What can we learn about high energy QCD by studying azimuthal angle observables at the LHC?

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Work with F. Caporale, F. G. Celiberto, D. Gordo Gomez and A. Sabio Vera

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LHC and the Standard Model: Physics and Tools,
19 June 2017, CERN

LHC and the Standard Model: Physics and Tools

EXPERIMENTS

FOCUS ON QCD

PHENOMENOLOGY

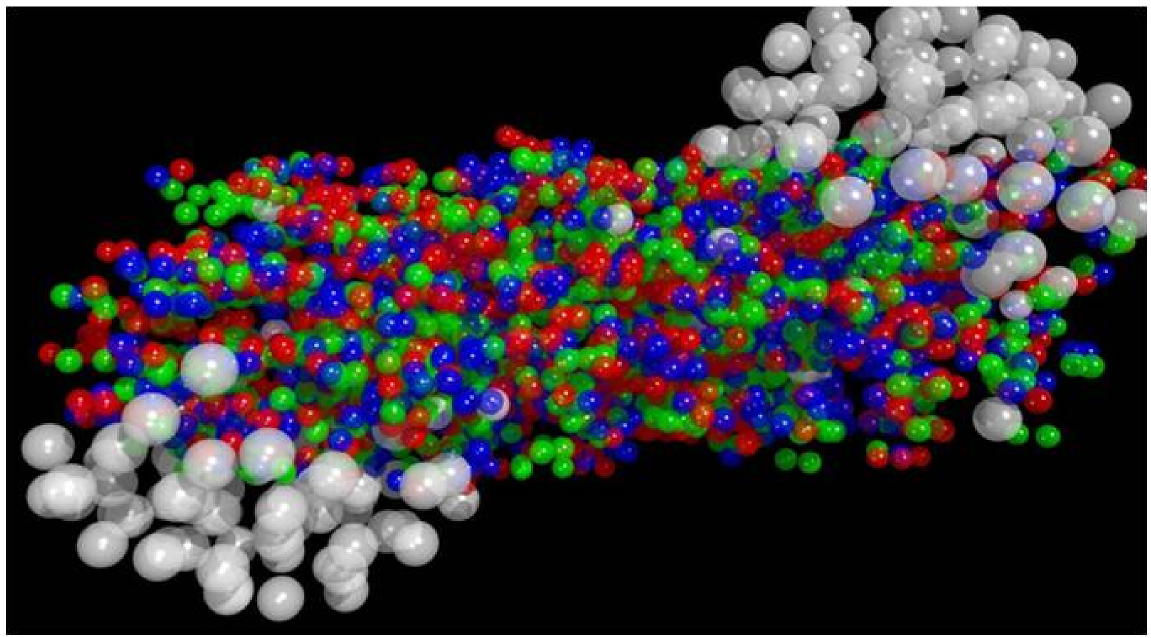
Session: BEYOND DGLAP (?)

Phenomenology

- Phenomenology is not having a list of processes in your pocket that you need to calculate and then compare to experimental data
- Phenomenology is a complicated effort to find unifying patterns –even within a single framework of a theory, like QCD– that will allow a much deeper understanding of how Nature works
- Finding unifying patterns is not easy because you have –still within a single framework of a theory– many different ways of viewing things that serve well for a given purpose but do not necessarily combine in a straightforward manner.

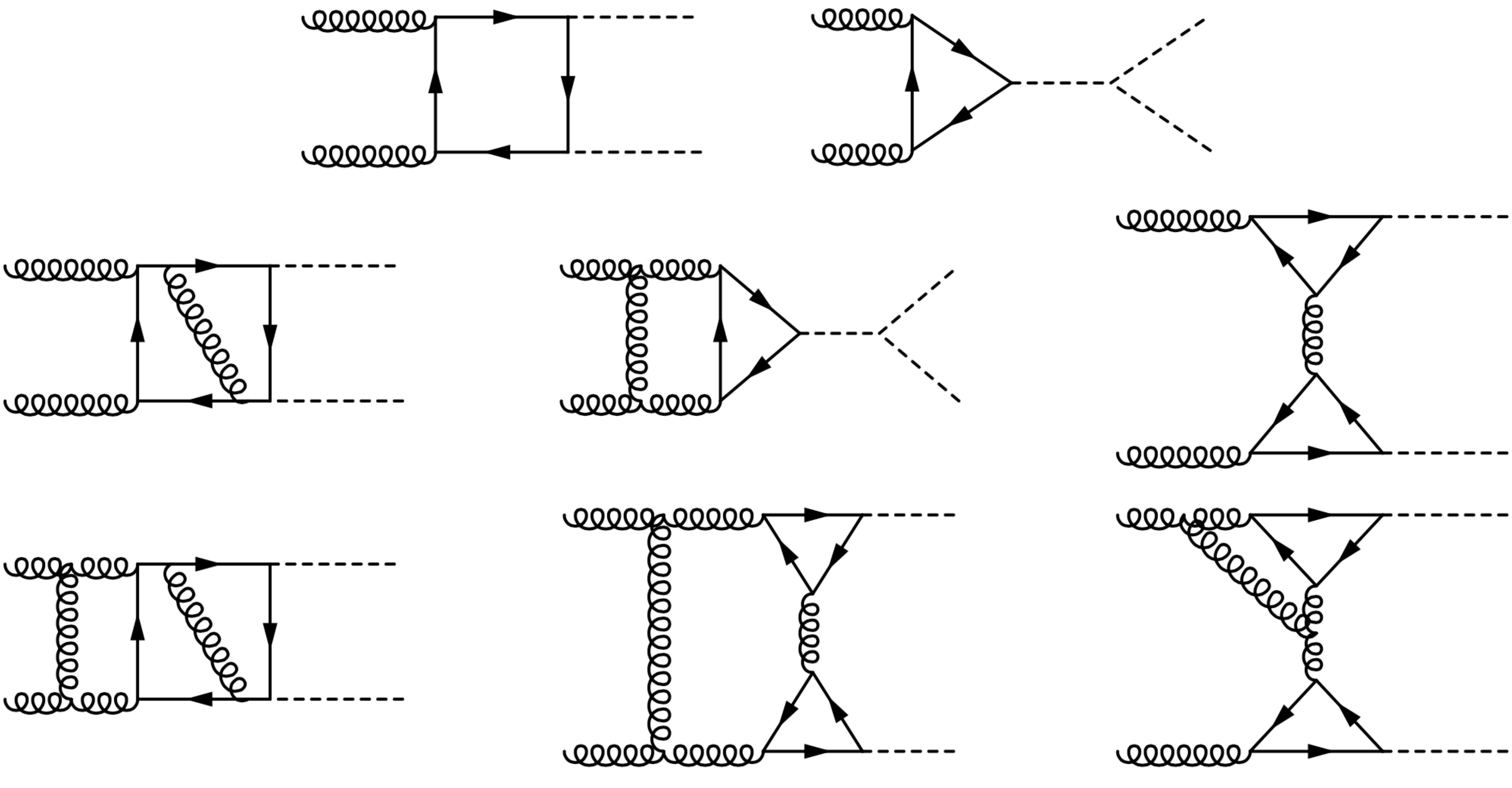
-Papa, what will you work on?
-QCD, son!
-Theory or experiment?
-Theory.
-QCD, eh?... What will you do exactly?

