

# BFKL phenomenology: Resummation of high-energy logs in inclusive processes

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Based on

- ⌚ [F. G. Celiberto, D. Yu. Ivanov, M. M. A. M, A. Papa ,*Eur. Phys. J. C* 81, 293]
- ⌚ [F. G. Celiberto, D. Yu. Ivanov, A. Papa, *Phys. Rev. D* 102, 094019]

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# Outline

## 1 Introduction

- BFKL Resummation
- Typical BFKL observables

## 2 Recent new probes: the inclusive Higgs-plus-jet production

- Kinematic configurations
- Numerical results

## 3 ...the inclusive production of $\Lambda$ hyperons

- Kinematic configurations
- Numerical results

## 4 Conclusions

## BFKL Resummation..

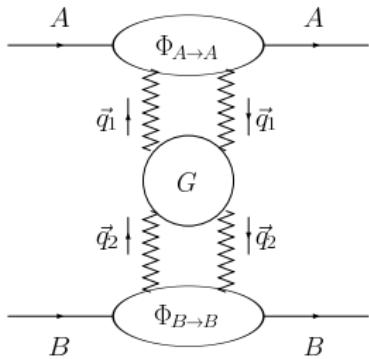
- hadronic scattering processes with a hard scale  $Q^2 \gg \Lambda_{\text{QCD}}^2$  described within pQCD
  - in high-energy limit  $s \gg Q^2$ :  $\Rightarrow \alpha_s(Q) \ln s/Q^2 \sim 1$  need to be resummed
  - BFKL resummation:**

**leading logarithmic approximation (LLA):**  $\alpha_s^n (\ln s)^n$

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

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

[V.S. Fadin,L.N. Lipatov, D. Ciafaloni, G. Gamici (1998)]



## BFKL factorization:

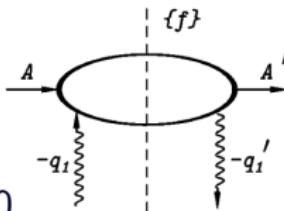
$$\sigma_{AB}(s) = \int\limits_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \int \frac{d^2 q_2}{2\pi \vec{q}_2^2} \int \frac{d^2 q_1}{2\pi \vec{q}_1^2} \left( \frac{s}{s_0} \right)^\omega$$

- **Green's function** is process-independent
    - determined through the BFKL equation
  - **Impact factors** are process-dependent
    - known in the NLA just for limited cases.

- Impact factors: account for the coupling of the Pomeron to the hadrons.

**Universal property:**  $\Phi(k, q)|_{\substack{k-q \rightarrow 0 \\ k \rightarrow 0}}$

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



$$\Phi_{AA'}(\vec{q}) = \sum_{\{f\}} \int \frac{dM_{AR}}{2\pi} \Gamma_{\{f\}A}^{(0)c} [\Gamma_{\{f\}A'}^{(0)c'}]^* d\rho_f$$

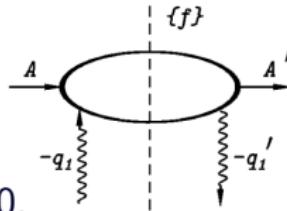
[V.S. Fadin ,R. Fiore (1998)]

- ## Effective vertices

Evaluated in the LLA or Born approximation



**Impact factors:** account for the coupling of the Pomeron to the hadrons.



Universal property:  $\Phi(k, q)|_{k \rightarrow 0}^{k-q \rightarrow 0} \rightarrow 0,$

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$$\boxed{\Phi_{AA'}(\vec{q}) = \sum_{\{f\}} \int \frac{dM_{AR}}{2\pi} \Gamma_{\{f\}A}^{(0)c} [\Gamma_{\{f\}A'}^{(0)c'}]^* d\rho_f}$$

[V.S. Fadin ,R. Fiore (1998)]



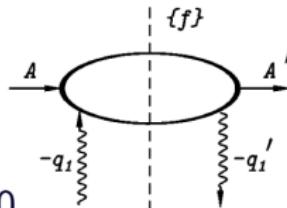
## Phase space

$$d\rho_f = (2\pi)^D \delta^{(D)} \left( P_A - q_1 - \sum_{\{f\}} I_f \right) \prod_{\{f\}} \frac{d^{D-1} I_f}{2\epsilon_f (2\pi)^{D-1}}$$

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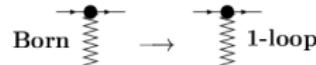
- particle-Reggeon squared **invariant mass**

$$M_{AR} = (P_A - q_1)^2 = (P_{A'} - q_1')^2$$

- In the NLA, modification needed..

