Inclusive three- and four-jet production in multi-Regge kinematics at the LHC

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based on

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Eur. Phys. J. C 76 (2016) no.3, 165 [arXiv:1512.03364]

arXiv:1603.07785; arXiv:1606.00574

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DIFFRACTION 2016

Outline

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How could we further and deeply probe BFKL?

1. **Study a less inclusive two-body final state...**

Di-hadron production

[F.G. C., D.Yu. Ivanov, B. Murdaca, A. Papa (2016)]

- inclusive production of a pair of charged light hadrons well separed in rapidity
- hadrons can be detected at the LHC at much smaller values of the transverse momentum than jets
- possibility to constrain not only the PDFs, but also the FFs!

2. **Study three- and four-body final state processes...**

Multi-jet production

- demand the tagging of one or/and two further jets in more central regions of the detectors with a relative separation in rapidity from each other
- definition of new, suitable BFKL observables...
- ...in order to further investigate the azimuthal distribution of the final state

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Looking for new observables...

! We would like to study observables for which the k_T (any k_T along the BFKL ladder) enters the game...

- ...to probe not only the general properties of the BFKL ladder, but also "to peek into the interior"...
- ...by studying azimuthal decorrelations where the k_T of extra particles introduces a new dependence...

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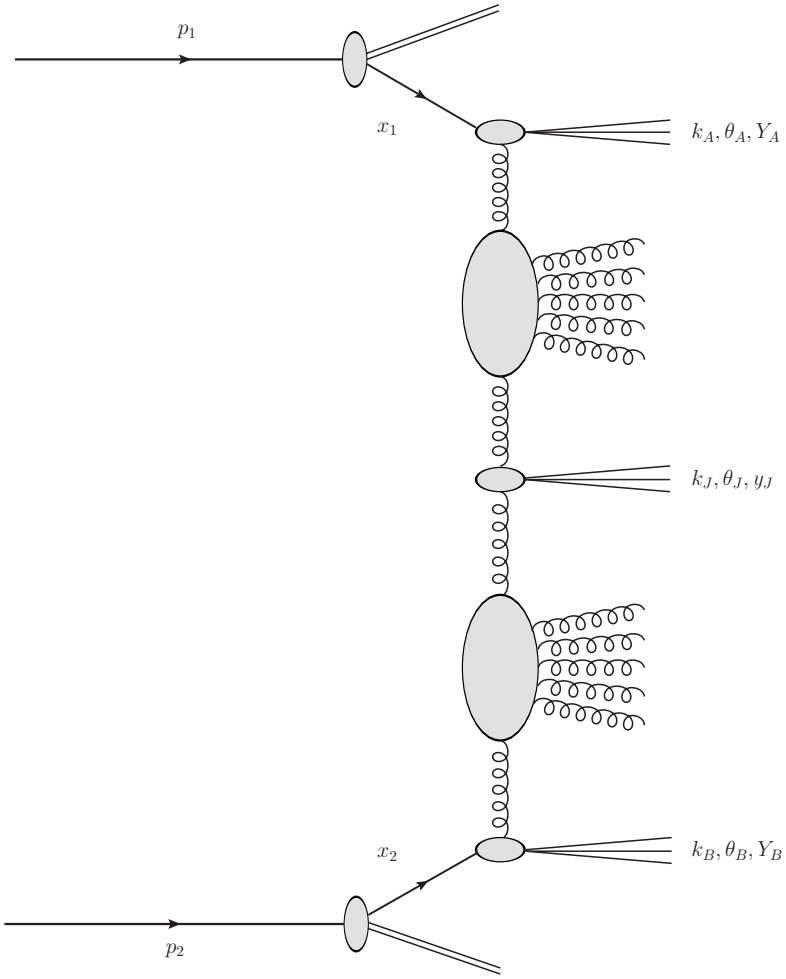
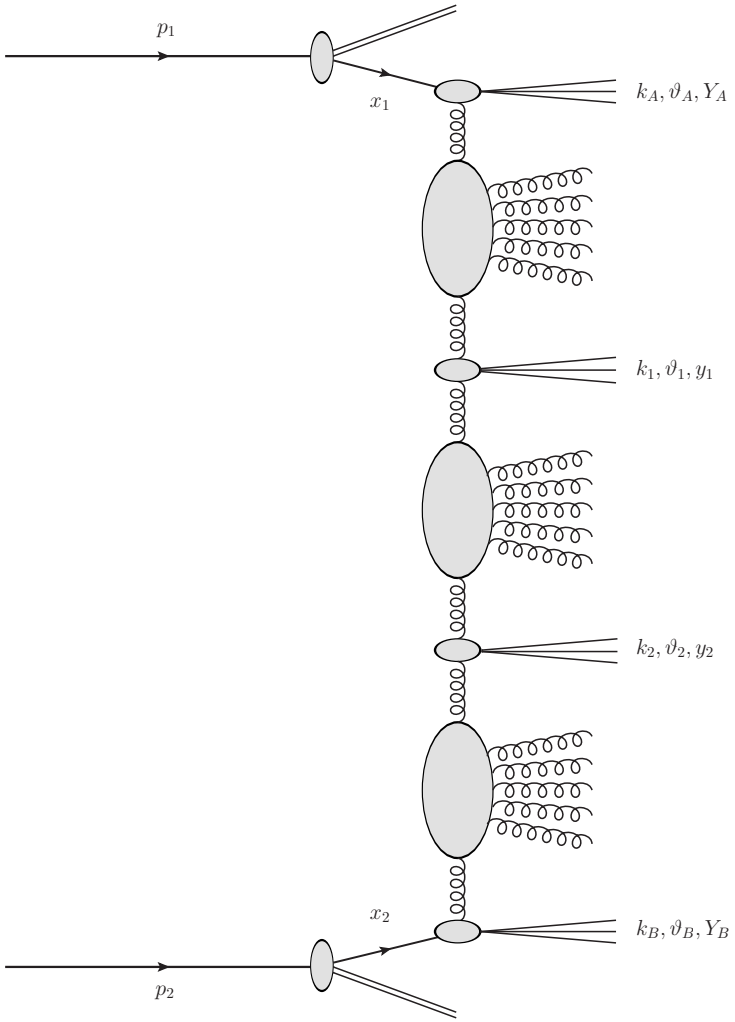
Three- and four-jet production





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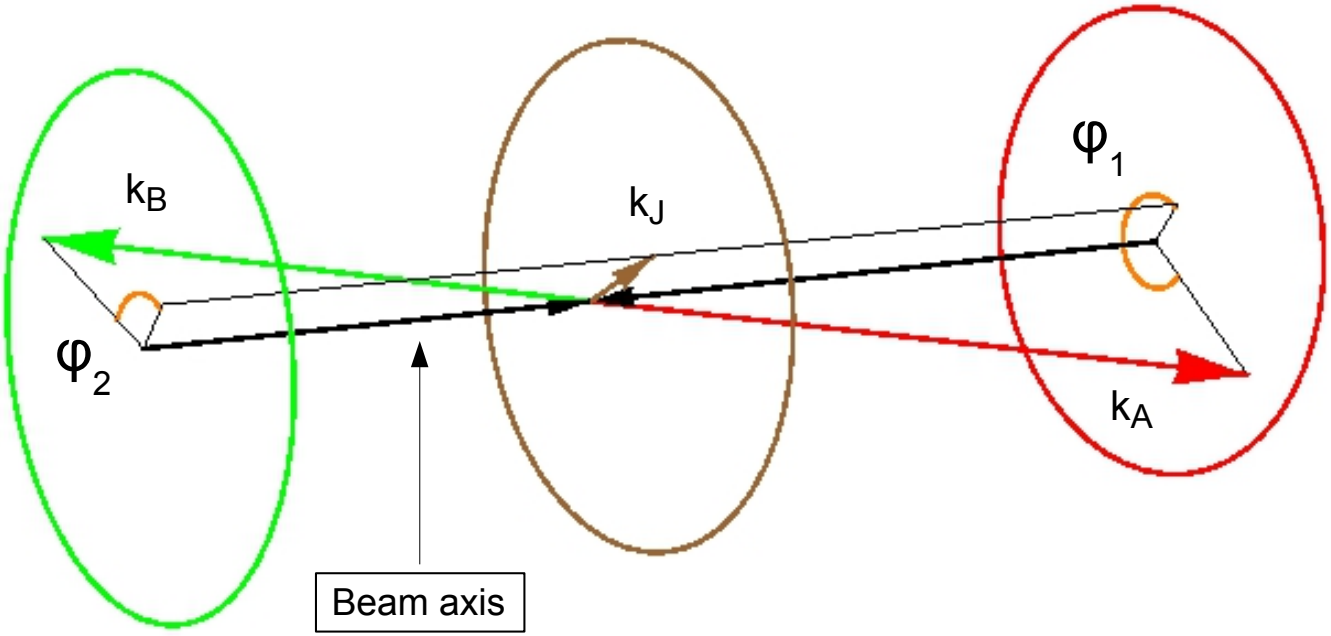
Outline

