Mueller-Navelet jets at LHC: discriminating BFKL from DGLAP by asymmetric cuts

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based on

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

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Outline

Outline

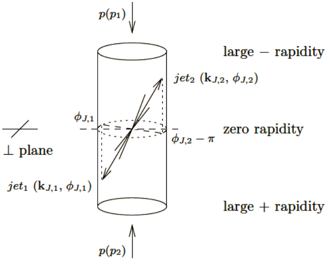
Mueller-Navelet jets

Process: $\mathrm{proton}(p_1) + \mathrm{proton}(p_2) \to \mathrm{jet}_1(k_1) + \mathrm{jet}_2(k_2) + X$ *...LHC physics!*

$$\frac{d\sigma}{dx_{J_1}\, dx_{J_2}\, d^2k_{J_1}\, d^2k_{J_2}} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2\, f_i(x_1,\mu) f_j(x_2,\mu) \frac{d\hat{\sigma}_{i,j}(x_1 x_2 s,\mu)}{dx_{J_1}\, dx_{J_2}\, d^2k_{J_1}\, d^2k_{J_2}}$$

- *large jet transverse momenta:* $\vec{k}_{J,1}^{\,2} \sim \vec{k}_{J,2}^{\,2} \gg \Lambda^2_{\mathrm{QCD}} \;\Rightarrow$ pQCD allowed
- *large rapidity gap between jets (high energies)* $\Rightarrow\; \Delta y = \ln \frac{x_{J,1} x_{J,2} s}{|\vec{k}_{J,1}||\vec{k}_{J,2}|}$

$\Rightarrow$ *BFKL resummation:* $\sum_n \left(a_n^{(0)}\; \alpha_s^n \ln^n s + a_n^{(1)}\; \alpha_s^n \ln^{n-1} s \right)$



Mueller-Navelet jets at LO:
a back-to-back di-jet reaction

Picture from
[D. Colferai, F. Schwennsen, L. Szymanowski, S. Wallon (2010)]

Outline

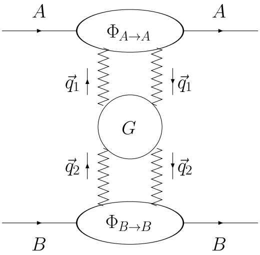
The BFKL resummation

pQCD, total cross section for $A+B \to X$: $\sigma_{AB}(s) = \frac{\mathcal{I}m_s\left(\mathcal{A}_{AB}^{AB}\right)}{s}$ $\Leftarrow$ **optical theorem**

- ◇ Pomeron channel: $t = 0$ + singlet colour representation in the t-channel
- ◇ Regge limit: $s \simeq -u \to \infty$, t not growing with s

- **BFKL resummation**:

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



- ▶ $\mathrm{Im}_s\left(\mathcal{A}_{AB}^{AB}\right)$ factorization:

  convolution of the **Green's function** of two interacting Reggeized gluons with the **impact factors** of the colliding particles.

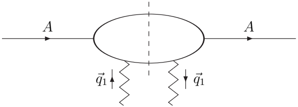
$$\mathrm{Im}_s\left(\mathcal{A}\right)=\frac{s}{(2\pi)^{D-2}}\int\frac{d^{D-2}q_1}{\vec{q}_1^{\,2}}\Phi_A(\vec{q}_1,s_0)\int\frac{d^{D-2}q_2}{\vec{q}_2^{\,2}}\Phi_B(-\vec{q}_2,s_0)\int\limits_{\delta-i\infty}^{\delta+i\infty}\frac{d\omega}{2\pi i}\left(\frac{s}{s_0}\right)^{\omega}G_\omega(\vec{q}_1,\vec{q}_2)$$

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

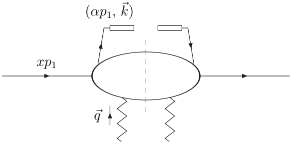
  ⟶ determined through the **BFKL equation**
  [Ya.Ya. Balitsky, V.S. Fadin, E.A. Kuraev, L.N. Lipatov (1975)]

