Inclusive Higgs-Jet production in high-energy hadron collisions

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Outline

Motivation

- Semi-hard processes in the large center-of-mass energy limit gives us an opportunity to further test the perturbative QCD
- The high-energy limit $s \gg Q^2 \gg \Lambda_{\rm QCD}$: $\Rightarrow \alpha_s(Q) \ln s/Q^2 \sim 1$ need to be resummed
- The Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach provides a general framework for this resummation: it predicts a peculiar behavior of amplitudes at high energies and is expected to precede the onset of saturation physics.
- Clearly, a significant question for collider phenomenology is measuring dependably 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.
- Here, we suggest a new one in the inclusive hadroproduction Higgs + jet separated in rapidity.

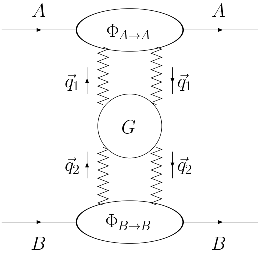
Outline

BFKL Resummation..

- **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:

$$\sigma_{AB}(s) = \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \int \frac{d^2 q_2}{2\pi \vec{q}_2^{\,2}} \int \frac{d^2 q_1}{2\pi \vec{q}_1^{\,2}} \left(\frac{s}{s_0}\right)^{\omega}$$
$$\times \Phi_A(\vec{q}_1, s_0) \quad G_\omega(\vec{q}_1, \vec{q}_2) \quad \Phi_B(-\vec{q}_2, s_0)$$

- **Green's function** is **process-independent**

  $\longrightarrow$ determined through the **BFKL equation**

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

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

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Outline

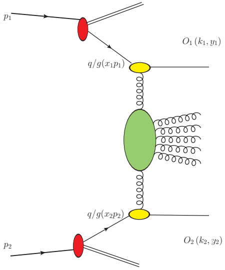
1. Introductory remarks
   - Motivation
   - BFKL Resummation
   - Typical BFKL observables
2. Inclusive Higgs-plus-jet production at the LHC
   - Kinematic configurations
   - Numerical results
3. Conclusions

Search for BFKL dynamics in inclusive processes

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

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

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



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

$$\frac{d\sigma}{dx_{O_1} dx_{O_2}\, d|\vec{k}_{O_1}|\, d|\vec{k}_{O_2}| d\phi_{O_1} d\phi_{O_2}} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\phi)\, \mathcal{C}_n\right]$$

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

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Azimuthal coefficients

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

$$= \frac{e^{\Delta Y}}{s} \int_{-\infty}^{+\infty} d\nu \left(\frac{x_{O_1} x_{O_2} s}{s_0}\right)^{\bar{\alpha}_s(\mu_R)\left\{\chi(n,\nu)+\bar{\alpha}_s(\mu_R)\left[\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left[-\chi(n,\nu)+\frac{10}{3}+2\ln\left(\frac{\mu_R^2}{\sqrt{\vec{k}_{O_1}^2 \vec{k}_{O_2}^2}}\right)\right]\right]\right\}}$$

$$\times \alpha_s^2(\mu_R) c_1(n,\nu,|\vec{k}_{O_1}|, x_{O_1})[c_2(n,\nu,|\vec{k}_{O_2}|, x_{O_2})]^*$$

$$\times \left\{1 + \alpha_s(\mu_R)\left[\frac{c_1^{(1)}(n,\nu,|\vec{k}_{O_1}|, x_{O_1})}{c_1(n,\nu,|\vec{k}_{O_1}|, x_{O_1})} + \left[\frac{c_2^{(1)}(n,\nu,|\vec{k}_{O_2}|, x_{O_2})}{c_2(n,\nu,|\vec{k}_{O_2}|, x_{O_2})}\right]^*\right]\right.$$

$$\left. + \bar{\alpha}_s^2(\mu_R) \ln\left(\frac{x_{O_1} x_{O_2} s}{s_0}\right) \frac{\beta_0}{4N_c} \chi(n,\nu) f(\nu)\right\} .$$