An event with three tagged jets

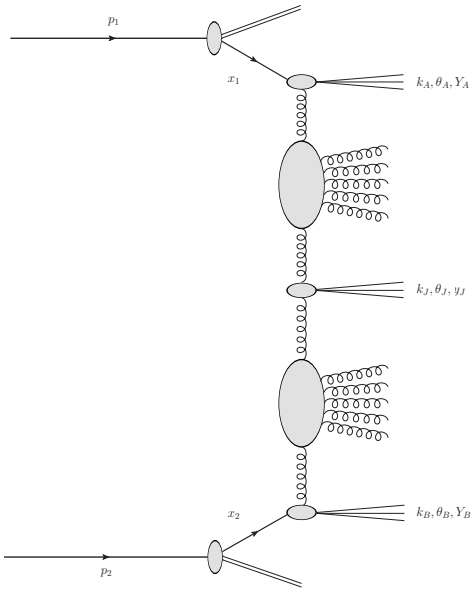


$$Y_B < y_J < Y_A$$

The three-jet partonic cross section

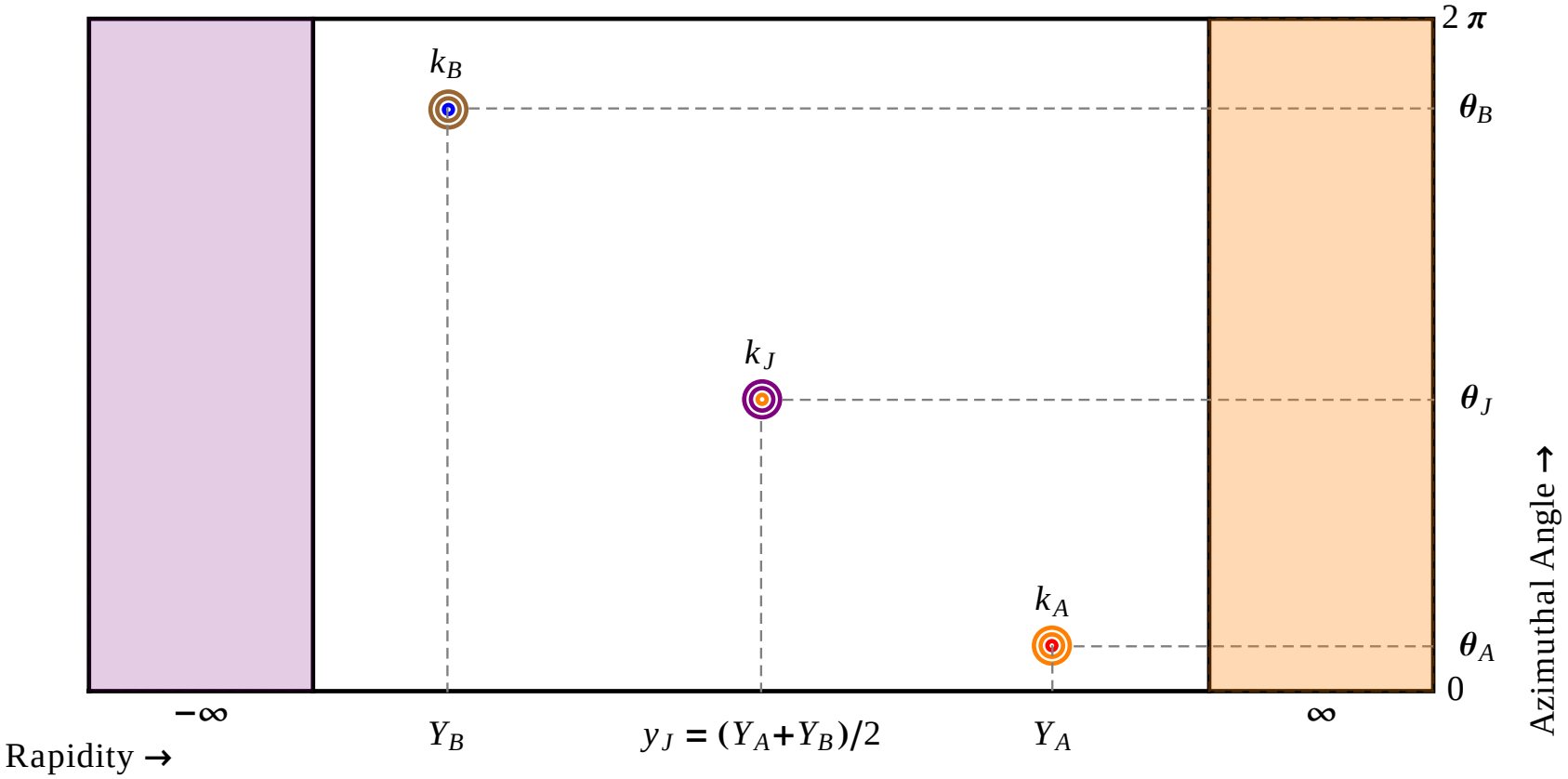
Starting point: differential partonic cross-section (no PDFs)

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



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

A three-jet primitive lego-plot



Generalized azimuthal correlations - partonic level

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

→ ...to define:

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

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

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

Main observables: **generalized azimuthal correlation momenta**

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

Remove the contribution from the zero conformal spin

$\xrightarrow{to}$ drastically reduce the dependence on collinear configurations

study $\mathcal{R}_{PQ}^{MN}$ with integer $M, N, P, Q > 0$

Outline

Next step: hadronic level predictions

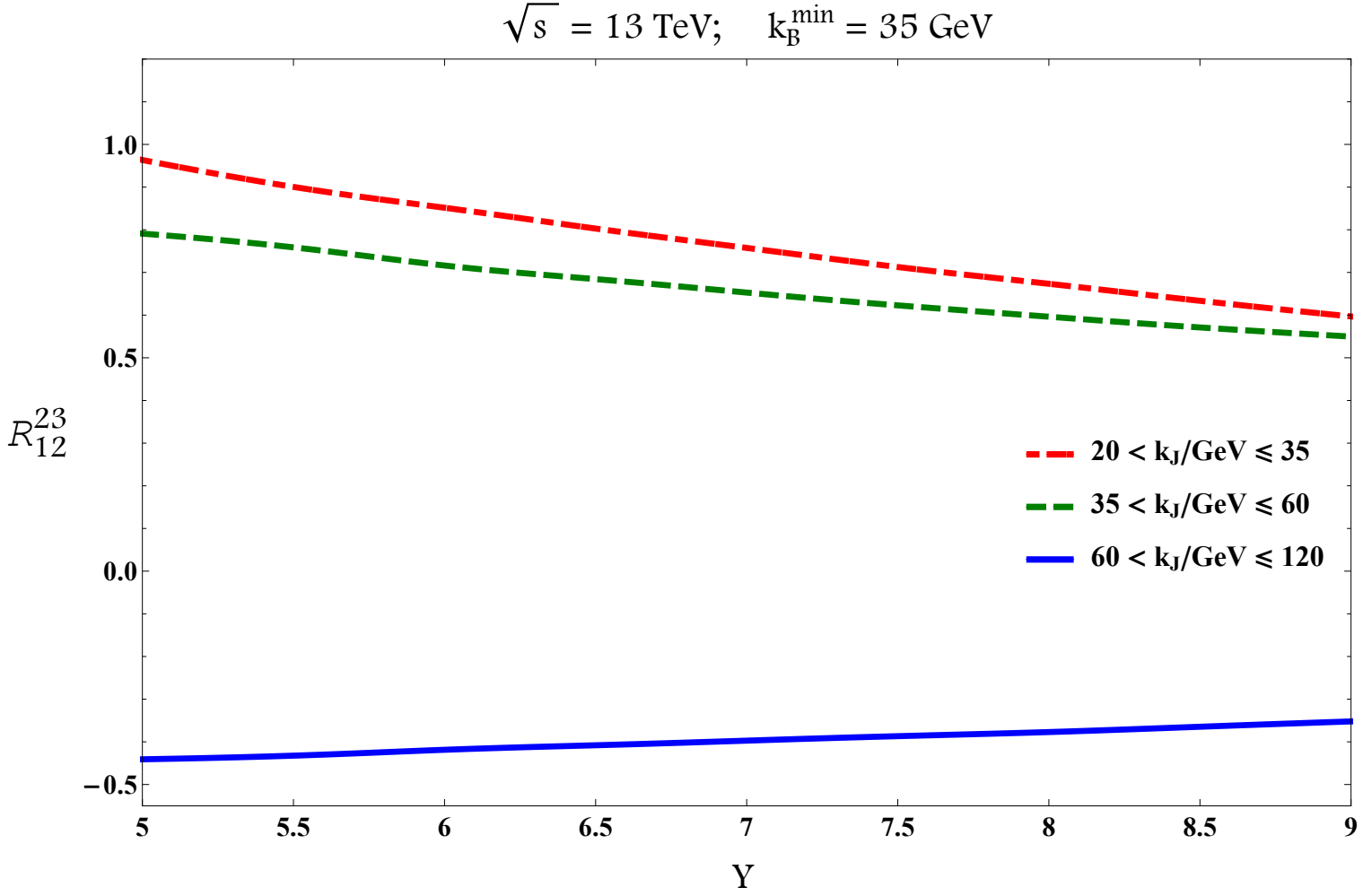
- Introduce PDFs and running of the strong coupling:

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

- Match the LHC kinematical cuts (integrate $d\sigma^{3-\text{jet}}$ on k_T and rapidities):
  - **1.** $k_A \geq 35$ GeV; $k_B \geq 35$ GeV; symmetric cuts
    2. $k_A \geq 35$ GeV; $k_B \geq 50$ 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 $Y = Y_A - Y_B$ for three different k_J bins

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



[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016)]

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

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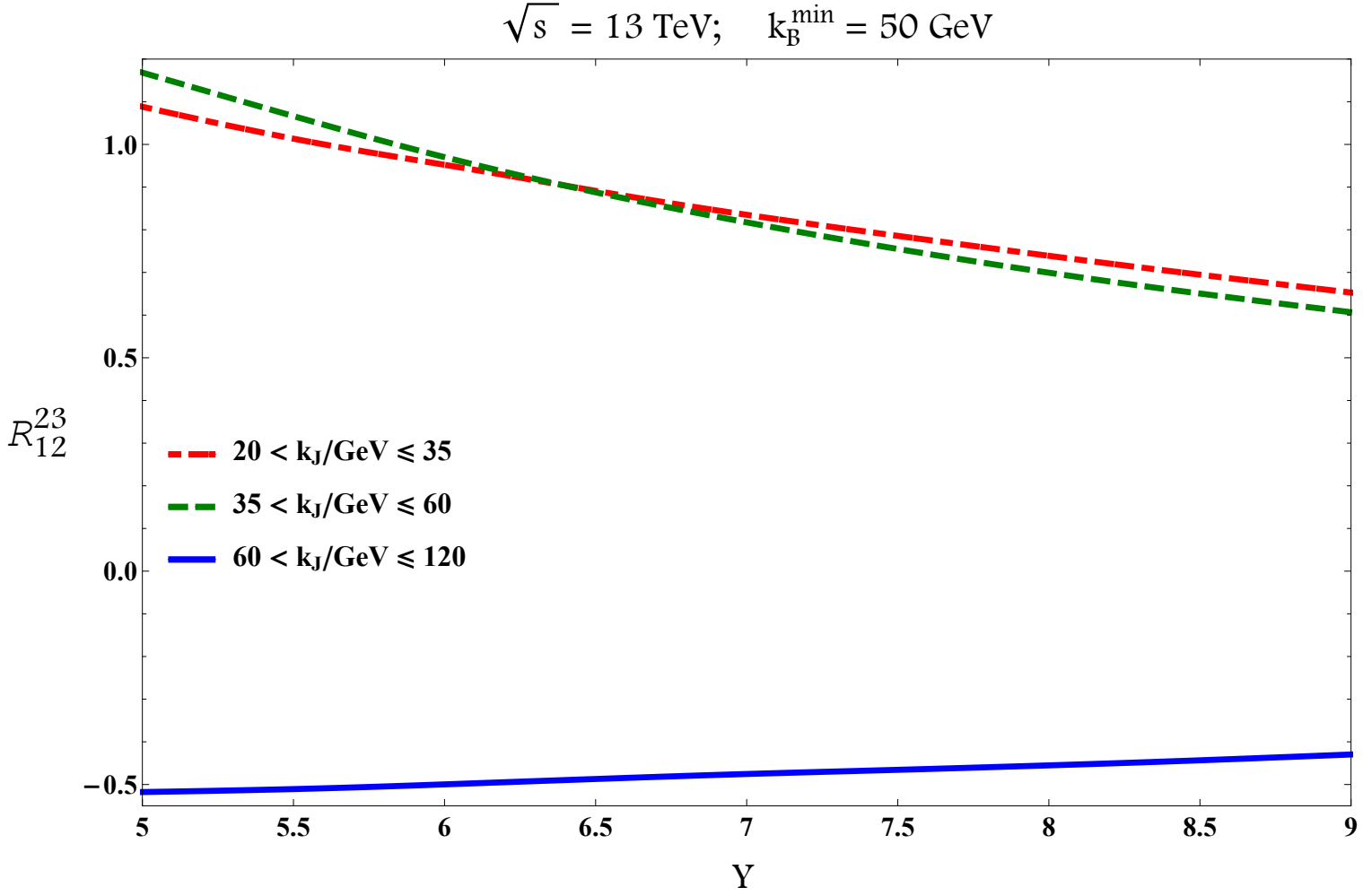

