Heavy flavored emissions in hybrid collinear/high energy factorization

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in collaboration with
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based on

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Outline

Introduction and motivations

BFKL resummation

Hybrid collinear/high-energy factorization

Heavy flavor production

- Open state production: Heavy-light dijet
- Bound state: Λ_c-baryon production
- Bound state: 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

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

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

- UGD sector

  The evolution of the Unintegrated gluon density,

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

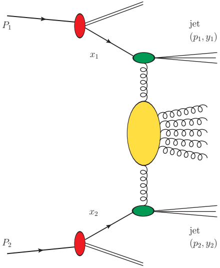
  as a function of $\ln(1/x) = \ln(s/Q^2)$, is governed by BFKL:

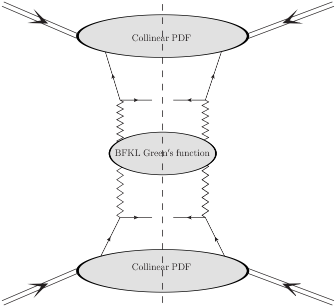
$$\frac{\partial \mathcal{F}}{\partial \ln(1/x)} = \mathcal{F} \otimes \mathcal{K}$$

Hybrid collinear/high-energy factorization

Mueller-Navelet jets

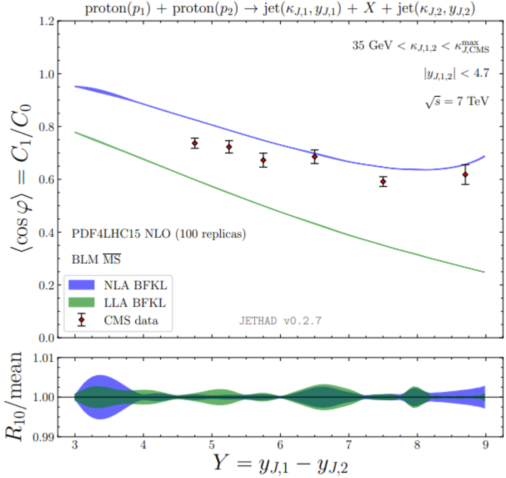
- Inclusive two jet production in proton-proton collision
- Large p_T and large rapidity separation
- Large energy logarithms → BFKL resummed partonic cross section
- Moderate values of parton x → collinear PDFs





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

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.G. 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

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

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:

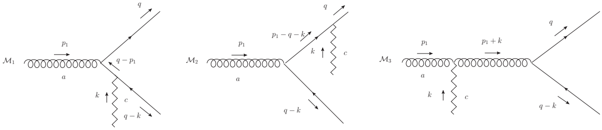
suppress NLO IFs + NLO Kernel β_0-dependent factors

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

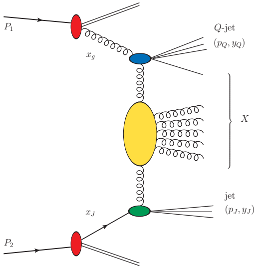
- Process:

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

- **Hadronic cross section**

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

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

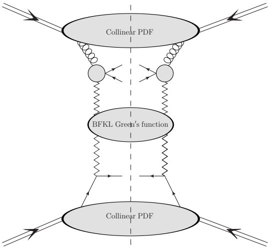


- **BFKL partonic cross section**

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

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

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



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

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

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

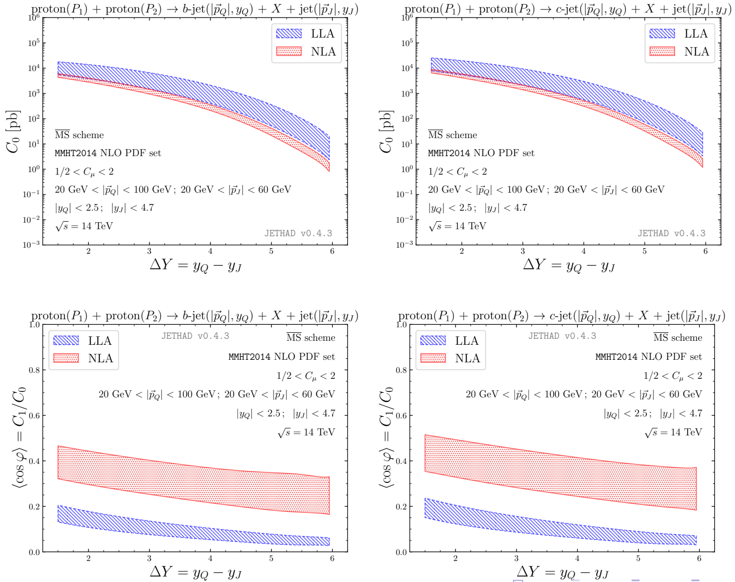
$$\times\ \alpha_s^3(\mu_R)\, c_Q(n,\nu,\vec{p}_Q,z_Q,x_g)\,[c_J(n,\nu,\vec{p}_J)]^*$$