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

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

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

- **Observables:**
  - ϕ-averaged cross section $\mathcal{C}_0$ and the ratio

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

  - Azimuthal-correlation moments

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

$\longrightarrow$ minimise further any contamination from collinear logarithms

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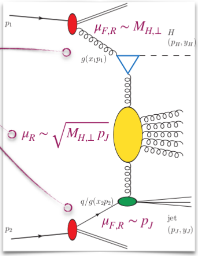
Inclusive Higgs-plus-jet production at the LHC

Process:

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

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

- Inclusive h.p. of a Higgs + jet system with high p_T and large rapidity separation, Y
- Large energy scales expected to **stabilize** the high-energy resummed series



$$\frac{d\hat{\sigma}_{r,s}(x_1 x_2 s, \mu)}{dy_H\, dy_J\, d^2\vec{p}_H\, d^2\vec{p}_J} = \frac{1}{(2\pi)^2} \times \int \frac{d^2\vec{q}_1}{\vec{q}_1^{\,2}} \mathcal{V}_H^{(r)}(\vec{q}_1, s_0, x_1, \vec{p}_H) \times \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{x_1 x_2 s}{s_0}\right)^{\omega} \mathcal{G}_\omega(\vec{q}_1, \vec{q}_2) \times \int \frac{d^2\vec{q}_2}{\vec{q}_2^{\,2}} \mathcal{V}_J^{(s)}(\vec{q}_2, s_0, x_2, \vec{p}_J)$$

Higgs vertex (off-shell amplitude)

jet vertex (off-shell amplitude)

BFKL gluon Green's function

[Slide by Francesco Giovanni Celiberto]

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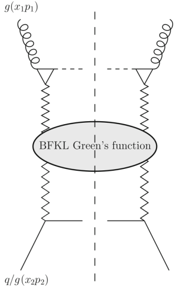
Cross section and azimuthal coefficients

$$\frac{d\sigma}{dy_H dy_J\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\phi)\, \mathcal{C}_n\right]$$



$$\mathcal{C}_n \equiv \int_0^{2\pi} d\varphi_H \int_0^{2\pi} d\varphi_J\, \cos(n\varphi)\, \frac{d\sigma}{dy_H dy_J\, d|\vec{p}_H|\, d|\vec{p}_J| d\varphi_H d\varphi_J}$$

$$= \frac{e^{\Delta Y}}{s} \frac{M_{H,\perp}}{|\vec{p}_H|}$$

$$\times \int_{-\infty}^{+\infty} d\nu \left(\frac{x_J x_H s}{s_0}\right)^{\bar{\alpha}_s(\mu_{R_c})\left\{\chi(n,\nu)+\bar{\alpha}_s(\mu_{R_c})\left[\bar{\chi}(n,\nu)+\frac{\beta_0}{8N_c}\chi(n,\nu)\left[-\chi(n,\nu)+\frac{10}{3}+4\ln\left(\frac{\mu_{R_c}}{\sqrt{\vec{p}_H\vec{p}_J}}\right)\right]\right]\right\}}$$

$$\times \left\{\alpha_s^2(\mu_{R_1}) c_H(n,\nu,|\vec{p}_H|,x_H)\right\} \left\{\alpha_s(\mu_{R_2})[c_J(n,\nu,|\vec{p}_J|,x_J)]^*\right\}$$

$$\times \left\{1 + \alpha_s(\mu_{R_1})\frac{c_H^{(1)}(n,\nu,|\vec{p}_H|,x_H)}{c_H(n,\nu,|\vec{p}_H|,x_H)} + \alpha_s(\mu_{R_2})\left[\frac{c_J^{(1)}(n,\nu,|\vec{p}_J|,x_J)}{c_J(n,\nu,|\vec{p}_J|,x_J)}\right]^*\right\},$$

