High energy effects in multi-jet production at LHC

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in collaboration with

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based on

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Outline

High energy limit

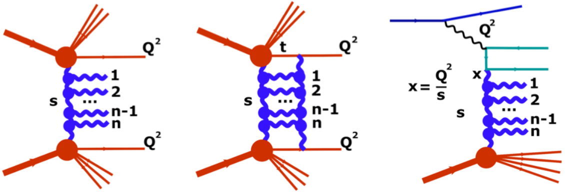
The high energy limit studies a limited part of the phase space, but allow us to compute things otherwise impractical

Purely theoretical

- CFT's
- AdS/CFT
- Special Functions
- Integrability Methods
- Spin Chains

High energy limit

Phenomenology



- ◇ Mueller-Navelet jets
- ◇ Muellet-Tang jets
- ◇ DIS at small x

With the advent of LHC we have access to higher energies: opportunity to test **pQCD in the high-energy limit** and the applicability of **BFKL resummation**.

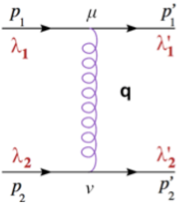
BFKL

BFKL does not cover all high energy energy scattering, but it is essential to understand some of its aspects.

Consider quark-quark scattering in the **Regge Limit**.

$$s >> |t| \sim Q^2 >> \Lambda^2_{QCD}$$

The amplitude at LO in α_s is

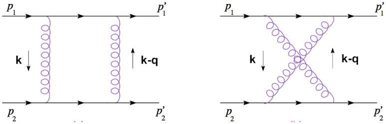


$$\propto \alpha_s \frac{s}{t}$$

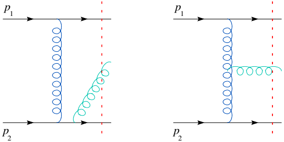
BFKL

If we go to NLO large logarithms appear $\mathcal{A}^{(1)} \propto \mathcal{A}^{(0)}\alpha_s \log \frac{s}{Q^2}$

Virtual corrections



Real corrections

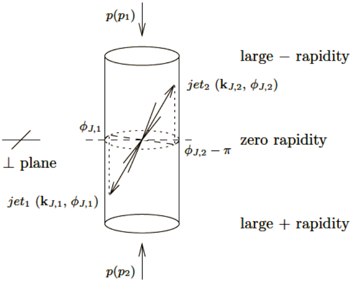


At arbitrary order, we will have terms proportional to $(\alpha_s)^p(\alpha_s \log \frac{s}{Q^2})^q$ that are not negligible in the Regge limit.

- LLA BFKL: $(\alpha_s \log \frac{s}{Q^2})^q$ terms
- NLLA BFKL: $\alpha_s(\alpha_s \log \frac{s}{Q^2})^q$ terms

All orders result in perturbation thery!

Rapidity variable



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

$$\tanh y = \frac{p_{\parallel}}{E}$$

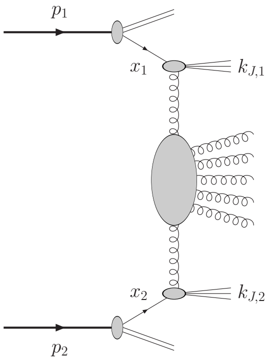
For m=0 it coincides with the pseudo-rapidity
$$\eta = y(m = 0) = -\log\tan\frac{\theta}{2}$$

Related to the angle of the momentum with the beam axis

... $2 \to 2$ elastic scattering at high energies $\Rightarrow$ $Y \equiv y_1 - y_2 = \log\frac{s}{|t|}$

... Muller-Navelet jets $\Rightarrow$ $Y = \ln\frac{x_1 x_2 s}{|\vec{k}_{J,1}||\vec{k}_{J,2}|}$

Warming up: Mueller–Navelet jets



It has been the playground for BFKL tests since it was proposed in

[A. H. Mueller, H. Navelet (1987)]

- At Y=0, no minijet radiation in the rapidity interval. Exact correlation $d\sigma \sim \delta^2(\vec{k}_{J,1} - \vec{k}_{J,2})$
- At large Y the BFKL approach predicts decorrelations (minijets)

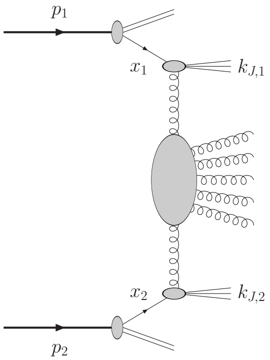
Key observable: correlation in the azimuthal angle of the 2 tagged jets.