(Reply 1)
-Heavy Ion collisions



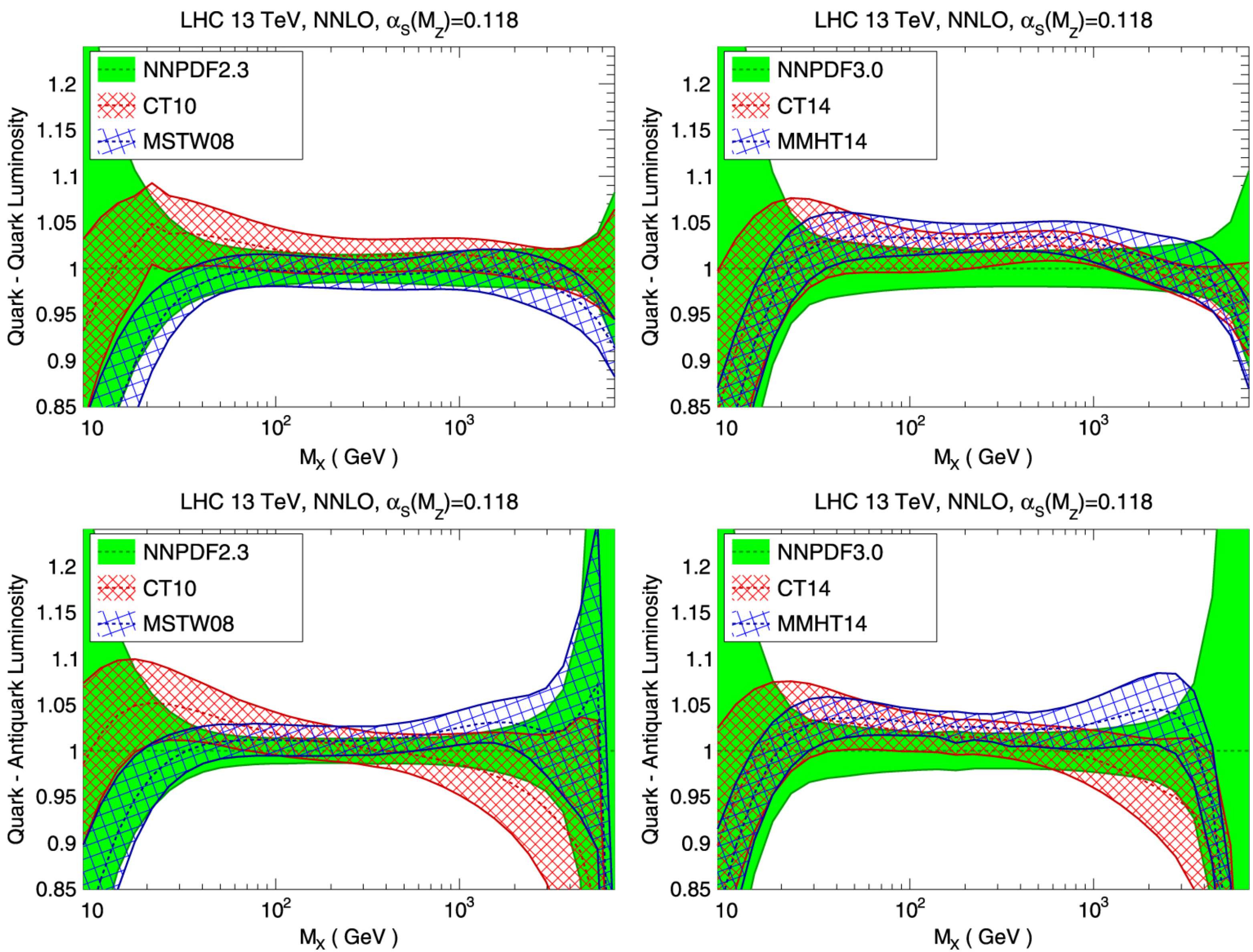
CERN Courier photo

(Reply 2)
-Precision calculations



Grigo, Hoff, Steinhauser, 2015

(Reply 3)
-PDF's

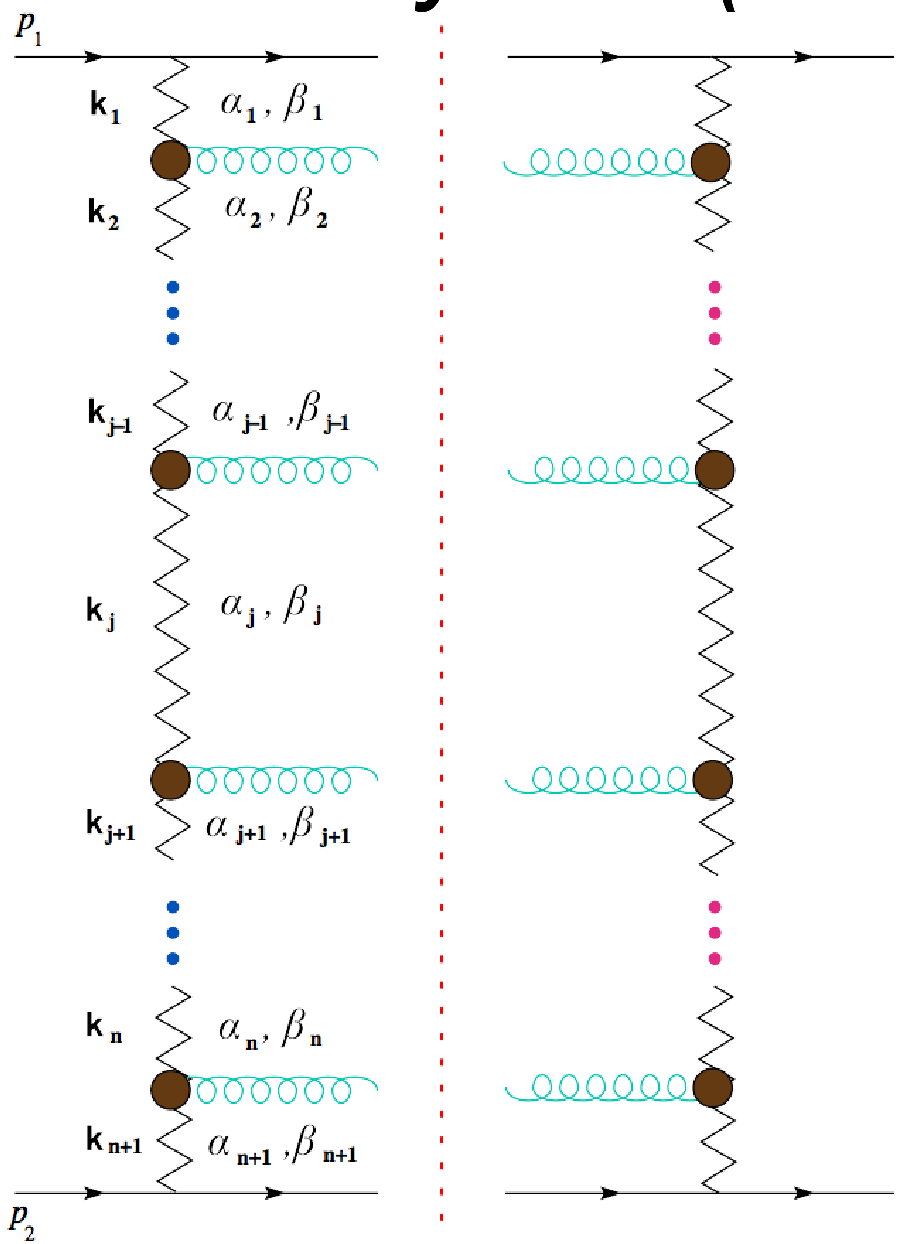


