Heavy flavor production in the high energy limit of strong interactions

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Outline

Motivation

BFKL resummation

Heavy-quark pair hadroproduction

- Theoretical set-up
- Numerical analysis

Towards bound state

- Flavor number schemes
- Heavy quark FFs
- Heavy-light mesons production

Conclusions and outlook

Motivation

- Heavy flavor physics has long been considered as a perfect framework for testing perturbative QCD at colliders, due to the smallness of the running coupling.
- However, at modern colliders, heavy-flavor production enters a two-scale regime, called semi-hard.
- Semi-hard collision process, featuring the scale hierarchy

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

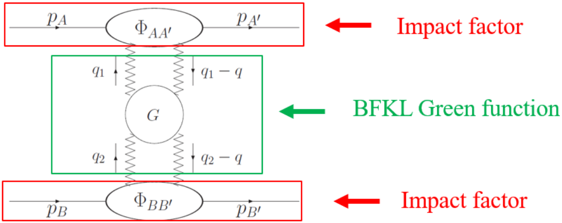
Regge kinematical region

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

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

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).



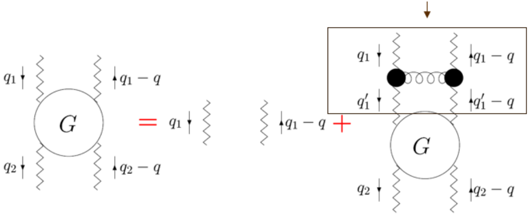
$$\Im\mathcal{A}_{AB}^{A'B'} = \frac{s}{(2\pi)^{D-2}} \int \frac{d^{D-2}q_1}{\vec{q}_1^{\,2}(\vec{q}_1 - \vec{q}\,)^2} \frac{d^{D-2}q_2}{\vec{q}_2^{\,2}(\vec{q}_2 - \vec{q}\,)^2}$$

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

BFKL resummation

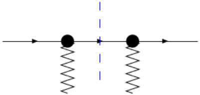
- $G_\omega^{(R)}(\vec{q}_1,\vec{q}_2;\vec{q}\,)$-Mellin transform of the Green function for the Reggeon-Reggeon scattering

$$\omega G_\omega^{(R)}(\vec{q}_1,\vec{q}_2;\vec{q}\,) = \vec{q}_1^{\,2}(\vec{q}_1-\vec{q}\,)^2\delta^{(D-2)}(\vec{q}_1-\vec{q}_2)$$
$$+\int\frac{d^{D-2}q_1'}{\vec{q}_1^{\,\prime 2}(\vec{q}_1^{\,\prime}-\vec{q}\,)^2}\mathcal{K}^{(R)}(\vec{q}_1,\vec{q}_1^{\,\prime};\vec{q}\,)G_\omega^{(R)}(\vec{q}_1^{\,\prime},\vec{q}_2;\vec{q}\,)$$



- $\Phi_{P'P}^{(R,\nu)}$- LO impact factor in the t-channel color state (R,ν)

$$\Phi_{PP'}^{(R,\nu)} = \langle cc'|\hat{\mathcal{P}}|\nu\rangle\sum_{\{f\}}\int\frac{ds_{PR}}{2\pi}d\rho_f\Gamma^c_{\{f\}P}(\Gamma^{c'}_{\{f\}P'})^*$$



Pomeron channel

- BFKL equation: $\vec{q}^{\,2} = 0$ and singlet color state representation [Ya. Ya. Balitsky, V. S. Fadin, E.A Kuraev, L.N Lipatov (1975)]

$$\text{Redefinition :} \qquad G_\omega(\vec{q}_1, \vec{q}_2) \equiv \frac{G_\omega^{(0)}(\vec{q}_1, \vec{q}_2, 0)}{\vec{q}_1^{\,2} \vec{q}_2^{\,2}} \;, \quad \mathcal{K}(\vec{q}_1, \vec{q}_2\;) \equiv \frac{\mathcal{K}^{(0)}(\vec{q}_1, \vec{q}_2\;, 0)}{\vec{q}_1^{\,2} \vec{q}_2^{\,2}}$$

$$\omega G_\omega(\vec{q}_1, \vec{q}_2) = \delta^{(D-2)}(\vec{q}_1 - \vec{q}_2) + \int d^{D-2} q_r \; \mathcal{K}(\vec{q}_1, \vec{q}_r\;) G(\vec{q}_r, \vec{q}_2)$$

