Hunting stabilization effects of the high-energy resummation via heavy flavor production at the LHC

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Based on

[F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, M. M. A. M., A. Papa [arXiv:2109.11875]],
to appear in *Phys. Rev. D*

Resummation, Evolution, Factorization (REF) 2021

Motivation

- The high-energy limit $s \gg Q^2 \gg \Lambda_{\text{QCD}}$: $\Rightarrow \alpha_s(Q) \ln s/Q^2 \sim 1$ need to be resummed.
- The Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach provides a general framework for this resummation.

[V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975, 1976, 1977)]
[Y.Y. Balitskii, L.N. Lipatov (1978)]

- A significant question for collider phenomenology is highlighting at which energies the BFKL dynamics becomes significant and cannot be overlooked.
- However, experimental evidences of the BFKL dynamics are not conclusive, thus motivating the proposal of new probes.

Last years:

Search for BFKL dynamics in inclusive processes

- ◇ jets or identified particles in the final state (di-hadron, hadron-jet, heavy-quark pair, multi-jet,...).
- ◇ straightforward adaptation of the BFKL factorization.
- ◇ shows **sensitivity** to the renormalization/factorization **scale choice**.

$\longrightarrow$ calls for some optimization procedure to make reliable predictions.

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Toward restoring the stability of the BFKL series

1. **Study processes characterized by natural energy scales...**

Inclusive Higgs-plus-jet production

- inclusive h.p of Higgs + jet with high p_T and large separated in rapidity.
- large energy scales expected to **stabilize** the high-energy resummed series.

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

2. **Study heavy-flavored emissions processes...**

Inclusive heavy-flavored emissions

- inclusive emission of a forward **heavy-flavored hadron** (**heavy-jet**)...
- ... accompanied by another backward **heavy-flavored hadron** (**heavy-jet**) or a backward light-flavored jet.

(**heavy-light dijet system**) **[A. D. Bolognino, F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, and A. Papa (2021)]**
(**heavy-flavored hadron**) **[F. G. Celiberto, M. Fucilla, D. Yu. Ivanov, and A. Papa (2021)]**

- tagged heavy-flavored particles dampen the **instabilities** of the BFKL series.
- further probes featuring the tag of heavier hadron species are needed.

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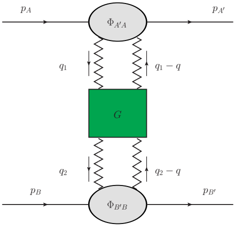
The high-energy resummation

- **BFKL resummation**:

  Scattering in $A + B \longrightarrow A' + B'$ Regge kinematical region $s \to \infty, t$ fixed.



$\to$ BFKL factorization for $Im_s \mathcal{A}$:

$$\Phi_A(\vec{q}_1, s_0) \otimes G_\omega(\vec{q}_1, \vec{q}_2) \otimes \Phi_B(-\vec{q}_2, s_0)$$

Valid both in

- leading logarithmic approximation (LLA): $\alpha_s^n (\ln s)^n$.
- next-to-leading logarithmic approximation (NLA): $\alpha_s^{n+1} (\ln s)^n$.

- **Green's function** is **process-independent** $\longrightarrow$ determined through the **BFKL equation**.

$$\omega G_\omega(\vec{q}_1, \vec{q}_2) = \delta^2(\vec{q}_1 - \vec{q}_2) + \int d^2\vec{q} K(\vec{q}_1, \vec{q}) G_\omega(\vec{q}, \vec{q}_1)$$

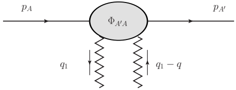
[Ya.Ya. Balitsky, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

- **Impact factors** are **process-dependent**

  $\longrightarrow$ known in the NLA just for limited cases.

  Universal property: $\Phi_{A'A}\Big|_{q \to 0}^{q_1 - q \to 0} \to 0,$

  which guarantees the infra-red finiteness of the BFKL amplitudes.