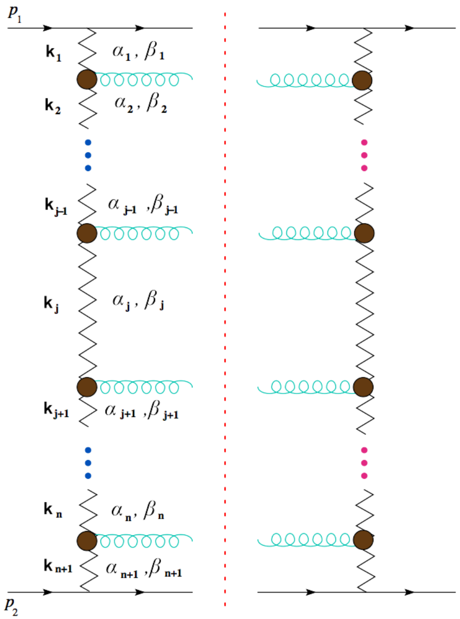
The PDF4LHC report, 2015

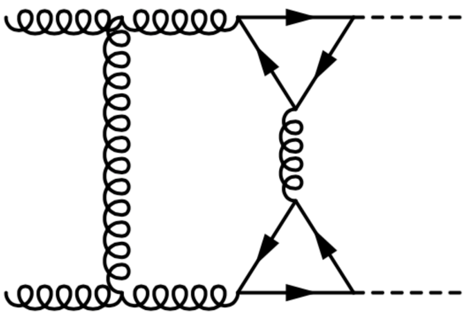
(Other replies ...)

(Yet another reply)

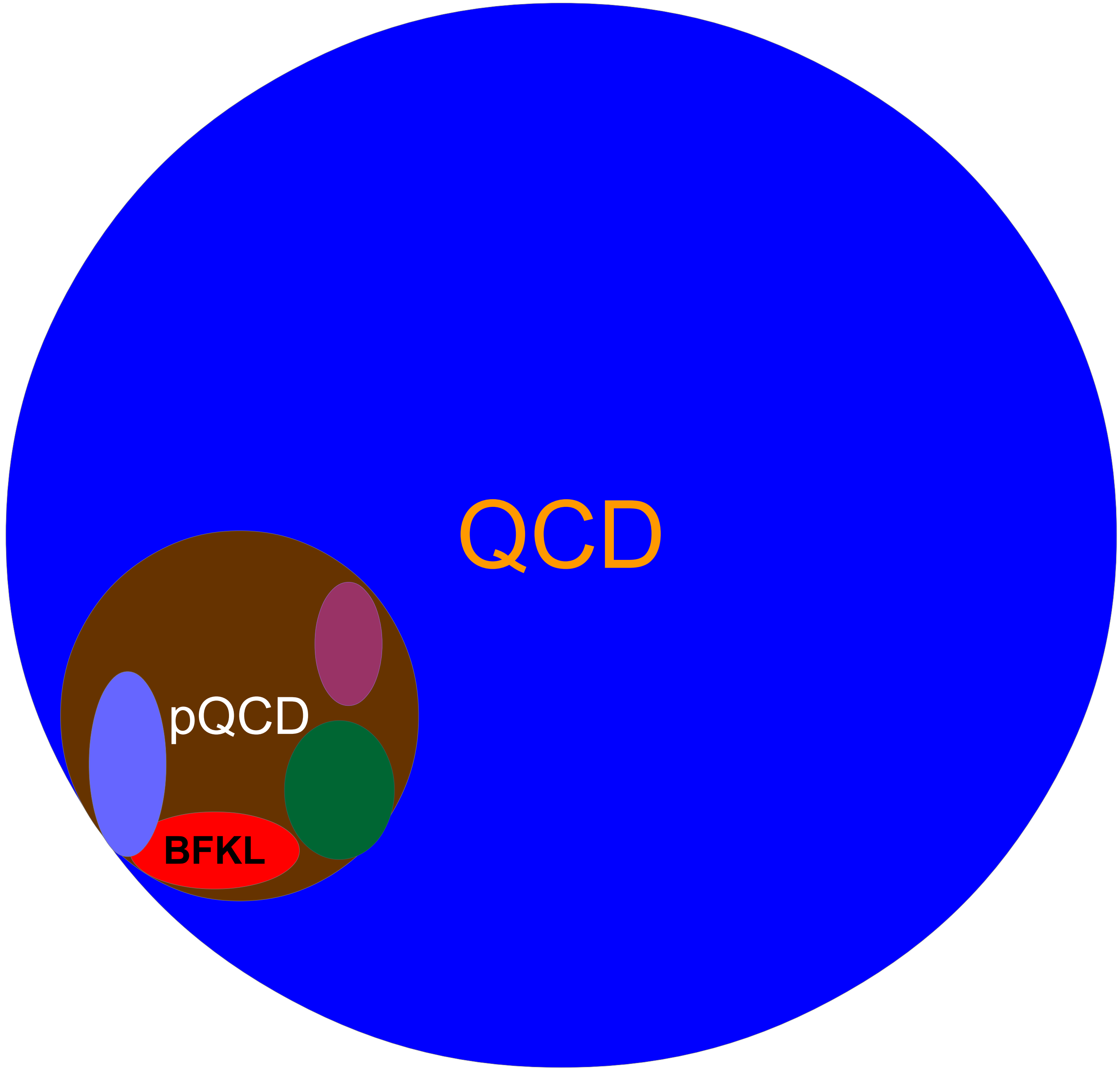
-Small x Physics (BFKL)