...large jet transverse momenta: $\vec{k}_{J,1}^{\,2} \sim \vec{k}_{J,2}^{\,2} \gg \Lambda^2_{\rm QCD}$
DGLAP evolution. pQCD applicable.

...large rapidity interval between jets: $Y = \ln \frac{x_1 x_2 s}{|\vec{k}_{J,1}||\vec{k}_{J,2}|}$

BFKL resummation effects $\alpha Y \sim 1$

Warming up: Mueller–Navelet jets



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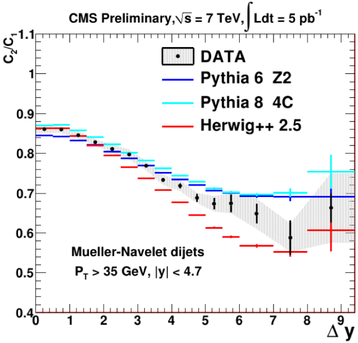
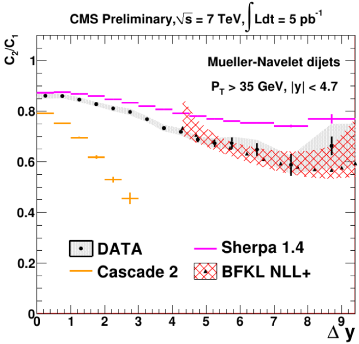
Key observable: correlation in the azimuthal angle of the 2 tagged jets.

$$\frac{d\sigma}{dx_1 dx_2\, d|\vec{k}_{J,1}|\, d|\vec{k}_{J,2}| d\theta_1 d\theta_2} = \frac{1}{(2\pi)^2}\left[\mathcal{C}_0 + \sum_{n=1}^{\infty} 2\cos(n\theta)\, \mathcal{C}_n\right]$$

Mueller–Navelet jets





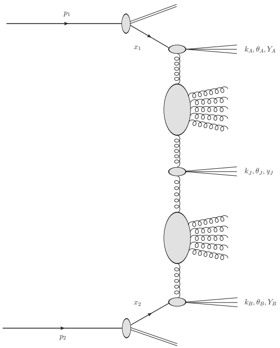
NLLA predictions against LHC data quite successful for large rapidities.

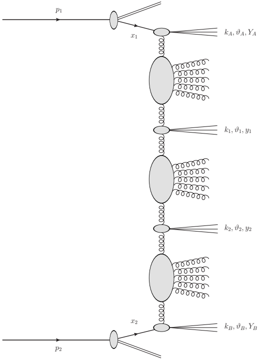
Mueller–Navelet jets

- Big dependence on high order corrections in $\mathcal{C}_0$ due to collinear contamination, better to define ratios.
- Focusing in azimuthal angle correlations is more fruitful than the usual "growth with energy" behaviour.
- Including more jets allow us to study azimuthal correlations and its dependence on transverse momentum. Less inclusive observables!

Multi-jet production!

Three- and four-jet production





[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2015)]
[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (2016)]

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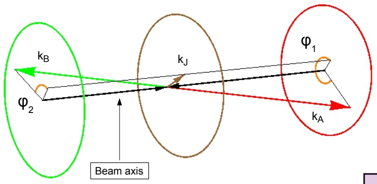
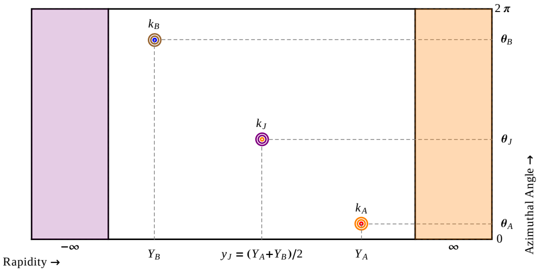
An event with three tagged jets