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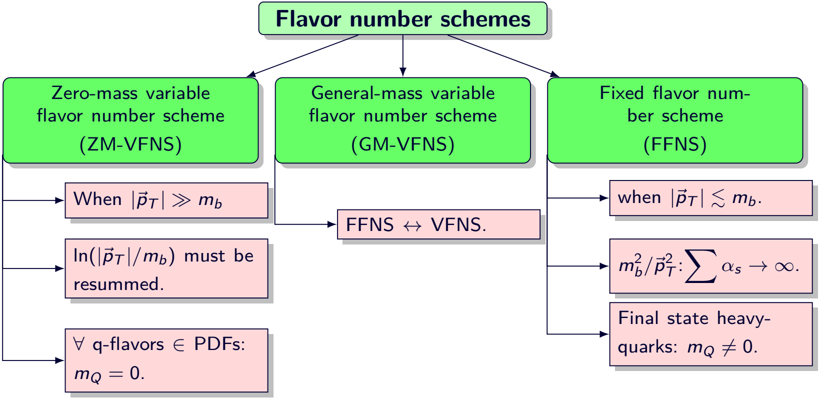
bottom-flavor phenomenology



- m_b plays a crucial role.
- different implementations of this scheme have been proposed so far.

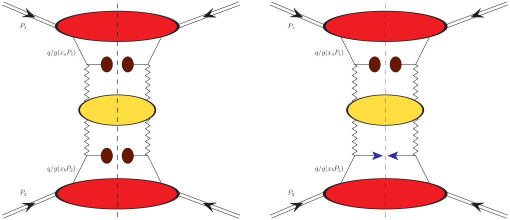
[M. Krämer, F. I. Olness, and D. E. Soper (2000)]
[S. Forte, E. Laenen, P. Nason, and J. Rojo, (2010)]
[J. Blümlein, A. De Freitas, C. Schneider, and K. Schönwald, (2018)]

- approaching particular kinematic regions $\to$ (gap of knowledge).

Inclusive b-hadron production

Processes:

$$\text{proton}(P_1) + \text{proton}(P_2) \;\to\; \mathrm{H_b}(\vec{p}_1, y_1) + \mathrm{X} + \mathrm{O_2}(\vec{p}_2, y_2), \quad \text{where} \quad \mathrm{O_2} \equiv \{\mathrm{H_b}, \text{jet}\}$$



$H_b + H_b$ $\qquad$ $H_b + \text{jet}$

- large transverse masses: $m_{1,2\perp} = \sqrt{|\vec{p}_{1,2}|^2 + m_{1,2}^2} \gg \Lambda_{QCD}$.
- QCD collinear factorization.
- large rapidity interval $\Delta y = y_1 - y_2 \;\Rightarrow$ BFKL resummation.

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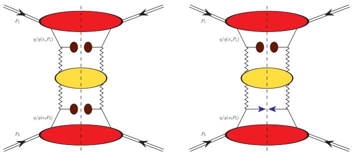

$H_b + H_b$ $\qquad$ $H_b + \text{jet}$

$$d\sigma^{[pp \to \mathbf{H_b H_b} \,/\, \mathbf{H_b jet}]}_{\text{coll.}} = \sum_{r,s=q,\bar{q},g} \int_0^1 dx_a \int_0^1 dx_b \; f_r(x_a)\, f_s(x_b)$$

$$\times \left\{ \begin{array}{c} \boxed{\int_{x_1}^1 \frac{d\beta_1}{\beta_1} \int_{x_2}^1 \frac{d\beta_2}{\beta_2} D_r^{H_b}\left(\frac{x_1}{\beta_1}\right) D_s^{H_b}\left(\frac{x_2}{\beta_2}\right)} \\ \boxed{\int_{x_1}^1 \frac{d\beta_1}{\beta_1} D_r^{H_b}\left(\frac{x_1}{\beta_1}\right)} \end{array} \right\} d\hat{\sigma}_{r,s}(\hat{s})$$