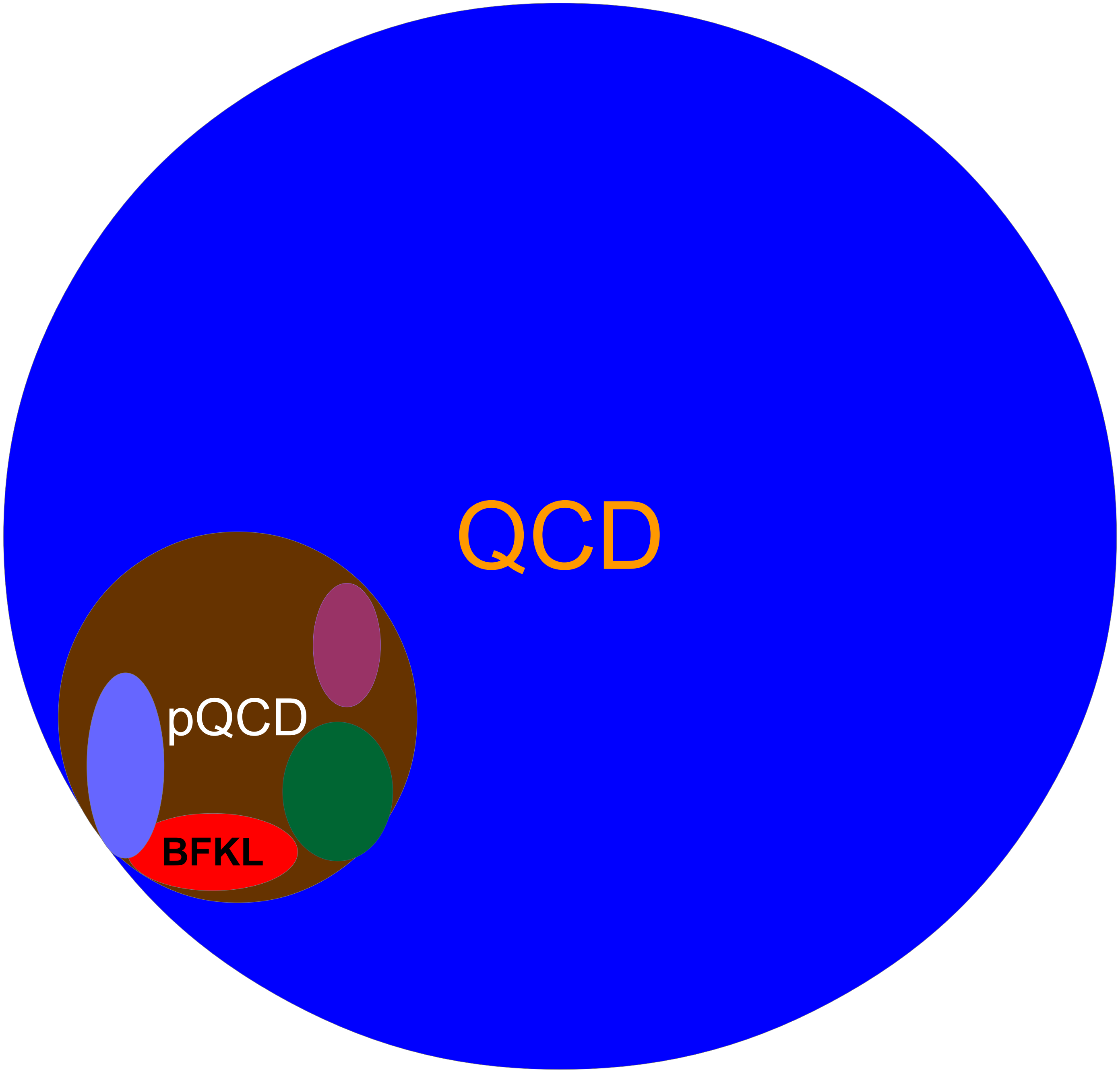






- Every reply has its own **language** which is the conceptualization of the underlying mathematical formalism.
- Each **language** is not only a tool to describe but ultimately a **tool to think** with (dialectics).
- We should know the range of applicability of each language, then we can trust it.
- If two languages are applicable on some generic space, then we might borrow elements from one to improve the other and altogether our overall understanding.


QCD
pQCD
BFKL



Key question: What is the applicability energy window for BFKL?
Is it at LHC energies?

What is BFKL?

- BFKL → Balitsky-Fadin-Kuraev-Lipatov
- It is a resummation program
- It resums large logarithms in energy
- It does so by using pQCD
- New degrees of freedom emerge (Reggeons)
- It has a whole new (actually, old) language and different ways of describing what happens in a high energy collision
- Why is it sometimes seen as an opposition to DGLAP?

Key question: What is the applicability energy window for BFKL? Is it at LHC energies?

CERN-PH-EP/2015-309
2016/01/26

CMS-FSQ-12-002

Key question: What is the applicability energy window for BFKL? Is it at LHC energies?

Azimuthal decorrelation of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS Collaboration*

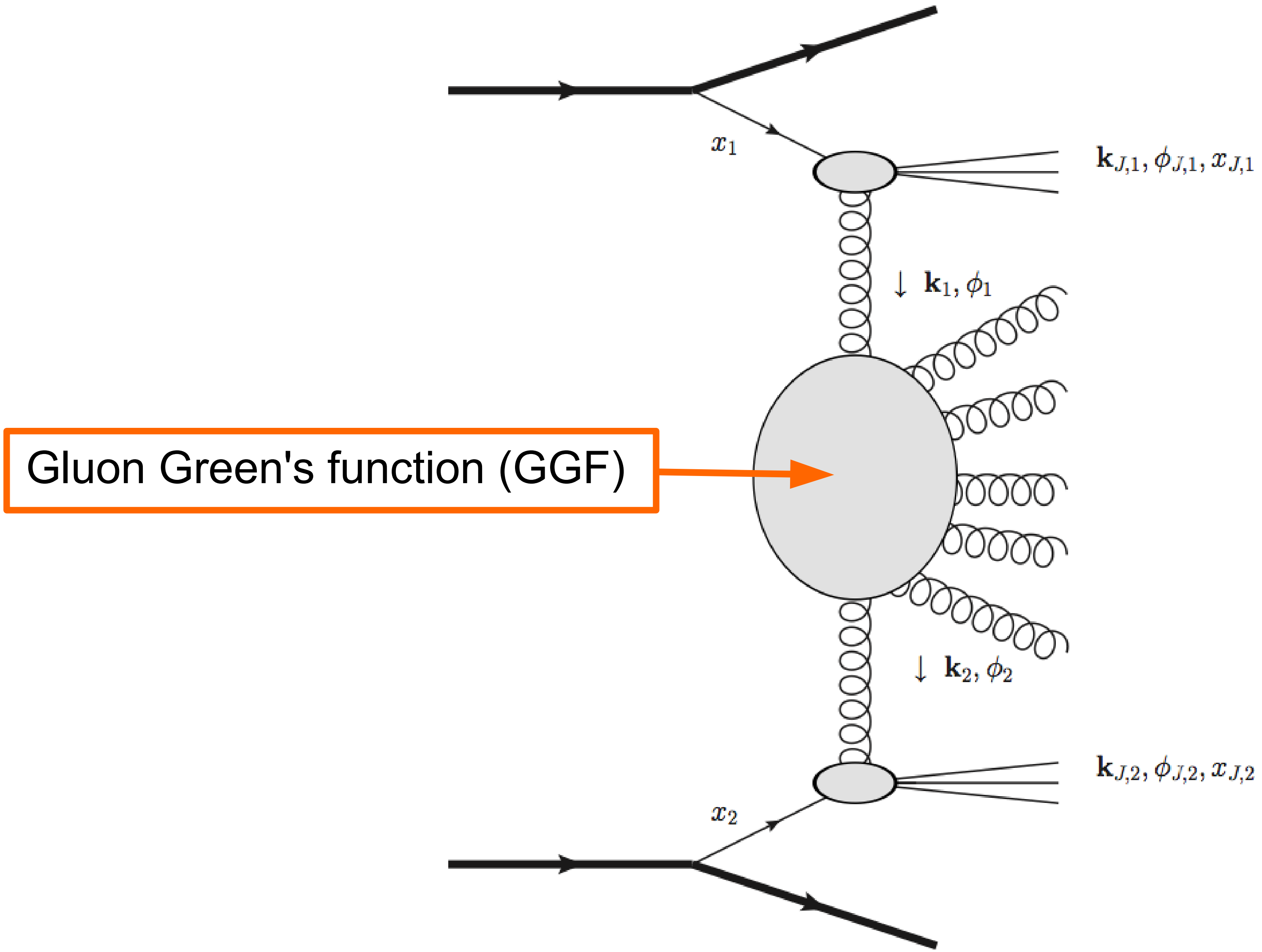
... Therein, in the section Conclusions it reads:

