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Azimuthal-angle Observables in Inclusive Three-jet Production

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arXiv:1612.05428 (accepted in Phys. Rev. D)

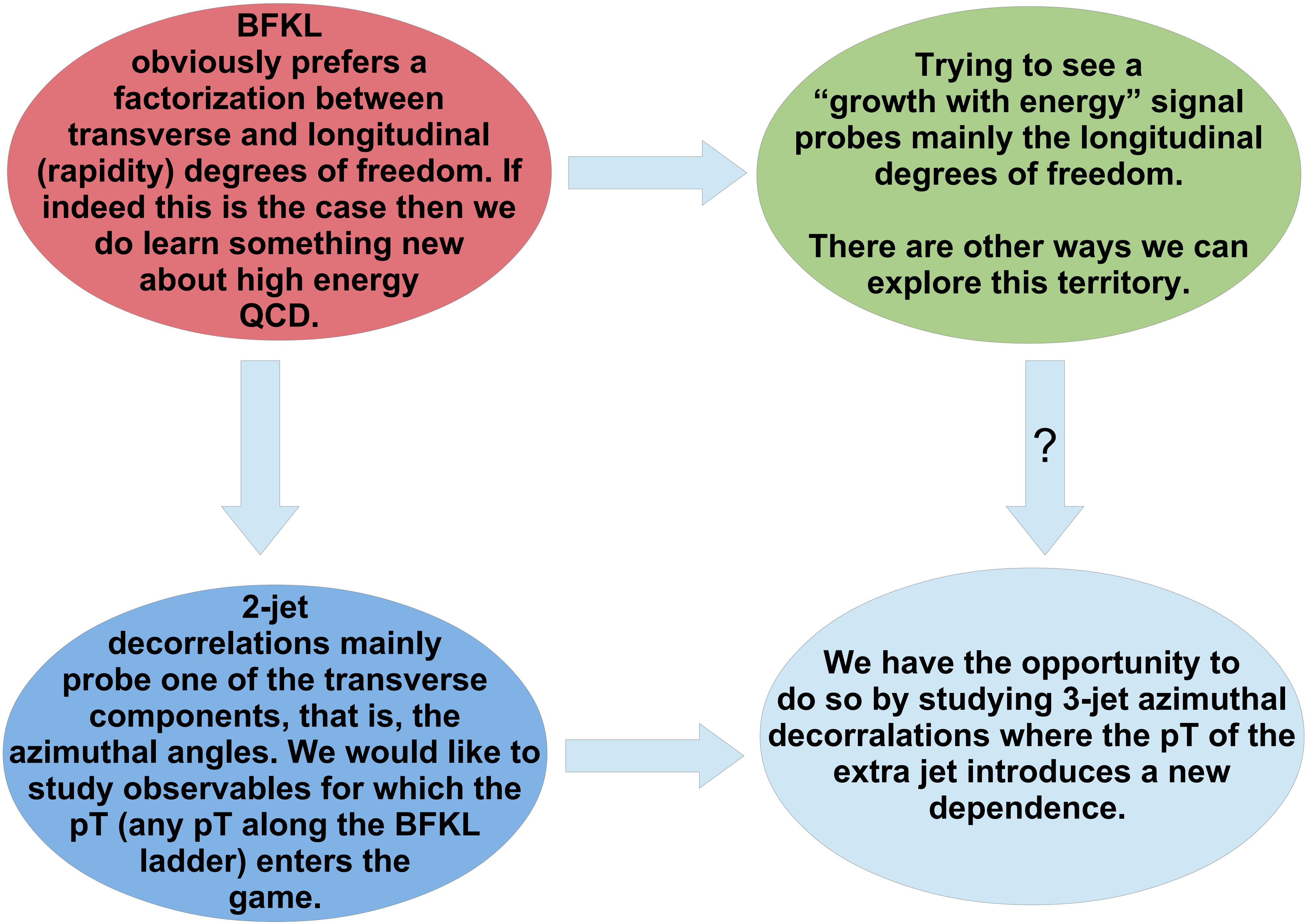
DIS 2017, 3-7 April 2017, Birmingham, UK

Outline

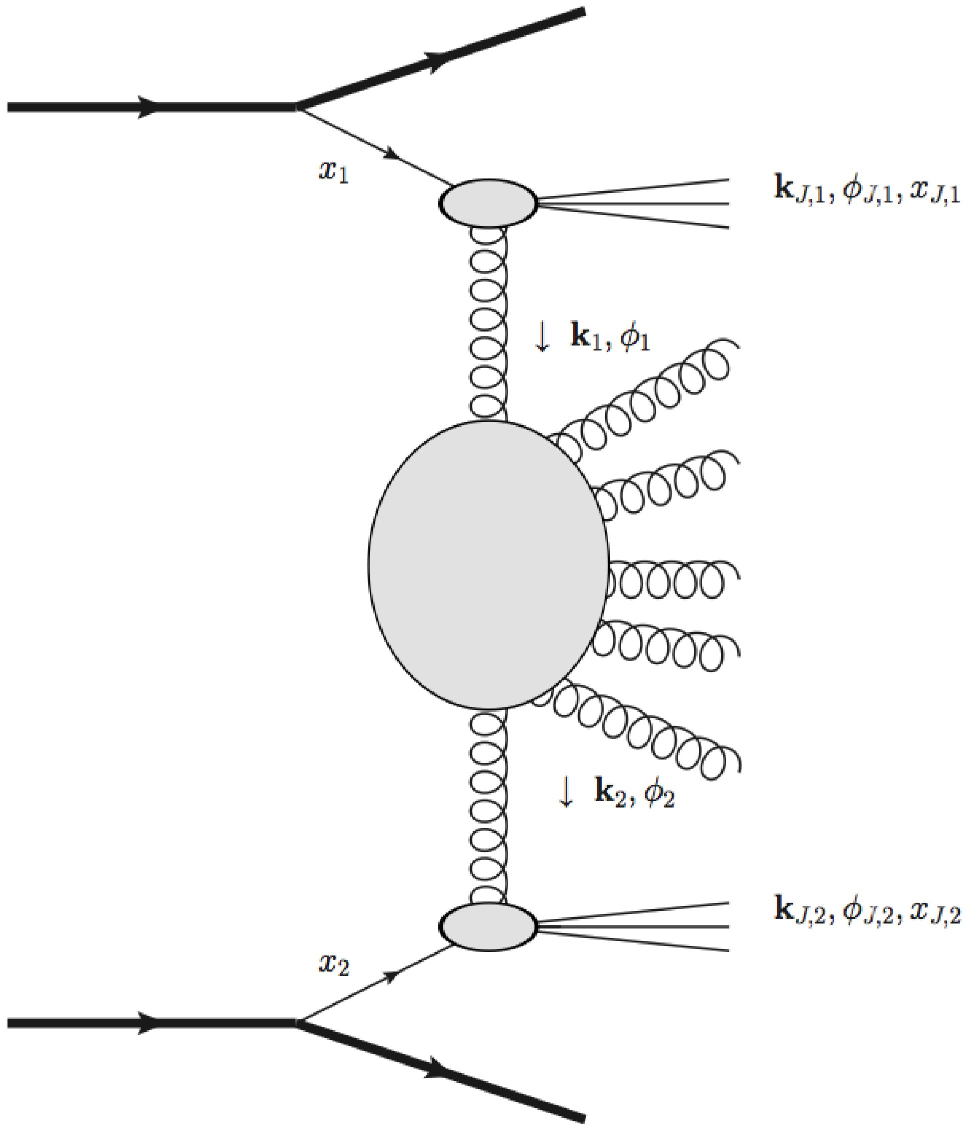
- Motivation
- Kinematics
- 3-jet production within the BFKL framework
- New observables relevant to 3-jet production
- Include higher order corrections and check stability
- Conclusions and outlook

BFKL phenomenology

- LHC has produced and will further produce an abundance of data
- This is the best time to investigate the applicability of the BFKL resummation program within the context of a hadron collider
- In the last years: the big hit from the theory/experimental side was the study of Mueller-Navelet jets (dijets). We only touch here one subfield for which BFKL is relevant, small-x physics/forward physics is much richer of course: Diffraction, Saturation, DPI etc.

