

Heavy flavor at high energies: from open states to Quarkonia

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based on

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Quarkonia As Tools 2021



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Outline

Introduction and motivations

BFKL resummation

Hybrid collinear/high-energy factorization

Heavy flavor production

LO heavy-quark impact factors

Open state: Heavy-light dijet

Flavor number schemes

D meson production

Inclusive J/ψ production

Conclusions and Outlook

Introduction and motivations

- Heavy-flavored emissions in hadronic and lepto-hadronic collisions are commonly recognized as excellent probe channels of the dynamics of strong interactions
- This resulted in remarkable interest over the last decades on both their formal and phenomenological aspects
- At modern colliders heavy-flavor production enters the two-scale regime: $s \gg m_Q^2 \gg \Lambda_{QCD}^2$
- Besides usual renormalization group logarithms, the perturbative series is affected by large energy-type logarithms

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

$$s \gg Q^2 \gg \Lambda_{\text{QCD}}^2, \quad Q^2 \text{ a hard scale,}$$

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

- **UGD sector**

The evolution of the **Unintegrated gluon density**,

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

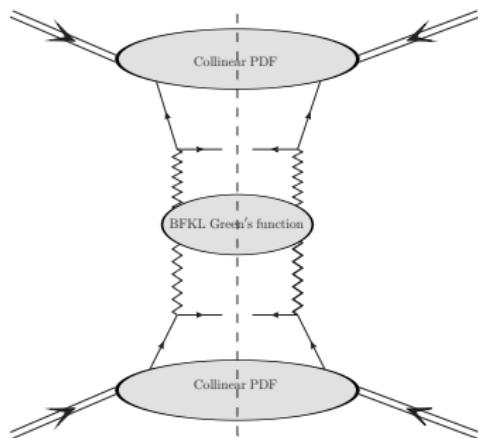
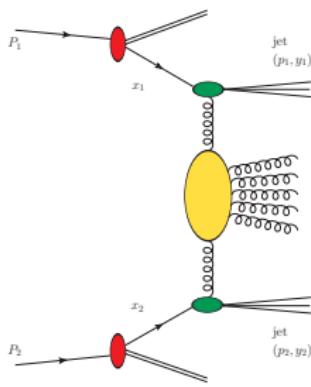
as a function of $\ln(1/x) = \ln(s/Q^2)$, is governed by BFKL:

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

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



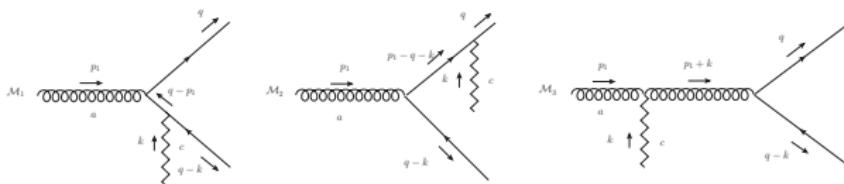
- **Hybrid** formalism: can be extended to several type of semi-hard reactions

LO heavy-quark impact factors

- Gluon-initiated impact factor

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

- Feynman diagrams



- Impact factor

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

- Projection onto the LO BFKL eigenfunctions

$$\frac{d\Phi_{gg}^{\{Q\bar{Q}\}}(n, \nu, \vec{q}, z)}{d^2 \vec{q} dz} \equiv \int \frac{d^2 \vec{k}}{\pi \sqrt{2}} (\vec{k}^2)^{i\nu - \frac{3}{2}} e^{in\theta} \frac{d\Phi_{gg}^{\{Q\bar{Q}\}}(\vec{k}, \vec{q}, z)}{d^2 \vec{q} dz} \equiv \alpha_s^2 e^{in\varphi} c(n, \nu, \vec{q}, z)$$

- Photon-initiated impact factor

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

Heavy-light dijet: Theoretical set-up

- Process:

$$\text{proton}(P_1) + \text{proton}(P_2) \rightarrow Q\text{-jet} + X + \text{jet}$$