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R_{33}^{12} vs Y at 13 TeV - NLLA preliminary results

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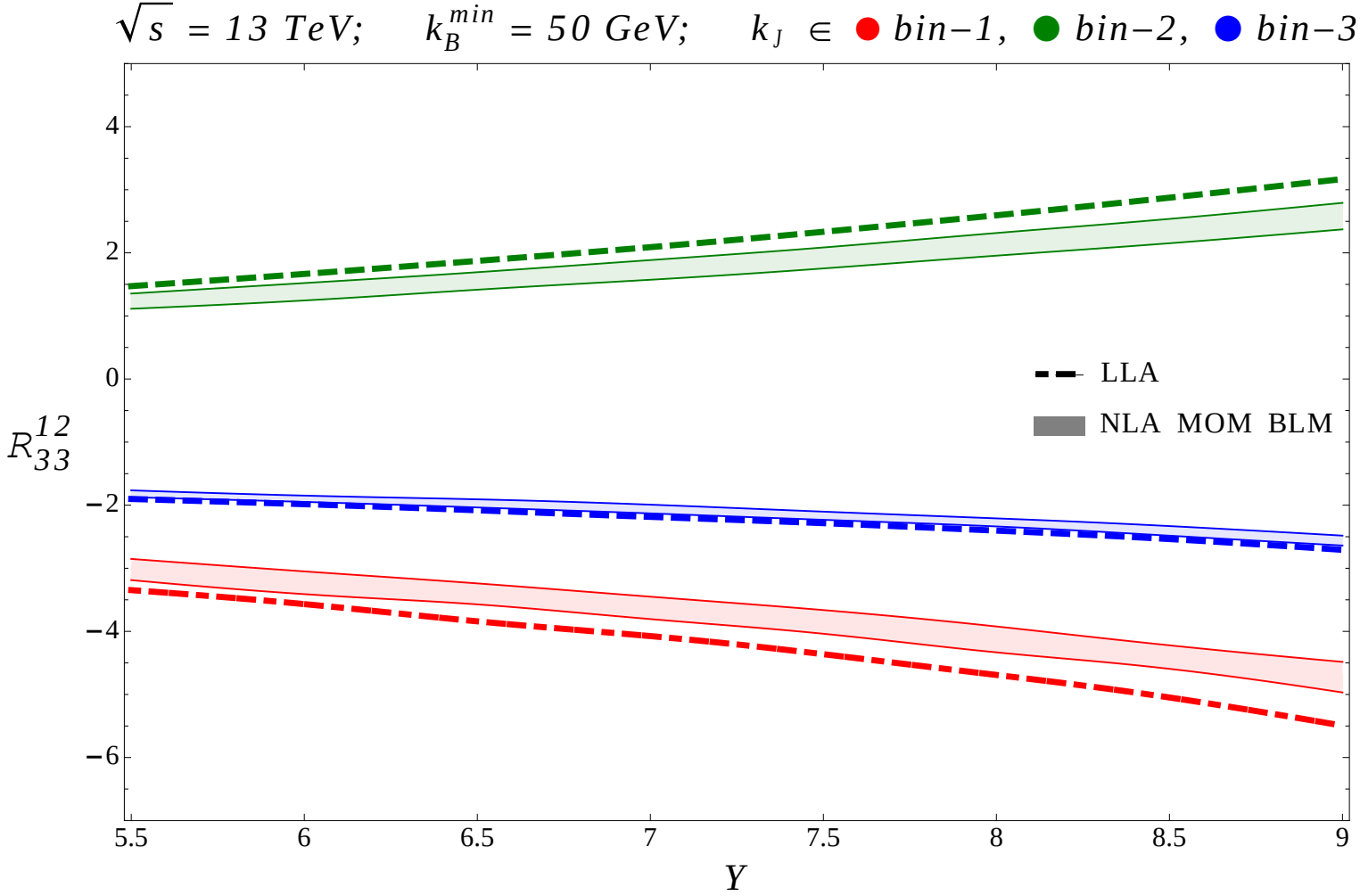

[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (in progress)]

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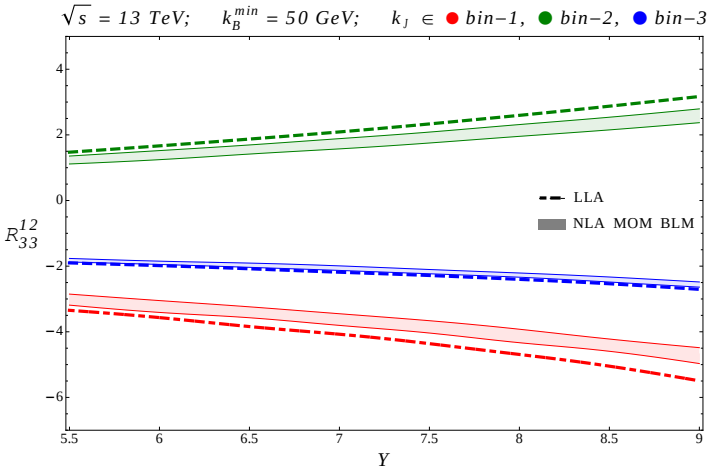
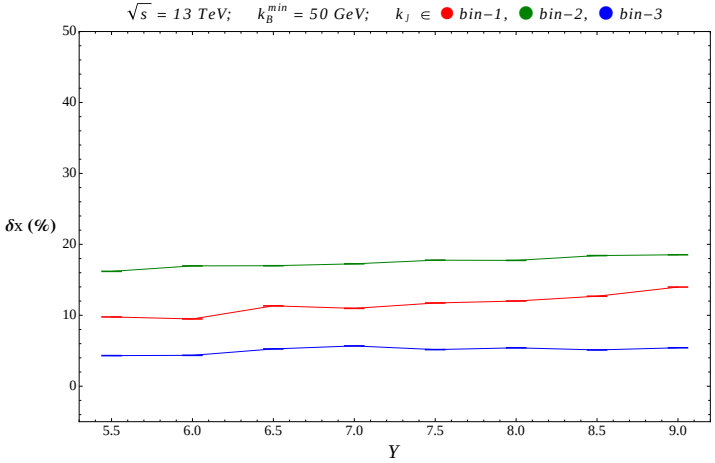
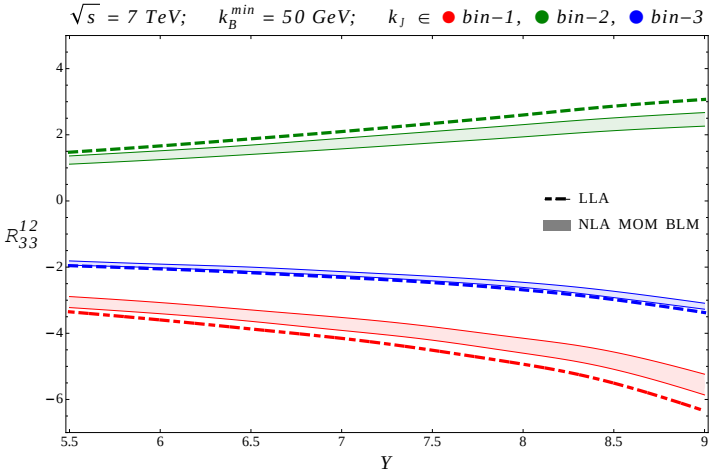
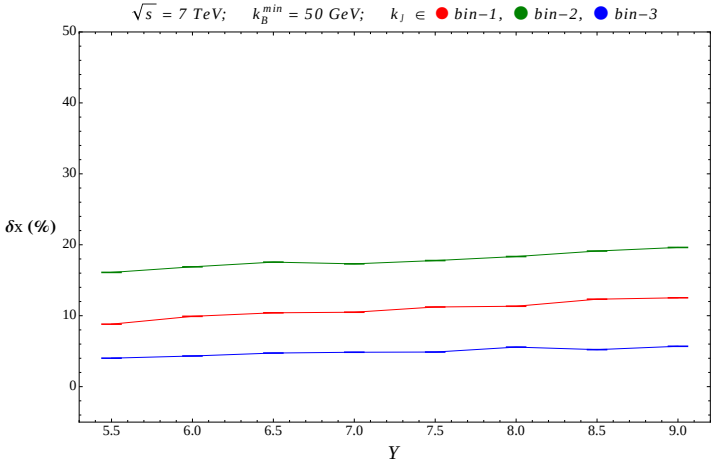
R_{33}^{12} vs Y at 13 and 7 TeV - NLLA preliminary results









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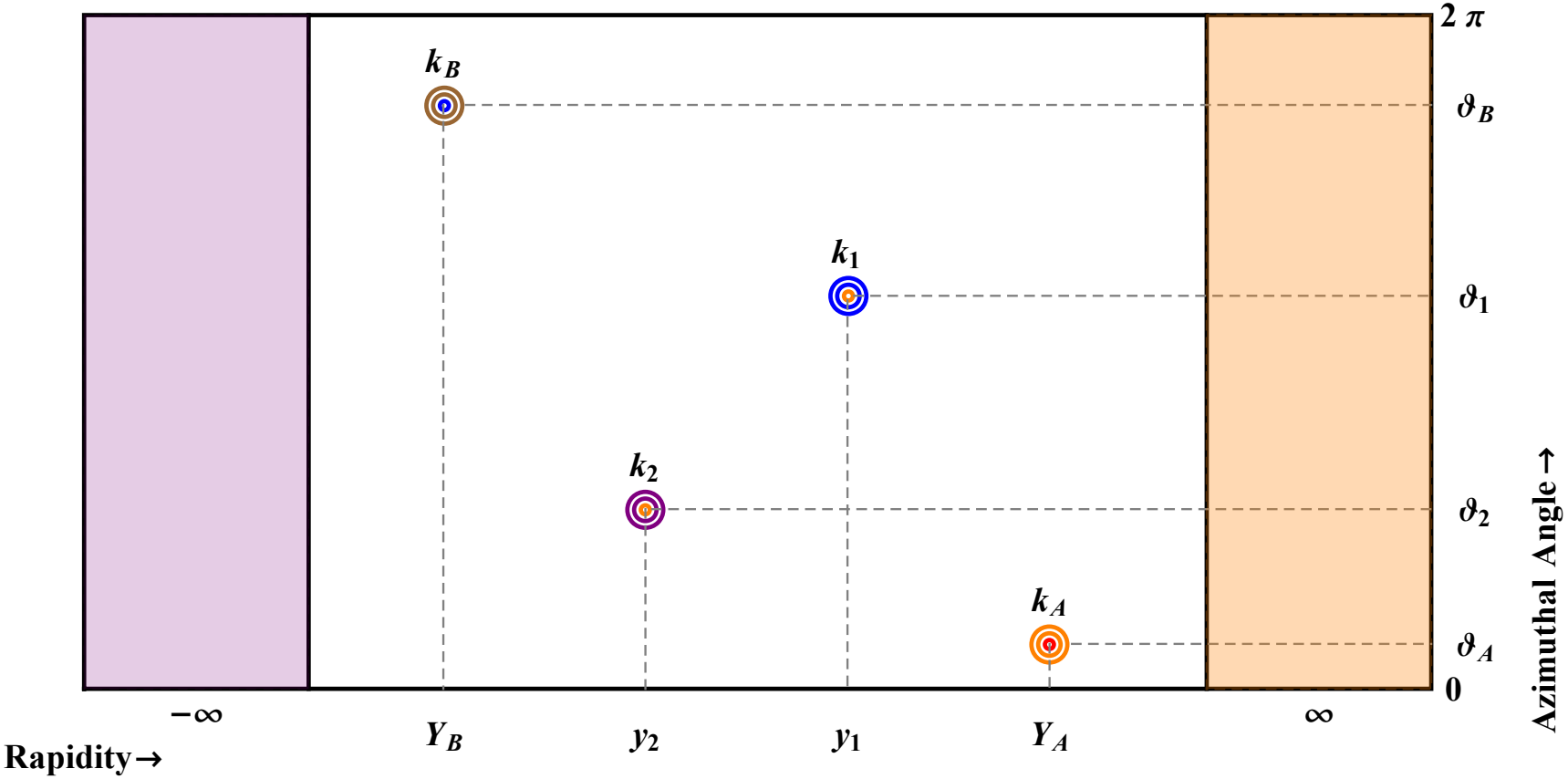
Outline

A four-jet primitive lego-plot



Generalized azimuthal correlations - partonic level

As for the three-jet case...

