Semi-hard reactions at the Forward Physics Facility

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in collaboration with
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Outline

BFKL resummation

Semi-hard sector

Conclusions

BFKL resummation

What is the BFKL resummation?

- The Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach is the general framework for the resummation of energy-type logarithms
  - Leading-logarithm-Approximation (LLA): $(\alpha_s \ln s)^n$
  - Next-to-leading-logarithm-Approximation (NLLA): $\alpha_s(\alpha_s \ln s)^n$

In which contexts can BFKL approach be applied?

- Semi-hard collision processes, featuring the scale hierarchy

$$s \gg Q^2 \gg \Lambda^2_{\rm QCD}, \qquad Q^2 \text{ a hard scale}$$

$$\alpha_s(Q^2)\ \ln\left(\frac{s}{Q^2}\right) \sim 1 \implies \text{all-order resummation needed}$$

- UGDs sector $\leftarrow$ [***Talk by F. Celiberto***]
  The evolution of the unintegrated gluon density

$$\mathcal{F}(x,\vec{k}) \quad \text{t.c.} \quad f^g(x,Q^2) = \int \frac{d^2\vec{k}}{\pi \vec{k}^2}\mathcal{F}(x,\vec{k})\theta(Q^2-\vec{k}^2)$$

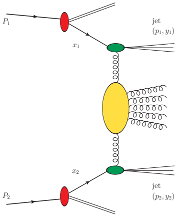
  as a function of $\ln(1/x) = \ln(s/Q^2)$, is governed by BFKL:

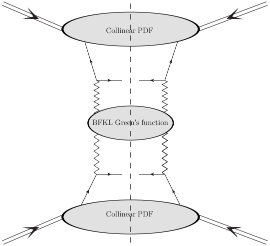
$$\frac{\partial \mathcal{F}}{\partial \ln(1/x)} = \mathcal{F} \otimes \mathcal{K}$$

Hybrid collinear/high-energy factorization

Mueller-Navelet jets

- Inclusive two jet production in proton-proton collision
- Large p_T and large rapidity separation
- Large energy logarithms $\rightarrow$ BFKL resummed partonic cross section
- Moderate values of parton x $\rightarrow$ collinear PDFs

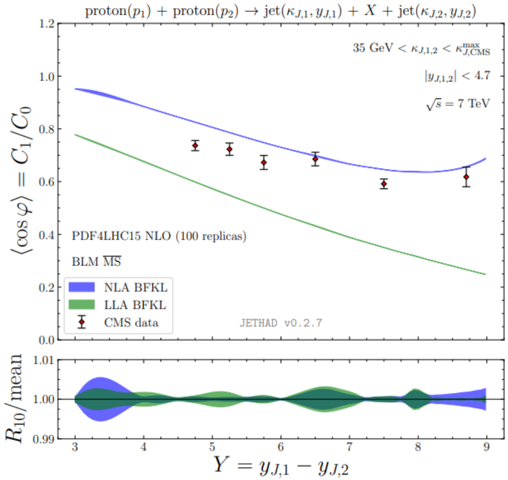




$$\frac{d\sigma_{pp}}{dy_Q\, dy_J\, d|\vec{p}_Q|\, d|\vec{p}_J|\, d\phi_1\, d\phi_2} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + 2\sum_{n=1}^{\infty}\cos(n\phi)\mathcal{C}_n\right]$$

- **Hybrid** formalism: can be extended to several type of semi-hard reactions

Muller-Navelet: Theory vs Experiment



[B. Ducloué, L. Szymanowski, S. Wallon (2013)]

[F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa (2014)]

In this slide: [F. Celiberto (2021)]

Mueller-Navelet: Theory vs Experiment

- CMS **@**7Tev with symmetric p_T-ragens, only!

  [CMS collaboration (2016)]

- LHC kinematic **domain** in between the sectors described by BFKL and DGLAP approaches
- Clearer manifestation of high-energy signatures expected at increasing energies (higher hadronic center-of-mass energy or higher rapidity difference between tagged jets)
- Need for more exclusive final states as well as more sensitive observables

- Strong manifestation of higher-order **instabilities** via scale variation

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NLA BFKL corrections to cross section with opposite sign with respect to the leading order (LO) result and large in absolute value...

◇ ...call for some optimization procedure...