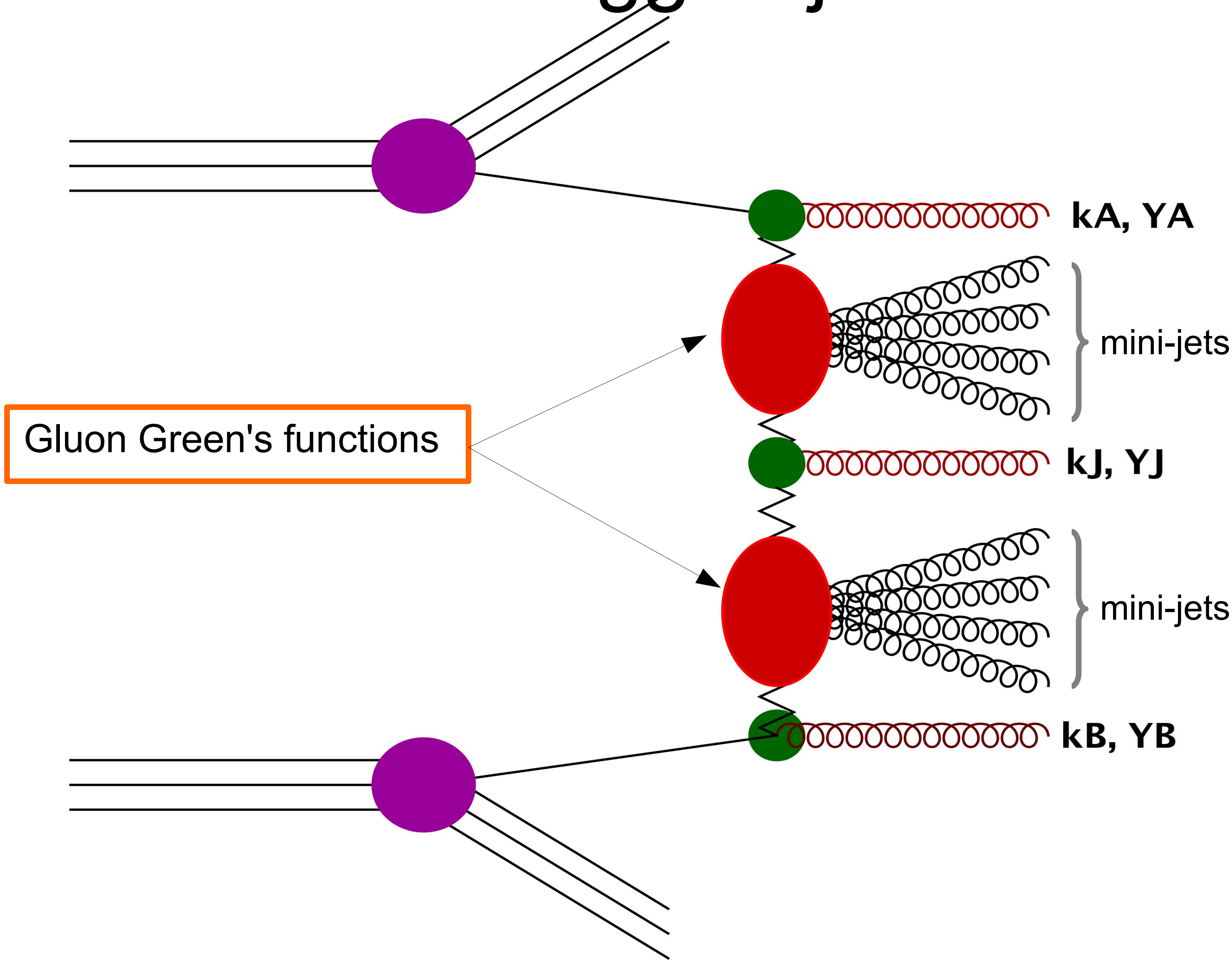

BFKL
obviously prefers a factorization between transverse and longitudinal (rapidity) degrees of freedom. If indeed this is the case then we do learn something new about high energy QCD.
Trying to see a “growth with energy” signal probes mainly the longitudinal degrees of freedom.
There are other ways we can explore this territory.
?
2-jet
decorrelations mainly probe one of the transverse components, that is, the azimuthal angles. We would like to study observables for which the pT (any pT along the BFKL ladder) enters the game.
We have the opportunity to do so by studying 3-jet azimuthal decorralations where the pT of the extra jet introduces a new dependence.