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

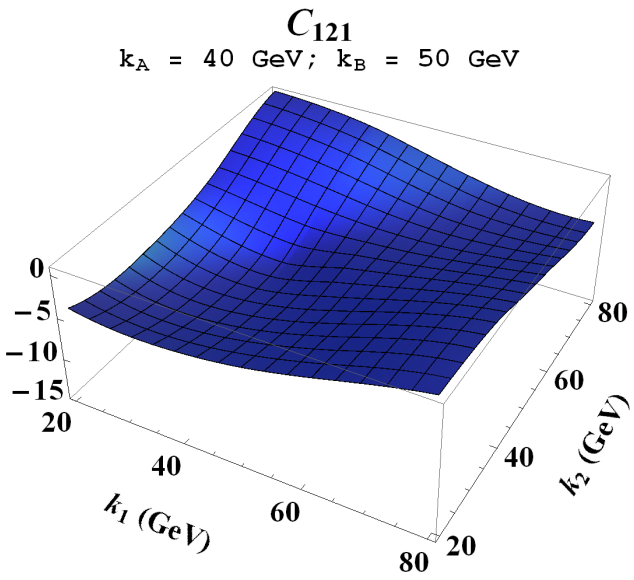
→ ...to define:

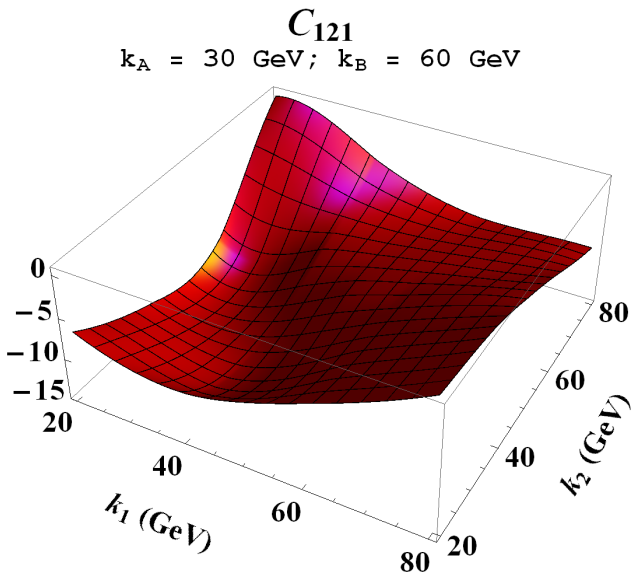
$$\mathcal{C}_{MNL} = \int_0^{2\pi} d\vartheta_A \int_0^{2\pi} d\vartheta_B \int_0^{2\pi} d\vartheta_1 \int_0^{2\pi} d\vartheta_2 \; \cos\left(M\left(\vartheta_A - \vartheta_1 - \pi\right)\right)$$
$$\cos\left(N\left(\vartheta_1 - \vartheta_2 - \pi\right)\right) \cos\left(L\left(\vartheta_2 - \vartheta_B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

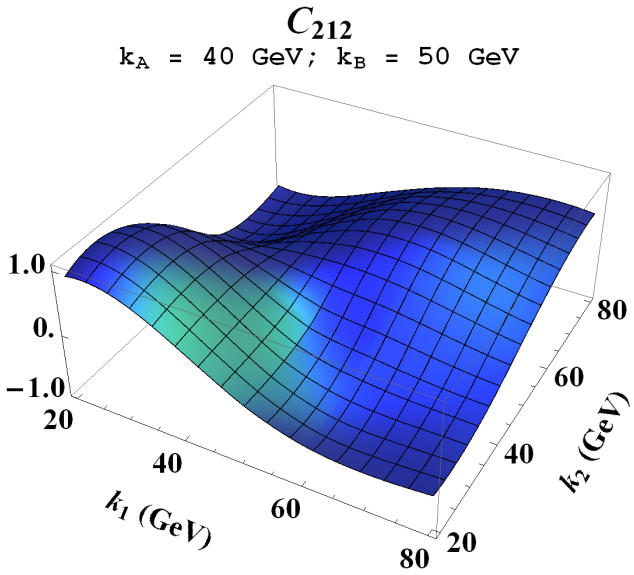
Main observables: **generalized azimuthal correlation momenta**

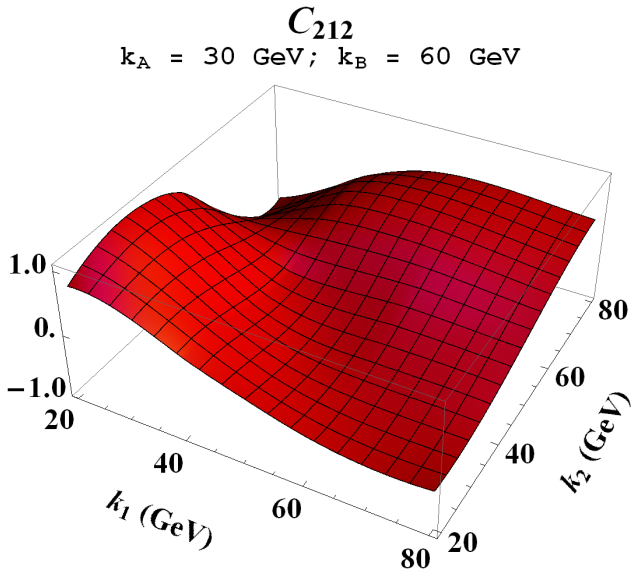
$$\mathcal{R}^{MNL}_{PQR} = \frac{\mathcal{C}_{MNL}}{\mathcal{C}_{PRQ}} = \frac{\langle \cos(M(\vartheta_A - \vartheta_1 - \pi)) \cos(N(\vartheta_1 - \vartheta_2 - \pi)) \cos(L(\vartheta_2 - \vartheta_B - \pi))\rangle}{\langle \cos(P(\vartheta_A - \vartheta_1 - \pi)) \cos(Q(\vartheta_1 - \vartheta_2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

Partonic prediction of C_{MNL} vs $k_{1,2}$



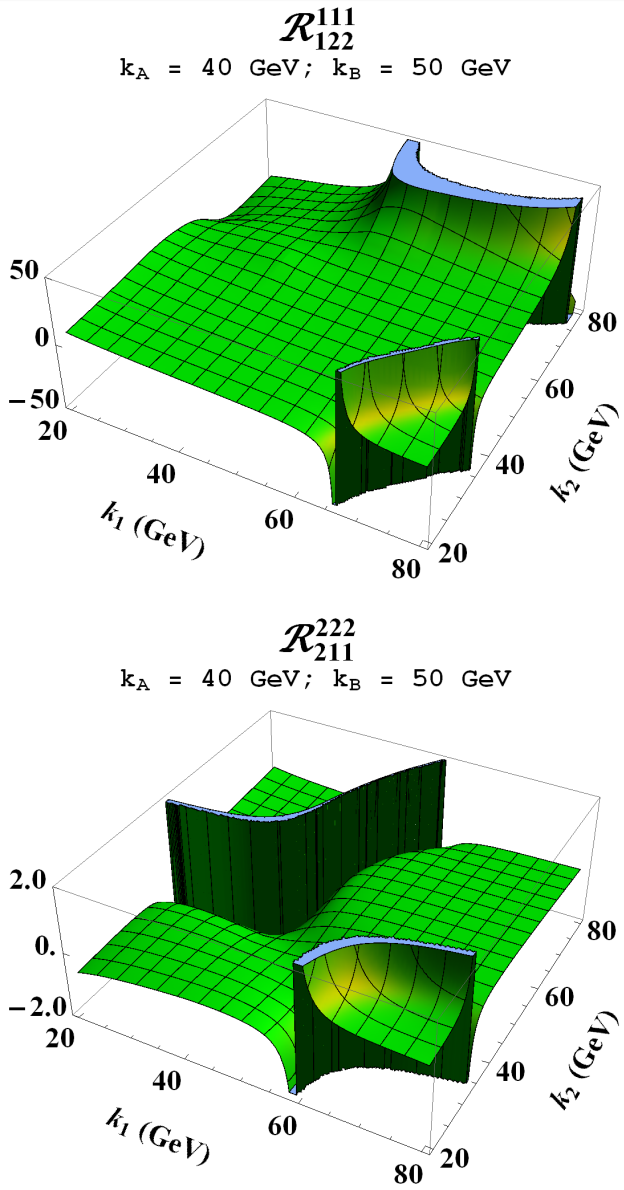


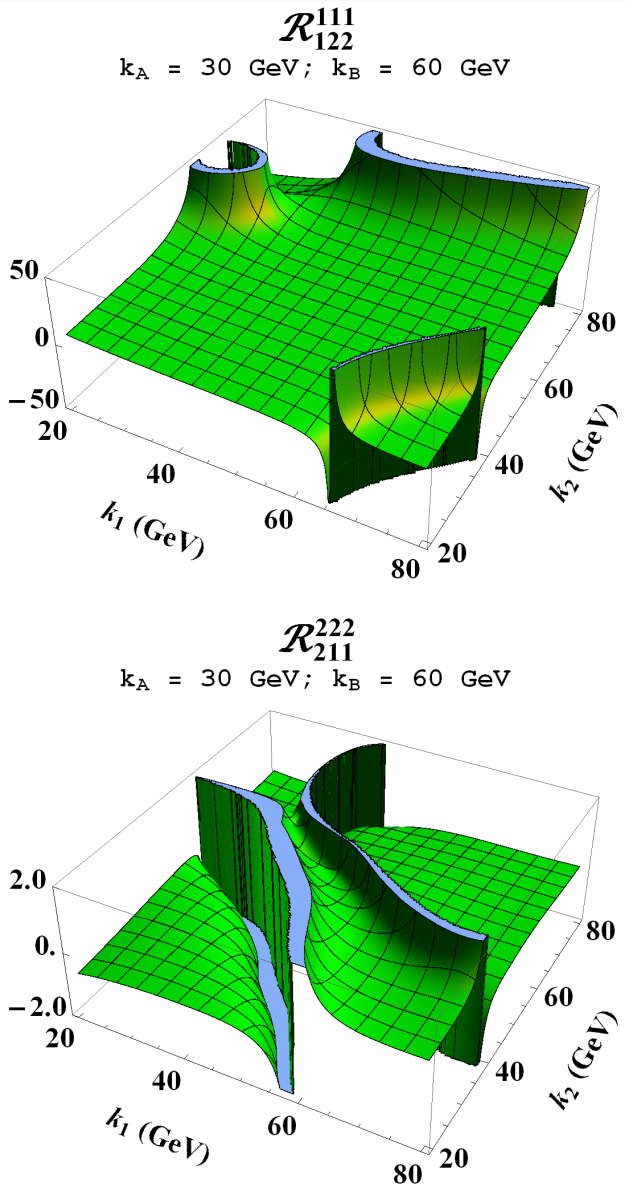




[F. Caporale, F.G. C., G. Chachamis, A. Sabio Vera (2016)]