- Partons **probability density**.
- Collinear **fragmentation** of the parton r into a hadron H_b.
  - project onto the eigenfunctions of the LO BFKL kernel.
  - suitable definition of the **azimuthal coefficients**:

$$\frac{d\sigma}{dy_1 dy_2 d|\vec{p}_1| d|\vec{p}_2| d\phi_1 d\phi_2} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\varphi)\, \mathcal{C}_n\right],$$

where $\varphi = \phi_1 - \phi_2 - \pi$

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Observables

Integrated coefficients over the phase space for the two emitted objects

$$C_n = \int_{y_1^{\min}}^{y_1^{\max}} dy_1 \int_{y_2^{\min}}^{y_2^{\max}} dy_2 \int_{p_1^{\min}}^{p_1^{\max}} d|\vec{p}_1| \int_{p_2^{\min}}^{p_2^{\max}} d|\vec{p}_2| \; \delta(\Delta Y - (y_1 - y_2)) \; \mathcal{C}_n$$

- **Observables:**
  - ΔY*-distribution* $(\mathcal{C}_0)$ and the ratio

$$\langle \cos [n(\phi_1 - \phi_2 - \pi)] \rangle \equiv \frac{\mathcal{C}_n}{\mathcal{C}_0}, \quad \text{with} \quad n = 1, 2, 3$$

  - *Azimuthal correlations*:

$$\frac{\langle \cos [2(\phi_1 - \phi_2 - \pi)] \rangle}{\langle \cos (\phi_1 - \phi_2 - \pi) \rangle} \equiv \frac{\mathcal{C}_2}{\mathcal{C}_1} \equiv R_{21}, \quad \frac{\langle \cos [3(\phi_1 - \phi_2 - \pi)] \rangle}{\langle \cos [2(\phi_1 - \phi_2 - \pi)] \rangle} \equiv \frac{\mathcal{C}_3}{\mathcal{C}_2} \equiv R_{32}.$$

$\longrightarrow$ minimise further any contamination from collinear logarithms

  - *Double differential* p_T*-distribution*:

$$\frac{d\sigma(|\vec{p}_{1,2}|, \Delta Y, s)}{d|\vec{p}_1| d|\vec{p}_2| d\Delta Y} = \int_{y_1^{\min}}^{y_1^{\max}} \mathrm{d}y_1 \int_{y_2^{\min}}^{y_2^{\max}} \mathrm{d}y_2 \; \delta(\Delta Y - (y_1 - y_2)) \; \mathcal{C}_0 \left(|\vec{p}_1|, |\vec{p}_2|, y_1, y_2\right)$$

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Numerical specifics

Kinematic settings:

- $\sqrt{s} = 13$ TeV.
- $|y_J| < 4.7$ and 35 GeV $< p_J < 60$ GeV.
- $|y_H| < 2.4$ and 20 GeV $< p_H < 60$ GeV.

The last two ranges are bracketed together as: asymmetric ranges

- $\mu_F = \mu_R \equiv \mu_N = \sqrt{m_{1\perp} m_{2\perp}}$,

  with $m_{1\perp} = \sqrt{|\vec{p}_1|^2 + m_{H_b}^2}$ and $m_{2\perp} = \begin{cases} \sqrt{|\vec{p}_2|^2 + m_{H_b}^2}, & (\text{double}H_b) \\ p_{2\perp}, & (\text{jet}) \end{cases}$
- define $C_\mu \equiv \mu_R/\mu_N$ and $C_\mu^{\rm BLM} \equiv \mu_R^{\rm BLM}/\mu_N$ (next slide).

Numerical tools:

$\rightarrow$ JETHAD $\rightarrow$ hybrid python + F modular package

[Francesco Giovanni Celiberto, *Eur.Phys.J.C 81 (2021) 8, 691*]

$+$ NLO **MMHT14** PDFs set

[L. Harland-Lang, A. Martin, P. Motylinski, R. Thorne, (2015)]

$+$ **KKSS07** NLO FFs

[B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger (2008)]

Renormalization scale fixing:

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)]

- ✓ fix the renormalization scale.
- ✓ resums the self-energy corrections to the gluon propagator at one loop into the running coupling.