- Hadronic cross section

$$\frac{d\sigma_{PP}}{dy_Q dy_J d^2 \vec{p}_Q d^2 \vec{p}_J}$$

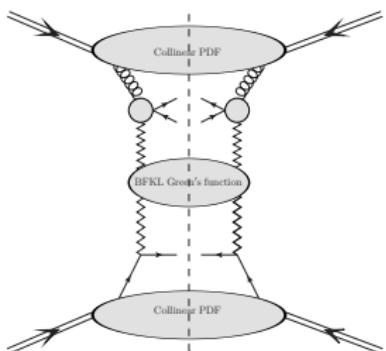
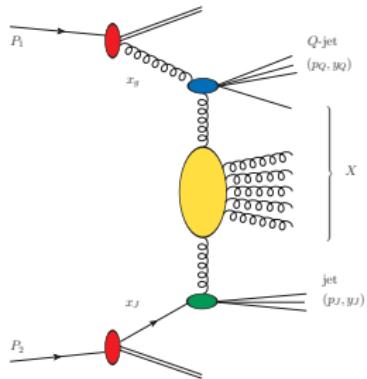
$$= \sum_x \int dx_g \int dx_J f_g(x_g, \mu_{F_Q}) f_r(x_J, \mu_{F_J}) \frac{d\hat{\sigma}}{dy_Q dy_J d^2 \vec{p}_Q d^2 \vec{p}_J}$$

- BFKL partonic cross section

$$\frac{d\hat{\sigma}}{dy_Q dy_J d^2 \vec{p}_Q d^2 \vec{p}_J} = \frac{1}{(2\pi)^2}$$

$$\times \int \frac{d^2 \vec{q}_1}{{\vec{q}_1}^2} V_Q(\vec{q}_1, x_g, \vec{p}_Q) \int \frac{d^2 \vec{q}_2}{{\vec{q}_2}^2} V_J(\vec{q}_2, x_J, \vec{p}_J)$$

$$\times \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_g x_J s}{s_0} \right)^\omega G_\omega(\vec{q}_1, \vec{q}_2)$$



Heavy-light dijet: Theoretical set-up

- Final structure of the hadronic **cross section**

$$\frac{d\sigma_{pp}}{dy_Q dy_J d|\vec{p}_Q| d|\vec{p}_J| d\phi_Q d\phi_J} = \frac{1}{(2\pi)^2} \left[C_0 + 2 \sum_{n=1}^{\infty} \cos(n\phi) C_n \right]$$

- Unintegrated azimuthal-angle coefficients

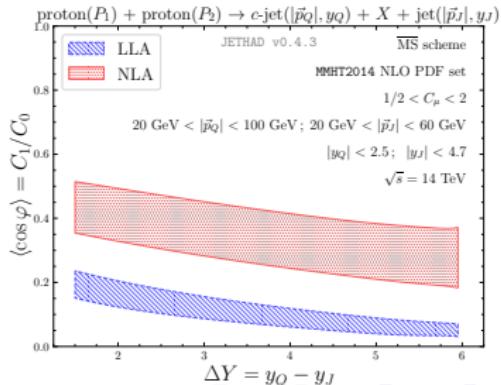
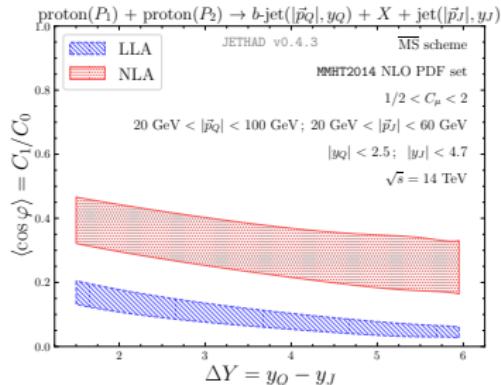
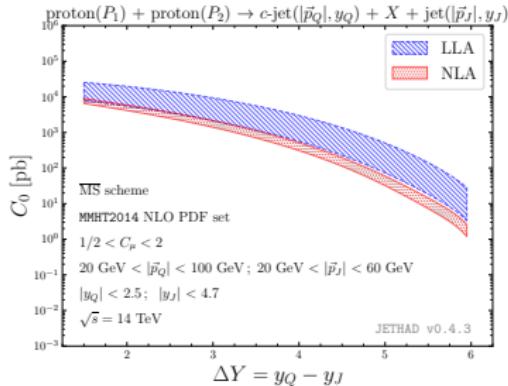
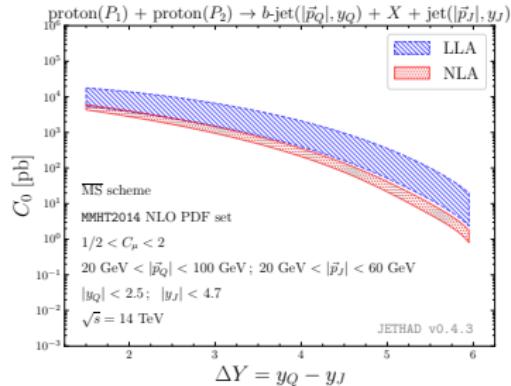
$$\begin{aligned} C_n &= \frac{e^{\Delta Y} |\vec{p}_Q| |\vec{p}_J|^2 M_{Q\perp}}{s} \int dx_g f_g(x_g, \mu_{F_1}) \tilde{f}(x_J, \mu_{F_2}) \\ &\quad \int_{-\infty}^{+\infty} d\nu \left(\frac{W^2}{s_0} \right)^{\bar{\alpha}_s(\mu_R) \chi(n, \nu) + \bar{\alpha}_s^2(\mu_R) \left[\bar{\chi}(n, \nu) + \frac{\beta_0}{8N_c} \chi(n, \nu) \left(-\chi(n, \nu) + \frac{10}{3} + 2 \ln \frac{\mu_R^2}{M_{Q\perp} |\vec{p}_J|} \right) \right]} \\ &\quad \times \alpha_s^3(\mu_R) c_Q(n, \nu, \vec{p}_Q, z_Q, x_g) [c_J(n, \nu, \vec{p}_J)]^* \\ &\times \left\{ 1 + \frac{c_Q^{(1)}(n, \nu, \vec{p}_Q, z_Q)}{c_Q(n, \nu, \vec{p}_Q, z_Q)} + \left[\frac{c_J^{(1)}(n, \nu, \vec{p}_J, x_J)}{c_J(n, \nu, \vec{p}_J)} \right]^* + \bar{\alpha}_s^2(\mu_R) \ln \left(\frac{W^2}{s_0} \right) \chi(n, \nu) f_Q(\nu) \right\} \end{aligned}$$

