutak, in preparation] (Z_0+jet production, comparison with data)

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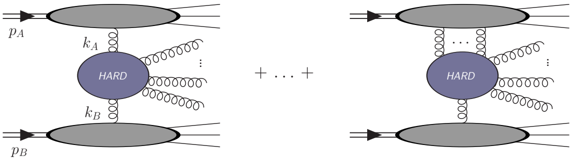
Hybrid High Energy Factorization (HEF)

Forward particle production

- one of the protons is probed at large $x = x_B \Rightarrow$ we assume that it is probed near the mass-shell and the collinear factorization applies for that proton
- the other proton is probed at small $x_A \ll x_B$ and k_T-factorization applies

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



$$k_A = x_A p_A + k_{T\,A},\; k_A^2 \neq 0$$

$$k_B = x_B p_B,\; k_B^2 = 0$$

$$x_A \ll x_B$$

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

- collinear PDFs $f_{b/B}\left(x_B, \mu\right)$
- unintegrated gluon density (UGD) $\mathcal{F}\left(x_A, k_{T\,A}, \mu\right)$
- 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 and Wilson lines

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

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

where k_i, e_i are momentum and "polarization" vector of an off-shell gluon can be defined as [PK, JHEP 1407 (2014) 128]

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

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

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

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

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

In the matrix element definition the limit $\epsilon \to 0$ is assumed.

$\tilde{\mathcal{M}}_{e_1 \dots e_n}(k_1, \dots, k_n; X)$ satisfies Ward identities.

Off-shell amplitudes and Wilson lines (cont.)

Comments:

- Used in `OGIME` = Off-shell Gauge Invariant Matrix Elements, program written in `FORM` (an open source symbolic manipulation system by J. Vermaseren)
  - version available to public is for gluons only
  - fermions and electroweak bosons are added (under development, some MEs already used for Z_0+jet)
  - agrees with off-shell amplitudes from BCFW recursion of A. van Hameren (see his talk today)
- "polarization" vectors are arbitrary vectors transverse to momenta $\Rightarrow$ wide applications
  - small x physics; we recover reggeized gluon amplitudes constructed e.g. from the Lipatov's effective action
    [E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135]
  - gauge invariant decompositions of QCD amplitudes (not fully explored yet)
  - Light Front Perturbation Theory (LFPT); Wilson line approach can give an interpretation to certain recursive relations for amplitudes obtained in LFPT
    [C.A. Cruz-Santiago, A. Stasto, Nucl.Phys. B875 (2013) 368-387]
    [L. Motyka, A. Stasto, Phys.Rev. D79 (2009) 085016]

Unintegrated Gluon Densities (UGDs)

UGDs we have used in our calculations:

- KS (unified BFKL+DGLAP with nonlinear term; fitted to HERA data by K. Kutak and S. Sapeta)

  [K. Kutak, A. Stasto, Eur.Phys.J. C41, 343 (2005)]
  [K. Kutak, S. Sapeta, Phys.Rev. D86, 094043 (2012)]

  no hard scale dependence ⇒ relevant mainly for saturation physics

- KS+Sudakov (hard scale dependence implemented into KS via the Sudakov form factor in such a way that the total cross section does not change)

  [A. van Hameren, PK, K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340]

- KSmu (hard scale dependence implemented into KS via the Sudakov form factor in such a way that the integrated gluon density does not change)

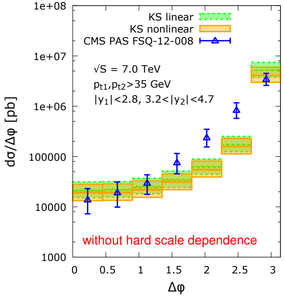
  [K. Kutak, arXiv:1409.3822]

- KMR (obtains unintegrated density from collinear PDFs)

  [M. Kimber, A. D. Martin, and M. Ryskin, Phys.Rev. D63, 114027 (2001)]

Forward-central dijet decorrelations at LHC

Inclusive dijets with the veto on the third jet



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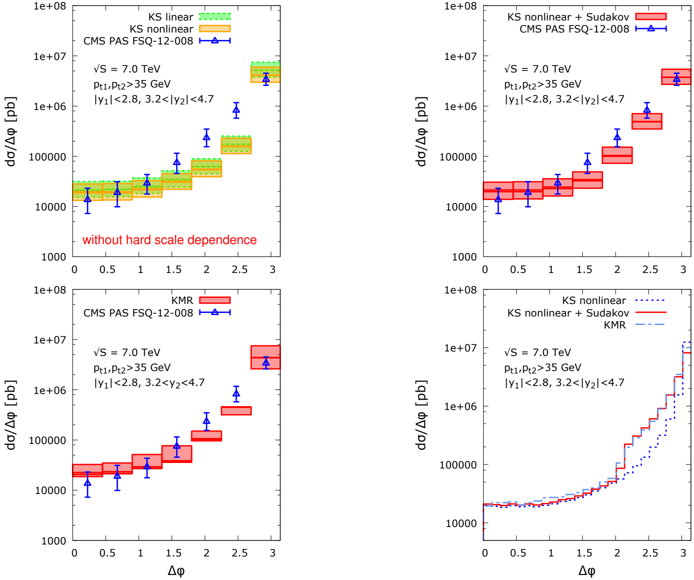
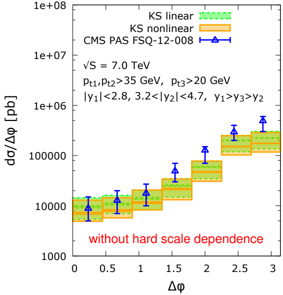
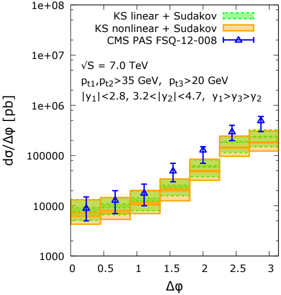