* "Exact" BLM:

suppress NLO IFs + NLO Kernel β_0-dependent factors.

Working in the MOM scheme, μ_R^{BLM}, is the value of μ_R that satisfies the condition:

$$C_n^{(\beta_0)}(s, \Delta Y) = \int \mathrm{d}\Phi(y_{1,2}, |\vec{p}_{1,2}|, \Delta Y)\; \mathcal{C}_n^{(\beta_0)} = 0$$

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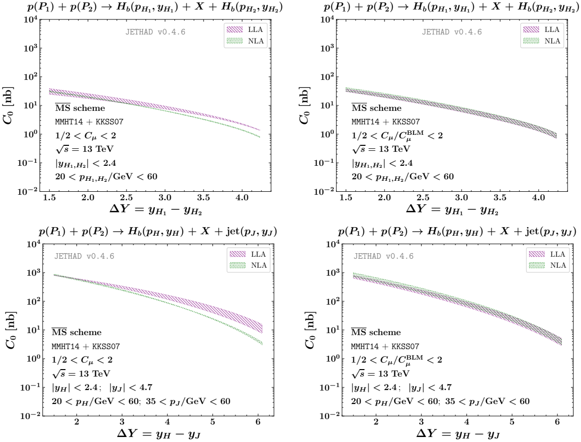
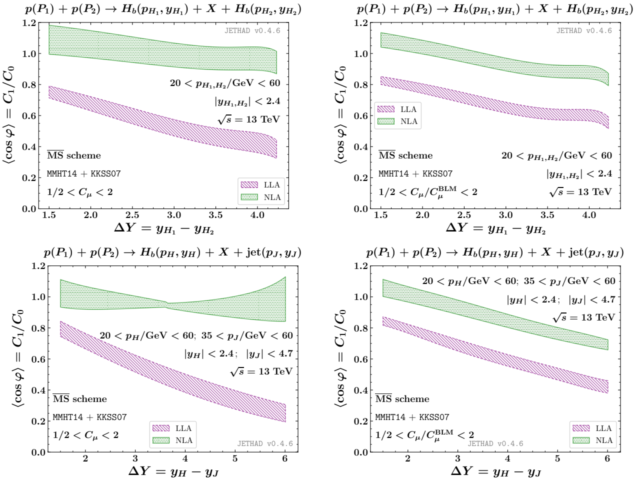
Phenomenology: ϕ-averaged cross section $\mathcal{C}_0$

$$C_0(\Delta Y, s) = \int_{p_1^{\min}}^{p_1^{\max}} d|\vec{p}_1| \int_{p_2^{\min}}^{p_2^{\max}} d|\vec{p}_2| \int_{y_1^{\min}}^{y_1^{\max}} dy_1 \int_{y_2^{\min}}^{y_J^{\max}} dy_2 \, \delta\left(y_1 - y_2 - \Delta Y\right) \mathcal{C}_0 \, ,$$



Phenomenology: Azimuthal correlations $R_{n0}(\Delta Y, s)$

$$R_{10}(\Delta Y, s) = C_1/C_0 \equiv \langle \cos \phi \rangle$$



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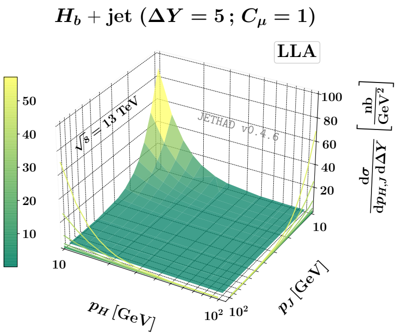
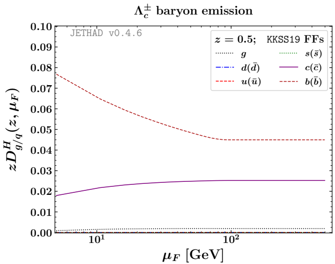
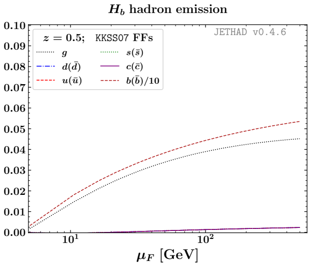
Phenomenology: double differential p_T-distribution