- Azimuthal-angle coefficients

$$C_n(\Delta Y, s) = \int_{p_Q^{\min}}^{p_Q^{\max}} d|\vec{p}_Q| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_Q^{\min}}^{y_Q^{\max}} dy_Q \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_Q - y_J - \Delta Y) C_n$$

Heavy-light dijet: Observables

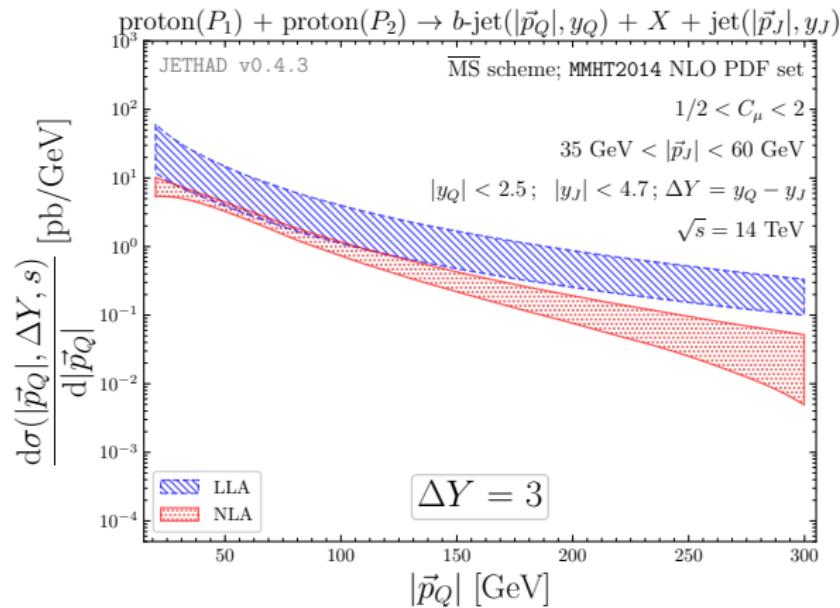
Azimuthal-angle coefficients and their ratios