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

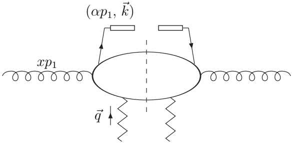
  ⟶ known in the NLA just for few processes



* forward jet production



quark jet vertex

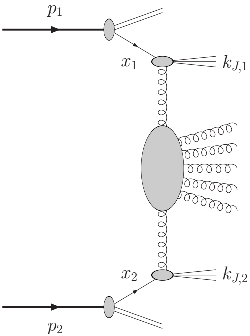


gluon jet vertex

[J. Bartels, D. Colferai, G.P. Vacca (2003)]
[F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa, A. Perri (2012)]
[D.Yu. Ivanov, A. Papa (2012)]
[D. Colferai, A. Niccoli (2015)]

Outline

The cross section



Azimuthal correlation momenta

$$\langle \cos\left[n\left(\phi_{J_1}-\phi_{J_2}-\pi\right)\right]\rangle \equiv \frac{\mathcal{C}_n}{\mathcal{C}_0},$$

$$\mathcal{R}_{m,n} = \frac{\langle\cos\left(m\Delta\phi\right)\rangle}{\langle\cos\left(n\Delta\phi\right)\rangle}$$

$$\frac{d\sigma}{dx_{J_1}\,dx_{J_2}\,d|\vec{k}_{J_1}|\,d|\vec{k}_{J_2}|d\phi_{J_1}\,d\phi_{J_2}} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\phi)\,\mathcal{C}_n\right]$$

...useful definitions:

$$Y = \ln\frac{x_{J_1}x_{J_2}s}{|\vec{k}_{J_1}||\vec{k}_{J_2}|}, \qquad Y_0 = \ln\frac{s_0}{|\vec{k}_{J_1}||\vec{k}_{J_2}|}$$

BFKL cross section...

$$\mathcal{C}_n^{BFKL} = \int_{-\infty}^{+\infty} d\nu \; e^{(Y-Y_0)\left[\bar{\alpha}_s(\mu_R)\chi(n,\nu)+\bar{\alpha}_s^2(\mu_R)K^{(1)}(n,\nu)\right]}\alpha_s^2(\mu_R)$$
$$\times c_1(n,\nu)\, c_2(n,\nu)\left[1+\alpha_s(\mu_R)\left(\frac{c_1^{(1)}(n,\nu)}{c_1(n,\nu)}+\frac{c_2^{(1)}(n,\nu)}{c_2(n,\nu)}\right)\right]$$

where

$$\chi(n,\nu) = 2\psi(1) - \psi\left(\frac{n}{2}+\frac{1}{2}+i\nu\right) - \psi\left(\frac{n}{2}+\frac{1}{2}-i\nu\right)$$

$$K^{(1)}(n,\nu) = \bar{\chi}(n,\nu) + \frac{\beta_0}{8N_c}\chi(n,\nu)\left(-\chi(n,\nu)+\frac{10}{3}+\imath\frac{d}{d\nu}\ln\left(\frac{c_1(n,\nu)}{c_2(n,\nu)}\right)+2\ln\left(\mu_R^2\right)\right)$$

...several NLA-equivalent expressions can be adopted for $\mathcal{C}_n$!
$\longrightarrow$ ...we use the *exponentiated* one

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

...high-energy DGLAP

◇ NLA BFKL expressions for the observables truncated to $\mathcal{O}\left(\alpha_s^3\right)$ **!**

$$\mathcal{C}_n^{DGLAP} = \int_{-\infty}^{+\infty} d\nu \; \alpha_s^2\left(\mu_R\right) c_1\left(n,\nu\right) c_2\left(n,\nu\right)$$
$$\times \left[1 + \bar{\alpha}_s\left(\mu_R\right)\left(Y - Y_0\right)\chi\left(n,\nu\right) + \alpha_s\left(\mu_R\right)\left(\frac{c_1^{(1)}\left(n,\nu\right)}{c_1\left(n,\nu\right)} + \frac{c_2^{(1)}\left(n,\nu\right)}{c_2\left(n,\nu\right)}\right)\right]$$

Why asymmetric cuts?