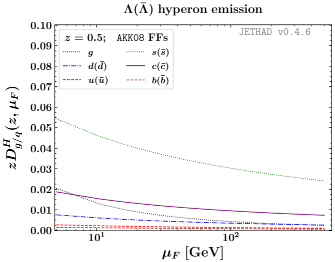
$$\frac{d\sigma(|\vec{p}_{1,2}|, \Delta Y, s)}{d|\vec{p}_1| d|\vec{p}_2| d\Delta Y} = \int_{y_2^{\min}}^{y_2^{\max}} dy_2 \int_{y_1^{\min}}^{y_J^{\max}} dy_1 \, \delta\left(y_1 - y_2 - \Delta Y\right) \mathcal{C}_0 \,,$$



Stabilizing effects of b-flavor fragmentation







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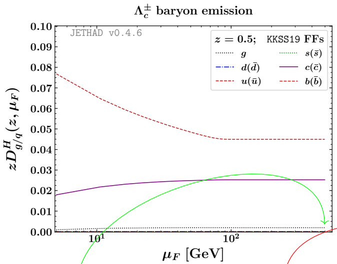
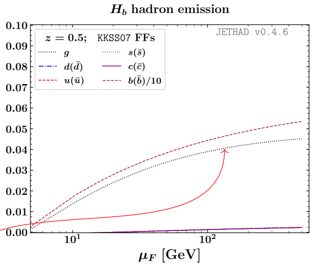
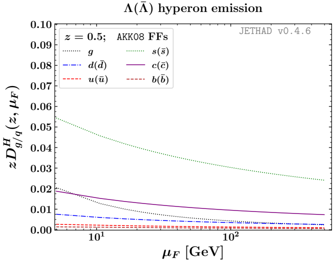
Stabilizing effects of b-flavor fragmentation





- non-decreasing (for KKSS19 Λ_c) and **growth** (KKSS07) with μ_F gluon FF $\Longrightarrow$ (stability).



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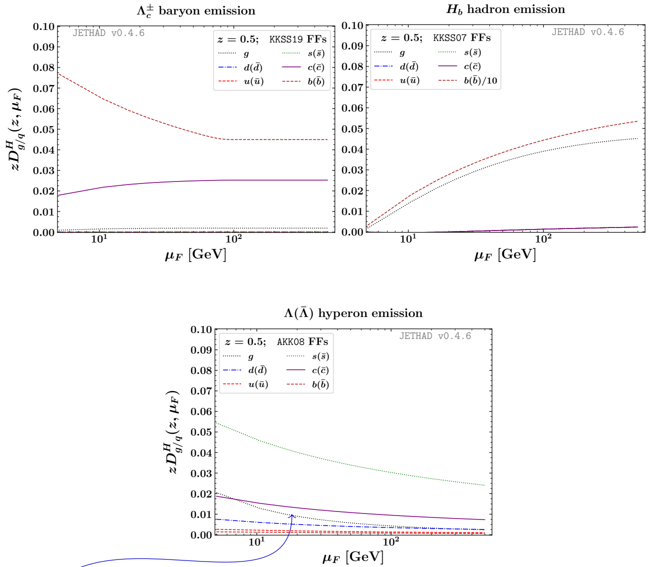
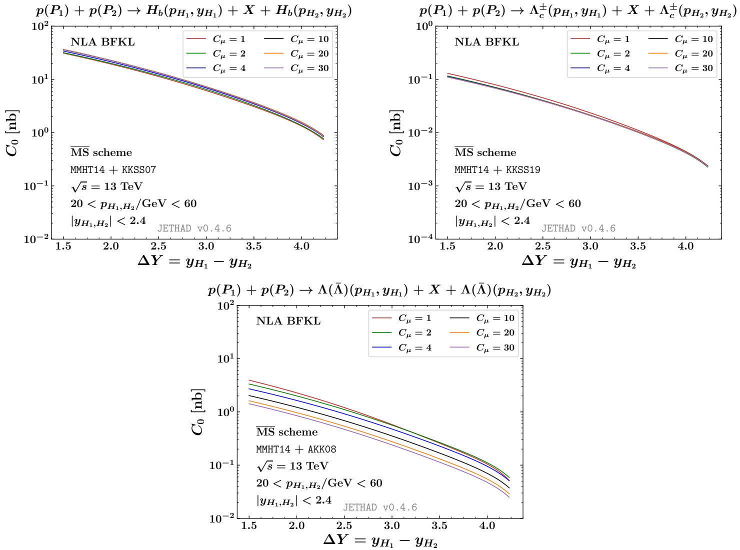
Stabilizing effects of b-flavor fragmentation