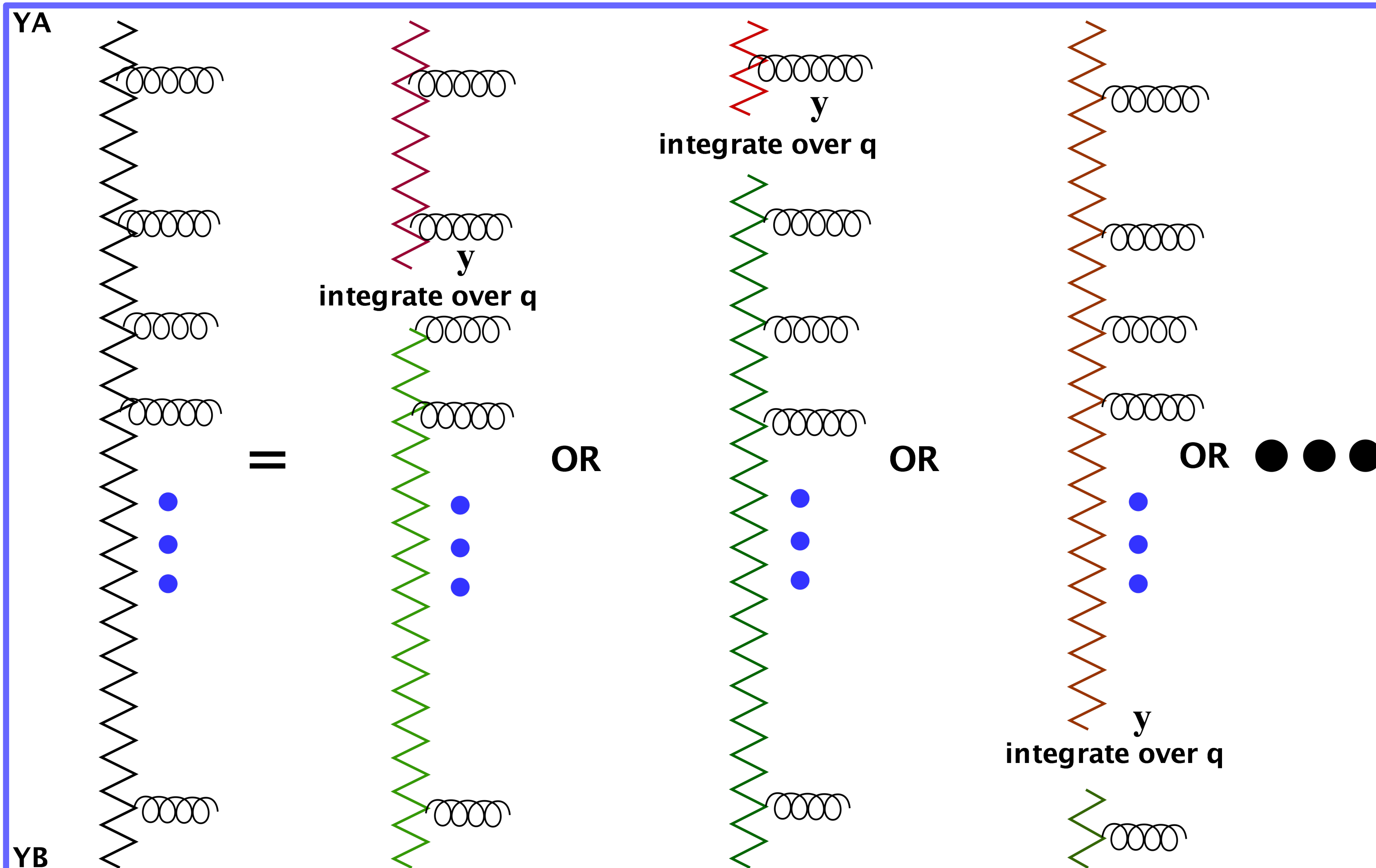
Mueller-Navelet jets



Colferai, Schwennsen, Szymanowski, Wallon 2010

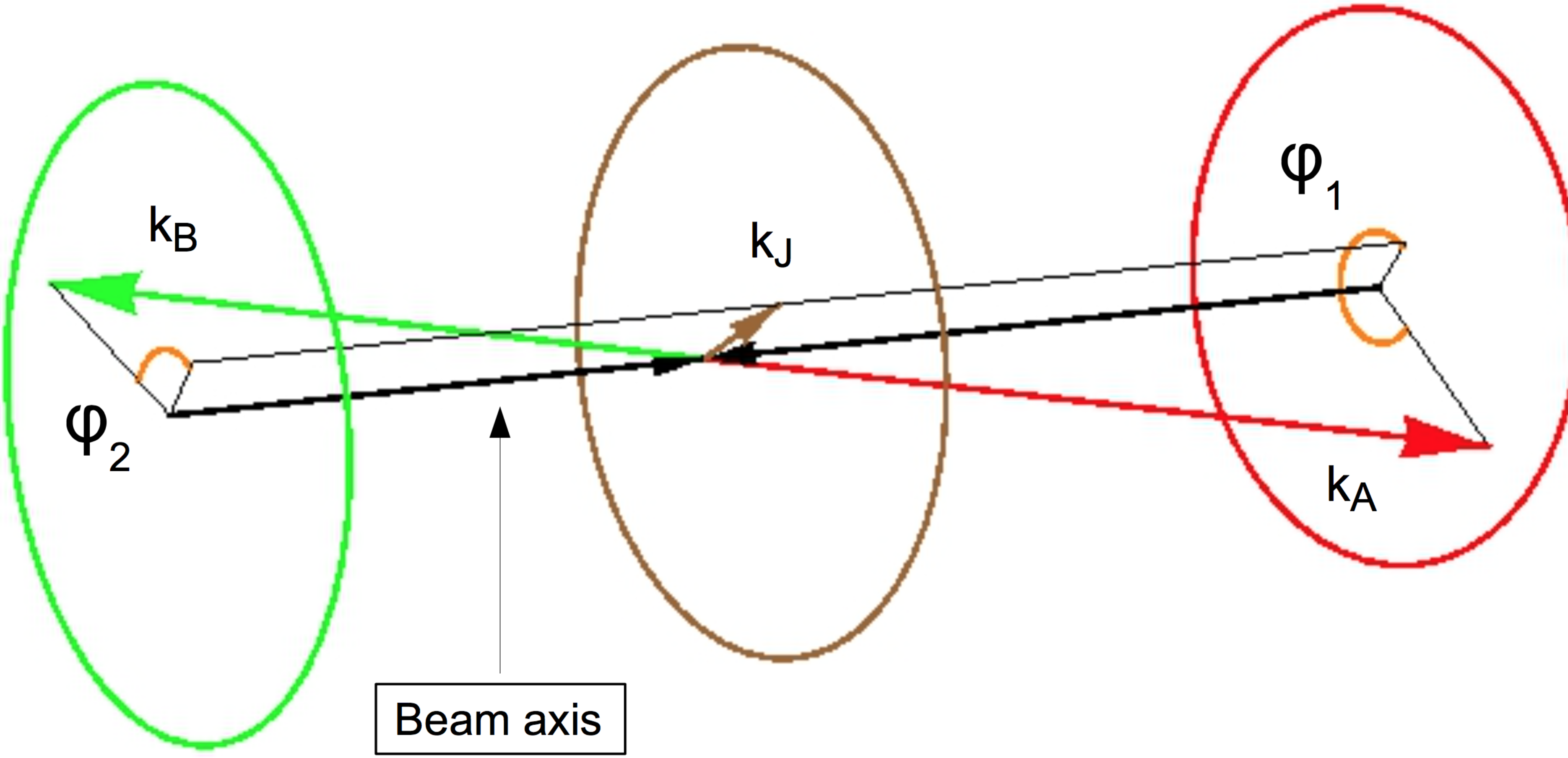
Now, let us move to events with three tagged jets



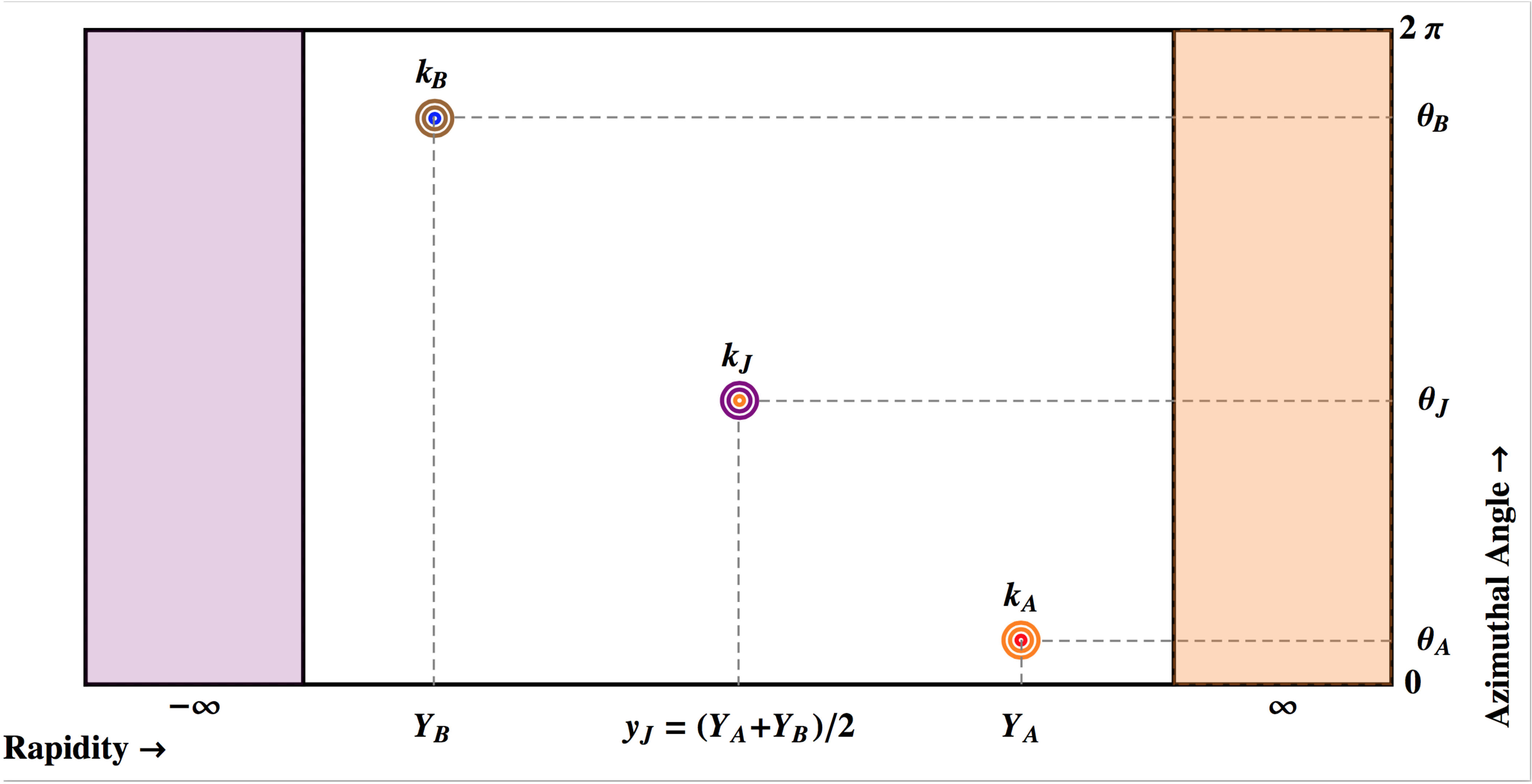


$$f(k_A, k_B, Y_A - Y_B) = \int d^2q\, f(k_A, q, Y_A - y) f(q, k_B, y - Y_B)$$

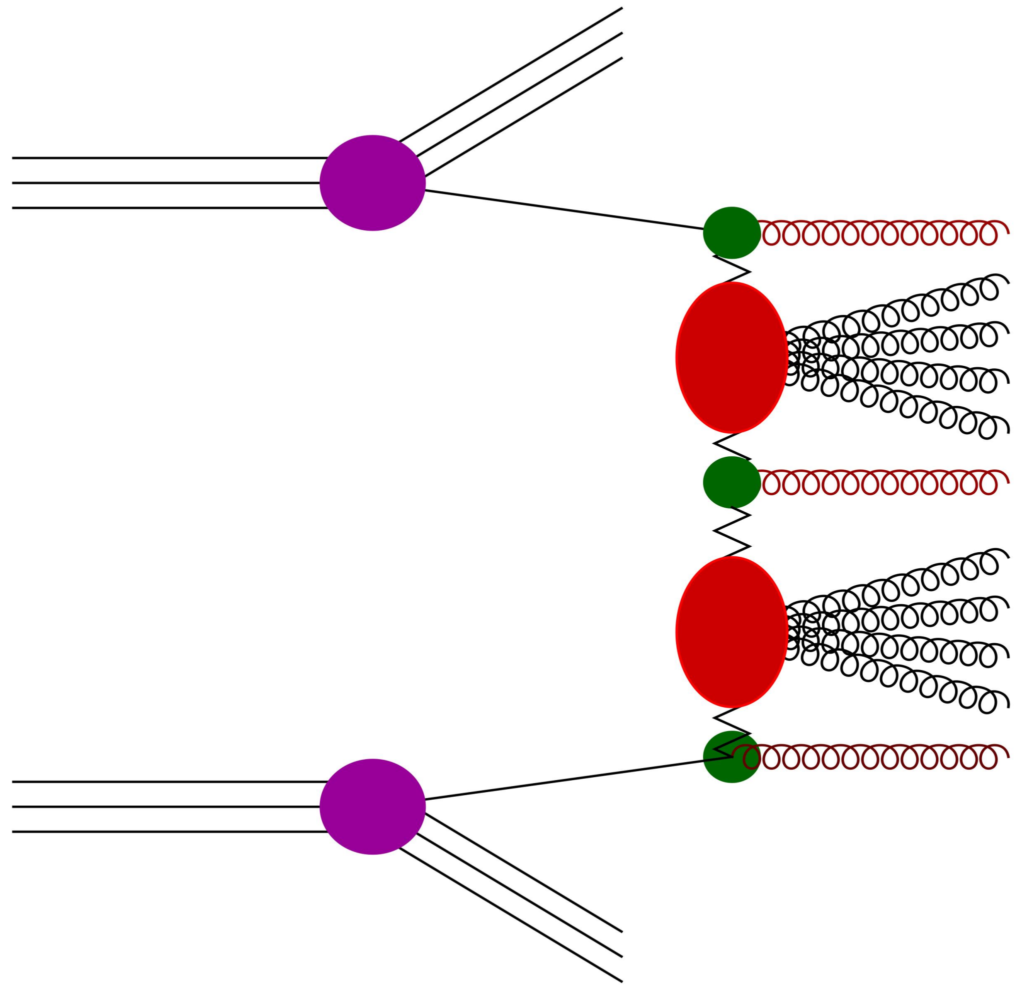
An event with three tagged jets (detector view)