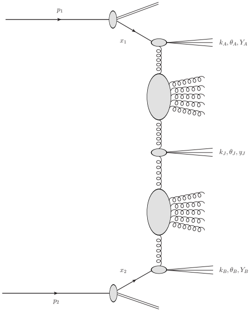
$$Y_B < y_J < Y_A$$



The three-jet partonic cross section

Starting point: differential partonic cross-section (no PDFs)

$$\frac{d^3\hat{\sigma}^{3-\text{jet}}}{dk_J d\theta_J dy_J} = \frac{\bar{\alpha}_s}{\pi k_J} \int d^2\vec{p}_A \int d^2\vec{p}_B \, \delta^{(2)}\left(\vec{p}_A + \vec{k}_J - \vec{p}_B\right) \times$$
$$\times \quad \varphi\left(\vec{k}_A, \vec{p}_A, Y_A - y_J\right) \varphi\left(\vec{p}_B, \vec{k}_B, y_J - Y_B\right)$$



- *Multi-Regge kinematics* rapidity ordering: $Y_B < y_J < Y_A$
- k_J lie above the experimental resolution scale
- φ is the BFKL gluon Green function (LLA or NLLA)
- $\bar{\alpha}_s = \alpha_s N_c / \pi$

Generalized azimuthal correlations - partonic level

Prescription: integrate over all angles after using the projections on the two azimuthal angle differences indicated below...

→ ...to define:

$$\int_0^{2\pi} d\theta_A \int_0^{2\pi} d\theta_B \int_0^{2\pi} d\theta_J \cos\left(M\left(\theta_A-\theta_J-\pi\right)\right)\cos\left(N\left(\theta_J-\theta_B-\pi\right)\right)\frac{d^3\hat{\sigma}^{3-\text{jet}}}{dk_J d\theta_J dy_J}$$

$$= \bar{\alpha}_s \sum_{L=0}^{N} \binom{N}{L} \left(k_J^2\right)^{\frac{L-1}{2}} \int_0^\infty dp^2 \, \left(p^2\right)^{\frac{N-L}{2}} \int_0^{2\pi} d\theta \, \frac{(-1)^{M+N}\cos\left(M\theta\right)\cos\left((N-L)\theta\right)}{\sqrt{\left(p^2+k_J^2+2\sqrt{p^2k_J^2}\cos\theta\right)^N}}$$

$$\times \, \phi_M\left(k_A^2, p^2, Y_A-y_J\right)\phi_N\left(p^2+k_J^2+2\sqrt{p^2k_J^2}\cos\theta, k_B^2, y_J-Y_B\right)$$

Main observables: **generalized azimuthal correlation ratios** (w/o the 0 component)

$$\mathcal{R}^{MN}_{PQ} = \frac{\mathcal{C}_{MN}}{\mathcal{C}_{PR}} = \frac{\langle\cos(M(\theta_A-\theta_J-\pi))\cos(N(\theta_J-\theta_B-\pi))\rangle}{\langle\cos(P(\theta_A-\theta_J-\pi))\cos(Q(\theta_J-\theta_B-\pi))\rangle}$$

Next step: hadronic level predictions

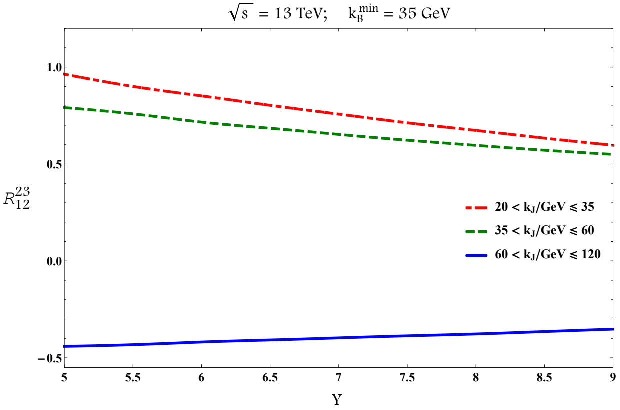
- Introduce PDFs and running of the strong coupling:

$$\frac{d\sigma^{3-\text{jet}}}{dk_A\, dY_A\, d\theta_A\, dk_B\, dY_B\, d\theta_B\, dk_J\, dy_J d\theta_J} =$$
$$\frac{8\pi^3\, C_F\, \bar{\alpha}_s\,(\mu_R)^3}{N_C^3}\, \frac{x_{J_A}\, x_{J_B}}{k_A\, k_B\, k_J} \int d^2\vec{p}_A \int d^2\vec{p}_B\, \delta^{(2)}\left(\vec{p}_A + \vec{k}_J - \vec{p}_B\right)$$
$$\times \left(\frac{N_C}{C_F} f_g(x_{J_A}, \mu_F) + \sum_{r=q,\bar{q}} f_r(x_{J_A}, \mu_F) \right)$$
$$\times \left(\frac{N_C}{C_F} f_g(x_{J_B}, \mu_F) + \sum_{s=q,\bar{q}} f_s(x_{J_B}, \mu_F) \right)$$
$$\times\, \varphi\left(\vec{k}_A, \vec{p}_A, Y_A - y_J\right) \varphi\left(\vec{p}_B, \vec{k}_B, y_J - Y_B\right)$$