- Higher order corrections to  
 $\Gamma_{AA'} \rightarrow \Gamma_{AA'}^{(0)} + \Gamma_{AA'}^{(1)}$
  - Extra gluons:

- Extra gluons:
    - fragmentation region
    - central region



$$\Phi_{AA'}(\vec{q}, s_0) = \sum_{\{f\}} \int \frac{dM_{AR} d\rho_f}{2\pi} \Gamma_{\{f\}A}^c [\Gamma_{\{f\}A'}^{c'}]^* \theta(M_\Lambda - M_{AR})$$

$$-\frac{1}{2} \int \frac{d^{D-2}q'}{\vec{q}'^2 (\vec{q}' - \vec{q})^2} \Phi_{A'A}^{(B)}(\vec{q}', \vec{q}) \mathcal{K}_r^{(B)}(\vec{q}', \vec{q}_R) \ln \left( \frac{s_\Lambda^2}{(\vec{q}' - \vec{q}_R)s_0} \right)$$

[V.S. Fadin ,R. Fiore (1998)]

- Full NLA:

▷ shortened by the narrow list of available IFs at NLO:

(mn-jets)[B. Ducloué, L. Szymanowski, S. Wallon (2014)]

[F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa (2014)]

[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2015)]

(di-hadron)[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A.Papa (2016,2017)]

(hadron-jet)[A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, M.M.A.M, A.Papa (2018)]

- Partial NLA:

▷ inclusion of the two IFs with a universal NLO part, along with the full NLA BFKL kernel:

(four-jet)[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2016)]

[F. Caporale, F.G. Celiberto, G. Chachamis, A. Sabio Vera (2016)]

(multi-jet)[F. Caporale, F.G. Celiberto, G. Chachamis, D.G. Gomez, A. Sabio Vera (2016,2017)]

( $J/\psi$ -jet production)[R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]

(Drell-Yan pair -jet)[K. Golec-Biernat, L. Motyka, T. Stebel (2018)]

(photoproduction)[F.G. Celiberto, D.Yu. Ivanov, B. Murdaca, A. Papa (2018)]

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

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

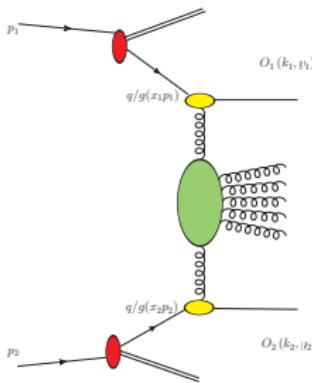
(Higgs-jet) [F. G. Celiberto, D. Yu. Ivanov, M. M. A. M, A. Papa (2020)]

# BFKL cross section...

Process: proton( $p_1$ ) + proton( $p_2$ )  $\rightarrow O_1(\vec{k}_1, y_1) + X + O_2(\vec{k}_2, y_2)$ ,

where  $O_{1,2}$  are emitted with **high**  $k_{1,2} >> \Lambda_{\text{QCD}}$ , and **large rapidity separation**  $\Delta Y = |y_1 - y_2|$

$$\frac{d\sigma}{dx_{O_1} dx_{O_2} d^2 k_{O_1} d^2 k_{O_2}} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 f_i(x_1, \mu) f_j(x_2, \mu) \frac{d\hat{\sigma}_{i,j}(x_1 x_2 s, \mu)}{dx_{O_1} dx_{O_2} d^2 k_{O_1} d^2 k_{O_2}}$$



- ➊ slight change of variable in the final state
- ➋ project onto the eigenfunctions of the LO BFKL kernel, i.e. transfer from the reggeized gluon momenta to the  $(n, \nu)$ -representation
- ➌ suitable definition of the **azimuthal coefficients**

$$\frac{d\sigma}{dx_{O_1} dx_{O_2} d|\vec{k}_{O_1}| d|\vec{k}_{O_2}| d\phi_{O_1} d\phi_{O_2}} = \frac{1}{(2\pi)^2} \left[ C_0 + \sum_{n=1}^{\infty} 2 \cos(n\phi) C_n \right]$$

with  $\phi = \phi_{O_1} - \phi_{O_2} - \pi$

# Typical BFKL observables

$$\mathcal{C}_n \equiv \int_0^{2\pi} d\phi_{O_1} \int_0^{2\pi} d\phi_{O_2} \cos[n(\phi_{O_1} - \phi_{O_2} - \pi)] \frac{d\sigma}{dy_1 dy_2 d|\vec{k}_{O_1}| d|\vec{k}_{O_2}| d\phi_1 d\phi_2}$$