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

- Azimuthal-angle coefficients

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

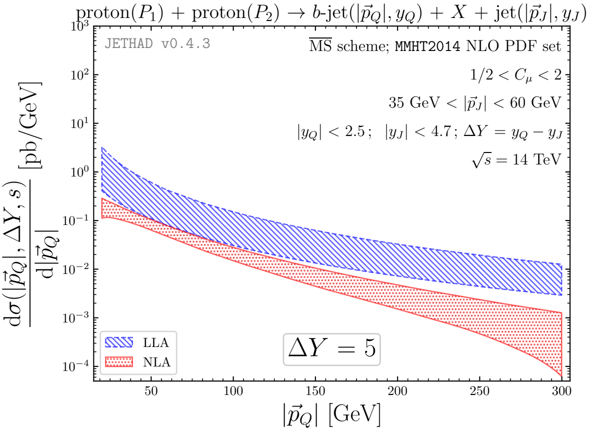
Azimuthal-angle coefficients and their ratios



Heavy-light dijet: Observables

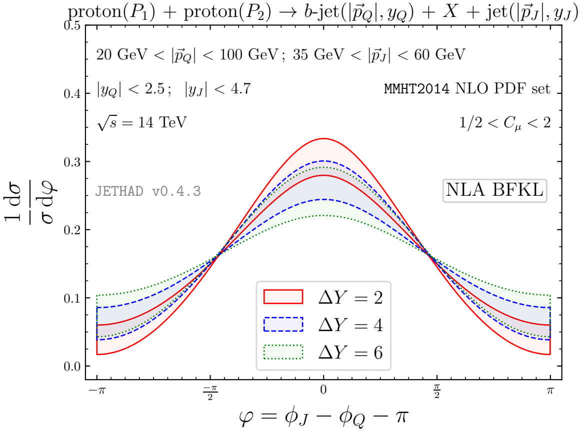
Heavy-jet p_T-distribution

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



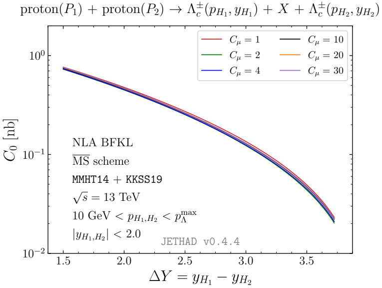
Azimuthal distribution

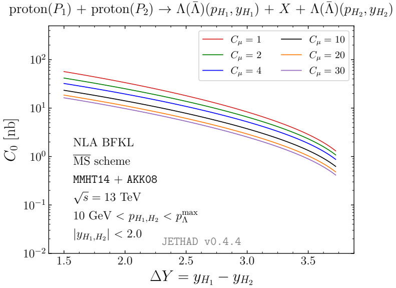
$$\frac{d\sigma_{pp}(\varphi, \Delta Y, s)}{\sigma_{pp} d\varphi} = \frac{1}{\pi}\left\{\frac{1}{2} + \sum_{n=1}^{\infty} \cos(n\varphi)\langle\cos(n\varphi)\rangle\right\} \equiv \frac{1}{\pi}\left\{\frac{1}{2} + \sum_{n=1}^{\infty} \cos(n\varphi) R_{n0}\right\}$$



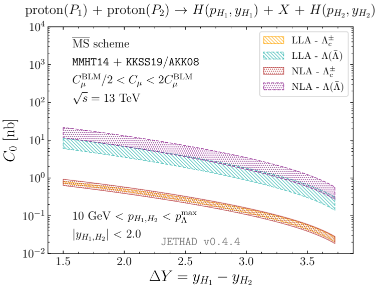
Λ-baryon production

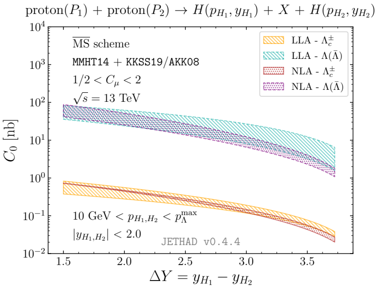
- Process: proton(p_1) + proton(p_2) $\to \Lambda + X + \Lambda$
  [F.G. Celiberto, M. F., Dmitry Yu. Ivanov, Alessandro Papa (2021)]
- Zero-mass variable flavor number scheme (ZM-VFNS)
- Light parton NLO impact factors $\to$ Heavy baryon NLO impact factor
  [M. Ciafaloni and G. Rodrigo (2000)] [V.S. Fadin et al. (2000)]
  [D.Yu. Ivanov, A. Papa (2012)]
- Lambda FFs
  - heavy species $\longrightarrow \Lambda_c$
    KKSS19 [B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger (2020)]
  - light species $\longrightarrow \Lambda^0$
    AKK08 [S.Albino, B.A. Kniehl, and G. Kramer (2008)]