◇ ...choose scales to mimic the most relevant subleading terms

- BLM [S.J. Brodsky, G.P. Lepage, P.B. Mackenzie (1983)]
  - ✓ preserve the conformal invariance of an observable...
  - ✓ ...by making vanish its β_0-dependent part

* "Exact" BLM:

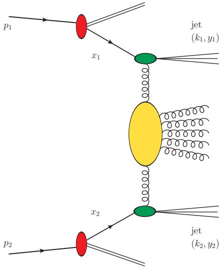
suppress NLO IFs + NLO Kernel β_0-dependent factors

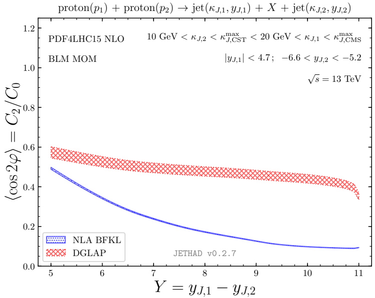
- BFKL vs High-energy DGLAP

[F.G. Celiberto, D. Yu. Ivanov, B. Murdaca, A. Papa (2015)]

[F.G. Celiberto (2020)]

  - NLA BFKL expression for the observables truncated to $O(\alpha_s^3)$
  - Investigated process: Mueller-Navelet jets production, Inclusive di-hadron production, Inclusive hadron-jet production
  - Asymmetric p_T-ranges in order to suppress the Born contribution to the cross-section C_0 (back-to-back).





- Main outcome
"Disjoint intervals for the transverse momenta of the emitted objects allow for a better discrimination of high energy effects"

Heavy-quark hadroproduction: Open states

- LO Heavy-quark pair hadroproduction

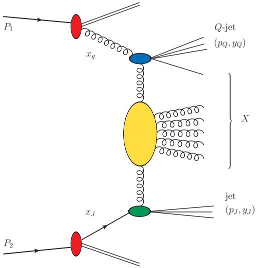
  [A.D. Bolognino, F.G. Celiberto, M.F., D.Yu. Ivanov, A. Papa (2019)]

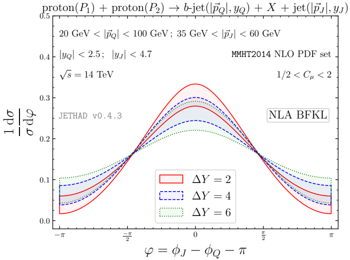
- Heavy-light dijet system

  [A.D. Bolognino, F.G. Celiberto, M.F., D.Yu. Ivanov, A. Papa (2021)]

  - LO heavy-quark impact factor (plus NLO universal corrections)
  - NLA BFKL Green function
  - NLO jet impact factor

$$\frac{d\sigma_{pp}(\varphi,\Delta Y,s)}{\sigma_{pp}d\varphi}=\frac{1}{\pi}\left\{\frac{1}{2}+\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}\equiv\frac{1}{\pi}\left\{\frac{1}{2}+\sum_{n=1}^{\infty}\cos(n\varphi)\frac{C_n}{C_0}\right\}$$





- Λ_c-baryon hadroproduction (VFNS)

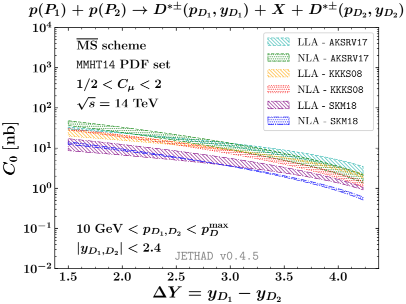
  [F.G. Celiberto, M.F., D.Yu. Ivanov, A. Papa (2021, submitted)]
- Double D-meson hadroproduction (VFNS vs FFNS)

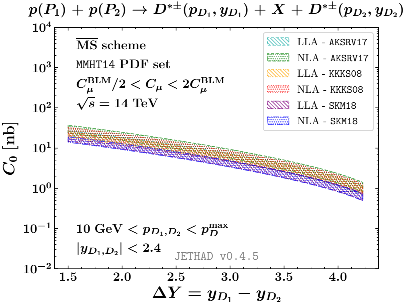
  [F.G. Celiberto, M. Di Pace, M.F., D.Yu. Ivanov, A. Papa (in progress)]