$$\begin{aligned}
 &= \frac{e^{\Delta Y}}{s} \int_{-\infty}^{+\infty} d\nu \left( \frac{x_{O_1} x_{O_2} s}{s_0} \right)^{\bar{\alpha}_s(\mu_R)} \left\{ \chi(n, \nu) + \bar{\alpha}_s(\mu_R) \left[ \bar{\chi}(n, \nu) + \frac{\beta_0}{8N_c} \chi(n, \nu) \left[ -\chi(n, \nu) + \frac{10}{3} + 2 \ln \left( \frac{\mu_R^2}{\sqrt{\vec{k}_{O_1}^2 \vec{k}_{O_2}^2}} \right) \right] \right] \right\} \\
 &\quad \times \alpha_s^2(\mu_R) c_1(n, \nu, |\vec{k}_{O_1}|, x_{O_1}) [c_2(n, \nu, |\vec{k}_{O_2}|, x_{O_2})]^* \\
 &\quad \times \left\{ 1 + \alpha_s(\mu_R) \left[ \frac{c_1^{(1)}(n, \nu, |\vec{k}_{O_1}|, x_{O_1})}{c_1(n, \nu, |\vec{k}_{O_1}|, x_{O_1})} + \left[ \frac{c_2^{(1)}(n, \nu, |\vec{k}_{O_2}|, x_{O_2})}{c_2(n, \nu, |\vec{k}_{O_2}|, x_{O_2})} \right]^* \right] \right. \\
 &\quad \left. + \bar{\alpha}_s^2(\mu_R) \ln \left( \frac{x_{O_1} x_{O_2} s}{s_0} \right) \frac{\beta_0}{4N_c} \chi(n, \nu) f(\nu) \right\}.
 \end{aligned}$$

➊ Rapidity gap:  $\Delta Y = \ln \frac{x_{O_1} x_{O_2} s}{|\vec{k}_{O_1}| |\vec{k}_{O_2}|}$

➋ LO BFKL kernel:

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

➌ NLO correction to the BFKL kernel

# Typical BFKL observables

Integrated coefficients over the phase space for the two emitted objects,  $O_{1,2}(\vec{k}_{1,2}, y_{1,2})$ , while their rapidity distance,  $\Delta Y = y_1 - y_2$ , is kept fixed

$$C_n^{NLA/LLA}(\Delta Y, s) = \int_{k_1^{\min}}^{k_1^{\max}} d|\vec{k}_1| \int_{k_2^{\min}}^{k_2^{\max}} d|\vec{k}_2| \int_{y_1^{\min}}^{y_1^{\max}} dy_1 \int_{y_2^{\min}}^{y_2^{\max}} dy_2 \delta(y_1 - y_2 - \Delta Y) C_n^{NLA/LLA}$$

## Observables:

- $\phi$ -averaged cross section  $\mathcal{C}_0$  and the ratio

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

- Azimuthal-correlation moments

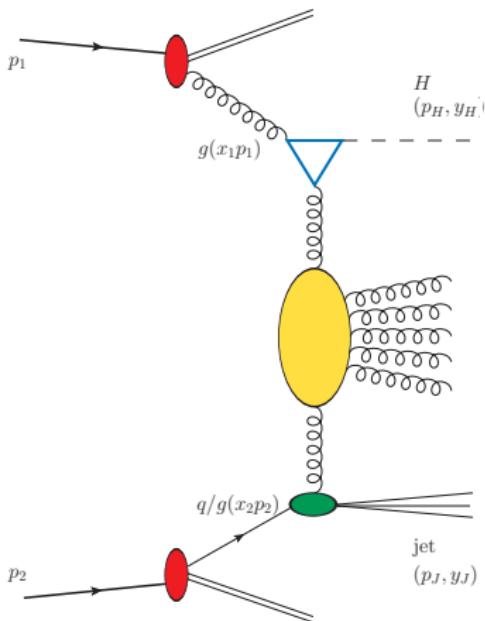
$$\frac{\langle \cos[2(\phi_1 - \phi_2 - \pi)] \rangle}{\langle \cos(\phi_1 - \phi_2 - \pi) \rangle} \equiv \frac{\mathcal{C}_2}{\mathcal{C}_1} \equiv R_{21}, \quad \frac{\langle \cos[3(\phi_1 - \phi_2 - \pi)] \rangle}{\langle \cos[2(\phi_1 - \phi_2 - \pi)] \rangle} \equiv \frac{\mathcal{C}_3}{\mathcal{C}_2}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