Partonic prediction of $\mathcal{R}^{MNL}_{PQR}$ vs $k_{1,2}$





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

Outline

Next step: hadronic level predictions

- Introduce PDFs and running of the strong coupling

- Use realistic LHC kinematical cuts:

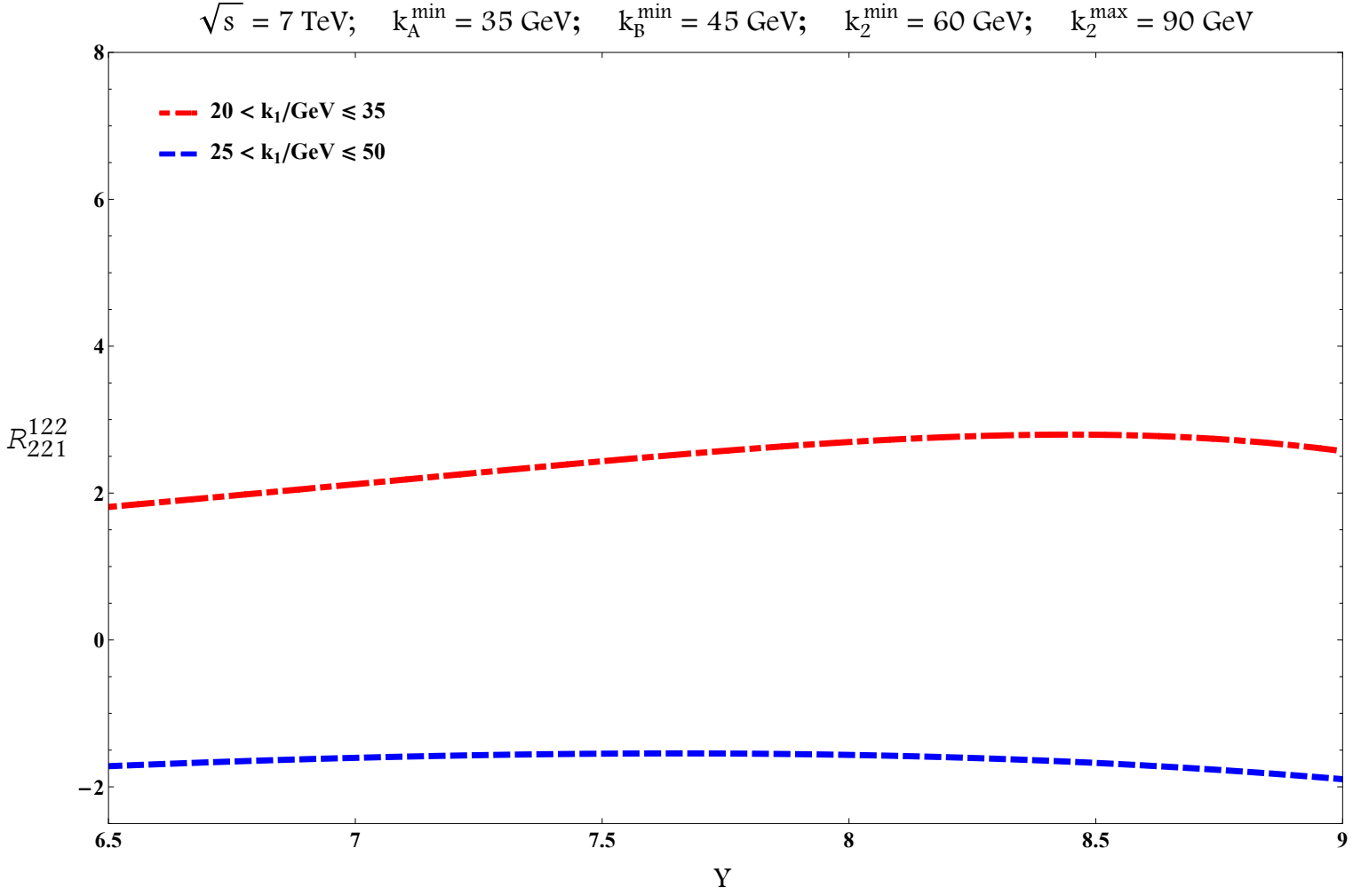
  - **1.** $k_A^{min} = 35\,\text{GeV}$, $k_A^{max} = 60\,\text{GeV}$
    $k_B^{min} = 45\,\text{GeV}$, $k_B^{max} = 60\,\text{GeV}$
    $k_1^{min} = 20\,\text{GeV}$, $k_1^{max} = 35\,\text{GeV}$
    $k_2^{min} = 60\,\text{GeV}$, $k_2^{max} = 90\,\text{GeV}$

    2. $k_A^{min} = 35\,\text{GeV}$, $k_A^{max} = 60\,\text{GeV}$
    $k_B^{min} = 45\,\text{GeV}$, $k_B^{max} = 60\,\text{GeV}$
    $k_1^{min} = 25\,\text{GeV}$, $k_1^{max} = 50\,\text{GeV}$
    $k_2^{min} = 60\,\text{GeV}$, $k_2^{max} = 90\,\text{GeV}$

  - $Y = Y_A - Y_B$ fixed;
    $Y_A - y_1 = y_1 - y_2 = y_2 - Y_B = Y/3$

  - $\sqrt{s} = 7, 13$ TeV

R_{221}^{122} at $\sqrt{s} = 7$ TeV vs $Y = Y_A - Y_B$ for two k_1 bins



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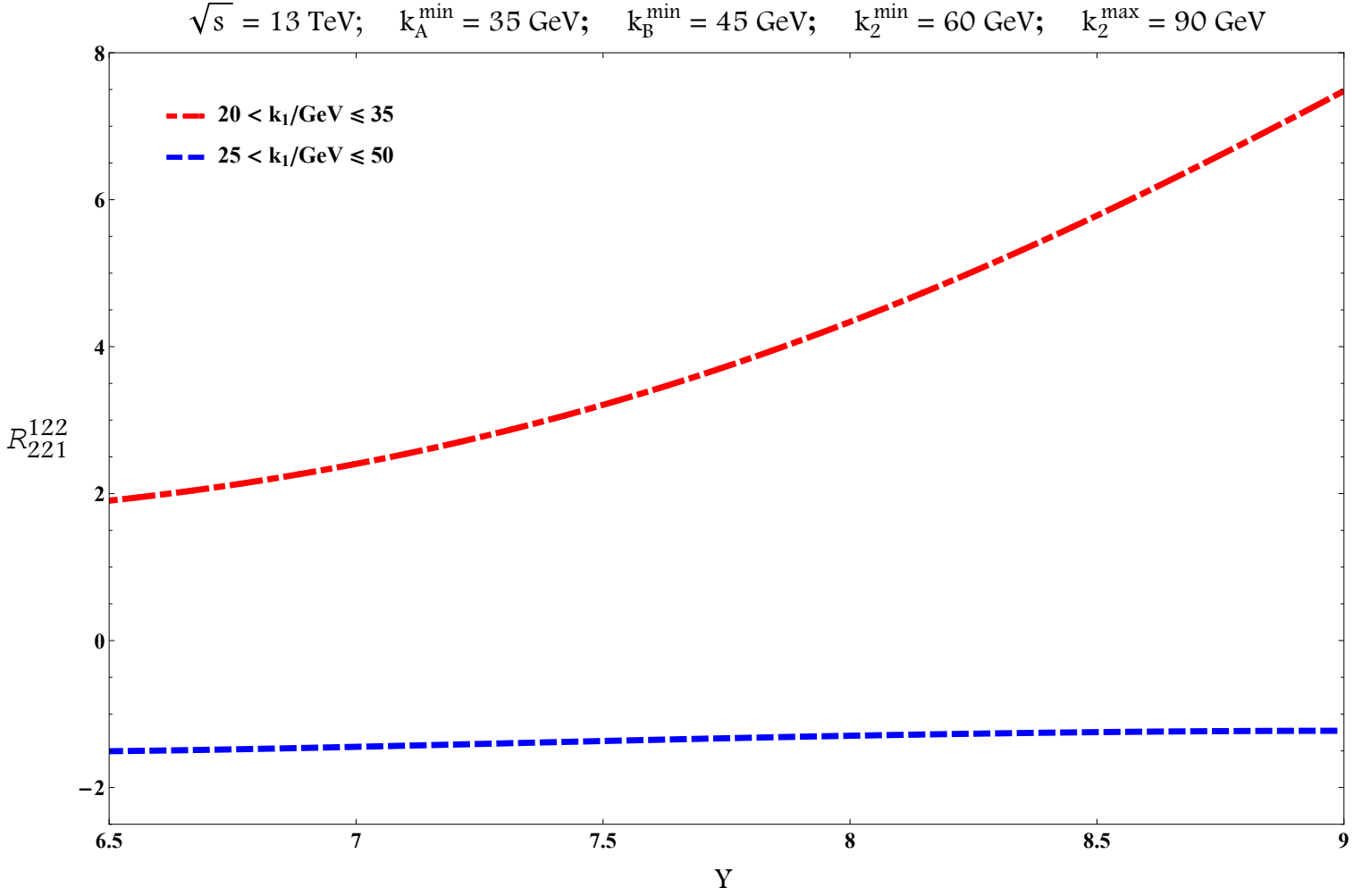
R_{221}^{122} at $\sqrt{s} = 13$ TeV vs $Y = Y_A - Y_B$ for two k_1 bins