Heavy-light dijet: Observables

Heavy-jet p_T -distribution

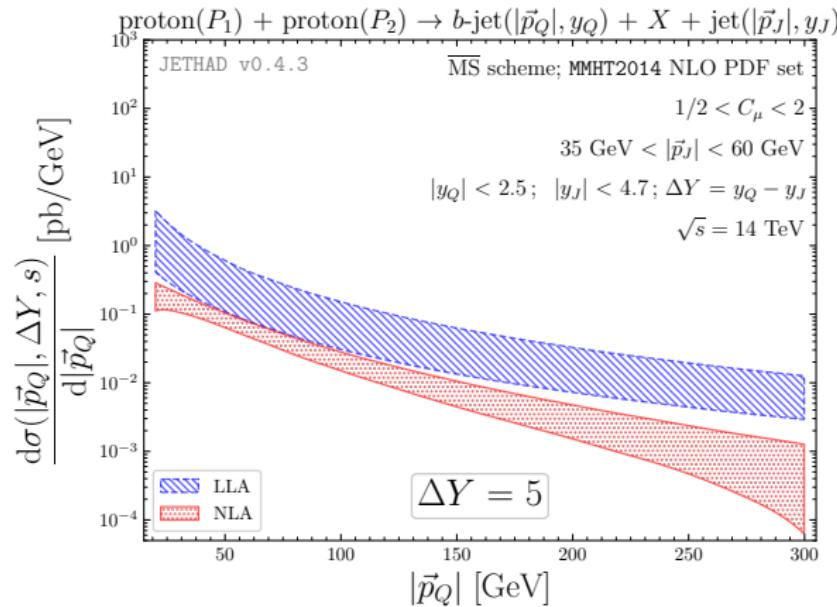
$$\frac{d\sigma_{pp}(|\vec{p}_Q|, \Delta Y, s)}{d|\vec{p}_Q| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_Q^{\min}}^{y_Q^{\max}} dy_Q \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_Q - y_J - \Delta Y) \mathcal{C}_0$$



Heavy-light dijet: Observables

Heavy-jet p_T -distribution

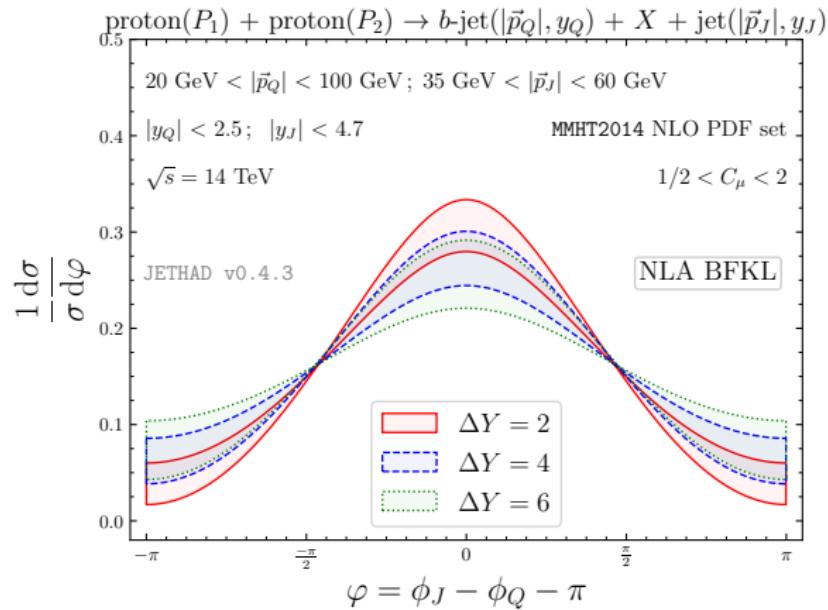
$$\frac{d\sigma_{pp}(|\vec{p}_Q|, \Delta Y, s)}{d|\vec{p}_Q| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_Q^{\min}}^{y_Q^{\max}} dy_Q \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_Q - y_J - \Delta Y) \mathcal{C}_0$$



Heavy-light dijet: Observables

Azimuthal distribution

$$\frac{d\sigma_{pp}(\varphi, \Delta Y, s)}{\sigma_{pp} d\varphi} = \frac{1}{\pi} \left\{ \frac{1}{2} + \sum_{n=1}^{\infty} \cos(n\varphi) \langle \cos(n\varphi) \rangle \right\} \equiv \frac{1}{\pi} \left\{ \frac{1}{2} + \sum_{n=1}^{\infty} \cos(n\varphi) R_{n0} \right\}$$