→ minimise further any **contamination** from collinear logarithms

# **inclusive Higgs-plus-jet production at the LHC**

## Process:

$$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow H(\vec{p}_H, y_H) + X + \text{jet}(\vec{p}_J, y_J)$$



- large Higgs/jet transverse momenta:  
 $\vec{p}_H^2 \sim \vec{p}_J^2 \gg \Lambda_{\text{QCD}}^2 \Rightarrow pQCD$
  - large rapidity intervals between the tagged particles (high energies)  $\Rightarrow \Delta y = \ln \frac{x_H x_J s}{|\vec{p}_H| |\vec{p}_J|} \Rightarrow \text{BFKL resummation}$

[F. G. Celiberto, D. Yu. Ivanov, M. M. A. M, A. Papa ,(2020)]

# Observables and kinematics

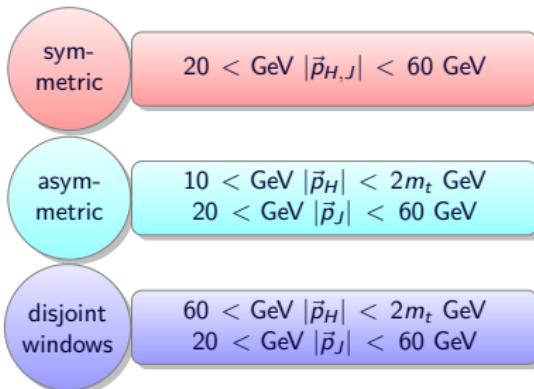
- $\phi$ -averaged cross section  $\mathcal{C}_0$

$$C_n(\Delta Y, s) = \int_{p_H^{\min}}^{p_H^{\max}} d|\vec{p}_H| \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_H - y_J - \Delta Y) \mathcal{C}_n,$$

- $p_H$  -distribution:

$$\frac{d\sigma(|\vec{p}_H|, \Delta Y, s)}{d|\vec{p}_H| d\Delta Y} = \int_{p_J^{\min}}^{p_J^{\max}} d|\vec{p}_J| \int_{y_H^{\min}}^{y_H^{\max}} dy_H \int_{y_J^{\min}}^{y_J^{\max}} dy_J \delta(y_H - y_J - \Delta Y) \mathcal{C}_0,$$

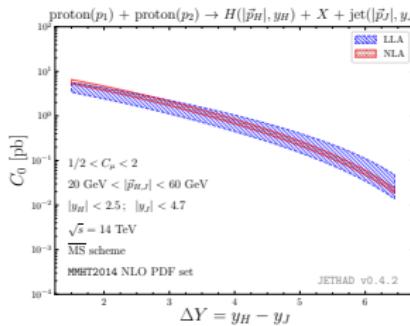
with  $|y_H| < 2.5, |y_J| < 4.7$  inside the CMS rapidity acceptances.



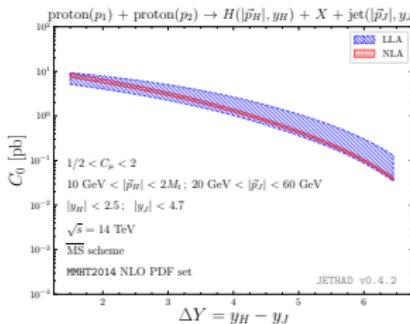
- An appropriate region to Search for pure **BFKL** signal.
- The realistic LHC cuts.
- Maximum exclusiveness in the final state.

# Numerical results:

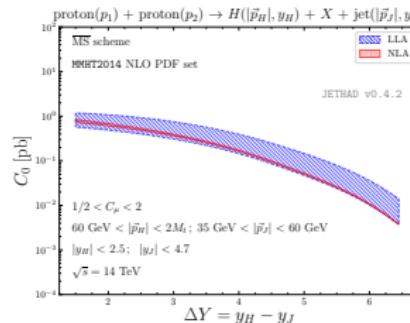
$\Delta Y$ -dependence of the  $\phi$ -averaged cross section in the three considered  $p_T$  -range