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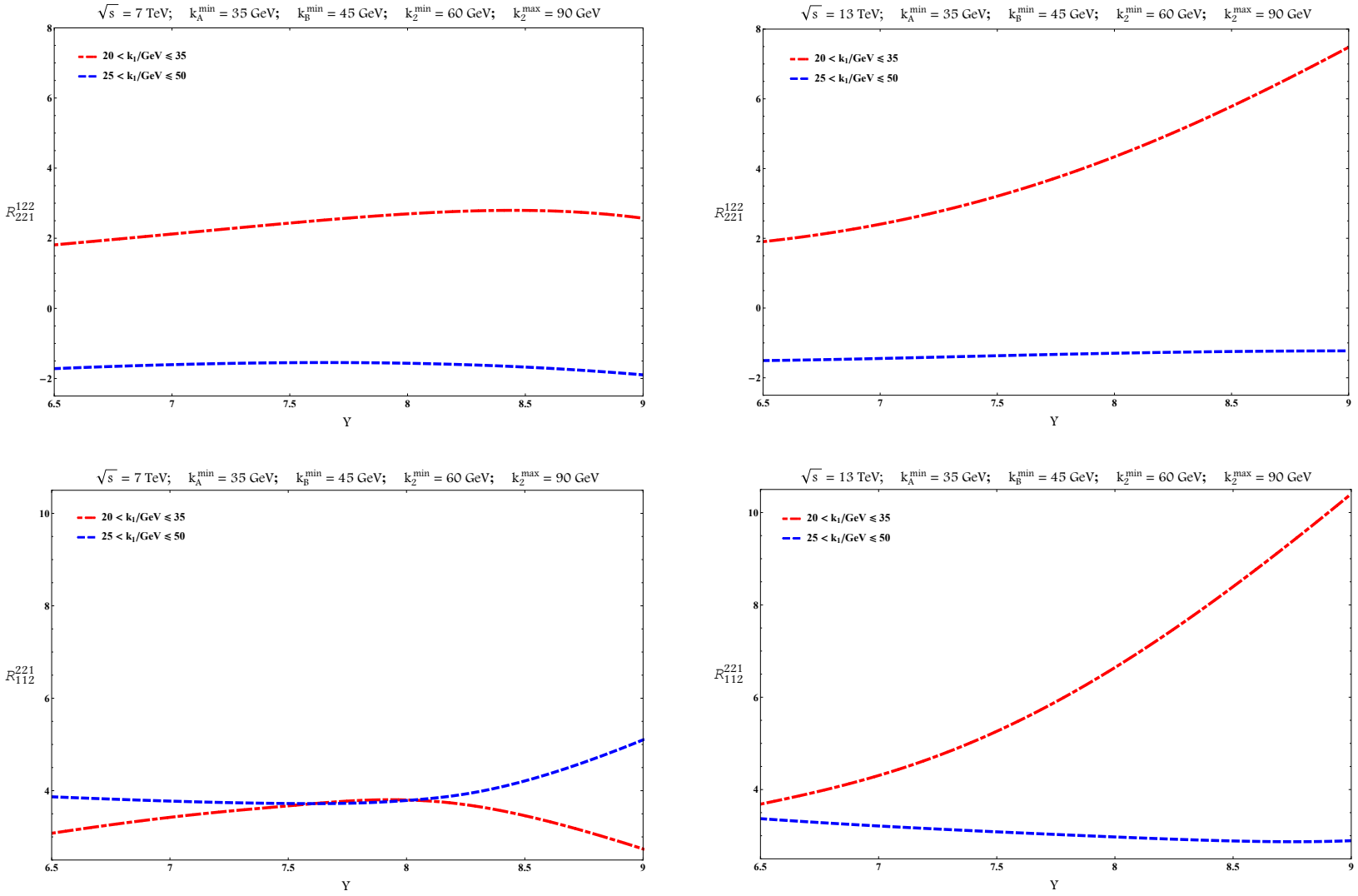
R_{221}^{122} and R_{112}^{221} vs $Y = Y_A - Y_B$ and $\sqrt{s}$ for two k_1 bins



[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016)]

Conclusions...

- Study of processes with **three** and **four** tagged jets to propose new, more exclusive, BFKL observables: **generalized azimuthal correlation momenta**
- Ratios of correlation functions used to minimize the influence of higher order corrections
- Comparison with experimental data suggested and needed

...Outlook

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

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

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

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

- Comparison with analyses where the four-jet predictions stem from two independent gluon ladders

  [R. Maciula, A. Szczurek (2014, 2015)]
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- Probe BFKL through other processes...
  - Di-hadron production in the full NLLA
  - Heavy quark pair production

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

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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)]

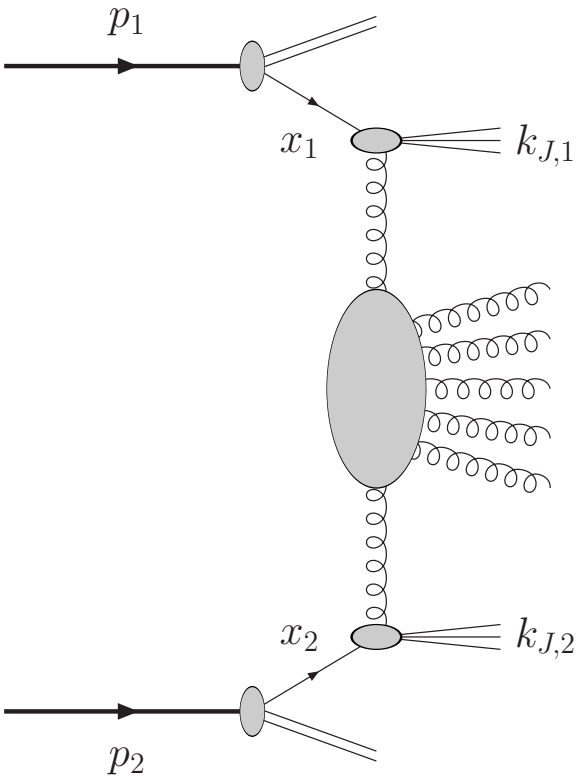
Last years:

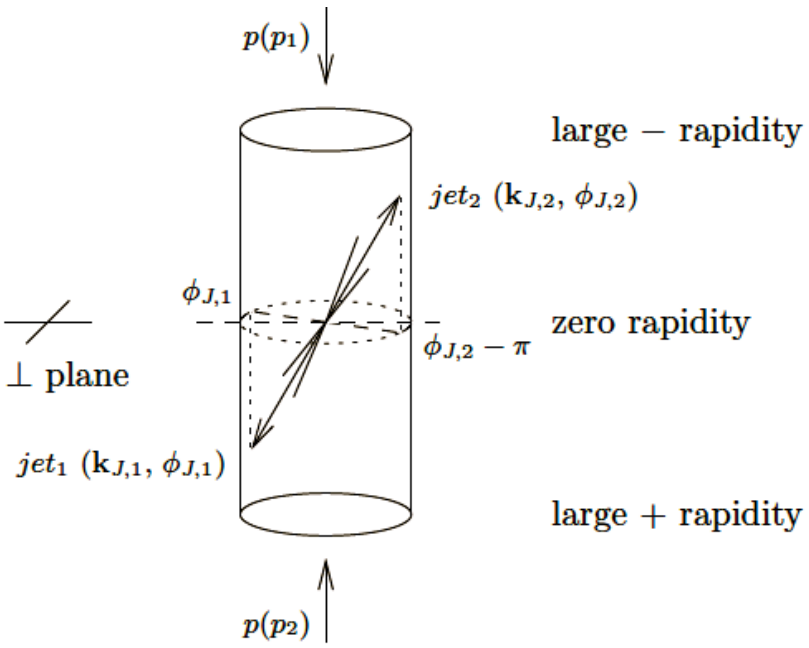
hadroproduction of two jets featuring high transverse momenta and well separed in rapidity, so called **Mueller–Navelet jets**...

- ◇ ...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)]

Mueller–Navelet jets



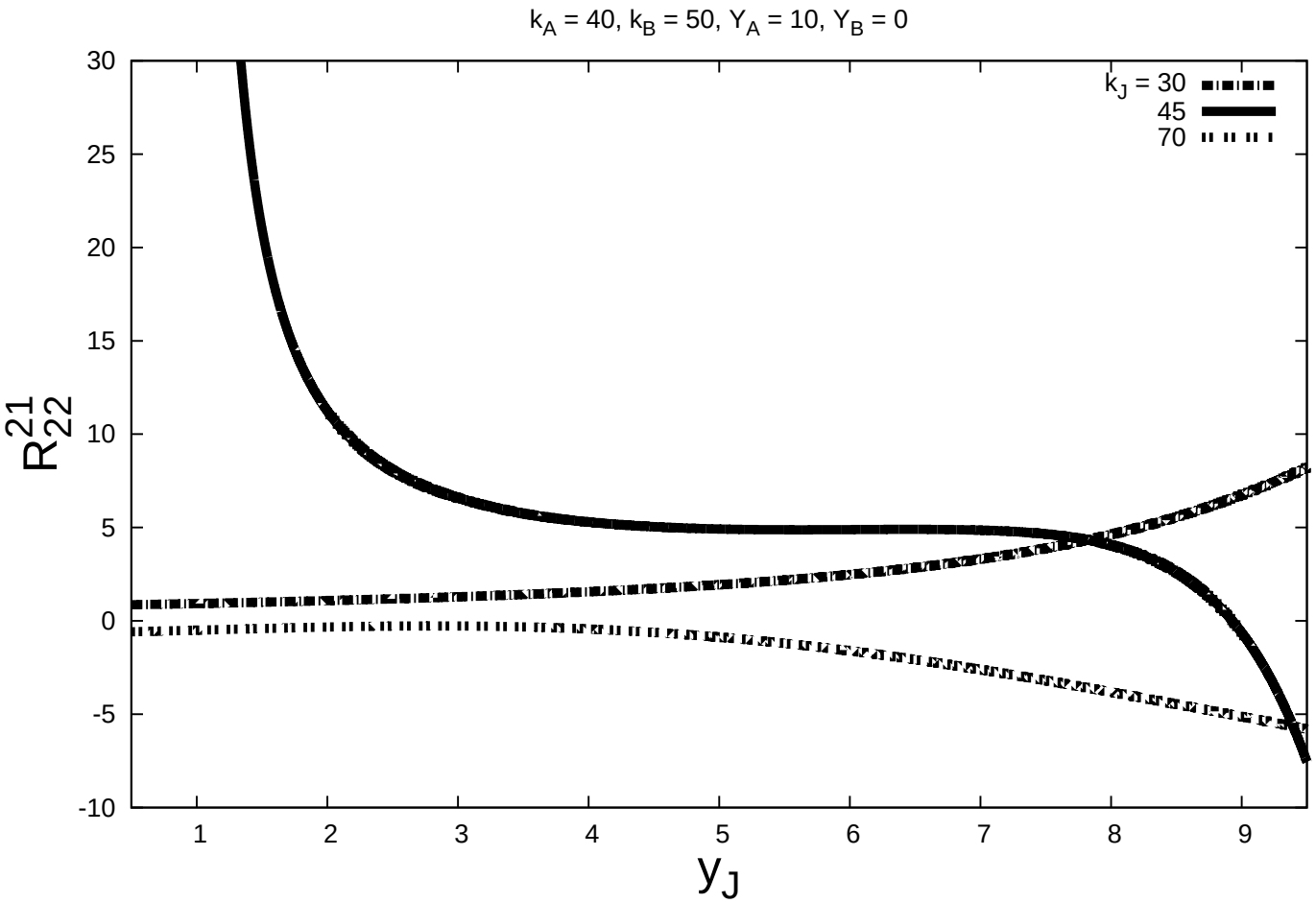


Pictures from
[D. Colferai, F. Schwennsen, L. Szymanowski, S. Wallon (2010)]

