Hybrid high-energy/collinear factorization in a heavy-light dijets system reaction

Michael Fucilla

Università della Calabria & INFN - Cosenza

in collaboration with
A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, A. Papa

based on

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UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI FISICA

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Istituto Nazionale di Fisica Nucleare

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

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

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

- UGD sector

  The evolution of the Unintegrated gluon density,

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

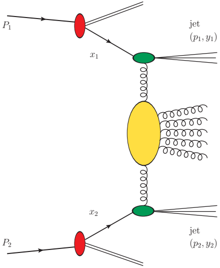
  as a function of $\ln(1/x) = \ln(s/Q^2)$, is governed by BFKL:

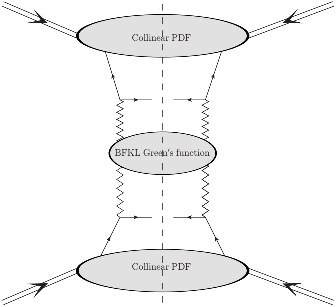
$$\frac{\partial\mathcal{F}}{\partial\ln(1/x)} = \mathcal{F}\otimes\mathcal{K}$$

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 → BFKL resummed partonic cross section
- Moderate values of parton x → collinear PDFs





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

Mueller-Navelet jets: 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 dynamics in 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)]
- Hadron - hadron production
  1. NLO hadron vertex [D.Yu. Ivanov, A. Papa (2012)]
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     [F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2016,2017)]
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  [A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, M.M.A. Mohammed, A. Papa (2018)]

BFKL dynamics in partially inclusive processes

- Three / four jet production (partial NLA)

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- Drell-Yan pair - jet (partial NLA)

  [K. Golec-Biernat, L. Motyka, T. Stebel (2018)]

- Higgs - jet (partial NLA)

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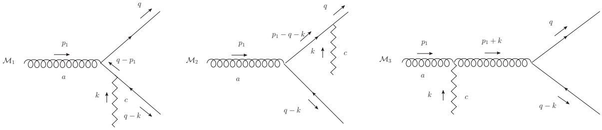
What about Heavy flavor physics?

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

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

- 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:

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

Heavy-light dijet: Theoretical set-up

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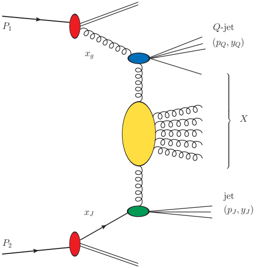
  proton(P_1) + proton$(P_2) \to Q-$jet $+ X +$ jet

- **Hadronic cross section**

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

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



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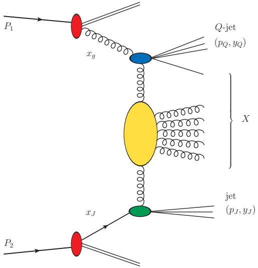
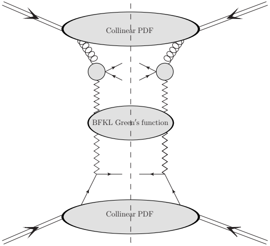


- **BFKL partonic cross section**

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

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

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



Heavy-light dijet: Theoretical set-up

- Final structure of the hadronic cross section

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

- Unintegrated azimuthal-angle coefficients

$$\mathcal{C}_n = \frac{e^{\Delta Y}|\vec{p}_Q||\vec{p}_J|^2 M_{Q\perp}}{s}\int dx_g f_g(x_g,\mu_{F_1})\tilde{f}(x_J,\mu_{F_2})$$

$$\int_{-\infty}^{+\infty} d\nu \left(\frac{W^2}{s_0}\right)^{\bar{\alpha}_s(\mu_R)\chi(n,\nu)+\bar{\alpha}_s^2(\mu_R)\left[\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left(-\chi(n,\nu)+\frac{10}{3}+2\ln\frac{\mu_R^2}{M_{Q\perp}|\vec{p}_J|}\right)\right]}$$

$$\times\ \alpha_s^3(\mu_R)\, c_Q(n,\nu,\vec{p}_Q,z_Q,x_g)\,[c_J(n,\nu,\vec{p}_J)]^*$$