Symmetric



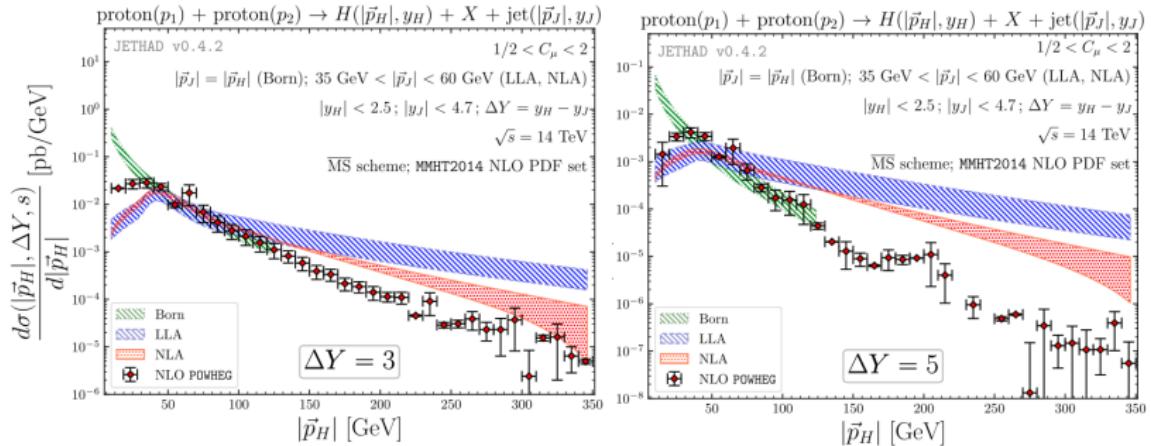
Asymmetric



Disjoint

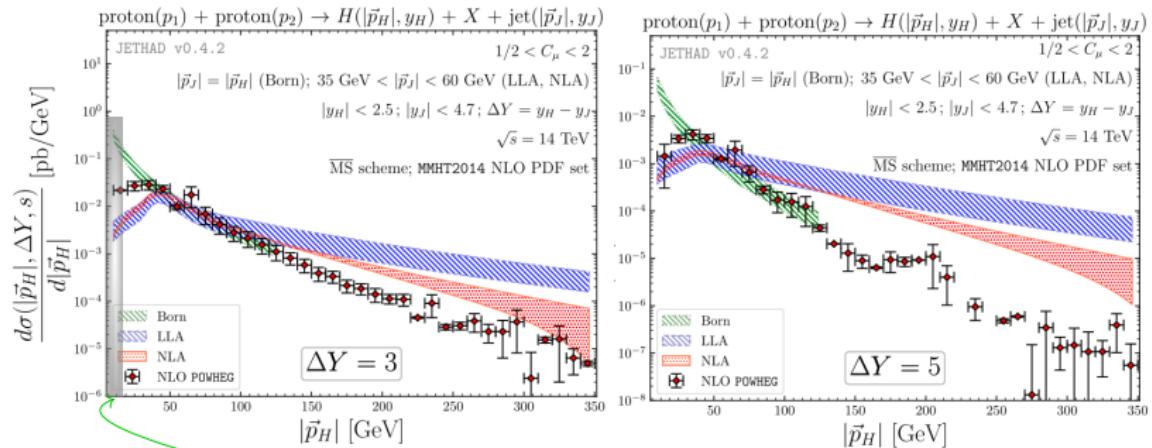
# Numerical results:

$p_T$ -dependence of the cross section for  $35 \text{ GeV} < |\vec{p}_J| < 60 \text{ GeV}$



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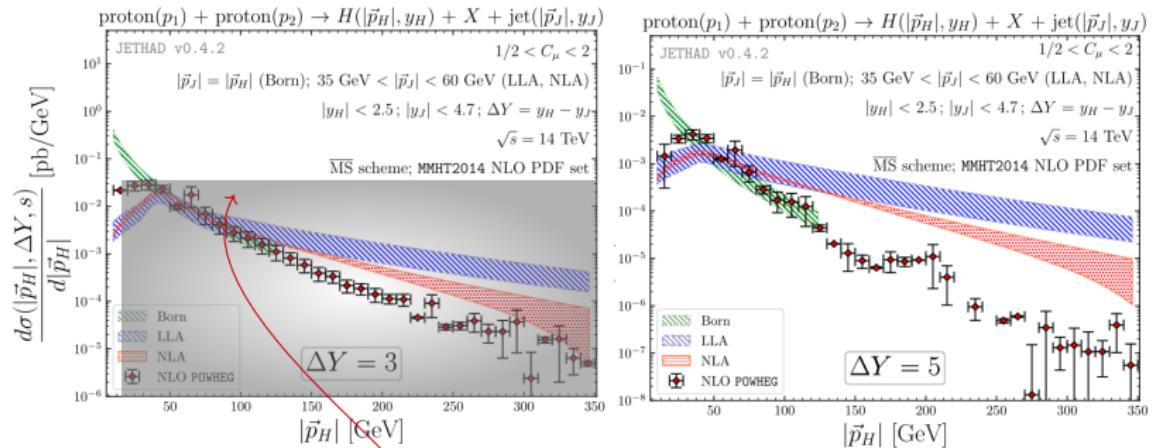
$p_T$ -dependence of the cross section for  $35 \text{ GeV} < |\vec{p}_J| < 60 \text{ GeV}$