...large jet transverse momenta: $\vec{k}_{J,1}^{\,2} \sim \vec{k}_{J,2}^{\,2} \gg \Lambda_{\rm QCD}^2$

...large rapidity gap between jets (high energies) $\Rightarrow$ $\Delta y = \ln \frac{x_{J,1} x_{J,2} s}{|\vec{k}_{J,1}||\vec{k}_{J,2}|}$

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

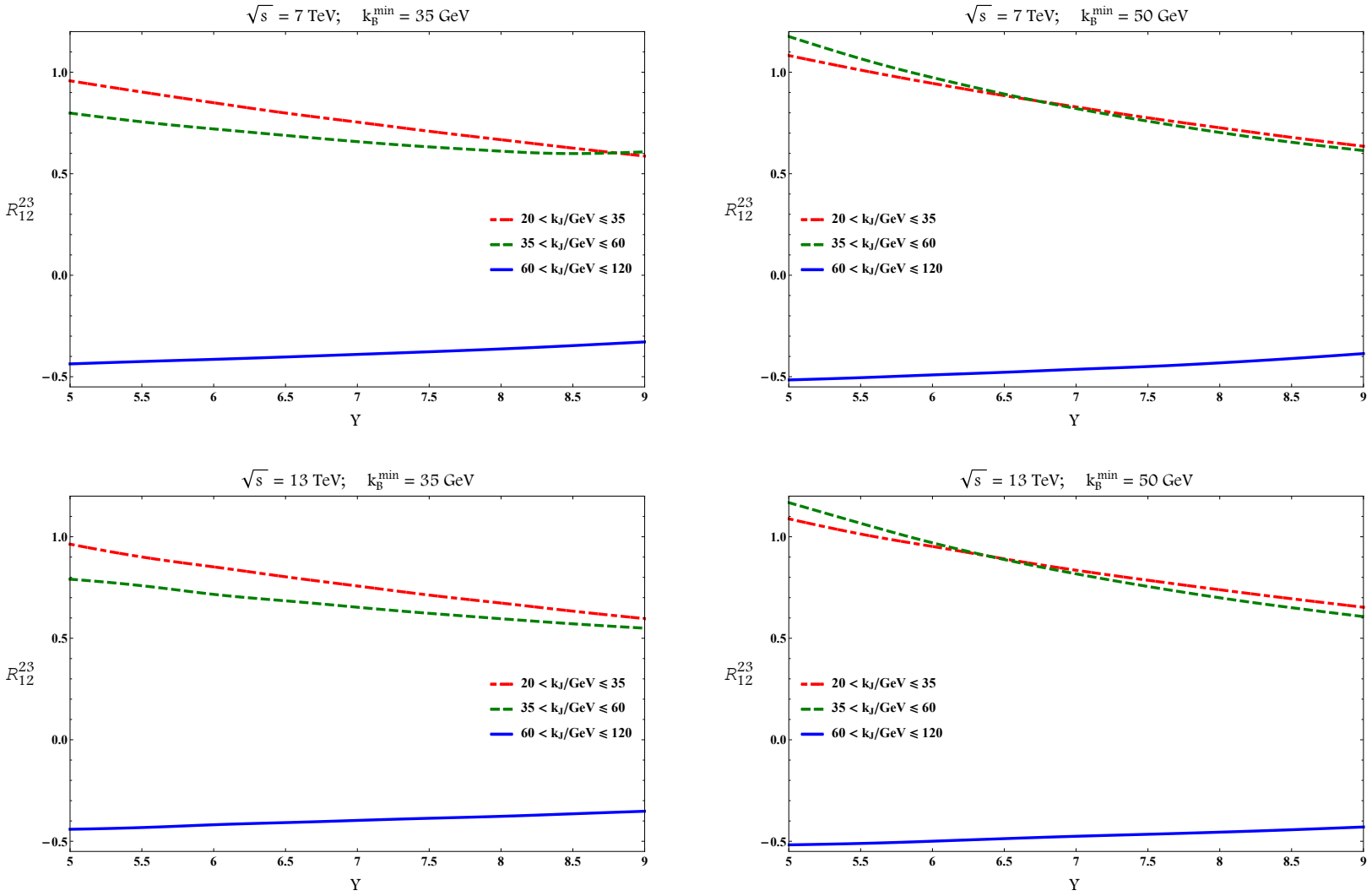


[F. Caporale, G. Chachamis, B. Murdaca, A. Sabio Vera (2015)]

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

BACKUP slides

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

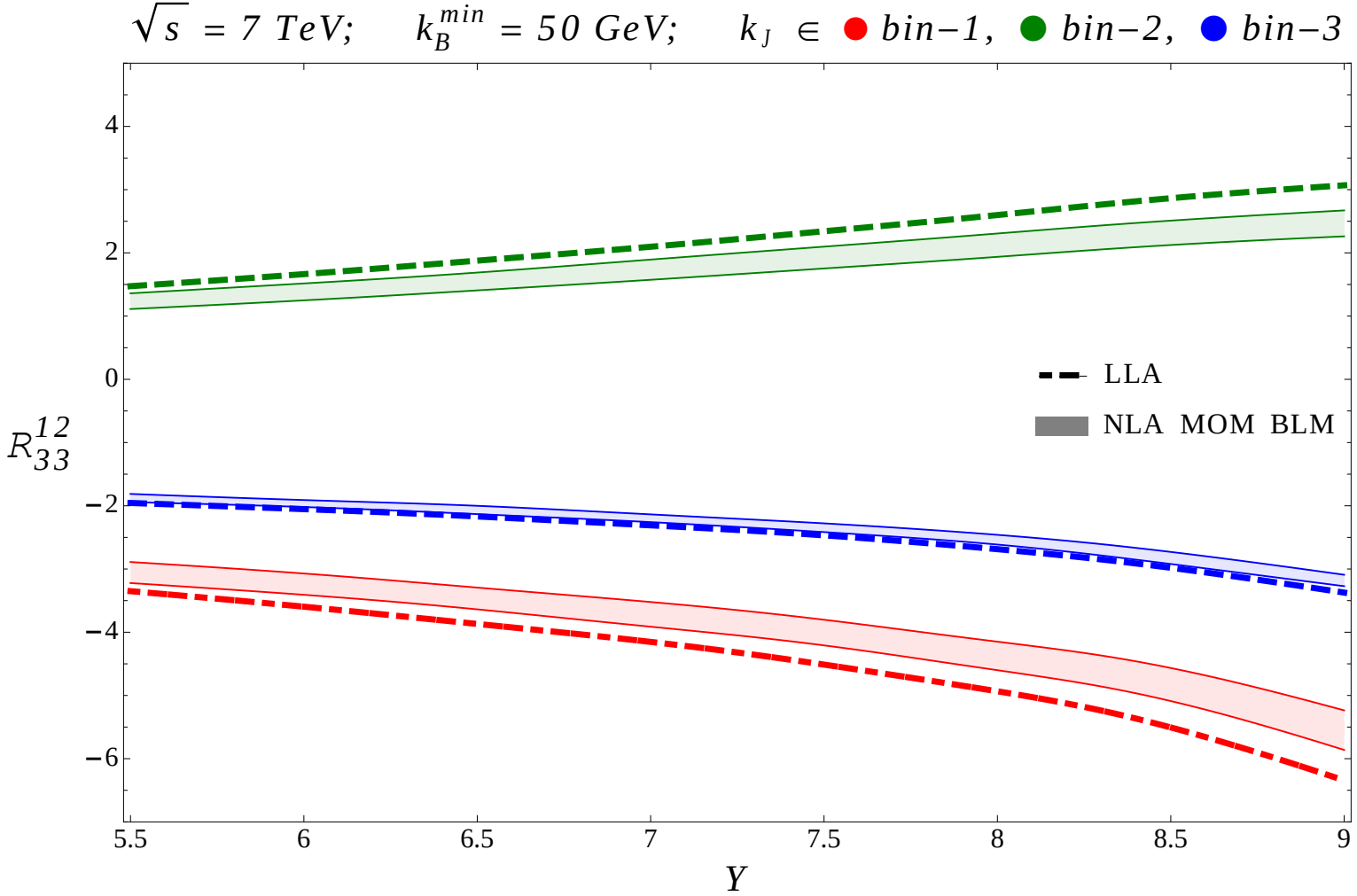


[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016)]

BACKUP slides

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

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

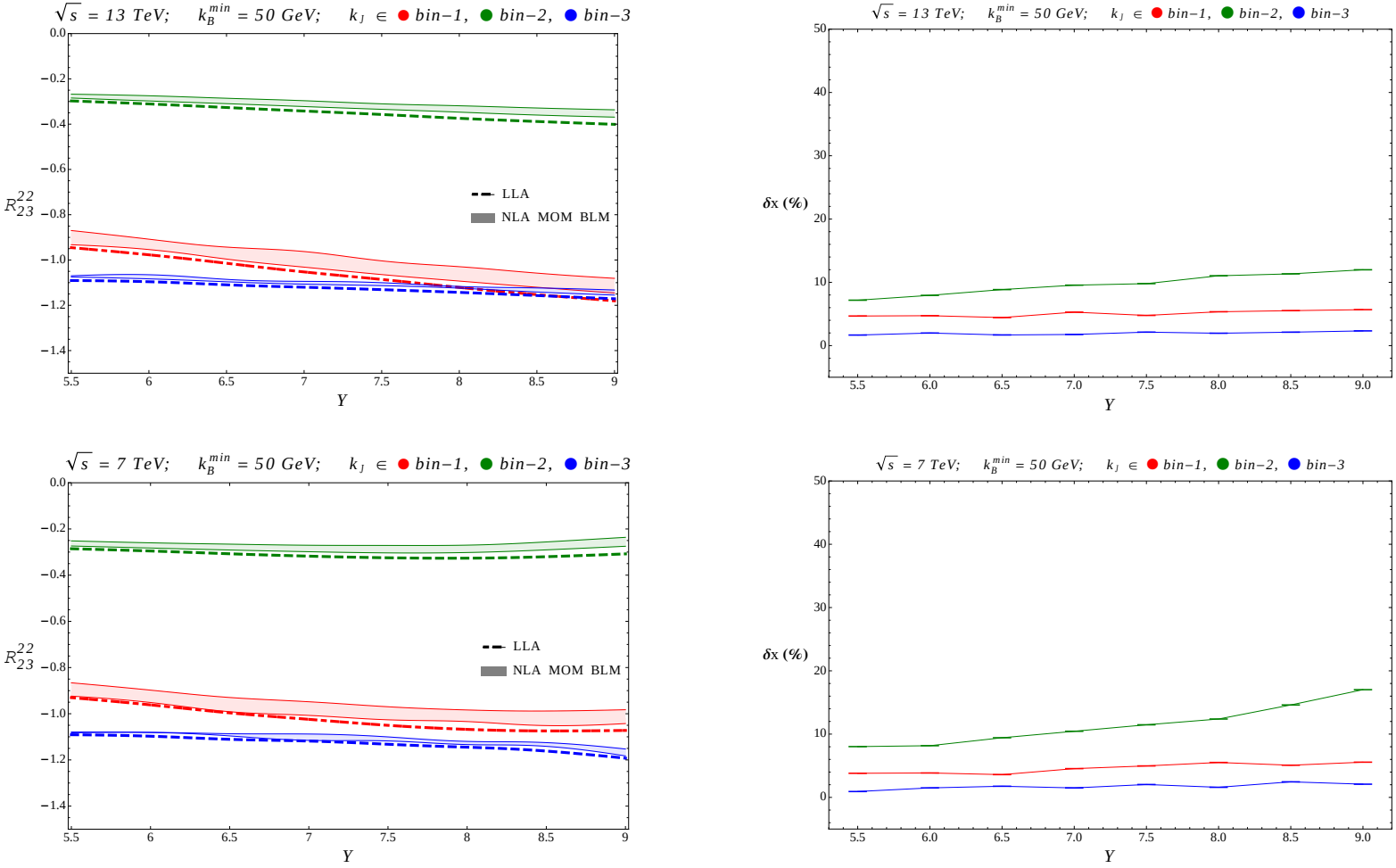


[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (in progress)]