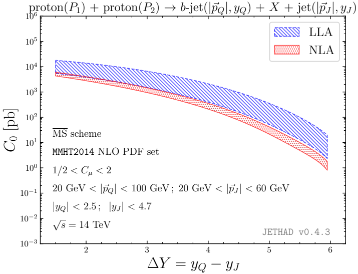
$$\times\left\{1+\frac{c_Q^{(1)}(n,\nu,\vec{p}_Q,z_Q)}{c_Q(n,\nu,\vec{p}_Q,z_Q)}+\left[\frac{c_J^{(1)}(n,\nu,\vec{p}_J,x_J)}{c_J(n,\nu,\vec{p}_J)}\right]^* + \bar{\alpha}_s^2(\mu_R)\ln\left(\frac{W^2}{s_0}\right)\chi(n,\nu)\, f_Q(\nu)\right\}$$

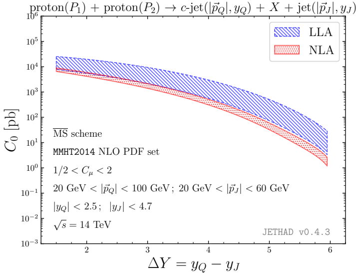
- Azimuthal-angle coefficients

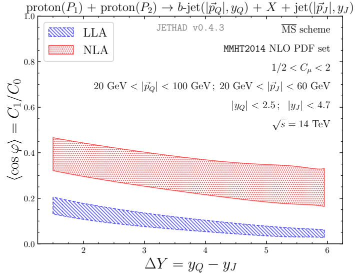
$$C_n(\Delta Y,s) = \int_{p_Q^{\rm min}}^{p_Q^{\rm max}} d|\vec{p}_Q| \int_{p_J^{\rm min}}^{p_J^{\rm max}} d|\vec{p}_J| \int_{y_Q^{\rm min}}^{y_Q^{\rm max}} dy_Q \int_{y_J^{\rm min}}^{y_J^{\rm max}} dy_J\, \delta\left(y_Q-y_J-\Delta Y\right)\, \mathcal{C}_n$$

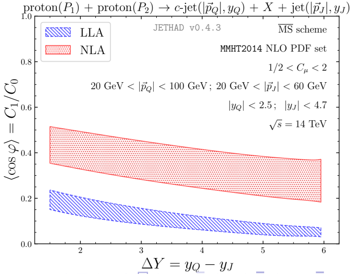
Heavy-light dijet: Observables

Azimuthal-angle coefficients and their ratios





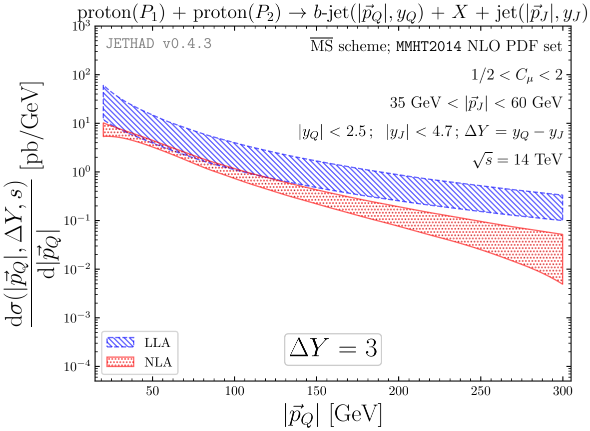




Heavy-light dijet: Observables

Heavy-jet p_T-distribution

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



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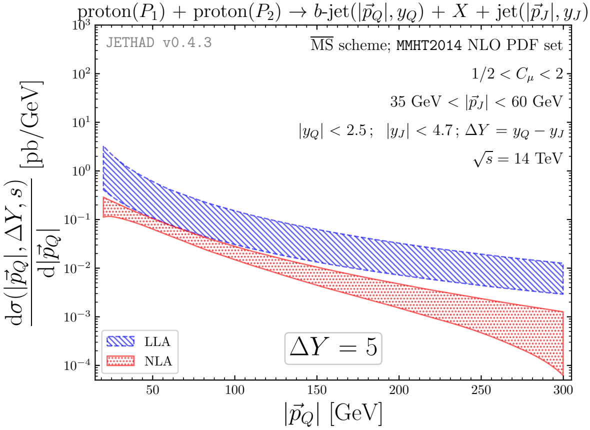
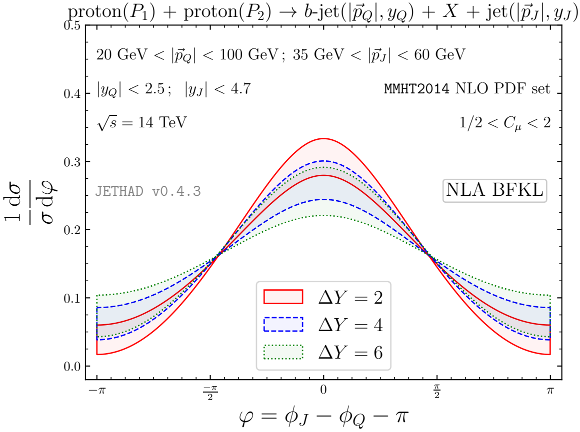