A primitive lego-plot (3-jets)



3-jets partonic cross section



Assuming that $Y_A > y_J > Y_B$ and also that k_A and k_B are fixed we can write for the differential cross section:

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

Starting point...
THEN:

The main idea is to integrate over all angles after using the **projections** on the **two azimuthal angle differences** between the central jet and k_A and k_B respectively

Integrate over all angles after using projections

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

$$
\begin{aligned}
&\int_0^{2\pi} d\theta_A \int_0^{2\pi} d\theta_B \int_0^{2\pi} d\theta_J \cos\left(M\left(\theta_A - \theta_J - \pi\right)\right) \\
&\qquad\qquad \cos\left(N\left(\theta_J - \theta_B - \pi\right)\right) \frac{d^3\sigma^{3-\text{jet}}}{d^2\vec{k}_J dy_J} \\
&= \bar{\alpha}_s \sum_{L=0}^{N} \binom{N}{L} \left(k_J^2\right)^{\frac{L-1}{2}} \int_0^{\infty} dp^2 \left(p^2\right)^{\frac{N-L}{2}} \\
&\qquad \int_0^{2\pi} d\theta \frac{(-1)^{M+N} \cos\left(M\theta\right) \cos\left((N-L)\theta\right)}{\sqrt{\left(p^2 + k_J^2 + 2\sqrt{p^2 k_J^2}\cos\theta\right)^N}} \\
&\times \phi_M\left(p_A^2, p^2, Y_A - y_J\right) \phi_N\left(p^2 + k_J^2 + 2\sqrt{p^2 k_J^2}\cos\theta, p_B^2, y_J - Y_B\right)
\end{aligned}
$$

Integrate over all angles after using projections

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

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

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

$$\langle \cos\left(M\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(N\left(\theta_J - \theta_B - \pi\right)\right) \rangle$$

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

... so that you can define new (partonic level) observables:

$$\boxed{\mathcal{R}^{M,N}_{P,Q} = \frac{\langle \cos\left(M\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(N\left(\theta_J - \theta_B - \pi\right)\right)\rangle}{\langle \cos\left(P\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(Q\left(\theta_J - \theta_B - \pi\right)\right)\rangle}}$$

How would an experimentalist measure this*?

$$\boxed{\mathcal{R}_{P,Q}^{M,N} = \frac{\langle \cos\left(M\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(N\left(\theta_J - \theta_B - \pi\right)\right)\rangle}{\langle \cos\left(P\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(Q\left(\theta_J - \theta_B - \pi\right)\right)\rangle}}$$

* Coming from theorists, this would appear to be more of a cooking recipe, apologies to our experimental colleagues in advance for any naivety here.

How would an experimentalist measure this?

1. For 7 (and 8) TeV energies, just pick up the data that were used for Mueller-Navelet studies. For 13 TeV, one may work in parallel.
2. From these data, isolate those events that have in addition a very central jet.
3. Choose integers M, N, P, Q, e.g. M=1, N=3, P=1, Q=2
4. For each event, measure the azimuthal angle difference between the forward-central jets, $\Delta\theta_1 = (\theta_A - \theta_J - \pi)$, and the backward-central jets, $\Delta\theta_2 = (\theta_J - \theta_B - \pi)$.
5. For each event calculate two quantities:
num = $\mathrm{Cos}(1^*\Delta\theta_1)^*\mathrm{Cos}^*(3^*\Delta\theta_2)$ and denom = $\mathrm{Cos}(1^*\Delta\theta_1)^*\mathrm{Cos}^*(2^*\Delta\theta_2)$.
6. Calculate the average of num (<num>) and denom (<denom>) over all the events. Divide <num> over <denom> to have the quantity below:

$$\boxed{\mathcal{R}_{P,Q}^{M,N} = \frac{\langle \cos\left(M\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(N\left(\theta_J - \theta_B - \pi\right)\right)\rangle}{\langle \cos\left(P\left(\theta_A - \theta_J - \pi\right)\right) \cos\left(Q\left(\theta_J - \theta_B - \pi\right)\right)\rangle}}$$

Now introduce PDF's and running of the strong coupling to get theoretical predictions on a hadronic level for various kinematical cuts

We have used two kinematical cuts

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

Here we will focus on the asymmetric one:

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

Introduce higher order corrections and check stability

- For the partonic cross section change from LLA GGF to NLLA GGF
- Jet vertex corrections are missing and need to be included
- Use BLM scheme

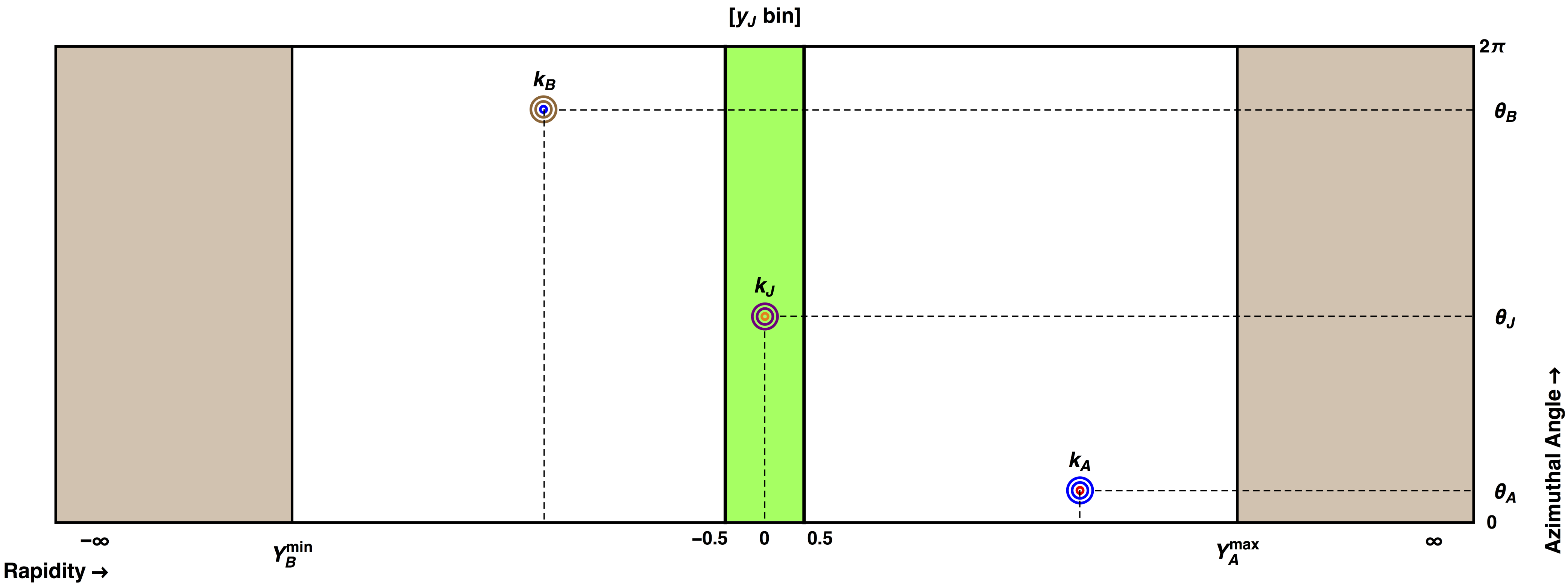
  [S.J. Brodsky, G.P. Lepage, P.B. Mackenzie, Phys. Rev. D 28, 228 (1983)]
- Consider three cases for the pT of the central jet