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

BACKUP slides

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



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

Four-jets: generalized azimuthal coefficients - partonic level

$$\mathcal{C}_{MNL} = \int_0^{2\pi} d\vartheta_A \int_0^{2\pi} d\vartheta_B \int_0^{2\pi} d\vartheta_1 \int_0^{2\pi} d\vartheta_2 \; \cos\left(M\left(\vartheta_A - \vartheta_1 - \pi\right)\right)$$

$$\cos\left(N\left(\vartheta_1 - \vartheta_2 - \pi\right)\right) \cos\left(L\left(\vartheta_2 - \vartheta_B - \pi\right)\right) \frac{d^6\sigma^{4-\mathrm{jet}}\left(\vec{k_A}, \vec{k_B}, Y_A - Y_B\right)}{dk_1\, dy_1\, d\vartheta_1\, dk_2\, d\vartheta_2\, dy_2}$$

$$= \frac{2\pi^2 \bar{\alpha}_s\left(\mu_R\right)^2}{k_1 k_2} (-1)^{M+N+L} \left(\tilde{\Omega}_{M,N,L} + \tilde{\Omega}_{M,N,-L} + \tilde{\Omega}_{M,-N,L}\right.$$

$$\left. + \tilde{\Omega}_{M,-N,-L} + \tilde{\Omega}_{-M,N,L} + \tilde{\Omega}_{-M,N,-L} + \tilde{\Omega}_{-M,-N,L} + \tilde{\Omega}_{-M,-N,-L}\right)$$

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

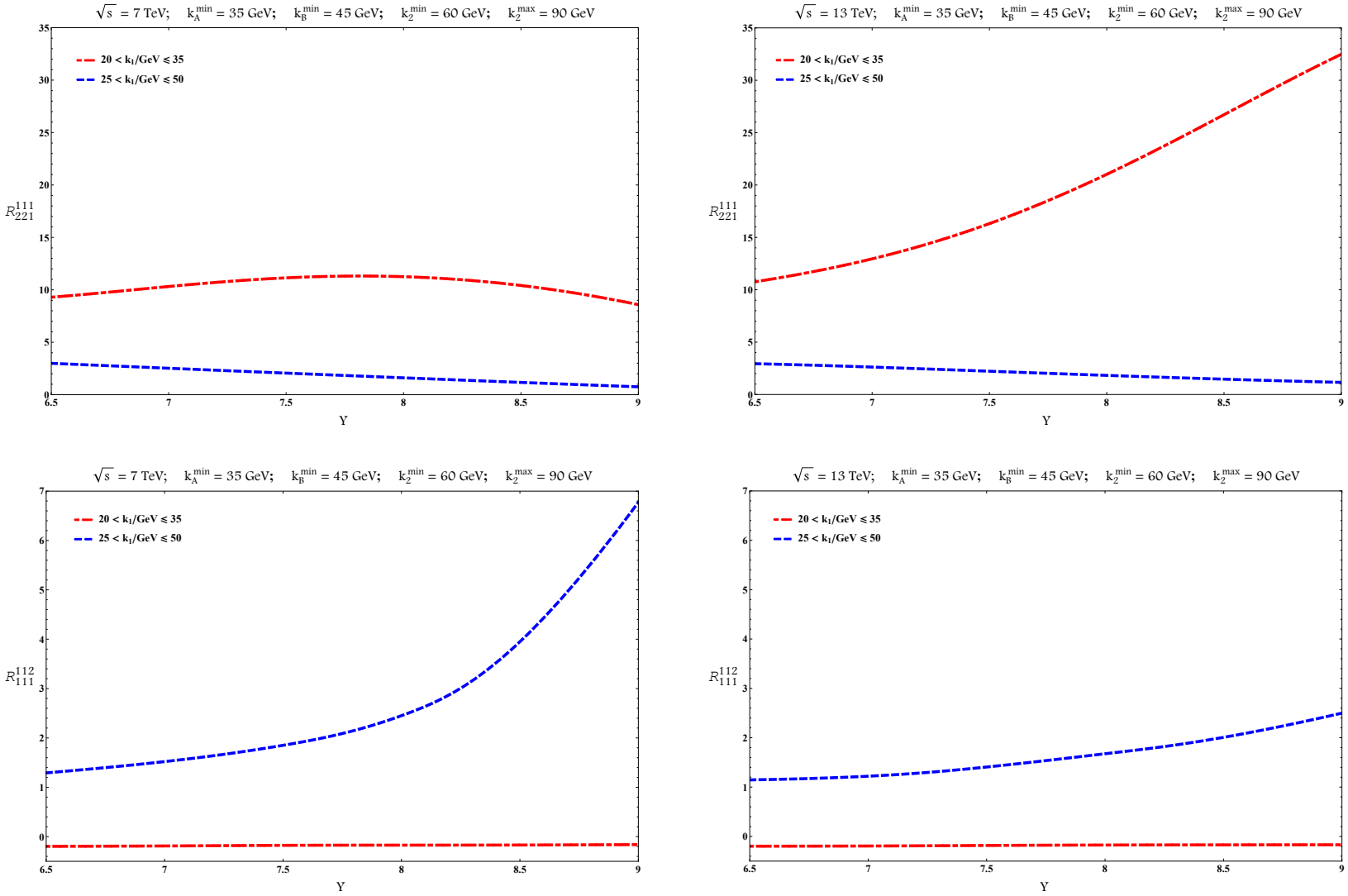
$$\mathcal{C}_{MNL} = \int_0^{2\pi} d\vartheta_A \int_0^{2\pi} d\vartheta_B \int_0^{2\pi} d\vartheta_1 \int_0^{2\pi} d\vartheta_2 \; \cos\left(M\left(\vartheta_A - \vartheta_1 - \pi\right)\right)$$
$$\cos\left(N\left(\vartheta_1 - \vartheta_2 - \pi\right)\right) \cos\left(L\left(\vartheta_2 - \vartheta_B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

Main observables: **generalized azimuthal correlation momenta**

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

BACKUP slides

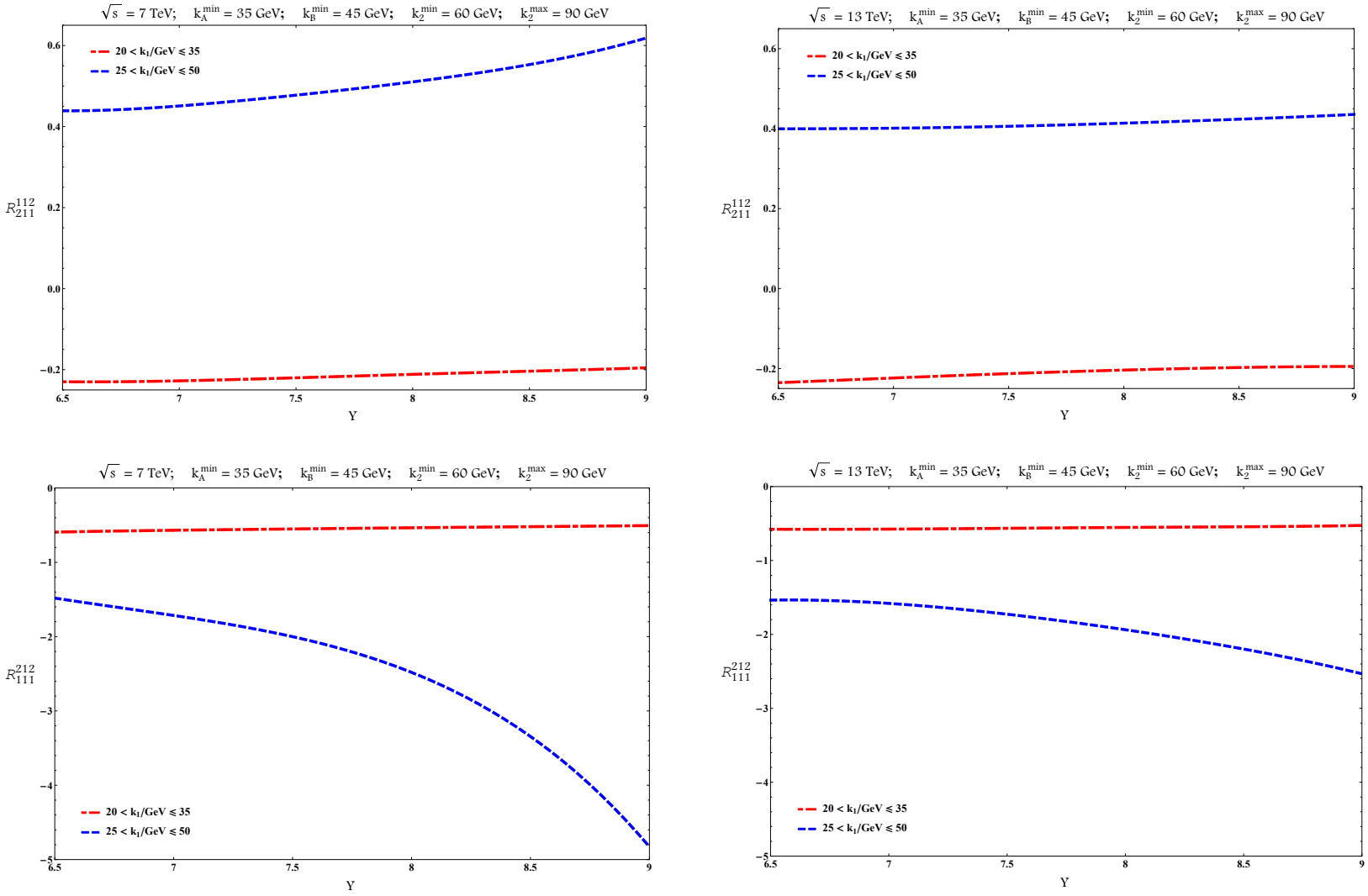
R^{111}_{221} and R^{112}_{111} vs $Y = Y_A - Y_B$ and $\sqrt{s}$ for two k_1 bins



[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016)]

BACKUP slides

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



[F. Caporale, F.G. C., G. Chachamis, D. Gordo Gómez, A. Sabio Vera (2016)]