Heavy-light dijet: Observables

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

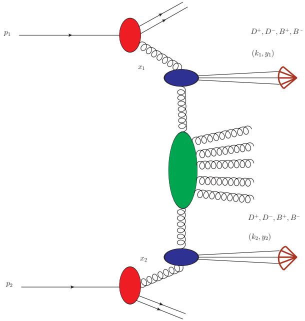
- The mass of light quarks ($q = u, d, s$) is always set to zero. They are always present in the initial state
- The presence in the initial state and the way one must treat the mass of an heavy-quark ($Q = c, b, t$) depends on kinematical conditions
- **Zero-mass variable flavor number scheme**
  -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

$$\text{proton}(p_1) + \text{proton}(p_2) \longrightarrow D_1^* + X + D_2^*$$

- Fixed flavor number scheme



- Heavy quark pair LO impact factor → Heavy meson LO impact factor

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

Models of Non-perturbative FFs

- 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

- PQCD FFs models
  1. FFs from Heavy-quark effective field theory [E. Braaten et al. (1994)]
  2. Suzuki FFs [M. Suzuki (1986)]
- String Hadronization FFs
  1. Lund Symmetric FF [B. Andersson et. al (1983)]
  2. Bowler FF [M. G. Bowler (1984)]
- "Reciprocity" inspired FFs
  1. Kartvelishvili FF [V.G. Kartvelishvili et al. (1978)]
  2. Collins-Spiller FF [P. D. B. Collins, T. P. Spiller (1985)]
- Others phenomenological FFs
  1. Peterson FF [C. Peterson et al. (1983)]
  2. Colangelo-Nason FF [G. Colangelo, P. Nason (1992)]
- Numerical analysis for D^* meson production in progress...

High-p_T D^*-meson production

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

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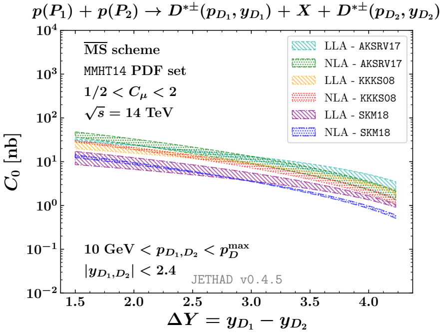
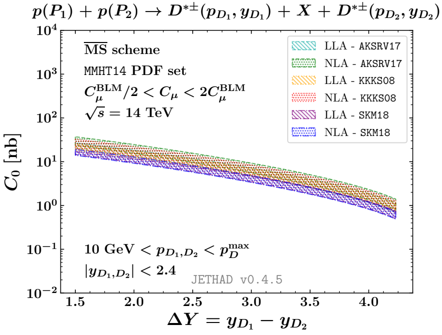
Preliminary

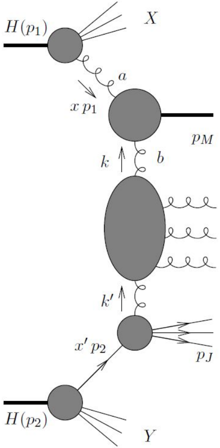




J/ψ production

- Process: proton(p_1) + proton(p_2) $\rightarrow J/\psi + X +$ 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-octect)
  - LO J/Ψ IF calculated in **color evaporation model (CEM)**
- Realistic 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 to shift the focus to the production of bound states
- BFKL as an additional tool to investigate heavy flavor production in wider kinematical ranges

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Outlook

- More phenomenological analysis on bound states (D* meson, J/Ψ,...)
- 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 small-x transverse-momentum-dependent gluon distribution (UGD)