Forward-central dijet decorrelations at LHC (cont.)

Dijets with the inside-jet tag



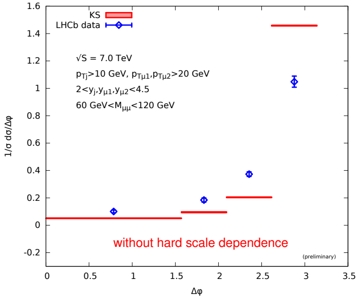


Comments:

- hard scale dependence is important for the veto case (previous slide)
- no MPIs needed for this observable (within HEF)

Forward Z_0+jet production at LHC

Azimuthal decorrelations between Z_0 and jet



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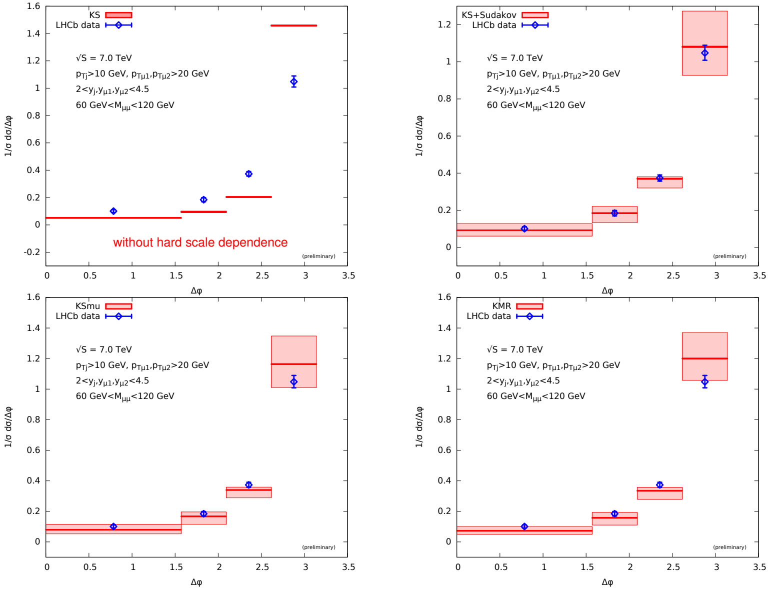
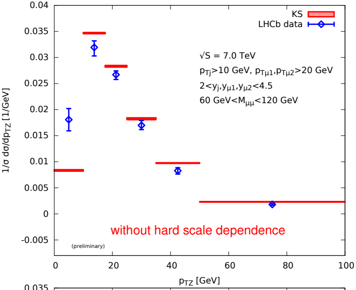
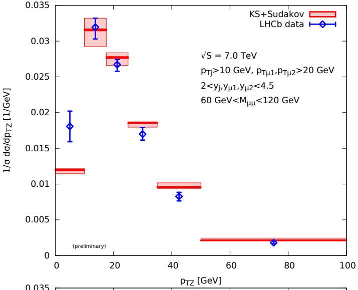
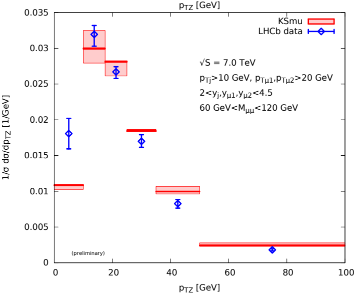


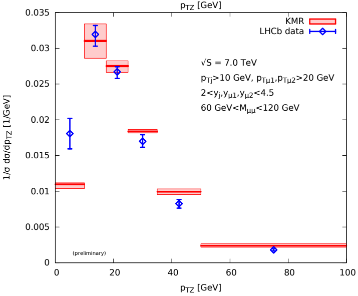
Forward Z_0+jet production at LHC (cont.)

p_T spectra of Z_0 boson









Forward Z_0+jet production at LHC (cont.)