$$\boxed{c_H(n,\nu,|\vec{p}_H|,x_H) = \frac{1}{v^2}\frac{|\mathcal{F}(\vec{p}_H^{\,2})|^2}{128\pi^3\sqrt{2(N_c^2-1)}}\left(\vec{p}_H^{\,2}\right)^{i\nu+1/2} f_g(x_H,\mu_{F_1})}$$

$$\boxed{c_J(n,\nu,|\vec{p}_J|,x_J) = 2\sqrt{\frac{C_F}{C_A}}\left(\vec{p}_J^{\,2}\right)^{i\nu-1/2}\left(\frac{C_A}{C_F} f_g(x_J,\mu_{F_2}) + \sum_{a=q,\bar{q}} f_a(x_J,\mu_{F_2})\right)}\ .$$

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Outline

Observables and kinematics

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

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

- p_H **-distribution:**

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

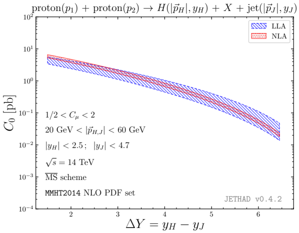
with $\boxed{|y_H| < 2.5, |y_J| < 4.7}$ inside the CMS rapidity acceptances.

sym-metric	$20 < \text{GeV } |\vec{p}_{H,J}| < 60 \text{ GeV}$	An appropriate region to Search for pure BFKL signal.
asym-metric	$10 < \text{GeV } |\vec{p}_H| < 2m_t \text{ GeV}$ $20 < \text{GeV } |\vec{p}_J| < 60 \text{ GeV}$	The realistic LHC cuts.
disjoint windows	$60 < \text{GeV } |\vec{p}_H| < 2m_t \text{ GeV}$ $20 < \text{GeV } |\vec{p}_J| < 60 \text{ GeV}$	Maximum exclusiveness in the final state.

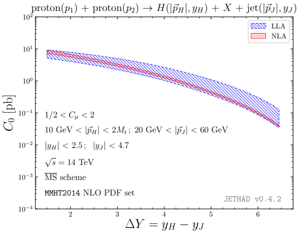
Outline

Numerical results:

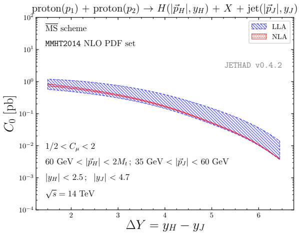
ΔY-dependence of the ϕ-averaged cross section in the three considered p_T -range



Symmetric



Asymmetric



Disjoint

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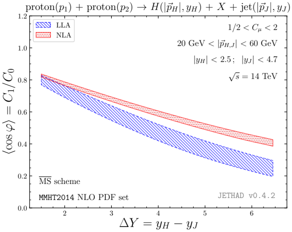
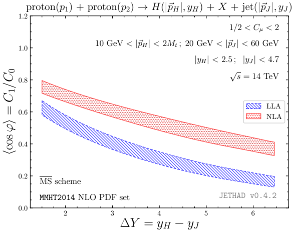
Numerical results:

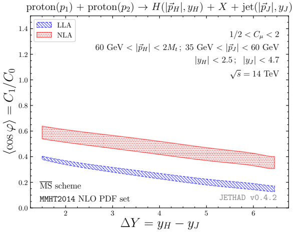
Azimuthal-correlation moments $R_{10} \equiv C_1/C_0$ in the three considered p_T -range