- Match the LHC kinematical cuts (integrate $d\sigma^{3-\text{jet}}$ on k_T and rapidities Y_A, Y_B):
  - **1.** 35 GeV $\leq k_A \leq$ 60 GeV; 35 GeV $\leq k_B \leq$ 60 GeV; symmetric cuts
    2. 35 GeV $\leq k_A \leq$ 60 GeV; 50 GeV $\leq k_B \leq$ 60 GeV; asymmetric cuts
  - $Y = Y_A - Y_B$ fixed;
    $y_J = (Y_A + Y_B)/2$
  - $\sqrt{s} = 7, 13$ TeV

R_{12}^{23} vs Y for three different k_J bins

$$k_A^{\min} = 35 \text{ GeV}, \; k_B^{\min} = 35 \text{ GeV}, \; k_A^{\max} = k_B^{\max} = 60 \text{ GeV (symmetric)}$$

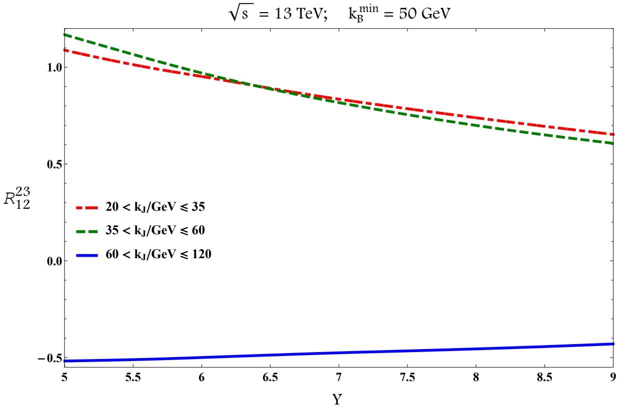


[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (2016)]

Y is the rapidity difference between the most forward/backward jet; $y_J = \frac{Y_A + Y_B}{2}$.

R_{12}^{23} vs Y for three different k_J bins

$k_A^{\rm min} = 35$ GeV, $k_B^{\rm min} = 50$ GeV, $k_A^{\rm max} = k_B^{\rm max} = 60$ GeV (asymmetric)



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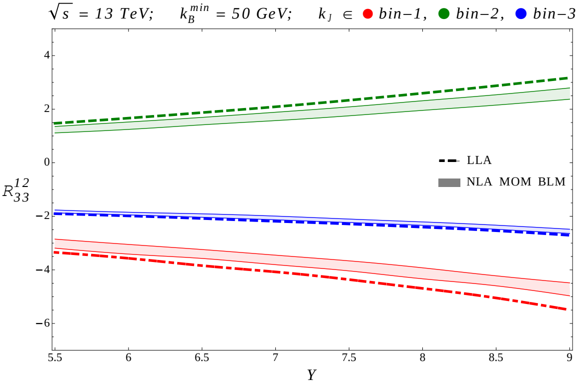
R^{12}_{33} vs Y at 13 TeV - NLLA

Preliminary results

$k_A^{\rm min} = 35$ GeV, $k_B^{\rm min} = 50$ GeV, $k_A^{\rm max} = k_B^{\rm max} = 60$ GeV (asymmetric)

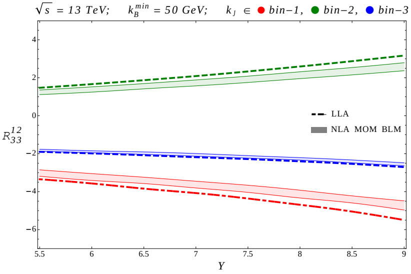


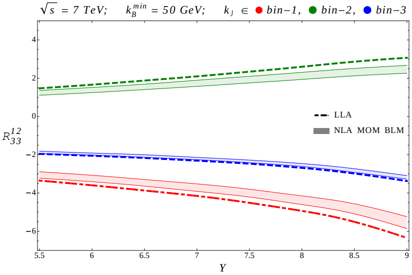
[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

Y is the rapidity difference between the most forward/backward jet; $y_J = \frac{Y_A+Y_B}{2}$.