Comments:

- hard scale dependence of UGDs is crucial
- good description for normalized distributions
- we get approx. two times smaller total cross section ⇒ DPS is important (but gives only the pedestal for the decorrelations)
- only $g^* q \to q\mu^+\mu^-$, $g^* \overline{q} \to \overline{q}\mu^+\mu^-$ MEs included (off-shell quarks may give contribution here)

Summary

- new results for forward jets at LHC within High Energy Factorization have been presented:
  - forward-central jets (compared with CMS data)
  - forward Z_0+jet production (compared with LHCb data)
- hard scale dependence of unintegrated gluon densities is crucial
- MPIs are needed in the purely forward region

Future plans:

- final state parton shower is still missing
- calculations with off-shell quarks
- NLO calculation for jets (possibly using dipole subtraction method for massive partons [PK, W. Slominski, Phys.Rev. D86 (2012) 094008])
- better understand factorization issues of the "hybrid" HEF

My programs:

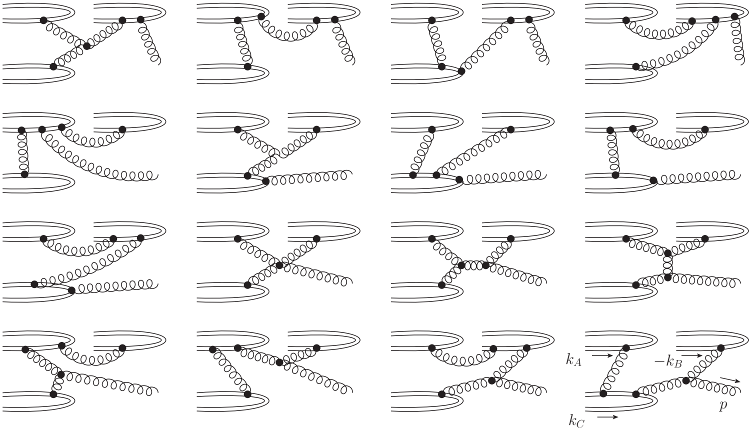
- `LxJet` [http://annapurna.ifj.edu.pl/~pkotko/LxJet.html] – MC C++ program for HEF (online version lacks the "Sudakov resummation model" and electroweak off-shell MEs)
- `OGIME` [http://annapurna.ifj.edu.pl/~pkotko/OGIME.html] – FORM program for analytic calculation of tree matrix elements of straight infinite Wilson lines

Backup

Example for ME of Wilson lines

Consider example: $g^*(k_A, e_A)\, g^*(k_C, e_C) \to g^*(k_B, e_B)\, g(p)$

There are 16 color-ordered (for simplicity) diagrams:



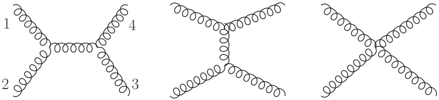
For $e_A, e_B, e_C \in \{n_+, n_-\}$ some of the diagrams vanish and the result is consistent with *RRRg* Lipatov's vertex

[M.A. Braun, M.Yu. Salykin, S.S. Pozdnyakov, M.I. Vyazovsky, Eur.Phys.J. C72 (2012) 2223]

Gauge invariant decompositions

Our off-shell amplitudes are defined for any “polarization vectors”. This allows to use them outside high-energy physics.

For example, consider a standard color-ordered four gluon amplitude



$$\mathcal{M}^{(1234)} = J_\mu^{(12)} \frac{ig^{\mu\nu}}{k_{12}^2} J_\nu^{(34)} + J_\mu^{(41)} \frac{ig^{\mu\nu}}{k_{14}^2} J_\nu^{(23)} + iV_4^{(1234)}$$

It is possible to write this amplitude in a manifestly gauge invariant way

$$\mathcal{M}^{(1,2,3,4)} = i\left(k_{12}^2\, \tilde{J}^{(1,2)} \cdot \tilde{J}^{(3,4)} + k_{14}^2\, \tilde{J}^{(4,1)} \cdot \tilde{J}^{(2,3)} + \tilde{V}_4^{(1,2,3,4)}\right)$$

where

$$\tilde{J}^{(ab)} \cdot \tilde{J}^{(cd)} = \sum_{i=0}^{2} \tilde{J}_i^{(ab)} \tilde{J}_i^{(cd)} d_i, \qquad \tilde{J}_i\left(\varepsilon_1, \varepsilon_2; k_{12}\right) \stackrel{*}{=} \langle k_1, \varepsilon_1; k_2, \varepsilon_2 | \mathcal{R}_{\epsilon_i}\left(k_{12}\right)|0\rangle$$

and $k \cdot \epsilon_i(k) = 0$, $\epsilon_i(k) \cdot \epsilon_j(k) = d_i(k)\,\delta_{ij}$, $d_0(k) = \pm 1$, $d_1(k) = d_2(k) = -1$,
$\sum_{i=0}^{2} \epsilon_i^{\nu}(k)\, \epsilon_i^{\mu}(k)\, d_i(k) = g^{\mu\nu} - k^\mu k^\nu / k^2$.

Off-shell Multigluon Amplitude

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

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

where

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

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