Dominated by large  $p_T$ -logs:  $\rightarrow$  all-order resummation needed

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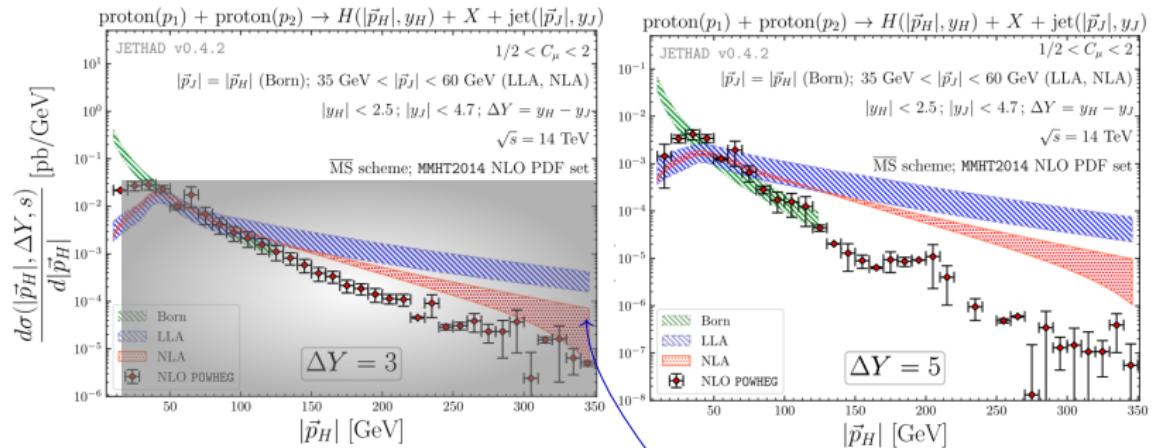
$p_T$ -dependence of the cross section for  $35 \text{ GeV} < |\vec{p}_J| < 60 \text{ GeV}$



- Expected BFKL semi-hard regime:

# Numerical results:

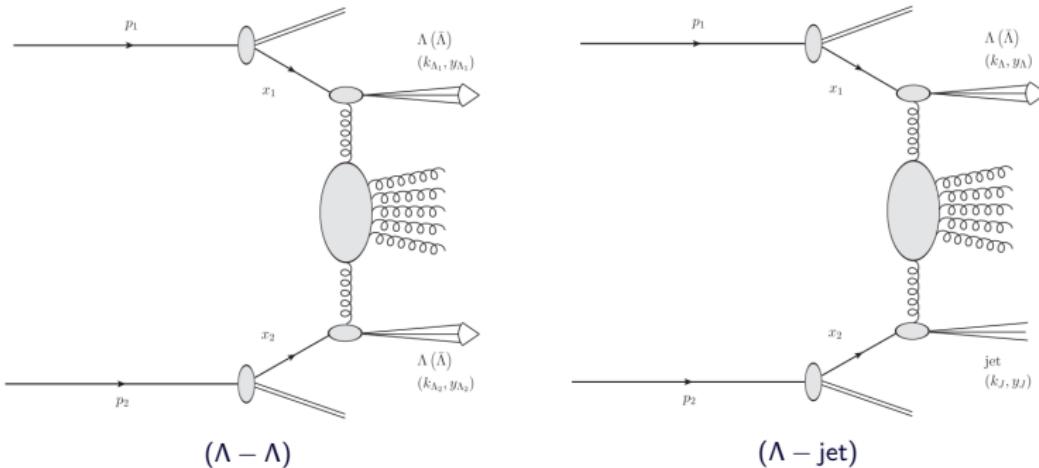
$p_T$ -dependence of the cross section for  $35 \text{ GeV} < |\vec{p}_J| < 60 \text{ GeV}$



- ➊ DGLAP-type logs + threshold effects → BFKL decoupling:

## Inclusive diffraction production of $\Lambda$ hyperons

$$\text{proton}(\vec{p}_1) + \text{proton}(\vec{p}_2) \rightarrow \Lambda(\vec{p}_H, y_H) + X + P(\vec{p}_J, y_J), \quad \text{where } P \equiv \{\Lambda, \text{jet}\}$$



- ▷ quench **minimum-bias** effects.
  - ▷ natural **asymmetric** kinematic configurations.
  - ▷ probe and constrain collinear **FFs**.