- Elastic amplitude factorization:

$$\Im \mathcal{A}_{AB}^{AB} = \frac{s}{(2\pi)^{D-2}} \int d^{D-2} q_1 d^{D-2} q_2$$

$$\times \frac{\Phi_{AA}^{(0)}(\vec{q}_1, s_0)}{\vec{q}_1^{\,2}} \int \frac{d\omega}{2\pi i} \left[\left(\frac{s}{s_0} \right)^\omega G_\omega(\vec{q}_1, \vec{q}_2) \right] \frac{\Phi_{BB}^{(0)}(-\vec{q}_2, s_0)}{\vec{q}_2^{\,2}}$$

- Optical Theorem:

$$\sigma_{AB} = \frac{\Im \mathcal{A}_{AB}^{AB}}{s}$$

- Impact factor in the color singlet state:

$$\Phi_{PP}^{(0)} = \langle cc' | \hat{\mathcal{P}} | 0 \rangle \sum_{\{f\}} \int \frac{d s_{PR}}{2\pi} d\rho_f \Gamma_{\{f\}P}^{c} (\Gamma_{\{f\}P}^{c'})^*$$

Heavy flavor production

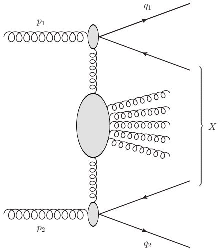
1)Inclusive heavy-quark pair hadroproduction

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

- Partonic process

$$g(p_1)+g(p_2) \longrightarrow Q\text{–jet}(q_1)+Q\text{–jet}(\mathrm{q}_2)+X$$

Q = charm, bottom (detected in the fragmentation regions)



- Partial NLLA resummation
- LO impact factor for the $g \to Q\text{-}\bar{Q}$ transition
- From the gluon-initiated process to the one initiated by proton-proton:

$$d\sigma_{pp} = f_{g_1}(x_1, \mu_{F_1}) f_{g_2}(x_2, \mu_{F_2}) d\sigma_{gg} dx_1 dx_2 \ ,$$

$f_{g_i}, \ i = 1, 2 \longrightarrow$ gluon collinear parton distribution functions

2)Inclusive heavy-quark pair photoproduction

[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2017)]

Theoretical set-up: Hadroproduction case

- General structure of the hadronic cross section

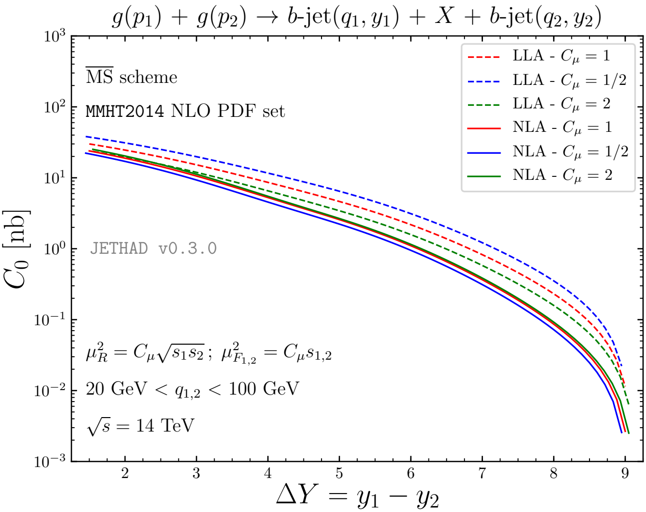
$$\frac{d\sigma_{pp}}{d(\Delta Y)d\varphi_1 d\varphi_2} = \frac{1}{(2\pi)^2}\left[C_0 + 2\sum_{n=1}^{\infty}\cos(n\varphi)C_n\right] , \qquad \varphi = \varphi_1 - \varphi_2 - \pi$$

$$C_n = \int_{q_{1,\min}}^{q_{1,\max}} d|\vec{q}_1| \int_{q_{2,\min}}^{q_{2,\max}} d|\vec{q}_2| \int_{y_{1,\min}}^{y_{1,\max}} dy_1 \int_{y_{2,\min}}^{y_{2,\max}} dy_2 \; \delta(y_1 - y_2 - \Delta Y)$$
$$\int_{e^{-(y_{1,\max}-y_1)}}^{1} dx_1 f_{g_1}(x_1, \mu_{F_1}) \int_{e^{-(y_{2,\max}+y_2)}}^{1} dx_2 f_{g_2}(x_2, \mu_{F_2}) \, \mathcal{C}_n$$