Thank you for the attention

Backup

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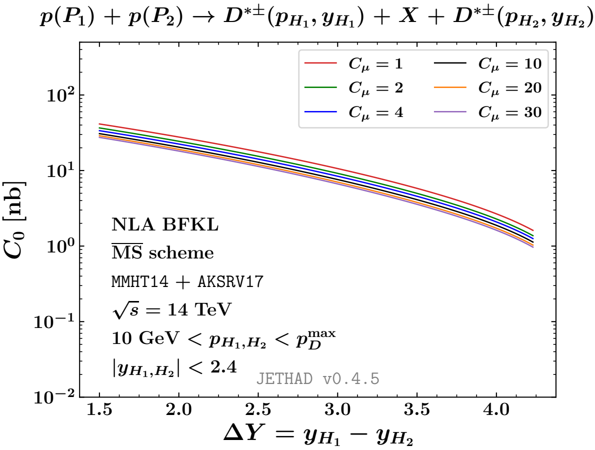
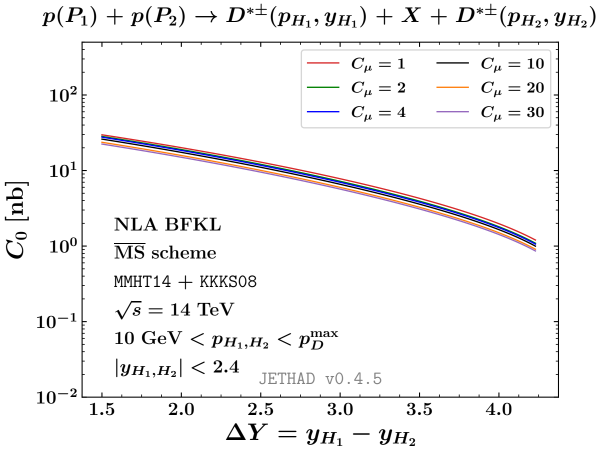


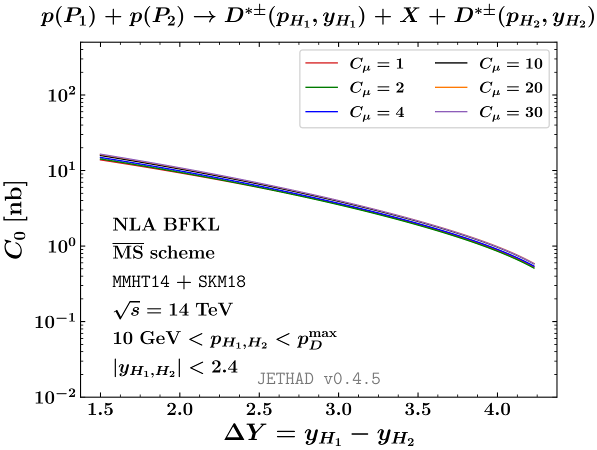
$p(P_1) + p(P_2) \to D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$
$C_\mu = 1$
$C_\mu = 2$
$C_\mu = 4$
$C_\mu = 10$
$C_\mu = 20$
$C_\mu = 30$
NLA BFKL
$\overline{\mathrm{MS}}$ scheme
MMHT14 + AKSRV17
$\sqrt{s} = 14$ TeV
10 GeV $< p_{H_1,H_2} < p_D^{\max}$
$|y_{H_1,H_2}| < 2.4$
JETHAD v0.4.5
C_0 [nb]
$\Delta Y = y_{H_1} - y_{H_2}$

Backup



$p(P_1) + p(P_2) \to D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$
$C_\mu = 1$
$C_\mu = 2$
$C_\mu = 4$
$C_\mu = 10$
$C_\mu = 20$
$C_\mu = 30$
C_0 [nb]
NLA BFKL
$\overline{\text{MS}}$ scheme
MMHT14 + KKKS08
$\sqrt{s} = 14$ TeV
10 GeV $< p_{H_1,H_2} < p_D^{\max}$
$|y_{H_1,H_2}| < 2.4$
JETHAD v0.4.5
$\Delta Y = y_{H_1} - y_{H_2}$

Backup



$p(P_1) + p(P_2) \to D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$
$C_\mu = 1$
$C_\mu = 2$
$C_\mu = 4$
$C_\mu = 10$
$C_\mu = 20$
$C_\mu = 30$
C_0 [nb]
NLA BFKL
$\overline{\text{MS}}$ scheme
MMHT14 + SKM18
$\sqrt{s} = 14$ TeV
10 GeV $< p_{H_1,H_2} < p_D^{\max}$
$|y_{H_1,H_2}| < 2.4$
JETHAD v0.4.5
$\Delta Y = y_{H_1} - y_{H_2}$