[F. G. Celiberto, D. Yu. Ivanov, A. Papa, *Phys. Rev. D* 102, 094019]

# Theoretical setup

- BFKL  $C_0^{NLA}$  and  $C_{n \geq 1}^{NLA}$  presented in (MOM) scheme with (BLM) renormalization scale fixing:

$$C_n^{NLA} = \frac{x_1 x_2}{k_1 k_2} \int_{-\infty}^{\infty} d\nu \left( \frac{\hat{s}}{k_1 k_2} \right)^{Y \bar{\alpha}_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \left[ \chi(n, \nu) + \bar{\alpha}_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \left( \tilde{\chi}(n, \nu) + \frac{T^{\text{conf}}}{3} \chi(n, \nu) \right) \right]} \left( \alpha_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \right)^2$$

$$\times c_1(n, \nu) [c_2(n, \nu)]^* \left\{ 1 + \bar{\alpha}_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \left[ \frac{\bar{c}_1^{(1)}(n, \nu)}{c_1(n, \nu)} + \left[ \frac{\bar{c}_2^{(1)}(n, \nu)}{c_2(n, \nu)} \right]^* + \frac{2T^{\text{conf}}}{3} \right] \right\}.$$

- LO  $\Lambda/\text{jet IF}$ :

$$c_i(n, \nu, |\vec{k}|, x) = 2 \sqrt{\frac{C_F}{C_A}} (\vec{k}^2)^{i\nu - 1/2} \int_x^1 d\beta \left( \frac{\beta}{x} \right)^{2i\nu - 1}$$

$$\times \left[ \frac{C_A}{C_F} f_g(\beta) S_g(x, \beta) + \sum_{r=q, \bar{q}} f_r(\beta) S_r(x, \beta) \right],$$

where

$$S_{g,r}(x, \beta) = \begin{cases} \frac{1}{\beta} D_{g,r}^\Lambda(x/\beta), & i \equiv \Lambda; \\ \delta(\beta - x), & i \equiv \text{Jet}. \end{cases}$$

- DGLAP azimuthal coefficients are introduced as truncation to the  $\mathcal{O}(\alpha_s^3)$  order of the corresponding NLA BFKL ones

$$C_n^{NLA} = \frac{x_1 x_2}{k_1 k_2} \int_{-\infty}^{\infty} d\nu \left( \alpha_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \right)^2 c_1(n, \nu) [c_2(n, \nu)]^*$$

$$\times \left\{ 1 + \alpha_s^{\text{MOM}}(\mu_R^{\text{BLM}}) \left[ \frac{C_A}{\pi} \ln \left( \frac{\hat{s}}{k_1 k_2} \right) \chi(n, \nu) + \frac{\bar{c}_1^{(1)}(n, \nu)}{c_1(n, \nu)} + \left[ \frac{\bar{c}_2^{(1)}(n, \nu)}{c_2(n, \nu)} \right]^* + \frac{2T^{\text{conf}}}{3} \right] \right\}.$$

# kinematic configurations and final state observable

## ● Kinematics:

- $\Lambda$  hyperon is detected in symmetric rapidity range: -2 to 2 and transverse momenta larger than 10 GeV < (typical CMS measurements) and less than 21.5 GeV.
- jet emission with two possibilities:
  - CMS:  $|y_J| < 4.7$  and  $35 \text{ GeV} < k_J^{\max} = 60 \text{ GeV}$
  - CASTOR:  $-6.6 < y_J < -5.2$  and  $10 \text{ GeV} < k_J^{\max} \simeq 17.68 \text{ GeV}$

## ● Observables:

- Correlation coefficients
- $R_{nm} = \frac{\mathcal{C}_n}{\mathcal{C}_m}$ , with  $m, n = 1, 2, 3$
- $\phi$ -averaged cross section  $\mathcal{C}_0$

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- constrained by the lower cutoff of the FF sets (AKK2008nlo)