- **decreasing** μ_F behavior of the gluon AKK08 $\Longrightarrow$ (increased energy-scale sensitivity).



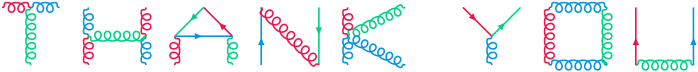
- Λ_c: gluon FF plays a dominant role.

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

- H_b: gluon FF grows with μ_F (compensated with the higher $\mu_R \implies$ stability).

Summary

- Inclusive processes are a promising testfield for the search of BFKL dynamics in current and future colliders.
- Heavy-flavored emissions of bound states act as fair stabilizers of the high-energy series.
- Stabilization effects are stronger present when b-flavored bound-state detections are considered.
- In the H_b + jet channel it was possible to study azimuthal moments at natural scales.
- The stability of our predictions motivates our interest in proposing the hybrid high-energy and collinear factorization as an additional tool to improve the fixed-order description.



FOR YOUR ATTENTION!!

BACKUP

[Slide by Michael Fucilla]

JETHAD

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.)

[Francesco Giovanni Celiberto, *Eur.Phys.J.C 81 (2021) 8, 691*]

Azimuthal coefficients

$$\mathcal{C}_n \equiv \int_0^{2\pi} \mathrm{d}\phi_1 \int_0^{2\pi} \mathrm{d}\phi_2 \, \cos(n\varphi) \, \frac{\mathrm{d}\sigma}{\mathrm{d}y_1 \mathrm{d}y_2 \mathrm{d}|\vec{p}_1| \mathrm{d}|\vec{p}_2| \mathrm{d}\phi_1 \mathrm{d}\phi_2}$$

$$= \frac{e^{\Delta Y}}{s} \int_{-\infty}^{+\infty} \mathrm{d}\nu \left(\frac{x_a x_b s}{s_0} \right)^{\bar{\alpha}_s(\mu_R) \left\{ \chi(n,\nu) + \bar{\alpha}_s(\mu_R) \left[\bar{\chi}(n,\nu) + \frac{\beta_0}{8N_c} \chi(n,\nu) \left[-\chi(n,\nu) + \frac{10}{3} + 2 \ln \left(\frac{\mu_R^2}{\sqrt{\vec{p}_1^2 \vec{p}_2^2}} \right) \right] \right] \right\}}$$

$$\times \, \alpha_s^2(\mu_R) \, c_1(n, \nu, |\vec{p}_1|, x_1) \, [c_2(n, \nu, |\vec{p}_2|, x_2)]^*$$

$$\times \left\{ 1 + \alpha_s(\mu_R) \left[\frac{c_1^{(1)}(n, \nu, |\vec{p}_1|, x_1)}{c_1(n, \nu, |\vec{p}_1|, x_1)} + \left[\frac{c_2^{(1)}(n, \nu, |\vec{p}_2|, x_2)}{c_2(n, \nu, |\vec{p}_2|, x_2)} \right]^* \right] + \bar{\alpha}_s^2(\mu_R) \Delta Y \frac{\beta_0}{4N_c} \chi(n, \nu) f(\nu) \right\} .$$