- Unintegrated coefficients

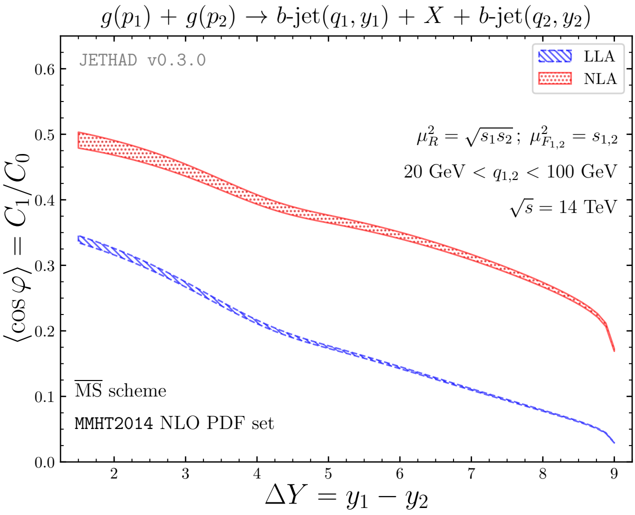
$$\mathcal{C}_n = \frac{|\vec{q}_1||\vec{q}_2|\sqrt{m_1^2+\vec{q}_1^{\,2}}\sqrt{m_2^2+\vec{q}_2^{\,2}}}{W^2} e^{\Delta Y}$$
$$\times \int_{-\infty}^{+\infty} d\nu \left(\frac{W^2}{s_0}\right)^{\bar{\alpha}_s(\mu_R)\chi(n,\nu)+\bar{\alpha}_s^2(\mu_R)\left(\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left(-\chi(n,\nu)+\frac{10}{3}+2\ln\frac{\mu_R^2}{\sqrt{s_1 s_2}}\right)\right)}$$
$$\times \alpha_s^4(\mu_R)\, c_1\left(n,\nu,\vec{q}_1^{\,2},z_1\right) c_2\left(n,\nu,\vec{q}_2^{\,2},z_2\right)\left\{1+\bar{\alpha}_s(\mu_R)\left(\frac{\bar{c}_1^{(1)}}{c_1}+\frac{\bar{c}_2^{(1)}}{c_2}\right)\right.$$
$$\left.+\bar{\alpha}_s(\mu_R)\frac{\beta_0}{2N_c}\left(\frac{5}{3}+\ln\frac{\mu_R^2}{s_1 s_2}+f(\nu)\right)+\bar{\alpha}_s^2(\mu_R)\ln\left(\frac{W^2}{s_0}\right)\frac{\beta_0}{4N_c}\chi(n,\nu)f(\nu)\right\} ,$$

- C_0
- b-jet ($m_b = 4.8$ GeV), $\sqrt{s} = 14$ TeV, $q_{\rm min} = 20$ GeV, $q_{\rm max} = 100$ GeV



Heavy-quark pair hadroproduction: Observables

- C_1/C_0
- b-jet ($m_b = 4.8$ GeV), $\sqrt{s} = 14$ TeV, $q_{\rm min} = 20$ GeV, $q_{\rm max} = 100$ GeV



Towards bound states: Flavor number schemes

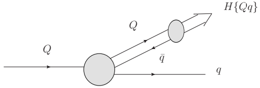
- The mass of light quarks ($q = u, d, s$) is always set to zero. They are always present in the initial state.
- The presence in the initial state and the way one must treat the mass of an heavy-quark ($Q = c, b, t$) depends on kinematical conditions.
- **Zero-mass variable flavor number scheme**
  - $m_Q = 0$
  - Heavy quark is present in the initial state above a fixed threshold.
  - Powers of $m_Q^2/p_{T,HQ}^2$ missed by the scheme
  - It is appropriate in region of high $p_{T,HQ}^2 \gg m_Q^2$
- **Fixed flavor number scheme**
  - $m_Q \neq 0$
  - Heavy quark is present only in the final state
  - Logarithms of $p_{T,HQ}^2/m_Q^2$ missed by the scheme
  - It is appropriate in regions of moderate $p_{T,HQ}^2$
- **General-mass variable flavor number schemes**
  - It is a matching between the previous schemes
  - There is some arbitrariness in the combination

Towards bound states: Heavy quark FFs

To describe the heavy-quark hadronization, many models of heavy-quark fragmentation functions (FFs) has been proposed.

- Peterson FF [C. Peterson, D. Schlatter, I. Schmitt, P. M. Zerwas (1983)]

$$D_Q^H(z) = N \frac{z(1-z)^2}{[(1-z)^2 + \epsilon_H z]^2}$$



$\epsilon_H = (m_q^2)/(m_Q^2)$. N is a normalization.