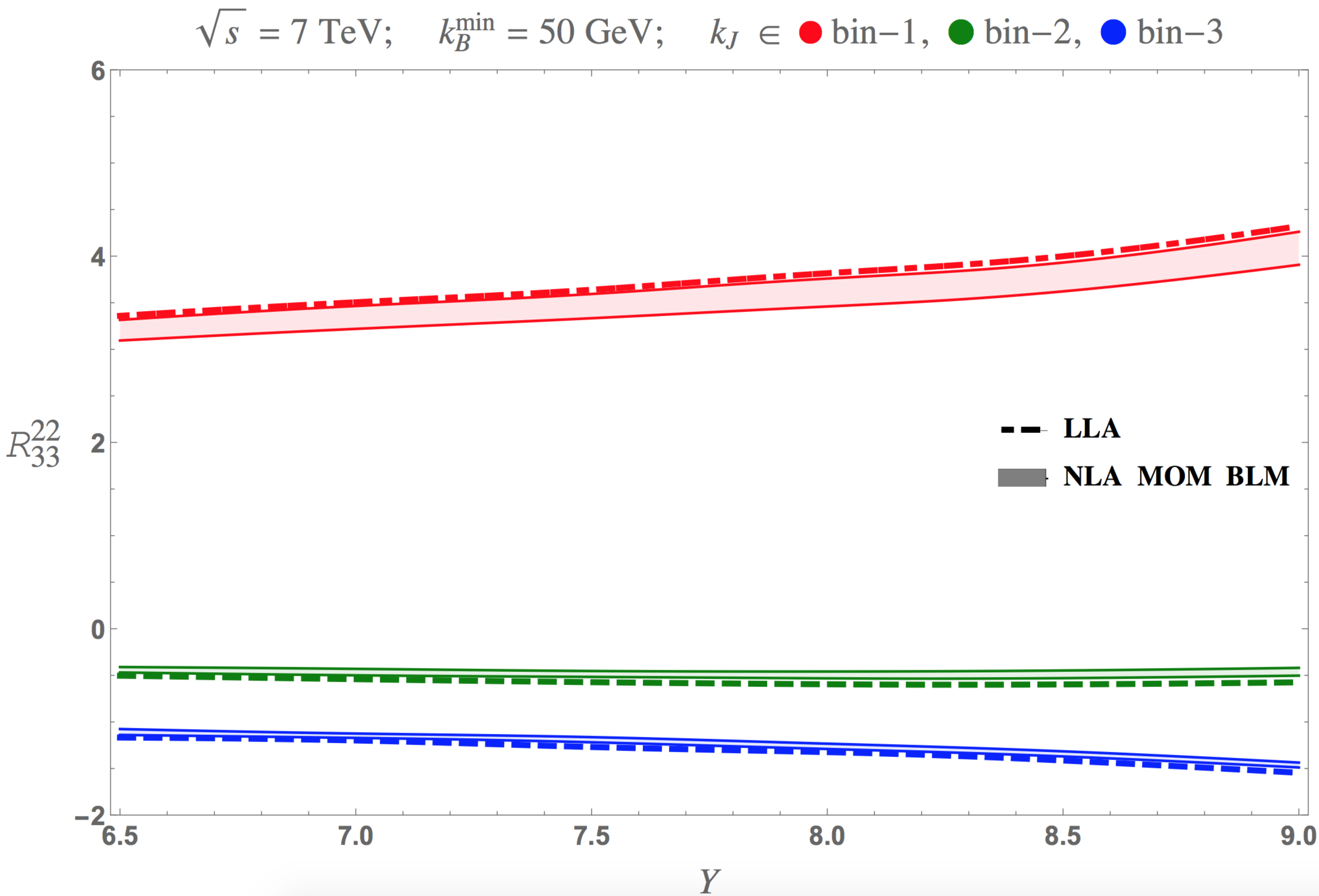
$$20\,\mathrm{GeV} < k_J < 35\,\mathrm{GeV} \;\; (\mathrm{bin\text{-}1})$$

$$35\,\mathrm{GeV} < k_J < 60\,\mathrm{GeV} \;\; (\mathrm{bin\text{-}2})$$

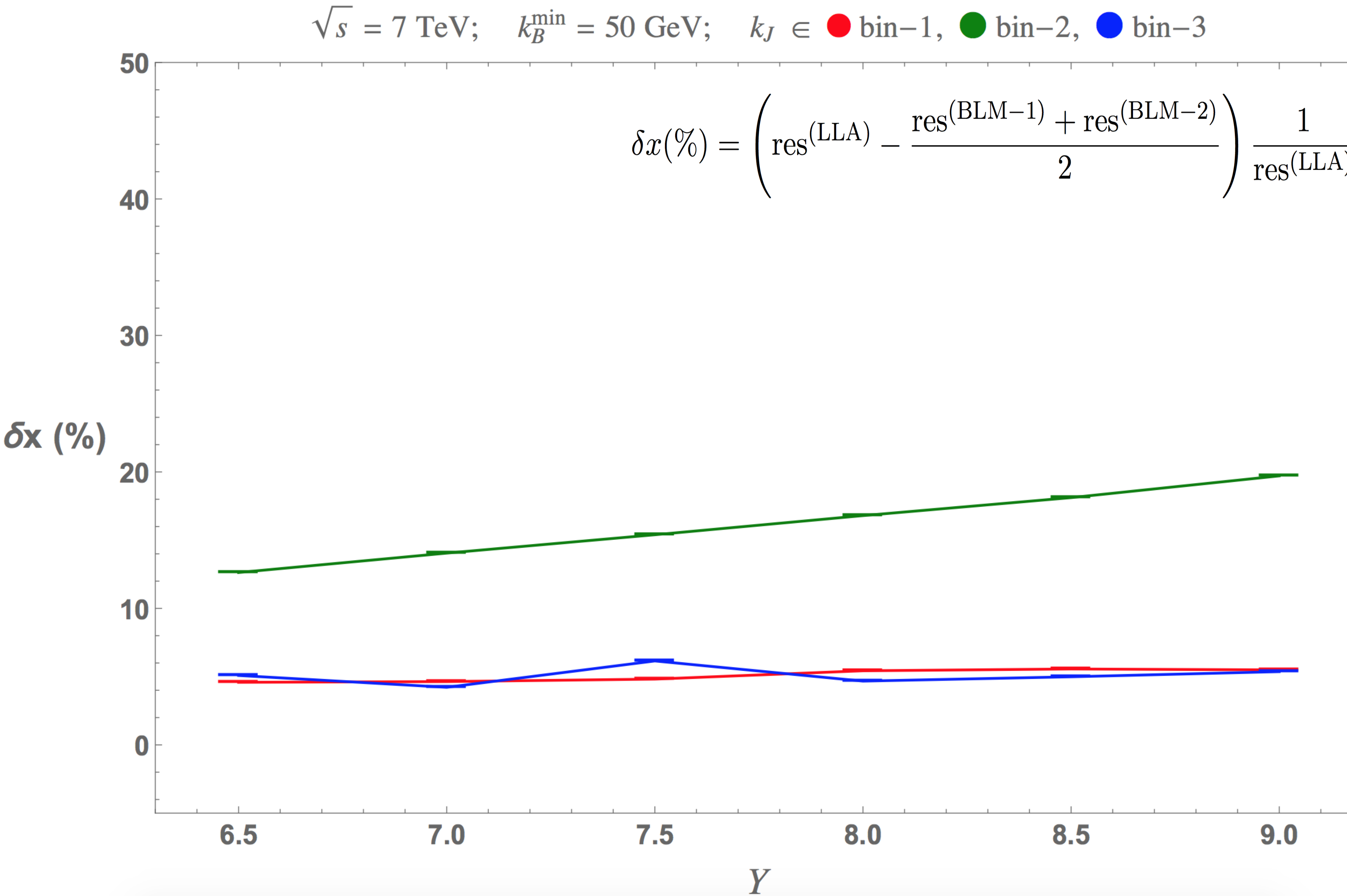
$$60\,\mathrm{GeV} < k_J < 120\,\mathrm{GeV} \;\; (\mathrm{bin\text{-}3})$$