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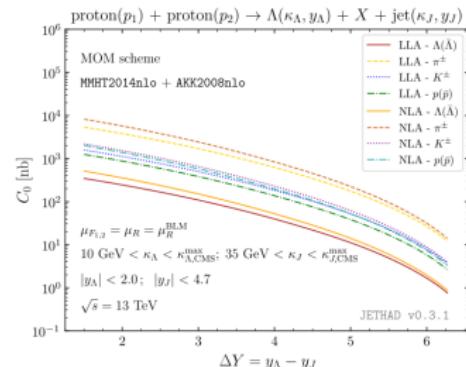
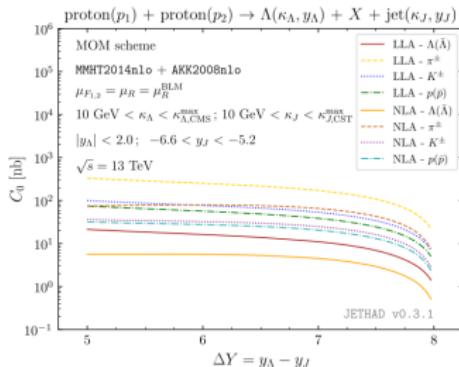
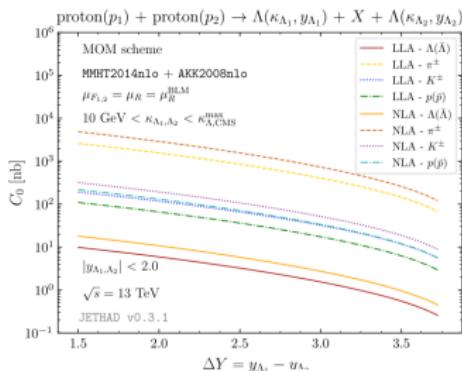
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- $\phi$ -averaged cross section  $\mathcal{C}_0$

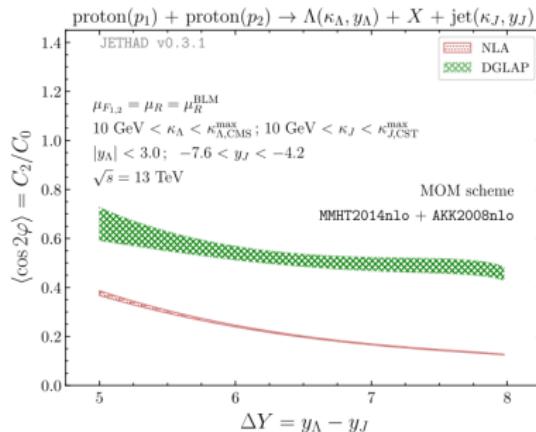
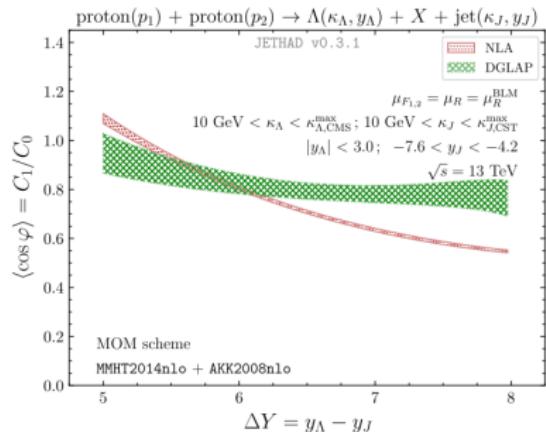
# Numerical results: $C_0$

NLA BFKL,  $\sqrt{s} = 13$  TeV



# BFKL Vs high-energy DGLAP predictions for $R_{10}$ and $R_{20}$

CASTOR-jet configuration with enlarged rapidity ranges

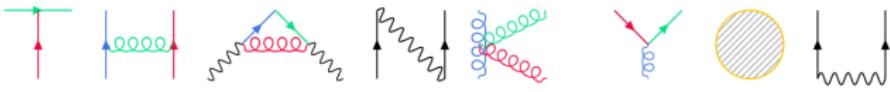


General remarks:

- ▷ distance between BFKL and DGLAP at large rapidity distances
- ▷ natural asymmetric selection for the transverse-momentum  $\rightarrow$  quenches the Born contribution
- ▷ same patterns found in the mn-jet channel and hadron-jet

# Conclusions

- Inclusive processes with tagged objects (jets and/or identified hadrons, Higgs, ...) in the final state featuring large **rapidity separation** are a promising **testfield** for the search of BFKL dynamics in current and future colliders.
- The different nature of the final state tagged particles affords us opportunity to access naturally **asymmetric** kinematic configurations, an essential ingredient to **discriminate** BFKL from other resummations
- Higgs-jet hadroproduction genuinely exhibits a solid **stability** under higher-order corrections.
- The cross section for  $\Lambda$  baryons production channel, suppressing contamination of the so-called **minimum-bias events**, which allows for an easier comparison with **experimental data**.
- The qualitative description for  $p_{HT}$ -distribution and processes with CASTOR-jet kinematics would rely on a **unified formalism** where distinct resummations are concurrently embodied.



**FOR YOUR ATTENTION!!**

All numerical analysis and (resulted plots) were performed and (generated) using the JETHAD.

[Francesco Giovanni Celiberto, arXiv:2008.07378]

## 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.)