- suppress Born contribution to ϕ-averaged cross section C_0 (back-to-back jets)
  - ◇ avoid instabilities observed in NLO fixed-order calculations
    [J.R. Andersen, V. Del Duca, S. Frixione, C.R. Schmidt, W.J. Stirling (2001)]
    [M. Fontannaz, J.P. Guillet, G. Heinrich (2001)]
  - ◇ **enhance effects of additional hard gluons** $\xrightarrow{\textit{emphasize}}$ **BFKL effects**
- violation of energy-momentum in NLA strongly suppressed respect to LLA
  [B. Ducloué, L. Szymanowski, S. Wallon (2014)]

Outline

BLM method

NLO BFKL corrections to C_0 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
  - ✓ $\overline{\text{MS}} \to \text{MOM} \quad + \quad \text{choose BLM scale} \quad + \quad \text{MOM} \to \overline{\text{MS}}$

* Partial (approximated) BLM:

a) $\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \; \exp\left[2\left(1+\frac{2}{3}I\right) - f\left(\nu\right) - \frac{5}{3}\right] \;\leftarrow\;$ NLO IFs β_0

b) $\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \; \exp\left[2\left(1+\frac{2}{3}I\right) - 2\, f\left(\nu\right) - \frac{5}{3} + \frac{1}{2}\chi\left(\nu, n\right)\right] \;\leftarrow\;$ NLO Kernel β_0

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

$f\left(\nu\right) = 0$ for this process

Outline

Observables and kinematics

- **Observables:**

$$\langle \cos [n(\phi_{J_1} - \phi_{J_2} - \pi)] \rangle \equiv \frac{\mathcal{C}_n}{\mathcal{C}_0}, \quad \text{with} \quad n = 1, 2, 3$$

$$\frac{\langle \cos [2(\pi - \Delta\phi)] \rangle}{\langle \cos (\pi - \Delta\phi) \rangle} = \frac{\mathcal{C}_2}{\mathcal{C}_1}, \quad \frac{\langle \cos [3(\pi - \Delta\phi)] \rangle}{\langle \cos [2(\pi - \Delta\phi)] \rangle} = \frac{\mathcal{C}_3}{\mathcal{C}_2}, \quad \text{with} \quad \Delta\phi = \phi_{J_2} - \phi_{J_1} .$$

◇ *Integrated coefficients:*

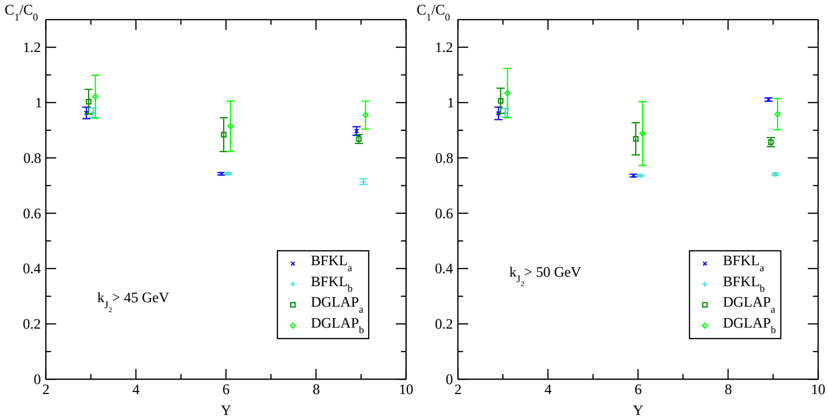
$$C_n = \int_{y_{1,\min}}^{y_{1,\max}} dy_1 \int_{y_{2,\min}}^{y_{2,\max}} dy_2 \int_{k_{J_1,\min}}^{\infty} dk_{J_1} \int_{k_{J_2,\min}}^{\infty} dk_{J_2} \delta(y_1 - y_2 - Y)\, \mathcal{C}_n(y_{J_1}, y_{J_2}, k_{J_1}, k_{J_2})$$