The observed sensitivity to the implementation of the colour-coherence effects in the DGLAP MC generators and the reasonable data-theory agreement shown by the NLL BFKL analytical calculations at large Δy, may be considered as indications that the kinematical domain of the present study lies in between the regions described by the DGLAP and BFKL approaches. Possible manifestations of BFKL signatures are expected to be more pronounced at increasing collision energies.

Outline

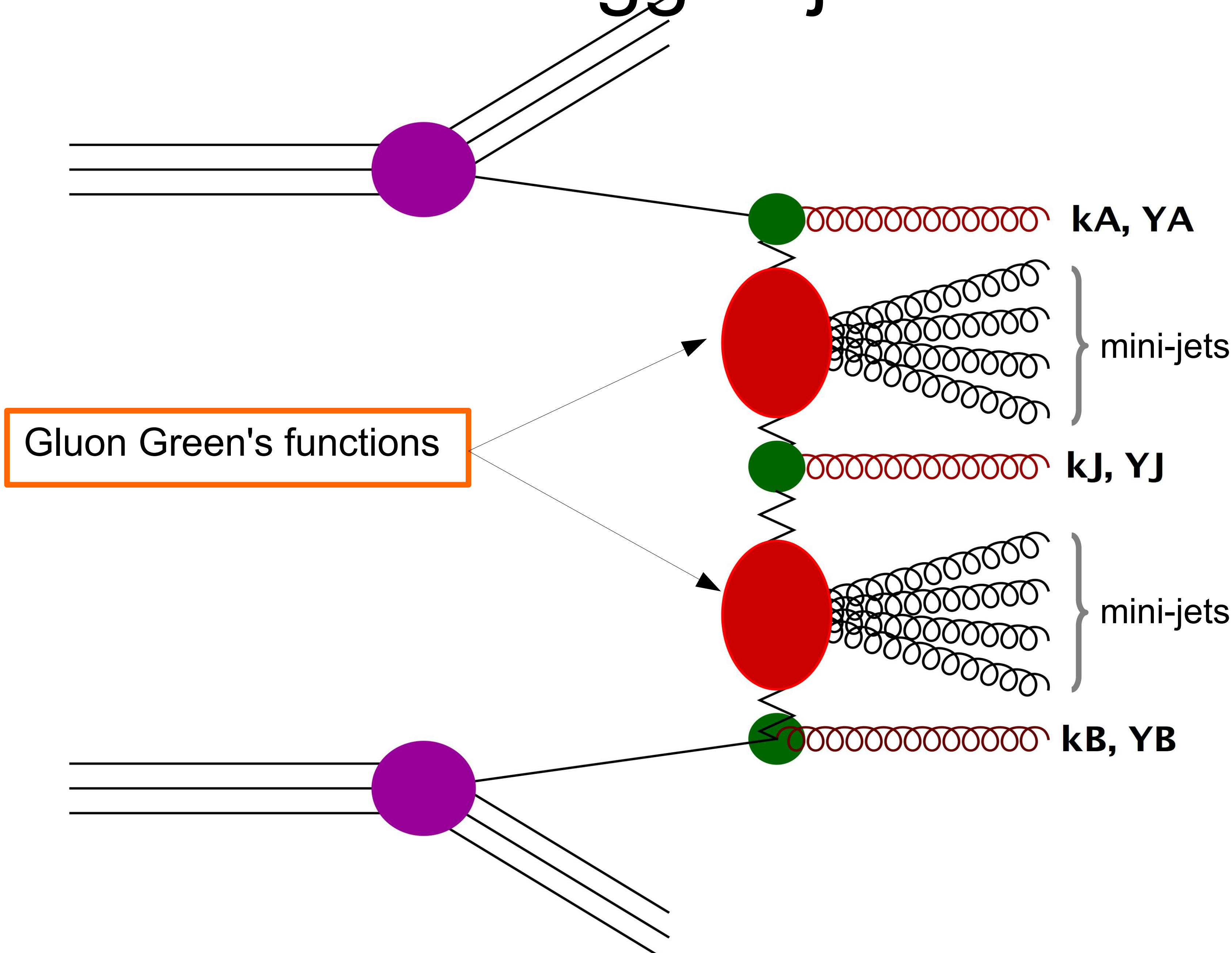
- Motivation (hopefully, already given)
- Proposal of new observables in inclusive 3-jet production at the LHC to disentangle a clear BFKL signal
    I. Kinematics
    II. Ratios of azimuthal angle differences
- Include higher order corrections and check stability
- Conclusions

Mueller-Navelet jets (dijets)