- Colangelo-Nason FF [G. Colangelo, P. Nason (1992)]

$$D_Q^H(z) = N(1-z)^\alpha z^\beta;$$

α, β are parameters. N is a normalization.

- Bowler FF [M.G. Bowler (1984)]
    - String hadronization model

$$D_Q^H(z) = \frac{N}{z^{1+bm_Q^2}} (1-z)^\beta e^{(-bm_{H,\perp}^2)/z}$$

b, β are parameters.

$m_Q = 0 \rightarrow$ Lund FF [B. Andersson, G. Gustafson, B. Soderberg (1983)]

Towards bound state: Heavy quark FFs

- Kartvelishvili FF [V.G. Kartvelishvili, A.K. Likehoded, V.A. Petrov (1978)]
  - Based on Gribov-Lipatov Reciprocity ($D_Q^H(z) \leftrightarrow f_H^Q(z)$) [V. N. Gribov and L. N. Lipatov (1971)]

$$D_Q^H(z) = (\alpha+1)(\alpha+2)z^{\alpha}(1-z)$$

- Collins-Spiller FF [P. D. B. Collins, T. P. Spiller (1985)]
- HQEFT FFs [E. Braaten, K. Cheung, S. Fleming (1994)]
  - Calculated using an effective field theory based on spin flavor symmetry (arising from the fact that $m_c, m_b, m_t \gg \Lambda_{QCD}$)

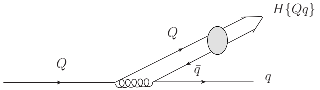
$$^1S_0 \longrightarrow D_{Q\to P}(z) = \frac{a(y)}{r} + b(y) + \mathcal{O}(r), \qquad ^3S_1 \longrightarrow D_{Q\to V}(z) = \frac{a^*(y)}{r} + b^*(y) + \mathcal{O}(r)$$

$$r = (m_H - m_Q)/(m_H), \qquad y = (1-(1-r)z)/(rz)$$

- Suzuki FFs [M. Suzuki (1986)]

$$^1S_0 \longrightarrow D_{Q\to P}(z)$$

$$^3S_1 \longrightarrow D_{Q\to V}(z)$$



Heavy-light mesons production

- Process

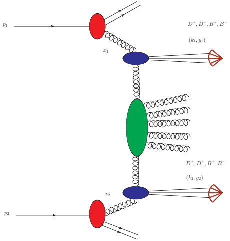
$$p_1 + p_2 \longrightarrow H_1 + X + H_2$$

- Heavy quark pair LO impact factor

$$\frac{d\Phi_{gg}^{\{Q\bar{Q}\}}(\vec{k},\vec{q},z)}{d^2\vec{q}dz} = \frac{\alpha_s^2\sqrt{N_c^2-1}}{2\pi N_c}\left[\left(m^2\left(R+\bar{R}\right)^2 + \left(z^2+\bar{z}^2\right)\left(\vec{P}+\vec{\bar{P}}\right)^2\right)\right.$$
$$\left. -\frac{N_c^2}{N_c^2-1}\left(2m^2R\bar{R} + \left(z^2+\bar{z}^2\right)2\vec{P}\cdot\vec{\bar{P}}\right)\right],$$

- Cross section factorization

$$d\sigma_{p,p}^{H_1,H_2} = D_{Q_1}^{H_1}(\alpha_1) \otimes D_{Q_2}^{H_2}(\alpha_2) \otimes d\sigma_{p,p}^{Q_1,Q_2}$$



- Heavy meson LO impact factor

$$\frac{d\Phi_{gg}^{\{H\bar{Q}\}}}{dz_h d^2\vec{h}}(\vec{k},\vec{h},z_h) = \int_{z_h}^{1}\frac{dz}{z\alpha^2}\,\mathcal{H}(\vec{k},\frac{\vec{h}}{\alpha},z)D_Q^H(\alpha)$$

- Numerical analysis in progress...

Conclusions and outlook

Conclusion

- Inclusive processes with jets and/or identified hadrons in the final state featuring large rapidity separation are a promising testfield in the search of BFKL dynamics in current and future colliders.
- Among them, the photo- or hadro-production of a pair of heavy-quarks/mesons is an interesting new possibility.
- Theoretical predictions, including a relevant part of the energy resummation in the NLLA, are available for both photo- and hadro-production cases.

Future projects

- Inclusion of subleading corrections from the impact factors, needed to produce full-NLLA predictions.
- Production of quarkonia state.
- Single forward heavy-flavored jet production, both in the LLA and in the NLLA, via the introduction of the small-x transverse-momentum-dependent gluon distribution (UGD).

Thank you for the attention

Backup

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)]