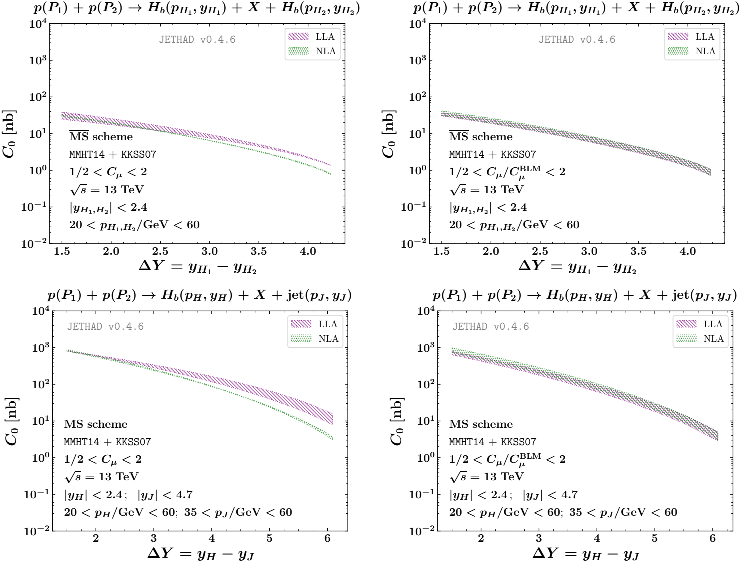
- Rapidity gap: $\Delta Y = y_1 - y_2 = \ln \frac{x_1 x_2 s}{|\vec{p}_1||\vec{p}_2|}$
- $\bar{\alpha}_s(\mu_R) \equiv \alpha_s(\mu_R) N_c/\pi$, with N_c the number of colors, β_0 is the first coefficient of the QCD β-function
- LO BFKL kernel:

$$\chi(n, \nu) = 2 \left\{ \psi(1) - \psi \left(\frac{n+1}{2} + i\nu \right) \right\}, \qquad \psi(z) \equiv \Gamma'(z)/\Gamma(z)$$

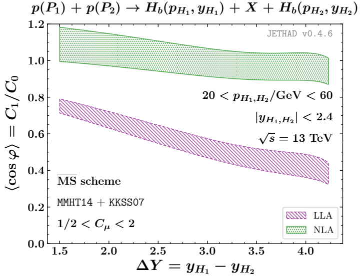
- **NLO correction to the BFKL kernel**

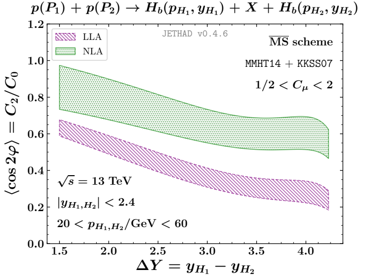
Results:

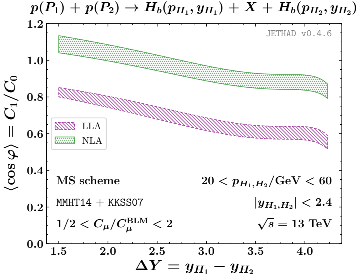
ΔY-shape of C_0 at natural and BLM-optimized scales for $\sqrt{s} = 13$ TeV