  - LO heavy-quark impact factor (plus NLO universal corrections) in FFNS
  - NLO light parton impact factor in VFNS
  - NLA BFKL Green function

$$C_0(\Delta Y, s) = \int_{p_Q^{\rm min}}^{p_Q^{\rm max}} d|\vec{p}_Q| \int_{p_J^{\rm min}}^{p_J^{\rm max}} d|\vec{p}_J| \int_{y_Q^{\rm min}}^{y_Q^{\rm max}} dy_Q \int_{y_J^{\rm min}}^{y_J^{\rm max}} dy_J \, \delta\left(y_Q - y_J - \Delta Y\right) \, \mathcal{C}_0$$

Preliminary

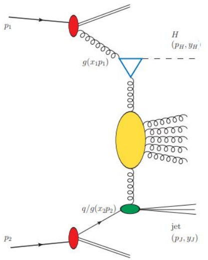


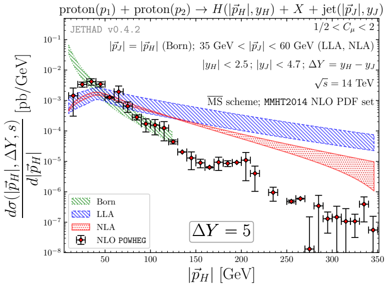


- Higgs + Jet hadroproduction
  - LO Higgs impact factor (plus NLO universal corrections)
  - NLA BFKL Green function
  - NLO jet impact factor

  [F.G. Celiberto, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2021)]

$$\frac{d\sigma\left(|\vec{p}_T|, \Delta Y, s\right)}{d|\vec{p}_T| d\Delta Y} = \int_{p_J^{min}}^{p_J^{max}} d|\vec{p}_J| \int_{y_H^{min}}^{y_H^{max}} dy_H \int_{y_J^{min}}^{y_J^{max}} dy_J \, \delta\left(y_H - y_J - \Delta Y\right) C_0$$





- Full NLO treatment (infinite top mass limit)

  [F.G. Celiberto, M.F, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (in progress)]
- Main outcome

  "Distributions in the production of Higgs, Heavy-quark jet and bound states show a stabilization under higher order corrections"

Conclusions

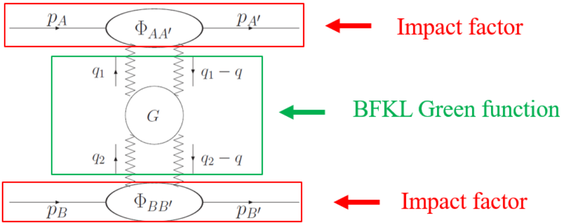
- The BFKL approach is an essential tool to study semi-hard reactions
- No less important is the possibility of using BFKL as a tool to increase our knowledge of other sectors of QCD:
  - Comparison and interpolation between DGLAP and BFKL (BFKL vs high energy DGLAP, collinear improvement, CCFM approach, ABF approach)
  - Understanding of the hadronic structure (PDFs and TMDs physics)
  - Investigation of a new class of interesting processes (Higgs sector, Heavy-flavor physics, Quarkonia)
- Experimental analyses at a **Forward Physics Facility** could significantly advance our knowledge of the high-energy regime of QCD

Thank you for the attention

Backup

BFKL resummation

- Diffusion $A + B \longrightarrow A' + B'$ in the Regge kinematical region
- Gluon Reggeization
- BFKL factorization for $\Im \mathcal{A}_{AB}^{A'B'}$: convolution of a Green function (process independent) with the Impact factors of the colliding particles (process dependent).



$$\Im \mathcal{A}_{AB}^{A'B'} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2} q_1}{\vec{q}_1^{\,2} (\vec{q}_1 - \vec{q}\,)^2} \frac{d^{D-2} q_2}{\vec{q}_2^{\,2} (\vec{q}_2 - \vec{q}\,)^2}$$
$$\times \sum_{\nu} \Phi_{A'A}^{(R,\nu)}(\vec{q}_1, \vec{q}, s_0) \int \frac{d\omega}{2\pi i} \left[\left(\frac{s}{s_0} \right)^{\omega} G_{\omega}^{(R)}(\vec{q}_1, \vec{q}_2; \vec{q}\,) \right] \Phi_{B'B}^{(R,\nu)}(-\vec{q}_2, \vec{q}, s_0)$$