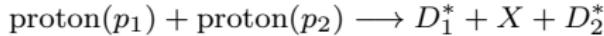


Towards bound states: Flavor number schemes

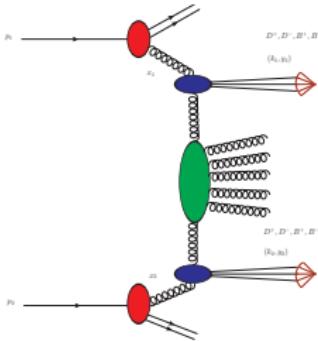
- The mass of light quarks ($q = u, d, s$) is always set to zero. They are always present in the initial state
- The presence in the initial state and the way one must treat the mass of an heavy-quark ($Q = c, b, t$) depends on kinematical conditions
- **Zero-mass variable flavor number scheme**
 - $m_Q = 0$
 - 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

Low- p_T D^* -meson production

- Double D^* -meson production



- Fixed flavor number scheme



- Cross section factorization

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

$D_{Q_i}^{H_i} \rightarrow$ NP-fragmentation function

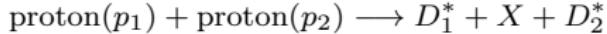
- Heavy quark pair LO impact factor \rightarrow Heavy meson LO impact factor

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

- Numerical analysis for D^* meson production in progress...

High- p_T D^* -meson production

- Double D^* -meson production



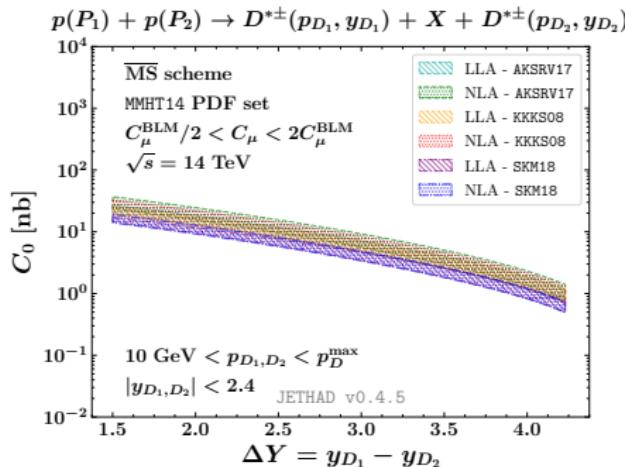
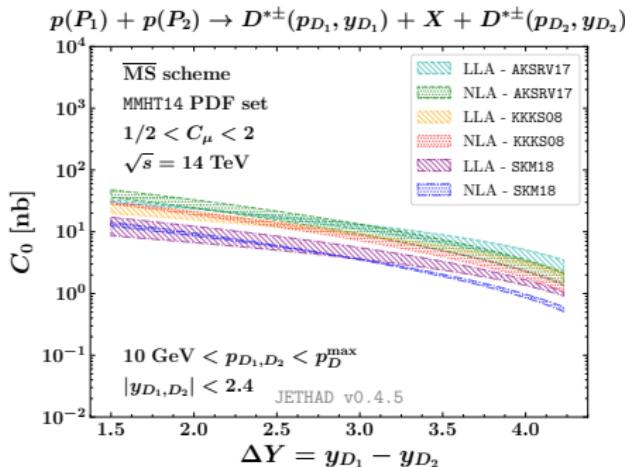
- Zero mass variable flavor number scheme
 - Light parton NLO impact factors → Heavy meson NLO impact factor

[M. Ciafaloni and G. Rodrigo (2000)]

[V.S. Fadin, R. Fiore, M.I. Kotsky, A. Papa (2000)]

[D.Yu. Ivanov, A. Papa (2012)]

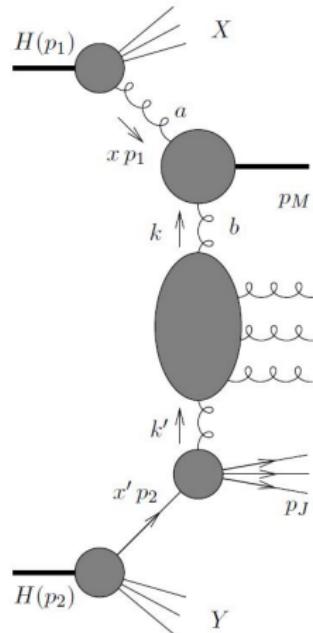
Preliminary



J/ψ production

- Process: proton(p_1) + proton(p_2) $\rightarrow J/\psi + X + \text{jet}$

- **hybrid collinear/BFKL approach**
- high-energy hadroproduction of a J/Ψ meson and a jet, with a remnant X
- both the J/Ψ and the jet emitted with large transverse momenta and well separated in rapidity
- NLA BFKL + NLO jet + LO J/Ψ
 - LO J/Ψ IF calculated in **NRQCD** (Color-singlet and Color-octet)
 - LO J/Ψ IF calculated in **color evaporation model (CEM)**
- Realist CMS and CASTOR rapidity ranges, fixed p_T final states