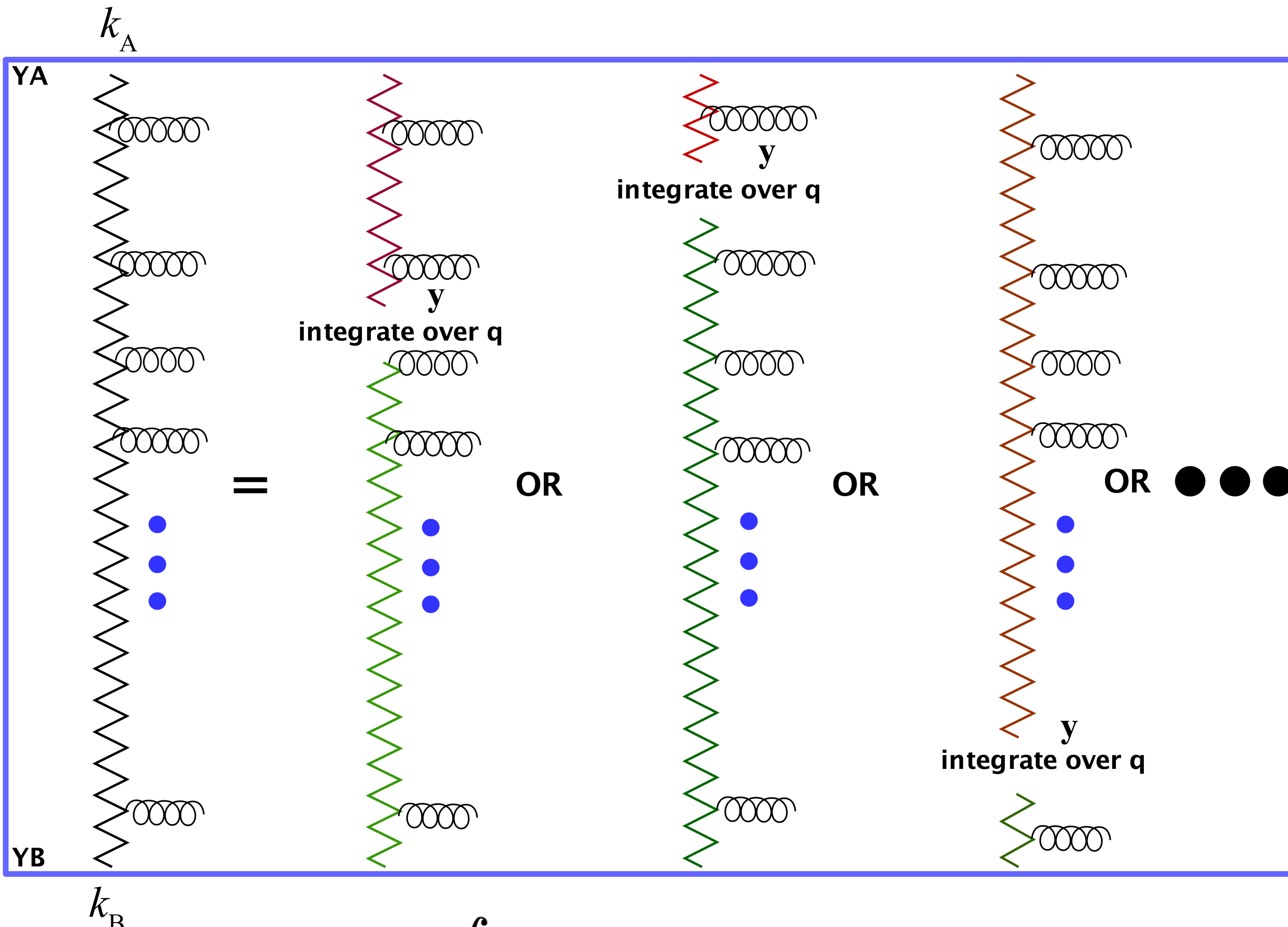


Picture from: Colferai, Schwennsen, Szymanowski, Wallon 2010

Now, let us move to events with three tagged jets

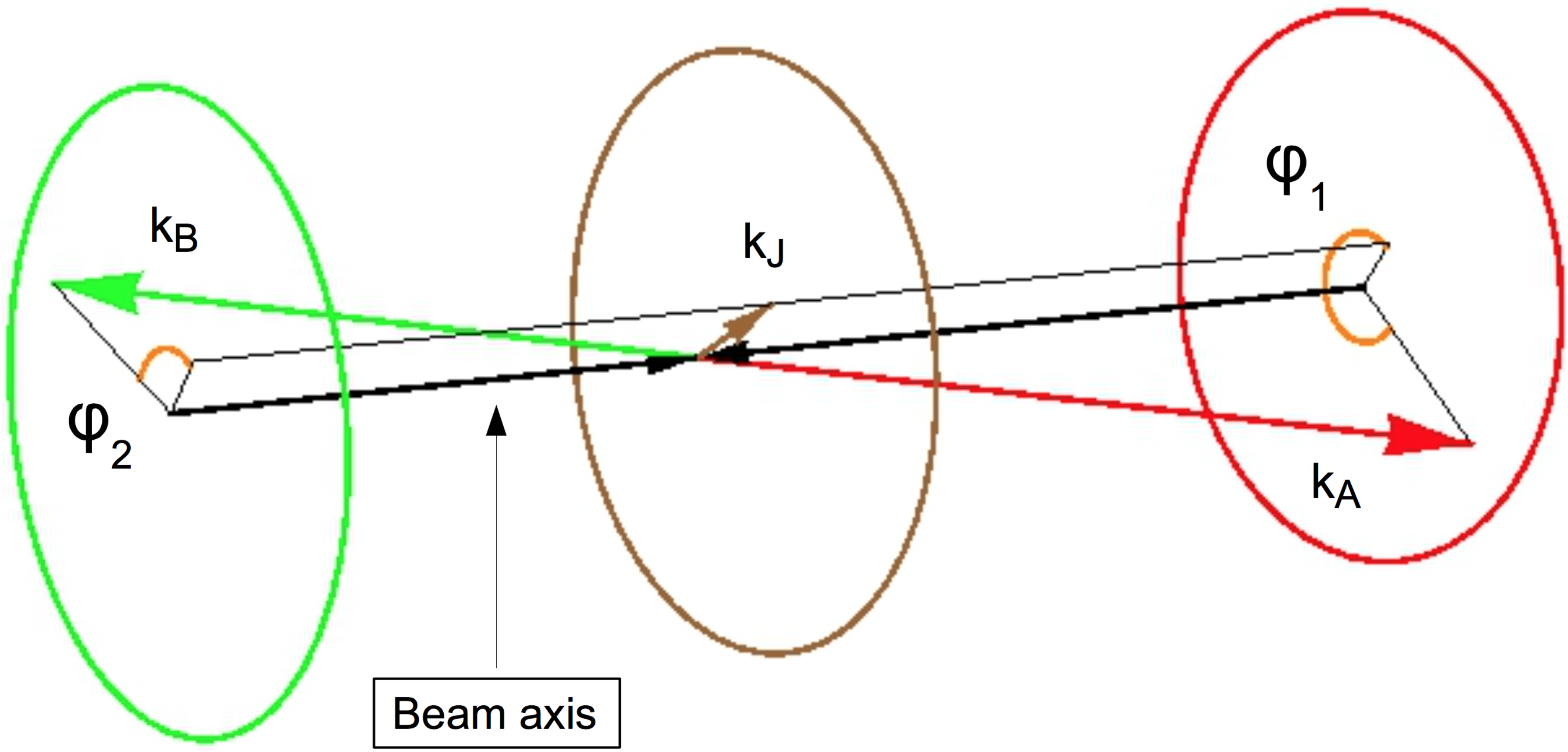


Cutting and sewing back a GGF

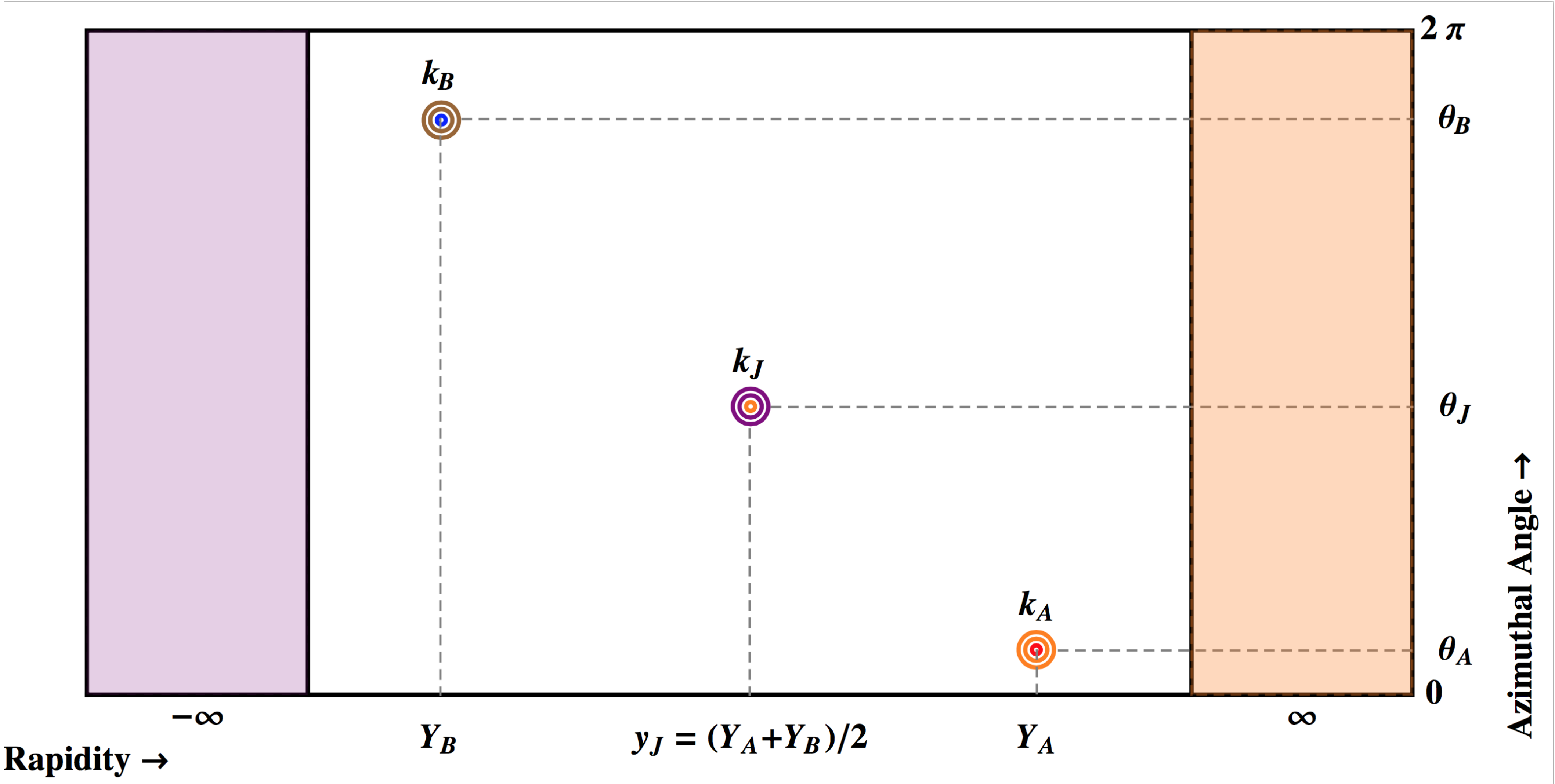


$$f(k_A, k_B, Y_A - Y_B) = \int d^2q\, f(k_A, q, Y_A - y) f(q, k_B, y - Y_B)$$

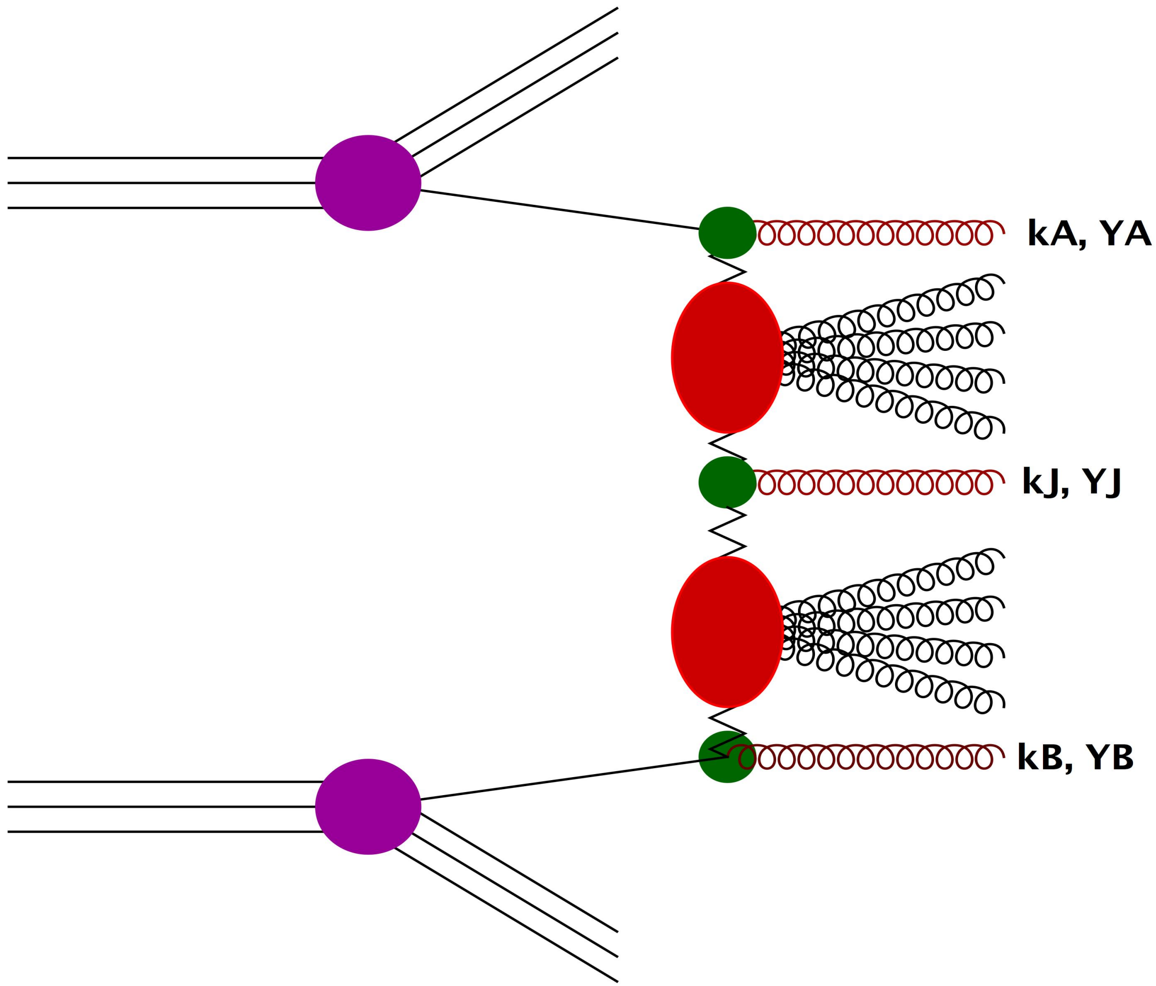
An event with three tagged jets (detector view)



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:

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

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

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

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

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

Integrate over all angles after using projections

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

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

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

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

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

... 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*?