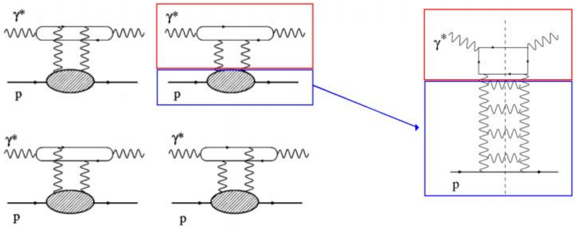
UGDs sector

- k_t-factorization (or small-x factorization)
  1. Inclusive or exclusive processes
  2. Small-x, large-k_T
  3. UGD
- Example

  Photoabsorption in k_T-factorization:

  $$\sigma_{tot}(\gamma^*\, p \to X) \propto Im_s\{\mathcal{A}(\gamma^*\, p \to \gamma^*\, p)\} \equiv \Phi_{\gamma^* \to \gamma^*} \;\otimes\; \mathcal{F}(x, \vec{k}^2)$$
- Small-x limit

  UGD = [BFKL gluon ladder] ⊗ [proton impact factor]



JETHAD, BFKL inspired but for HEP purposes!

It is a Fortran2008-Python3 hybrid library by Cosenza collaboration

- Main features:
  1. Modularity
  2. Extensive use of structures and dynamic memory
  3. Smart management of final-state phase-space integration
- Developed software:
  1. BFKL tools (BFKL kernel and Impact factors)
  2. UGD modular package
- External interfaces:
  1. LHAPDF and native FF parametrizations
  2. CUBA multi-dim integrators
  3. QUADPACK one-dim integrators
  4. CERNLIB (multi-dim integrators, special functions, MINUIT, etc.)

Semi-hard sector

Total inclusive and exclusive processes

- $A = A' =$ quark, $B = B' =$ gluon [M. Ciafaloni and G. Rodrigo (2000)]
  [V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]
- A $= \gamma_L^*$, A'$=$ V$_L$, with V$_L = \rho, \omega, \phi$ (forward)
  [D.Yu. Ivanov, M.I. Kotsky, A.Papa (2004)]
- $A = A' = \gamma^*$ (forward) [J. Bartels, S. Gieseke, C.F. Qiao (2001)]
  [J. Bartels, S. Gieseke, A. Kyrieleis (2002)]
  [J. Bartels, D. Colferai, S. Gieseke, A. Kyrieleis (2002)]
  [V.S. Fadin, D.Yu. Ivanov, M.I. Kotsky (2003)]
  [J. Bartels, A. Kyrieleis (2004)]
  [I. Balitsky, G.A. Chirilli (2013)] [G.A. Chirilli, Yu.V. Kovchegov (2014)]

Partially inclusive processes

- Mueller-Navelet jet production
  1. NLO jet vertex
     [J. Bartels, D. Colferai, G.P. Vacca (2003)]
     [F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, A. Perri (2011)]
     [D.Yu. Ivanov, A. Papa (2012)]
     [D. Colferai, A. Niccoli (2015)]
  2. Azimuthal correlations (full NLA)
     [B. Ducloué, L. Szymanowski, S. Wallon (2013,2014)]
     [F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa (2014)]
     [F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2015)]
  3. Compatible with CMS (7 TeV)

Semi-hard sector

- Hadron - hadron production
  1. NLO hadron vertex [D.Yu. Ivanov, A. Papa (2012)]
  2. Azimuthal correlations (full NLA)

  [F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2016,2017)]
- Hadron - jet production (full NLA)

  [A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]
- Three / four jet production (partial NLA)

  [F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2016)]

  [F. Caporale, F.G. Celiberto, G. Chachamis, A. Sabio Vera (2016)]

  [F. Caporale, F.G. Celiberto, G. Chachamis, D.G. Gomez, A. Sabio Vera (2016,2017)]
- J/Ψ - jet production (partial NLA)

  [R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]
- Drell-Yan pair - jet (partial NLA)

  [K. Golec-Biernat, L. Motyka, T. Stebel (2018)]
- Higgs - jet (partial NLA)

  [F.G. Celiberto, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2020)]
- Heavy-quark pair photoproduction (partial NLA)

  [F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2017)]
- Heavy-quark pair hadroproduction (partial NLA)

  [A.D. Bolognino, F.G. Celiberto, M.F, D.Yu. Ivanov, A. Papa (2019)]
- Heavy-light meson pair hadroproduction (partial NLA)

  [A.D. Bolognino, F.G. Celiberto, M.F, D.Yu. Ivanov, A. Papa (in preparation)]