R_{33}^{12} vs Y at 13 and 7 TeV - NLLA

Preliminary results





We have entered in an asymptotic regime!

[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

Conclusions

- Study of processes with **three** and **four** tagged jets to propose and **predict** new, more exclusive, BFKL observables: **generalized azimuthal correlation** with dependence on the transverse momenta of extra jets.
- Ratios of correlation functions used to minimize the influence of higher order corrections
- Comparison with other approaches such as fixed order calculations and Monte Carlo simulations are needed to determine if the observable is a genuine BFKL signal.
- Comparison with experimental data suggested and needed to know the window of applicability of the BFKL framework at LHC.

Outlook

- ◇ Three- and four-jets in the NLLA accuracy: improved kernel(s), scale optimization

  [F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

- ◇ Dependence on rapidity bins (asymmetric configurations for the central jet(s))

  [F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

- ◇ Comparison with analyses where the four-jet predictions stem from two independent gluon ladders (double parton scattering)

  [R. Maciula, A. Szczurek (2014, 2015)]
  [K. Kutak, R. Maciula, M. Serino, A. Szczurek, A. van Hameren (2016, 2016)]

Thanks for your attention!!

BACKUP slides

Motivation

So far, search for BFKL effects had these general drawbacks:

- ◇ too low $\sqrt{s}$ or rapidity intervals among tagged particels in the final state
- ◇ too inclusive observables, other approaches can fit them

Advent of LHC:

- → higher energies ↔ larger rapidity gaps
- → unique opportunity to **test pQCD in the high-energy limit**
- → disentangle applicability region of energy-log resummation (**BFKL approach**)

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

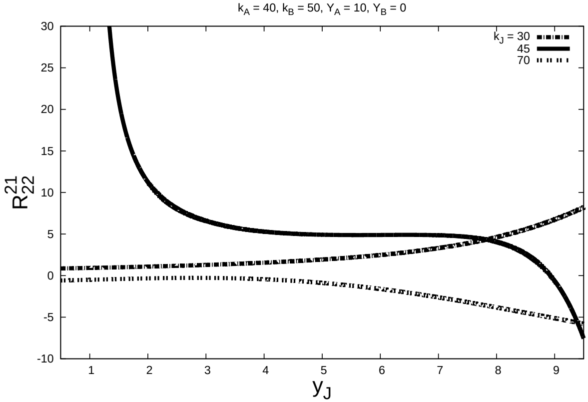
Last years:

hadroproduction of two jets featuring high transverse momenta and well separed in rapidity, so called **Mueller–Navelet jets**...

- ◇ ...possibility to define *infrared-safe* observables...
- ◇ ...and constrain the PDFs...
- ◇ ...theory vs experiment

[B. Ducloué, L. Szymanowski, S. Wallon (2014)]
[F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa (2014)]

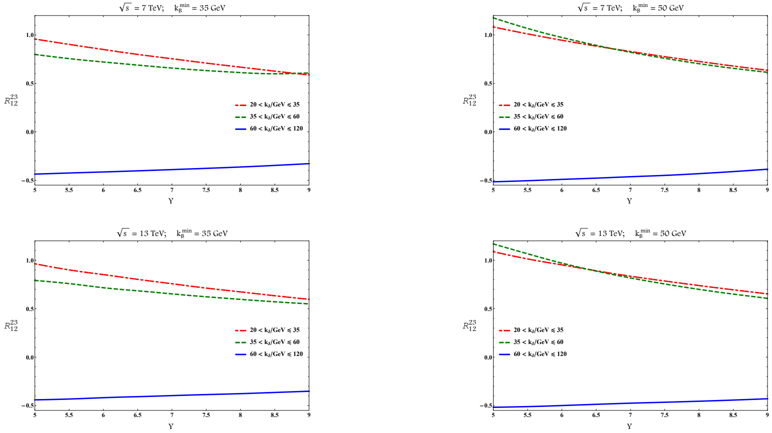
Partonic prediction of $\mathcal{R}_{22}^{21}$ for $k_J = 30, 45, 70$ GeV



[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2015)]

$Y_A - Y_B$ is fixed to 10; y_J varies beetwen 0.5 and 9.5.