[R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]

Conclusions and outlook

Conclusions

- Heavy flavored emissions represent a promising channel to investigate the semi-hard regime of QCD, providing with a **fair stability** of the BFKL series
- Theoretical predictions, including a relevant part of the energy resummation in the NLLA can be build in the context of the hybrid collinear/high-energy factorization
- Early efforts were made to shift the focus to the production of bound states

Outlook

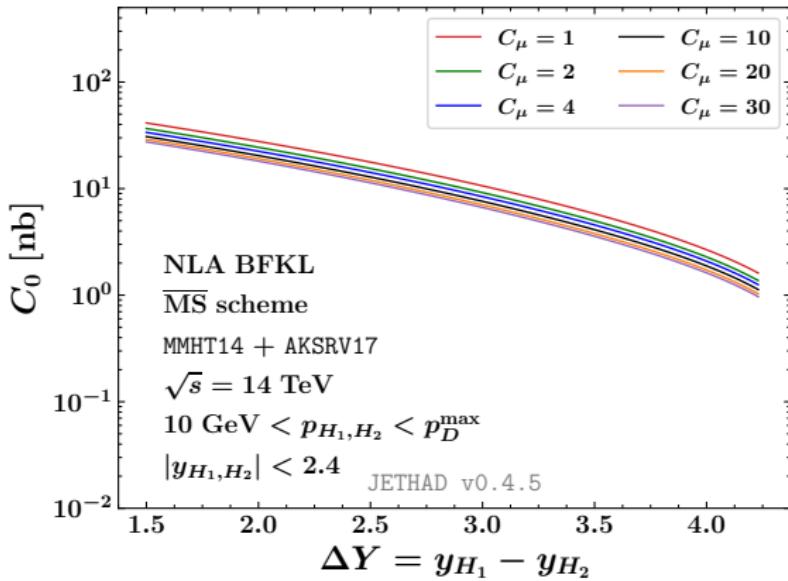
- More phenomenological analysis on bound states (D^* meson, $J/\Psi, \dots$)
- Inclusion of **subleading corrections** from the heavy-quark pair impact factors, needed to produce full-NLLA predictions
- Single forward heavy-flavored jet production, via the introduction of the **small- x transverse-momentum-dependent gluon distribution**
(UGD) —→ *Wednesday's talk by F.G. Celiberto*

Thank you for the attention

Backup

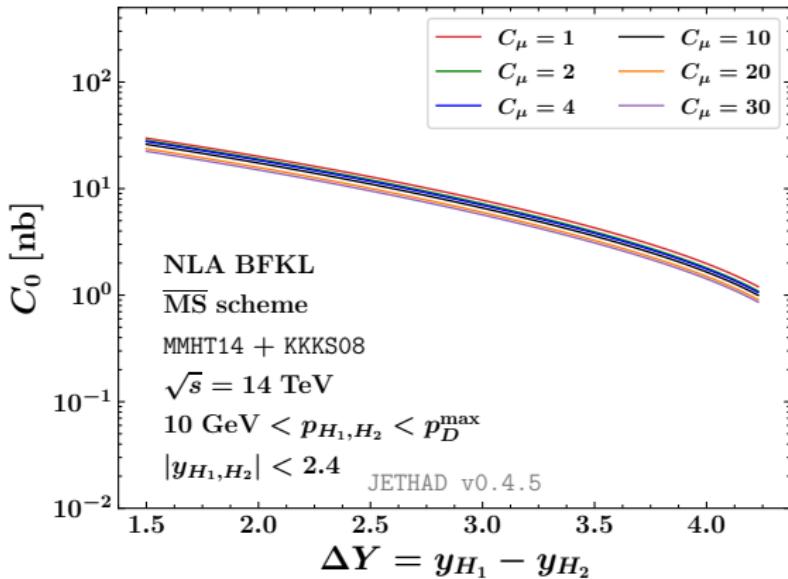
Backup

$$p(P_1) + p(P_2) \rightarrow D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$$



Backup

$$p(P_1) + p(P_2) \rightarrow D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$$



Backup

$$p(P_1) + p(P_2) \rightarrow D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$$