- **Kinematic settings:**
  - ◇ $R = 0.5$ and $\sqrt{s} = 7$ TeV
  - ◇ $-4.7 \leq y_i \leq 4.7$, with $i = 1, 2$
  - ◇ 35 GeV $\leq k_{J_1} \leq 60$ GeV
    $45 - 50$ GeV $\leq k_{J_2} \leq 60$ GeV

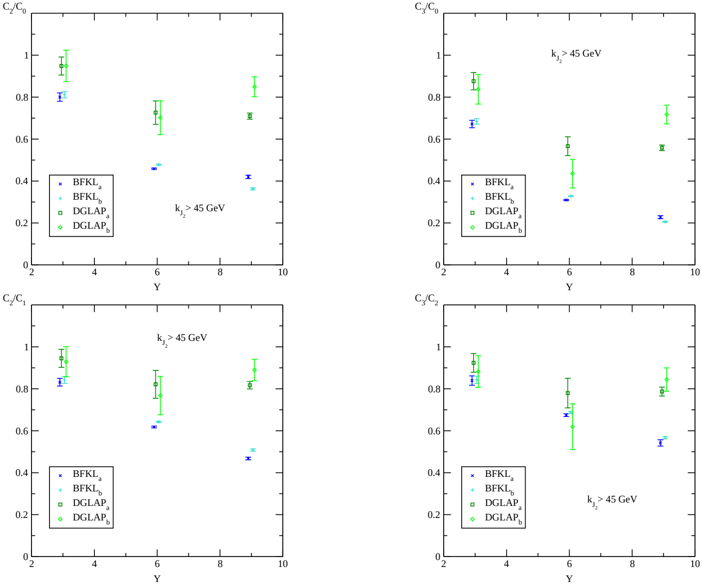
- **Numerical tools:** FORTRAN + NLO MSTW 2008 PDFs + CERNLIB
  → weak time dependence on multidimensional integration ranges

[A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, (2009)]
http://cernlib.web.cern.ch/cernlib

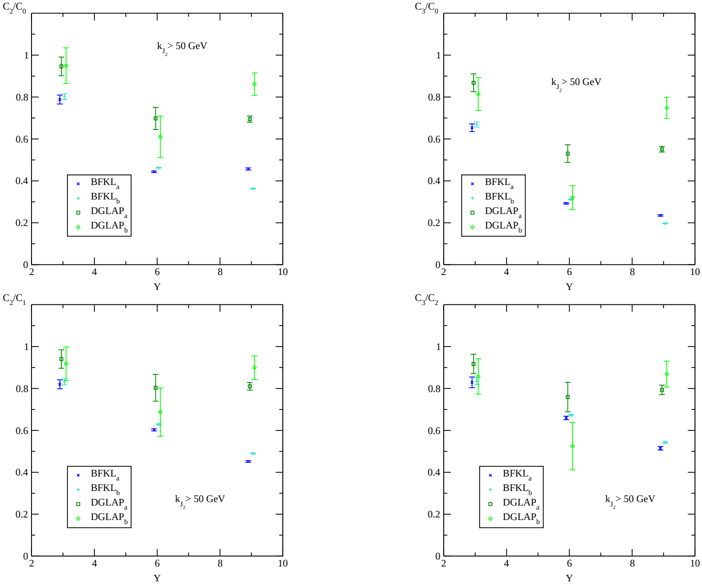
C_1 / C_0


C1/C0
1.2
1
0.8
0.6
0.4
0.2
0
2
4
6
8
10
Y
k_J2 > 45 GeV
k_J2 > 50 GeV
BFKL_a
BFKL_b
DGLAP_a
DGLAP_b

R_{nm} for $k_{J_2} > 45$ GeV



R_{nm} for $k_{J_2} > 50$ GeV



Conclusions

Comparison of predictions for several R_{nm} in full NLA BFKL approach and in NLO high-energy DGLAP.