R_{12}^{23} vs $Y = Y_A - Y_B$, $\sqrt{s}$ and $k_B^{\rm min}$ for three k_J bins



[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

R^{12}_{33} vs Y at 7 TeV - NLLA preliminary results

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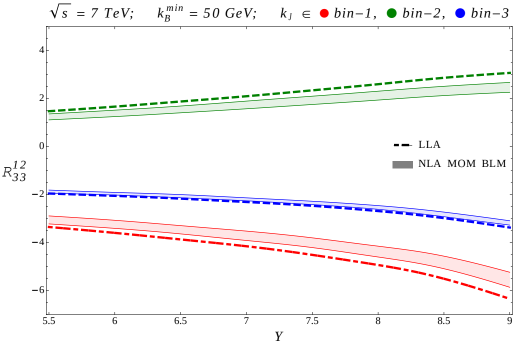
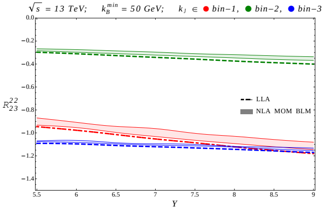
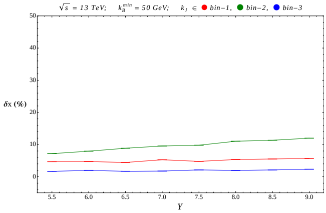


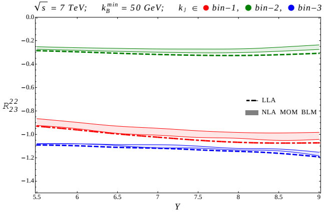
[F. Caporale, F.G. Celiberto, G. Chachamis, D. G.G., A. Sabio Vera (in progress)]

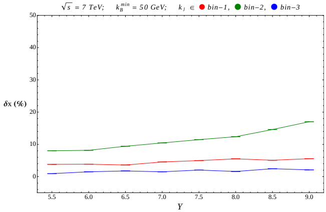
Y is the rapidity difference between the most forward/backward jet; $y_J = \frac{Y_A+Y_B}{2}$.

R^{22}_{23} vs Y at 13 and 7 TeV - NLLA preliminary results









[F. Caporale, F.G. Celiberto, G. Chachamis, D.G.G., A. Sabio Vera (in progress)]

Four-jets: generalized azimuthal coefficients - partonic level

$$\mathcal{C}_{MNL} = \int_0^{2\pi} d\vartheta_A \int_0^{2\pi} d\vartheta_B \int_0^{2\pi} d\vartheta_1 \int_0^{2\pi} d\vartheta_2 \; \cos\left(M\left(\vartheta_A - \vartheta_1 - \pi\right)\right)$$
$$\cos\left(N\left(\vartheta_1 - \vartheta_2 - \pi\right)\right) \cos\left(L\left(\vartheta_2 - \vartheta_B - \pi\right)\right) \frac{d^6\sigma^{4-\text{jet}}\left(\vec{k_A}, \vec{k_B}, Y_A - Y_B\right)}{dk_1\, dy_1\, d\vartheta_1\, dk_2\, d\vartheta_2\, dy_2}$$
$$= \frac{2\pi^2 \bar{\alpha}_s\left(\mu_R\right)^2}{k_1 k_2} \left(-1\right)^{M+N+L} \left(\tilde{\Omega}_{M,N,L} + \tilde{\Omega}_{M,N,-L} + \tilde{\Omega}_{M,-N,L}\right.$$
$$\left. + \tilde{\Omega}_{M,-N,-L} + \tilde{\Omega}_{-M,N,L} + \tilde{\Omega}_{-M,N,-L} + \tilde{\Omega}_{-M,-N,L} + \tilde{\Omega}_{-M,-N,-L}\right)$$

with

$$\tilde{\Omega}_{m,n,l} = \int_0^{+\infty} dp_A\, p_A \int_0^{+\infty} dp_B\, p_B \int_0^{2\pi} d\phi_A \int_0^{2\pi} d\phi_B$$
$$\frac{e^{-im\phi_A}\, e^{il\phi_B} \left(p_A e^{i\phi_A} + k_1\right)^n \left(p_B e^{-i\phi_B} - k_2\right)^n}{\sqrt{\left(p_A^2 + k_1^2 + 2p_A k_1 \cos\phi_A\right)^n} \sqrt{\left(p_B^2 + k_2^2 - 2p_B k_2 \cos\phi_B\right)^n}}$$
$$\varphi_m\left(|\vec{k_A}|, |\vec{p_A}|, Y_A - y_1\right) \varphi_l\left(|\vec{p_B}|, |\vec{k_B}|, y_2 - Y_B\right)$$
$$\varphi_n\left(\sqrt{p_A^2 + k_1^2 + 2p_A k_1 \cos\phi_A}, \sqrt{p_B^2 + k_2^2 - 2p_B k_2 \cos\phi_B}, y_1 - y_2\right)$$