Symmetric



Asymmetric



Disjoint

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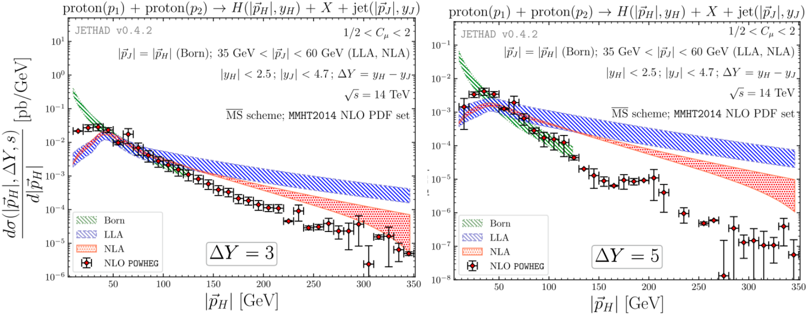
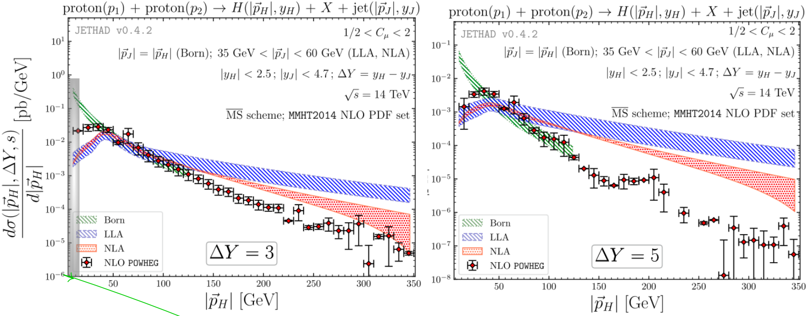
Numerical results:

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



Numerical results:

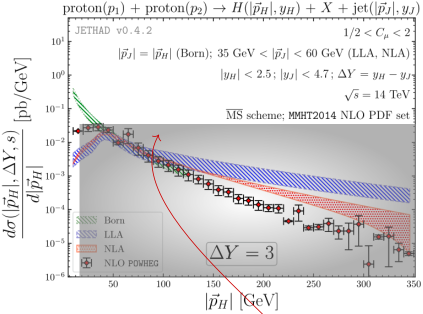
p_T-dependence of the cross section for 35 GeV $< |\vec{p}_J| <$ 60 GeV

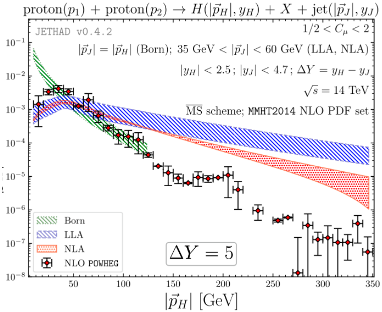


- Dominated by large p_T-logs: $\longrightarrow$ all-order resummation needed

Numerical results:

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

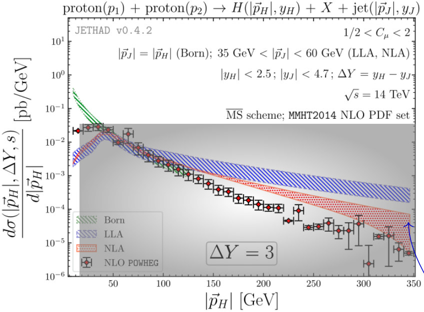


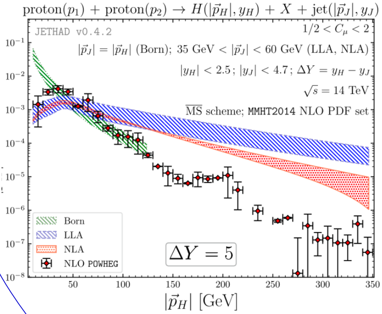


- Expected BFKL semi-hard regime:

Numerical results:

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





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

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. so that the renormalization scale needs not to be too large as for other processes where BLM optimization had to be used.
- Future, exhaustive studies of the inclusive Higgs-boson production, would benefit from the inclusion of high-energy effects in a many-sided formalism where distinct resummations are concurrently embodied

possible extension:

- Full NLO treatment (infinite top mass limit)

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

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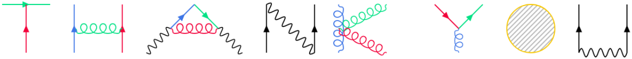

FOR YOUR ATTENTION!!

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.)

[Slide by Michael Fucilla]