- Implementation of a partial **BLM method** $\xrightarrow{with}$ two different optimized choices of scale!
- Asymmetric kinematics of detected jets:
  - $k_{J_1} > 35$ GeV and $k_{J_2} > 45$ GeV
  - $k_{J_1} > 35$ GeV and $k_{J_2} > 50$ GeV.

$\Rightarrow$ it exhibit a **difference** between **BFKL** and **DGLAP** growing with energy!

$\Downarrow \quad \Downarrow \quad \Downarrow$

We strongly suggest experimentalist collaborations to consider also asymmetric kinematics in all future analyses of Mueller-Navelet jet production process!

Thanks for your attention!!

BACKUP slides

The BFKL BLM cross section

a) $$\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \ \exp\left[2\left(1+\frac{2}{3}I\right) - f\left(\nu\right) - \frac{5}{3}\right] \sim 5^2 k_1 k_2$$

b) $$\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \ \exp\left[2\left(1+\frac{2}{3}I\right) - 2\ f\left(\nu\right) - \frac{5}{3} + \frac{1}{2}\chi\left(\nu, n\right)\right] < (11.5)^2 k_1 k_2$$

$$\mathcal{C}_n^{\mathrm{BFKL}_{(a)}} = \frac{x_{J_1} x_{J_2}}{|\vec{k}_{J_1}||\vec{k}_{J_2}|} \int_{-\infty}^{+\infty} d\nu \ e^{(Y-Y_0)\left[\bar{\alpha}_s(\mu_R)\chi(n,\nu)+\bar{\alpha}_s^2(\mu_R)\left(\bar{\chi}(n,\nu)-\frac{T^\beta}{C_A}\chi(n,\nu)-\frac{\beta_0}{8C_A}\chi^2(n,\nu)\right)\right]}$$
$$\times\, \alpha_s^2\left(\mu_R\right) c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1}) c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})$$
$$\times\left[1 - \frac{2}{\pi}\alpha_s\left(\mu_R\right) T^\beta + \alpha_s\left(\mu_R\right)\left(\frac{\bar{c}_1^{(1)}(n,\nu,|\vec{k}_{J_1}|,x_{J_1})}{c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1})} + \frac{\bar{c}_2^{(1)}(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}{c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}\right)\right]$$

$$\mathcal{C}_n^{\mathrm{BFKL}_{(b)}} = \frac{x_{J_1} x_{J_2}}{|\vec{k}_{J_1}||\vec{k}_{J_2}|} \int_{-\infty}^{+\infty} d\nu \ e^{(Y-Y_0)\left[\bar{\alpha}_s(\mu_R)\chi(n,\nu)+\bar{\alpha}_s^2(\mu_R)\left(\bar{\chi}(n,\nu)-\frac{T^\beta}{C_A}\chi(n,\nu)\right)\right]}$$
$$\times\, \alpha_s^2\left(\mu_R\right) c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1}) c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})$$
$$\times\left[1 + \alpha_s\left(\mu_R\right)\left(\frac{\beta_0}{4\pi}\chi\left(n,\nu\right) - 2\frac{T^\beta}{\pi}\right) + \alpha_s\left(\mu_R\right)\left(\frac{\bar{c}_1^{(1)}(n,\nu,|\vec{k}_{J_1}|,x_{J_1})}{c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1})} + \frac{\bar{c}_2^{(1)}(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}{c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}\right)\right]$$