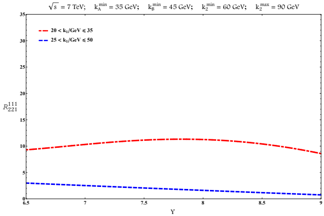
Four-jets: generalized azimuthal coefficients - partonic level

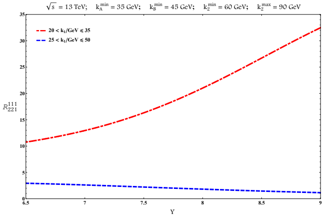
$$\mathcal{C}_{MNL} = \int_0^{2\pi} d\vartheta_A \int_0^{2\pi} d\vartheta_B \int_0^{2\pi} d\vartheta_1 \int_0^{2\pi} d\vartheta_2 \;\cos\left(M\left(\vartheta_A - \vartheta_1 - \pi\right)\right) \cos\left(N\left(\vartheta_1 - \vartheta_2 - \pi\right)\right) \cos\left(L\left(\vartheta_2 - \vartheta_B - \pi\right)\right) \frac{d^6\sigma^{4-\text{jet}}\left(\vec{k}_A, \vec{k}_B, Y_A - Y_B\right)}{dk_1 dy_1 d\vartheta_1 dk_2 d\vartheta_2 dy_2}$$

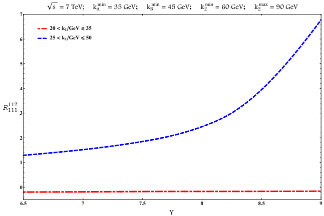
Main observables: **generalized azimuthal correlations**

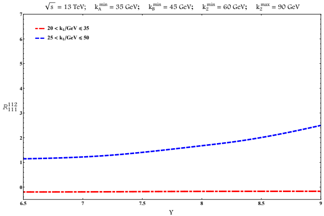
$$\mathcal{R}^{MNL}_{PQR} = \frac{C_{MNL}}{C_{PRQ}} = \frac{\langle\cos(M(\vartheta_A - \vartheta_1 - \pi))\cos(N(\vartheta_1 - \vartheta_2 - \pi))\cos(L(\vartheta_2 - \vartheta_B - \pi))\rangle}{\langle\cos(P(\vartheta_A - \vartheta_1 - \pi))\cos(Q(\vartheta_1 - \vartheta_2 - \pi))\cos(R(\vartheta_2 - \vartheta_B - \pi))\rangle}$$

R^{111}_{221} and R^{112}_{111} vs $Y = Y_A - Y_B$ and $\sqrt{s}$ for two k_1 bins









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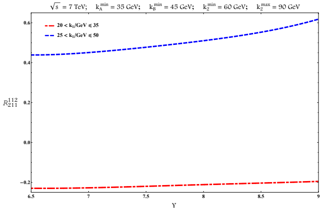
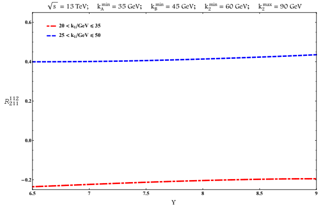
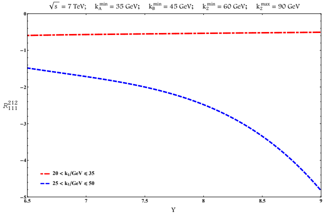
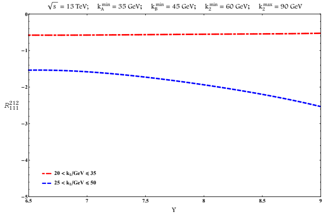
R_{211}^{112} and R_{111}^{212} vs $Y = Y_A - Y_B$ and $\sqrt{s}$ for two k_1 bins









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