Integrate over a central rapidity bin

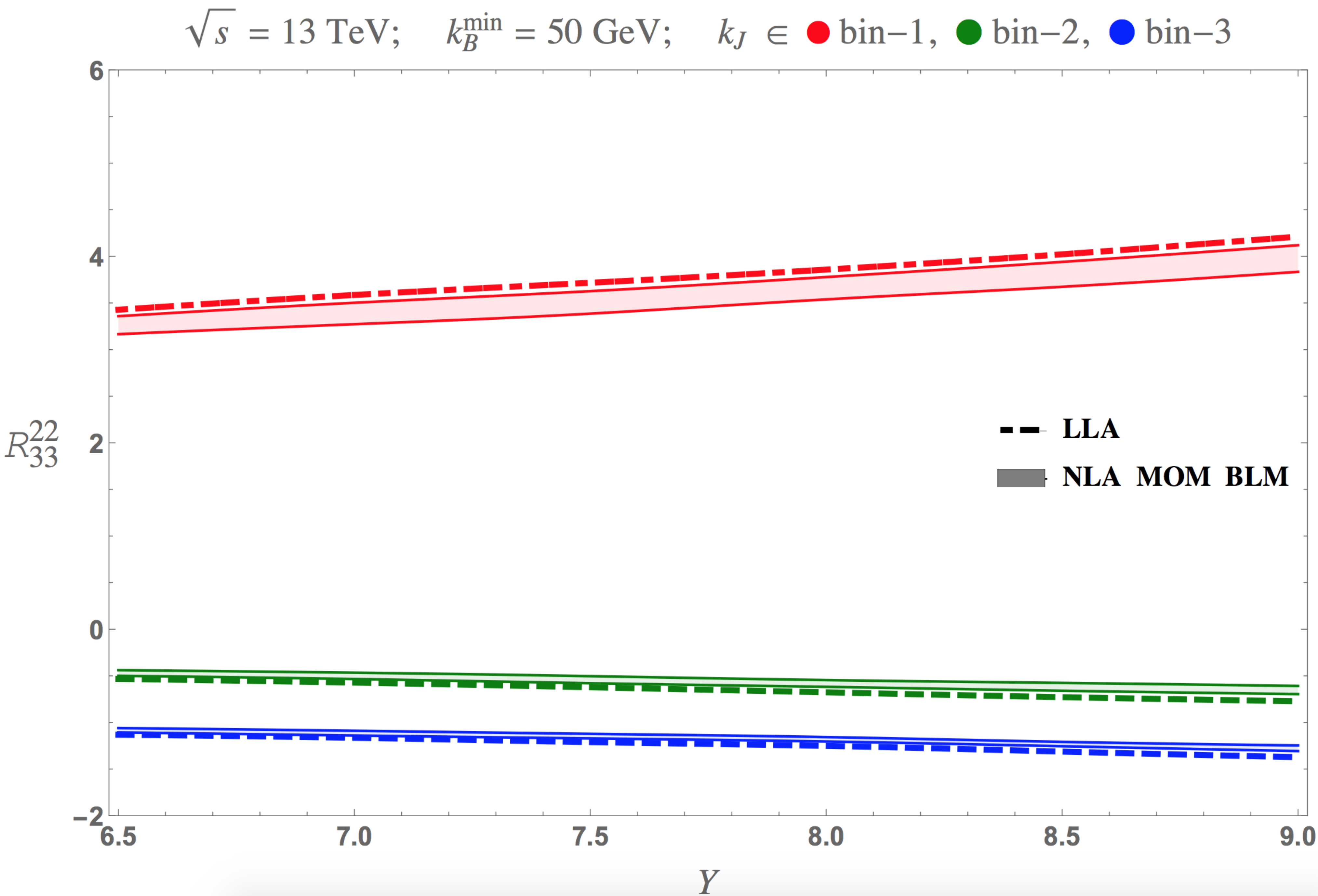




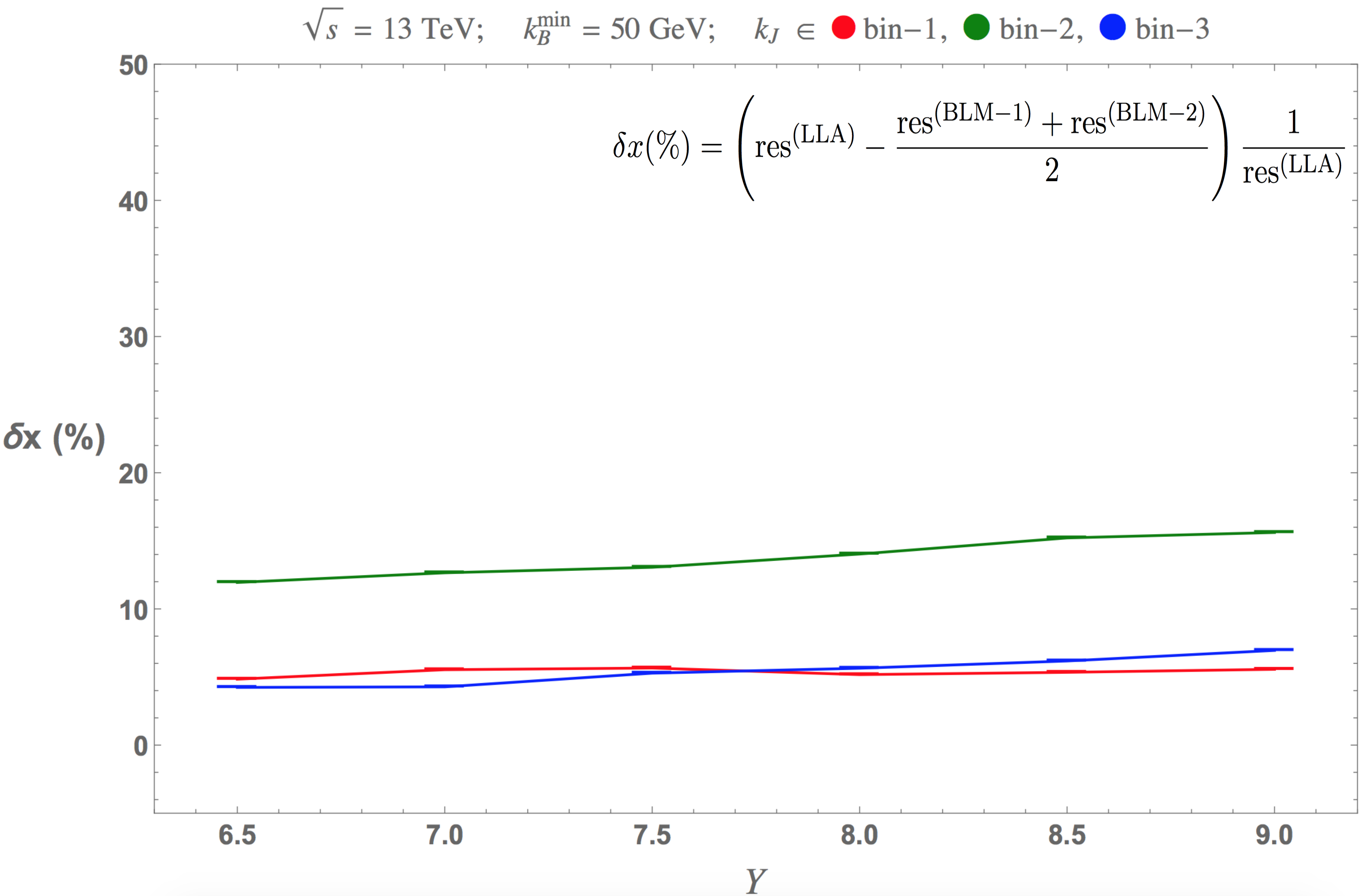
$\sqrt{s}$ = 7 TeV; $k_B^{\min}$ = 50 GeV; k_J ∈ bin−1, bin−2, bin−3
6
4
2
0
−2
R_{33}^{22}
LLA
NLA MOM BLM
6.5
7.0
7.5
8.0
8.5
9.0
Y



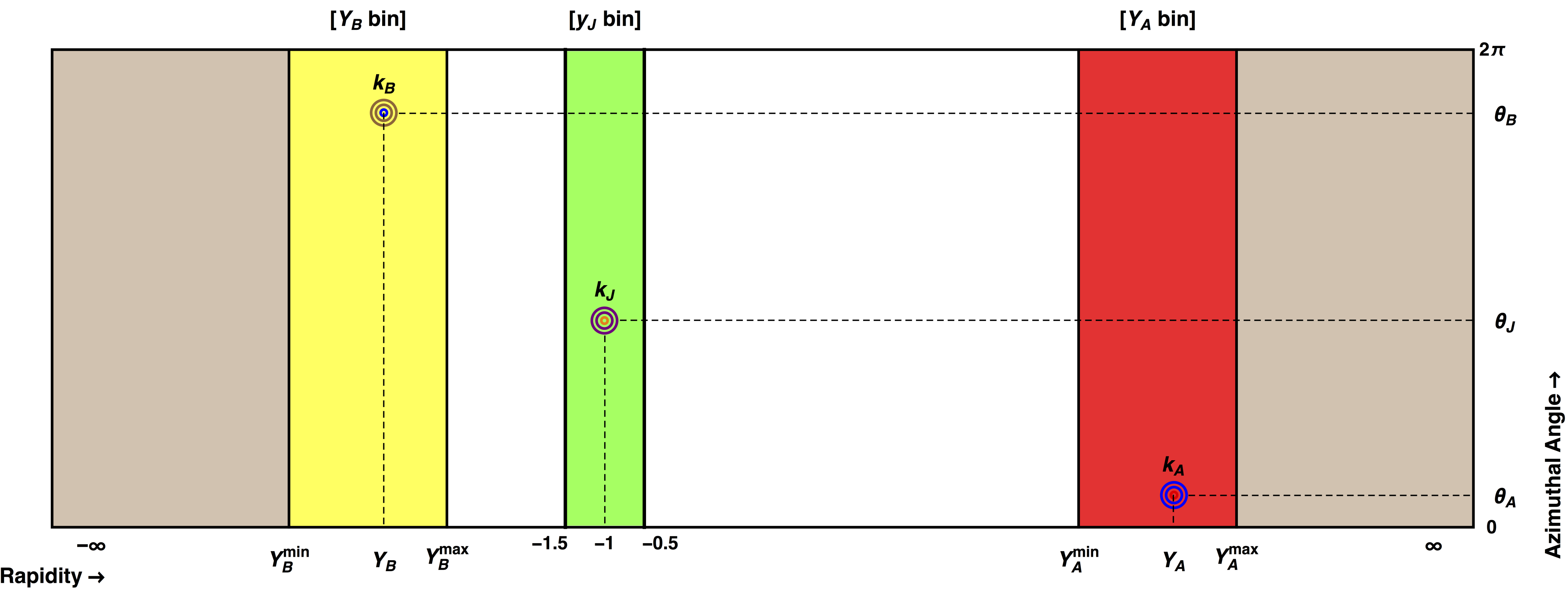
$\sqrt{s} = 7$ TeV; $k_B^{\min} = 50$ GeV; $k_J \in$ bin−1, bin−2, bin−3
$\delta x(\%) = \left(\mathrm{res}^{(\mathrm{LLA})} - \frac{\mathrm{res}^{(\mathrm{BLM-1})} + \mathrm{res}^{(\mathrm{BLM-2})}}{2}\right)\frac{1}{\mathrm{res}^{(\mathrm{LLA})}}$
δx (%)
50
40
30
20
10
0
6.5
7.0
7.5
8.0
8.5
9.0
Y