The DGLAP BLM cross section

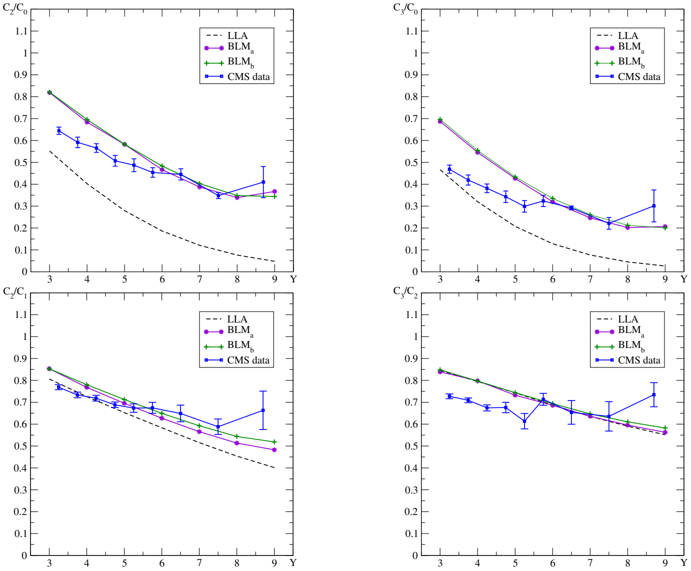
a) $\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \ \exp\left[2\left(1+\frac{2}{3}I\right) - f\left(\nu\right) - \frac{5}{3}\right] \sim 5^2 k_1 k_2$

b) $\left(\mu_R^{BLM}\right)^2 = k_1 k_2 \ \exp\left[2\left(1+\frac{2}{3}I\right) - 2\ f\left(\nu\right) - \frac{5}{3} + \frac{1}{2}\chi\left(\nu, n\right)\right] < (11.5)^2 k_1 k_2$

$$\mathcal{C}_n^{\rm DGLAP(a)} = \frac{x_{J_1} x_{J_2}}{|\vec{k}_{J_1}||\vec{k}_{J_2}|} \int_{-\infty}^{+\infty} d\nu \ \alpha_s^2\left(\mu_R\right) c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1}) c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})$$
$$\times \left[1 - \frac{2}{\pi}\alpha_s\left(\mu_R\right) T^\beta + \bar{\alpha}_s\left(\mu_R\right)\left(Y - Y_0\right)\chi\left(n,\nu\right)\right.$$
$$\left. + \alpha_s\left(\mu_R\right)\left(\frac{\bar{c}_1^{(1)}(n,\nu,|\vec{k}_{J_1}|,x_{J_1})}{c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1})} + \frac{\bar{c}_2^{(1)}(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}{c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}\right)\right]$$

$$\mathcal{C}_n^{\rm DGLAP(b)} = \frac{x_{J_1} x_{J_2}}{|\vec{k}_{J_1}||\vec{k}_{J_2}|} \int_{-\infty}^{+\infty} d\nu \ \alpha_s^2\left(\mu_R\right) c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1}) c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})$$
$$\times \left[1 + \alpha_s\left(\mu_R\right)\left(\frac{\beta_0}{4\pi}\chi\left(n,\nu\right) - 2\frac{T^\beta}{\pi}\right) + \bar{\alpha}_s\left(\mu_R\right)\left(Y - Y_0\right)\chi\left(n,\nu\right)\right.$$
$$\left. + \alpha_s\left(\mu_R\right)\left(\frac{\bar{c}_1^{(1)}(n,\nu,|\vec{k}_{J_1}|,x_{J_1})}{c_1(n,\nu,|\vec{k}_{J_1}|,x_{J_1})} + \frac{\bar{c}_2^{(1)}(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}{c_2(n,\nu,|\vec{k}_{J_2}|,x_{J_2})}\right)\right]$$

Why BLM? MN jets - symmetric kinematics



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