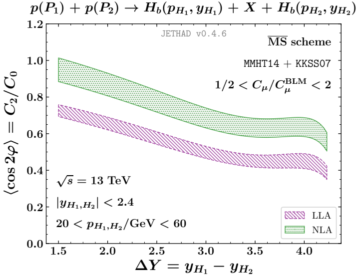


Results:
double H_b

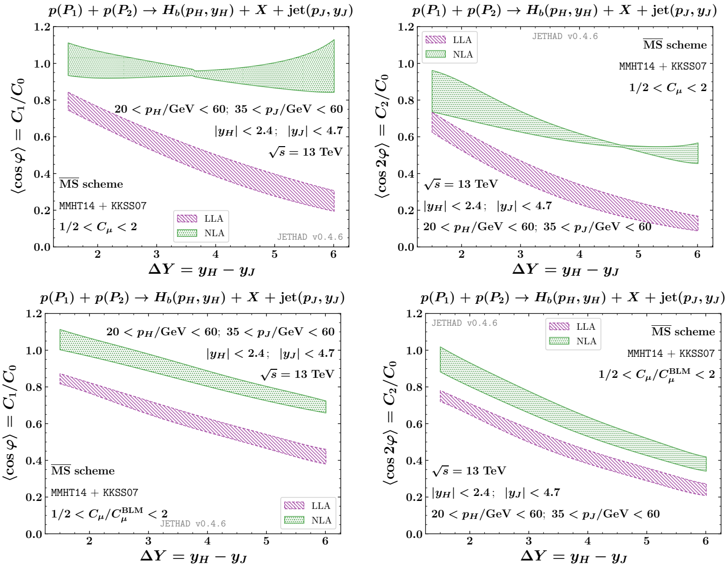


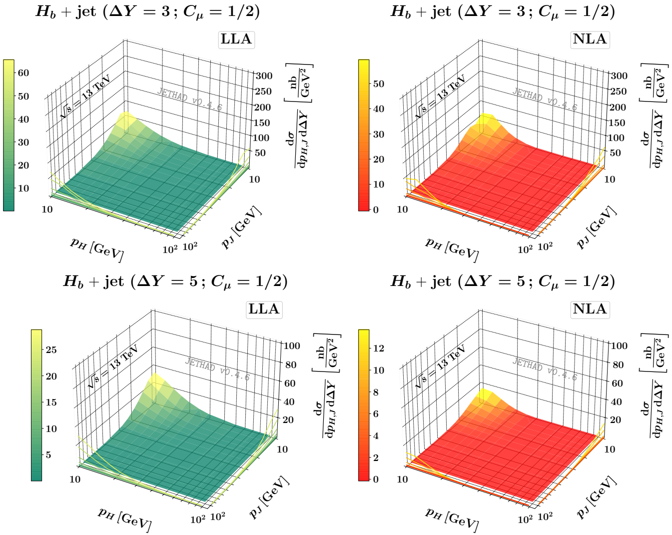






Results:
H_b+ jet





H_b + jet ($\Delta Y = 3$; $C_\mu = 1/2$)
LLA
$\sqrt{s} = 13$ TeV
JETHAD v0.4.6
60
50
40
30
20
10
300
250
200
150
100
50
$\frac{d\sigma}{dp_{H,J}\, d\Delta Y} \left[\frac{\text{nb}}{\text{GeV}^2}\right]$
10
10^2
p_H [GeV]
p_J [GeV]
H_b + jet ($\Delta Y = 3$; $C_\mu = 1/2$)
NLA
$\sqrt{s} = 13$ TeV
JETHAD v0.4.6
50
40
30
20
10
0
300
250
200
150
100
50
$\frac{d\sigma}{dp_{H,J}\, d\Delta Y} \left[\frac{\text{nb}}{\text{GeV}^2}\right]$
10
10^2
p_H [GeV]
p_J [GeV]
H_b + jet ($\Delta Y = 5$; $C_\mu = 1/2$)
LLA
$\sqrt{s} = 13$ TeV
JETHAD v0.4.6
25
20
15
10
5
100
80
60
40
20
$\frac{d\sigma}{dp_{H,J}\, d\Delta Y} \left[\frac{\text{nb}}{\text{GeV}^2}\right]$
10
10^2
p_H [GeV]
p_J [GeV]
H_b + jet ($\Delta Y = 5$; $C_\mu = 1/2$)
NLA
$\sqrt{s} = 13$ TeV
JETHAD v0.4.6
12
10
8
6
4
2
0
100
80
60
40
20
$\frac{d\sigma}{dp_{H,J}\, d\Delta Y} \left[\frac{\text{nb}}{\text{GeV}^2}\right]$
10
10^2
p_H [GeV]
p_J [GeV]