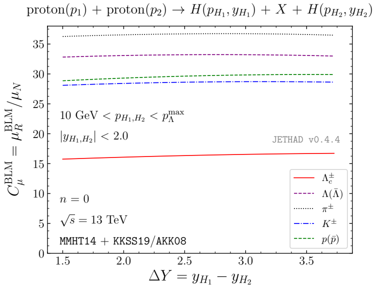




Λ-baryon production



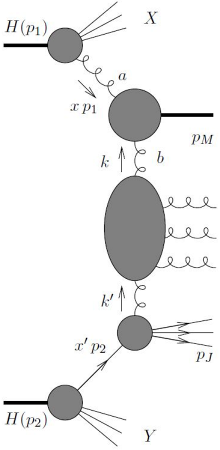




J/ψ production

- Process: proton(p_1) + proton(p_2) $\to J/\psi + X +$ 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 complete (or partial) NLLA effects 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/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 the small-x transverse-momentum-dependent gluon distribution (UGD)

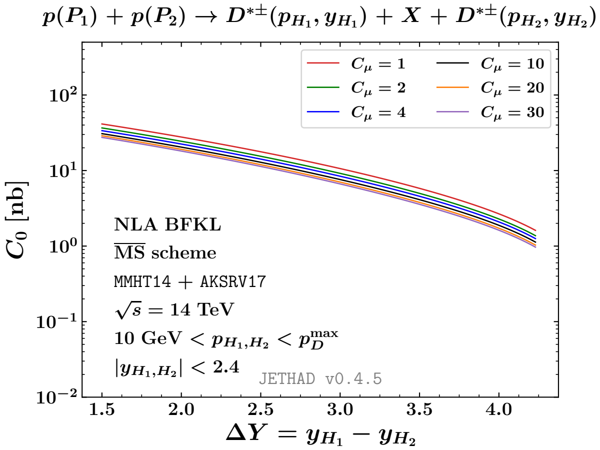
Thank you for the attention

Backup

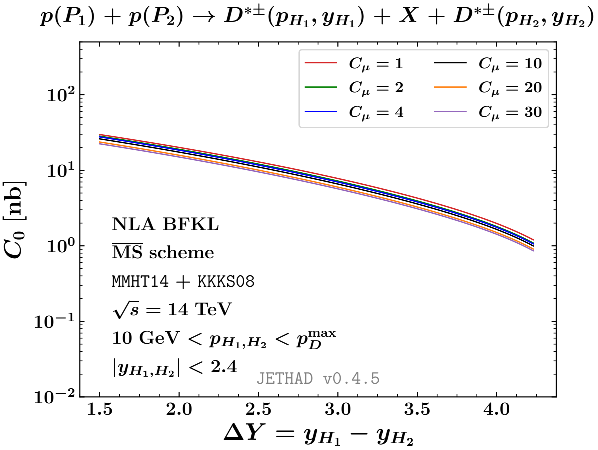
Towards bound states: Flavor number schemes

- 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

Backup


$p(P_1) + p(P_2) \to D^{*\pm}(p_{H_1}, y_{H_1}) + X + D^{*\pm}(p_{H_2}, y_{H_2})$
$C_\mu = 1$
$C_\mu = 2$
$C_\mu = 4$
$C_\mu = 10$
$C_\mu = 20$
$C_\mu = 30$
10^2
10^1
10^0
10^{-1}
10^{-2}
C_0 [nb]
NLA BFKL
$\overline{\text{MS}}$ 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
1.5
2.0
2.5
3.0
3.5
4.0
$\Delta Y = y_{H_1} - y_{H_2}$

Backup



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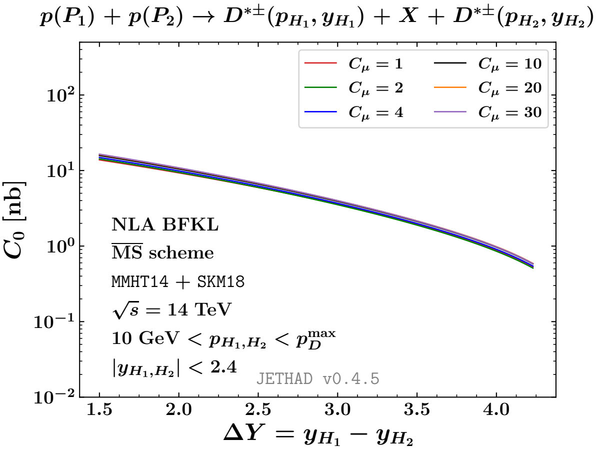

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