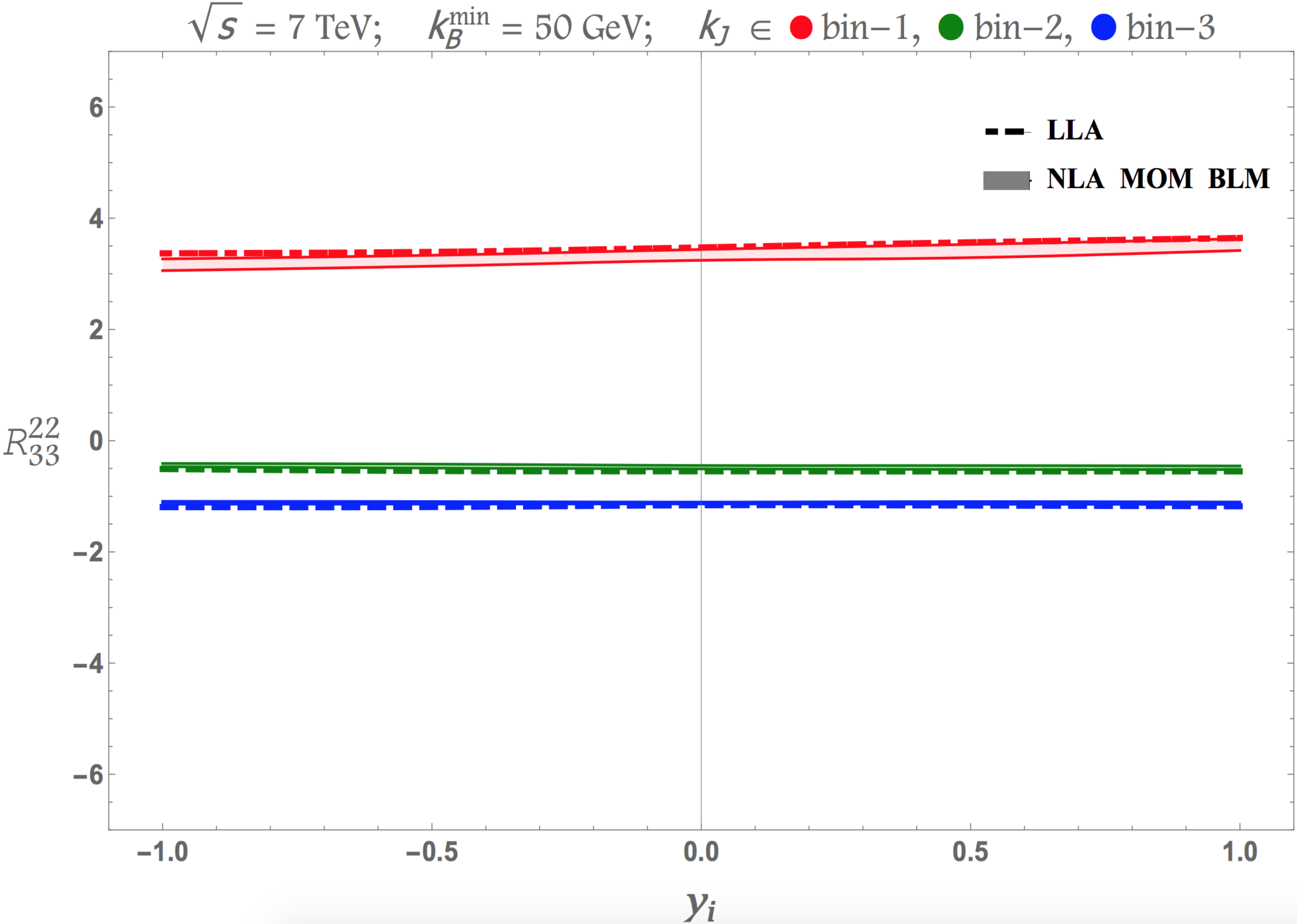
$\sqrt{s} = 13$ TeV; $k_B^{\min} = 50$ GeV; $k_J \in$ bin−1, bin−2, bin−3
R_{33}^{22}
6
4
2
0
−2
6.5
7.0
7.5
8.0
8.5
9.0
Y
LLA
NLA MOM BLM


$\sqrt{s}$ = 13 TeV; $k_B^{\rm min}$ = 50 GeV; k_J ∈ bin−1, bin−2, bin−3
$\delta x(\%) = \left(\mathrm{res}^{(\mathrm{LLA})} - \frac{\mathrm{res}^{(\mathrm{BLM-1})} + \mathrm{res}^{(\mathrm{BLM-2})}}{2}\right)\frac{1}{\mathrm{res}^{(\mathrm{LLA})}}$
δx (%)
50
40
30
20
10
0
6.5
7.0
7.5
8.0
8.5
9.0
Y

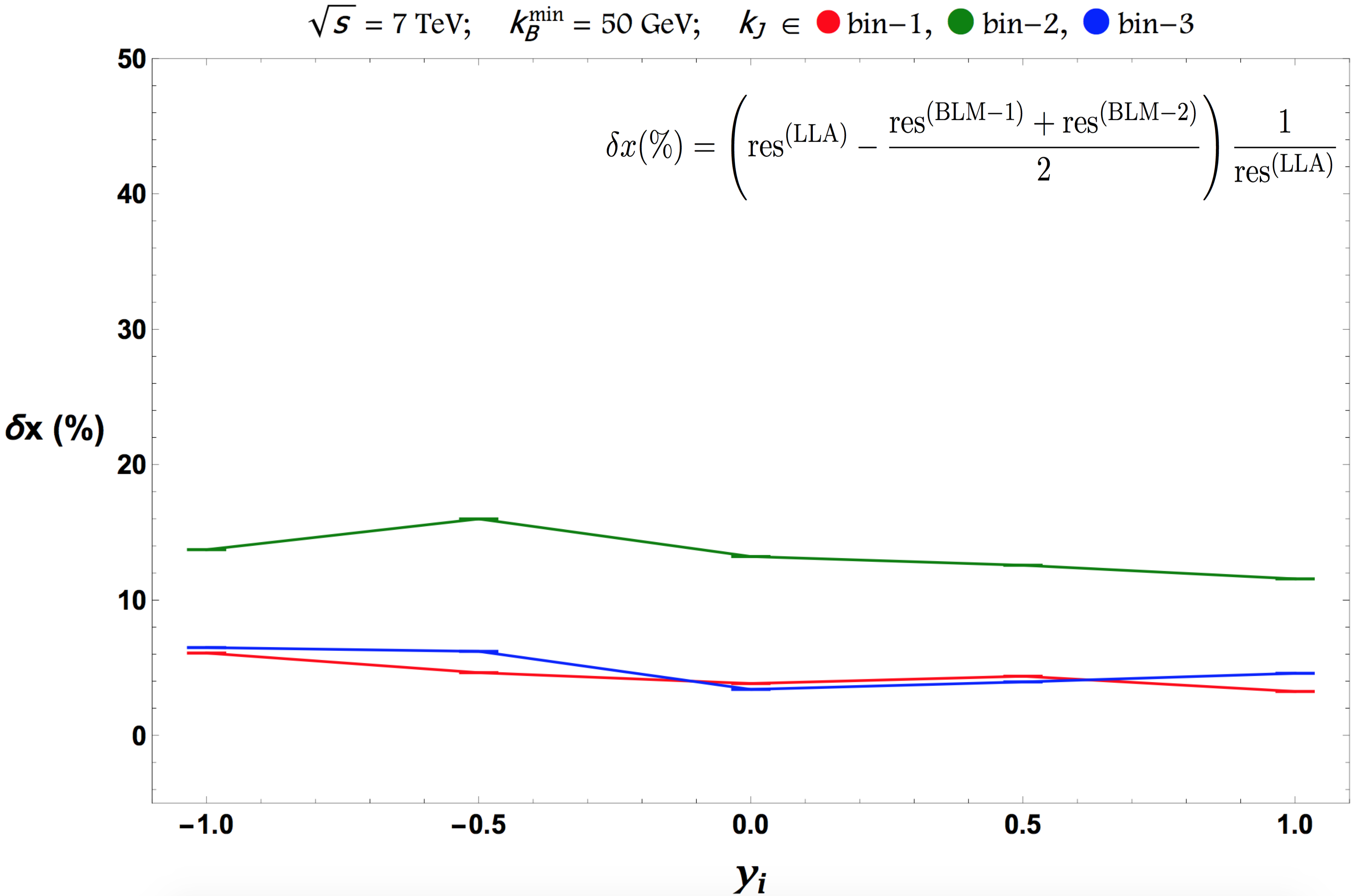
Integrate over a forward, backward and central rapidity bin



$$(Y_A^{\rm min} = 3) < Y_A < (Y_A^{\rm max} = 4.7)$$
$$(Y_B^{\rm min} = -4.7) < Y_B < (Y_B^{\rm max} = -3)$$



$\sqrt{s}$ = 7 TeV; k_B^{min} = 50 GeV; $k_J \in$ bin−1, bin−2, bin−3
LLA
NLA MOM BLM
R^{22}_{33}
y_i
6
4
2
0
−2
−4
−6
−1.0
−0.5
0.0
0.5
1.0



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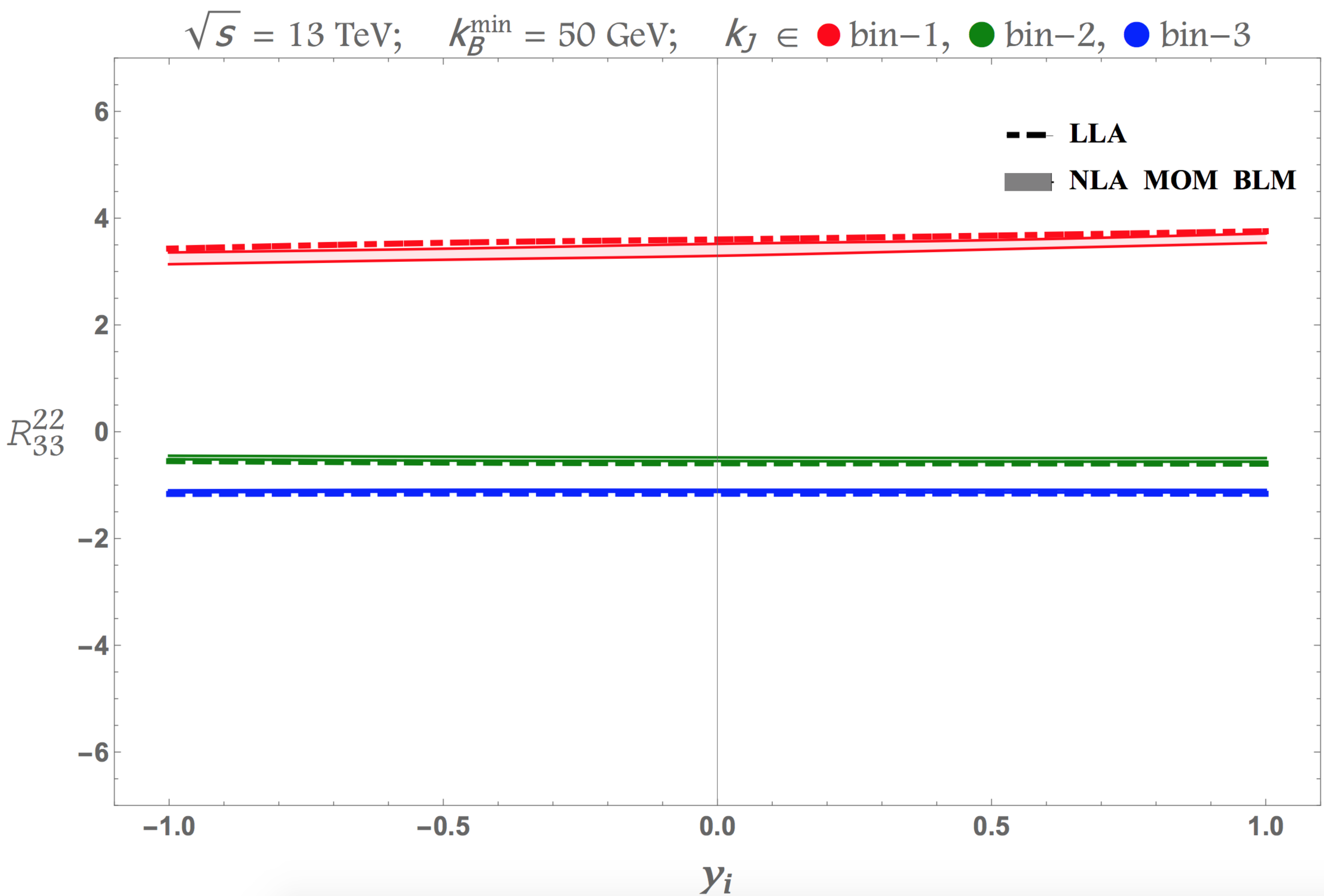
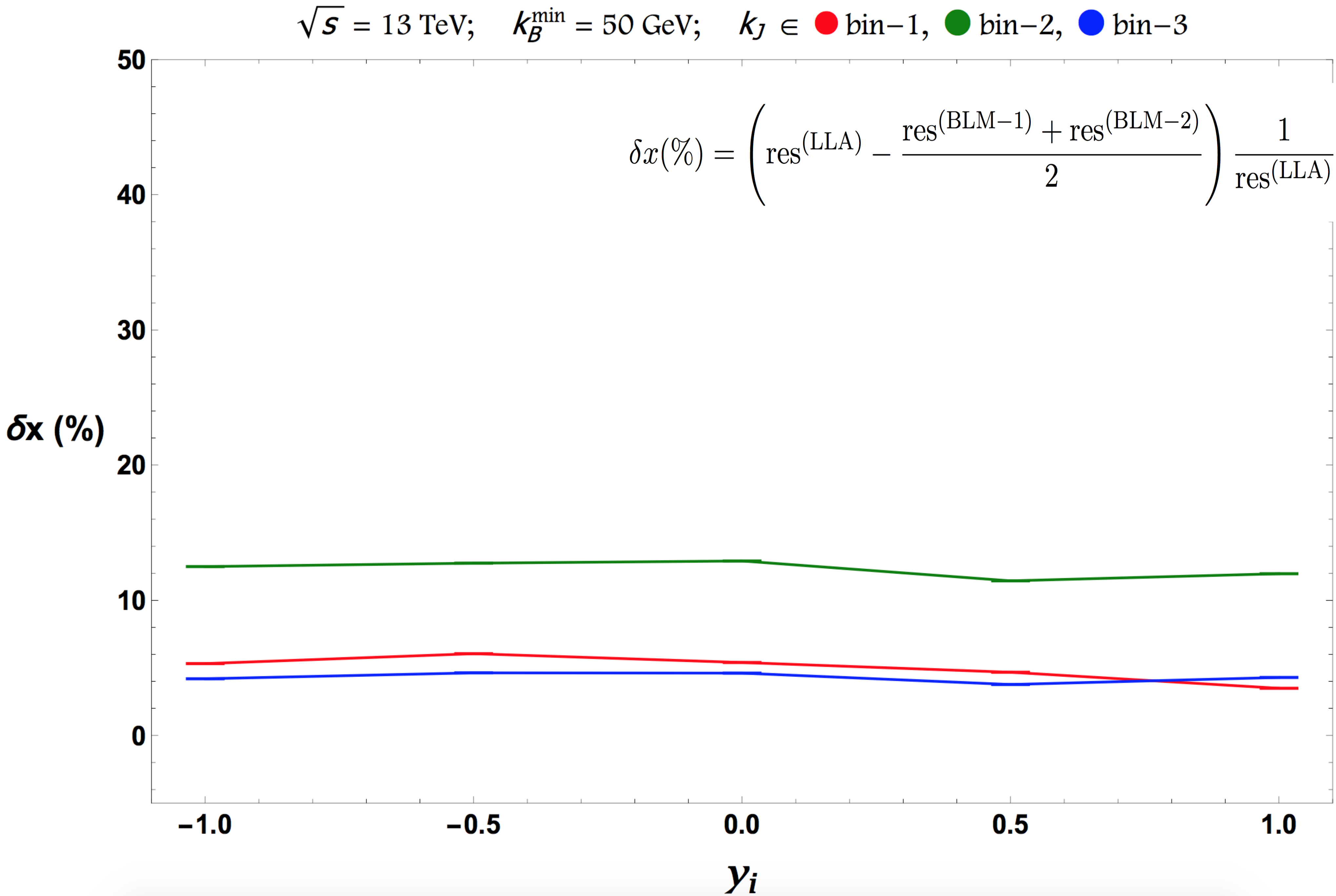
$\delta x(\%) = \left(\mathrm{res}^{(\mathrm{LLA})} - \frac{\mathrm{res}^{(\mathrm{BLM-1})} + \mathrm{res}^{(\mathrm{BLM-2})}}{2}\right)\frac{1}{\mathrm{res}^{(\mathrm{LLA})}}$
δx (%)
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0
y_i



$\sqrt{s}$ = 13 TeV; $k_B^{\min}$ = 50 GeV; k_J ∈ bin−1, bin−2, bin−3
LLA
NLA MOM BLM
R^{22}_{33}
6
4
2
0
−2
−4
−6
−1.0
−0.5
0.0
0.5
1.0
y_i



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$\delta x(\%) = \left(\mathrm{res}^{(\mathrm{LLA})} - \frac{\mathrm{res}^{(\mathrm{BLM-1})} + \mathrm{res}^{(\mathrm{BLM-2})}}{2}\right) \frac{1}{\mathrm{res}^{(\mathrm{LLA})}}$
δx (%)
y_i
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0

Conclusions & Outlook

- We use events with three tagged jets to propose **new observables** with a distinct signal of BFKL dynamics.
- We use **ratios** of correlation functions to **minimize the influence of higher order effects**.
- The **stability** of the azimuthal observables after introducing higher order corrections is very good.
- The measurement of the observables proposed here **poses no intricacies** in the analysis of the data. Any new input from the experimental side would be extremely valuable