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

* 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 TeV, just pick up the data that were used for Mueller-Navelet (MN) studies, for 8 and 13 TeV, pick up the data that will be used for MN.
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 = Cos(1*$\Delta\theta_1$)*Cos*(3*$\Delta\theta_2$) and denom = Cos(1*$\Delta\theta_1$)*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:

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

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

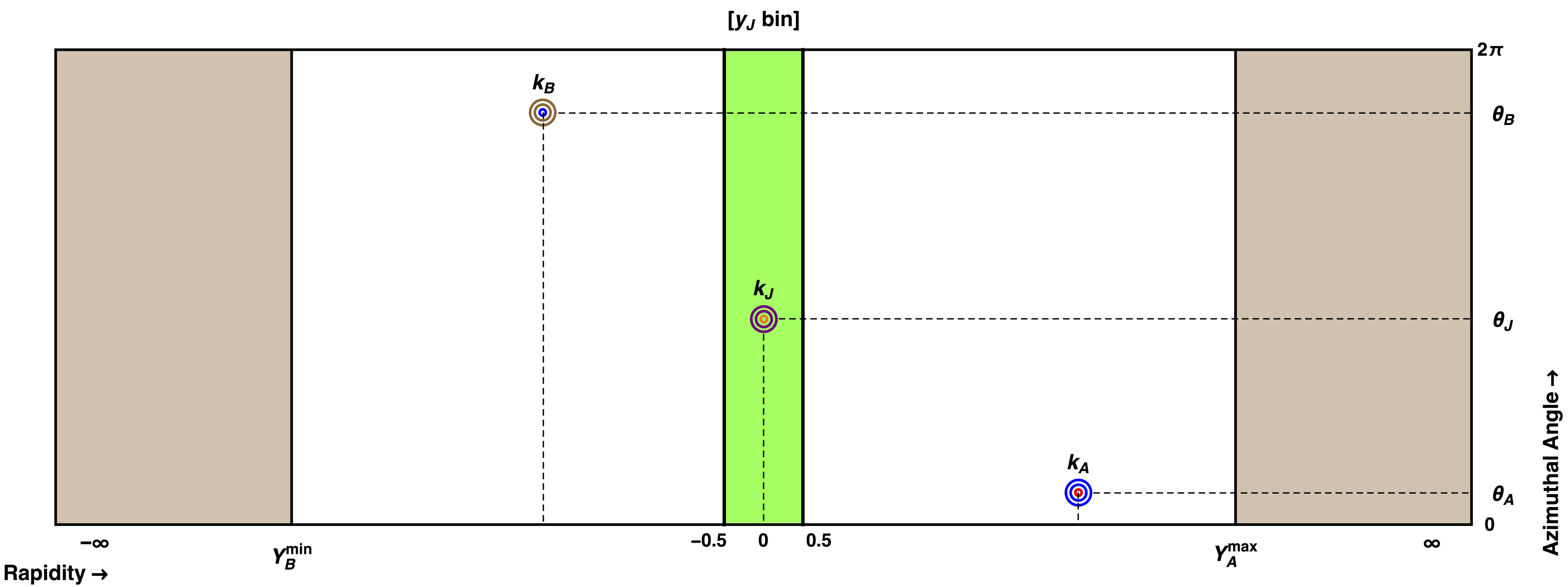
  [S.J. Brodsky, G.P. Lepage, P.B. Mackenzie, Phys. Rev. D 28, 228 (1983)]
- Consider three cases for the pT of the central jet

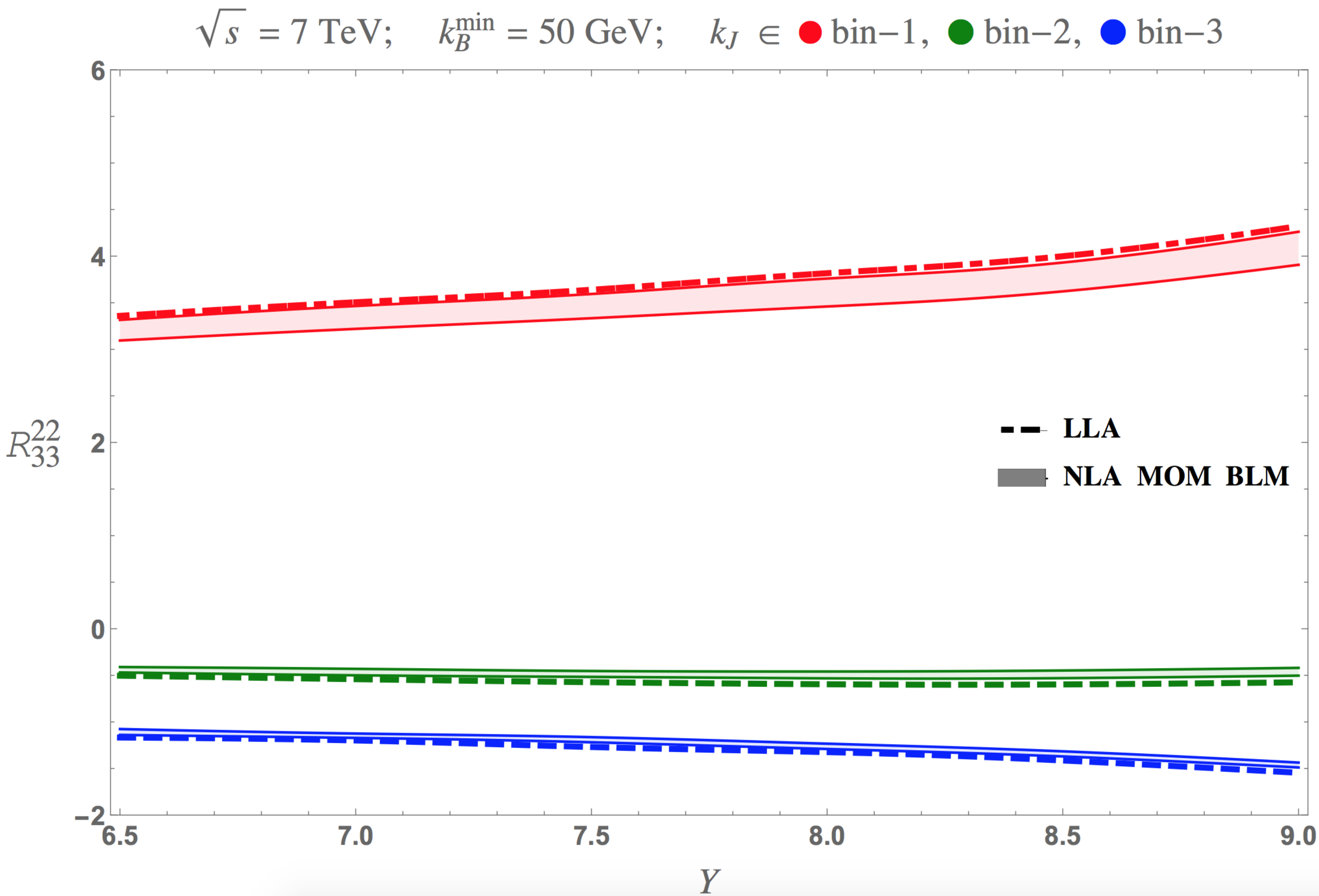
$$20\,\mathrm{GeV} < k_J < 35\,\mathrm{GeV} \;\; (\mathrm{bin}\text{-}1)$$

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

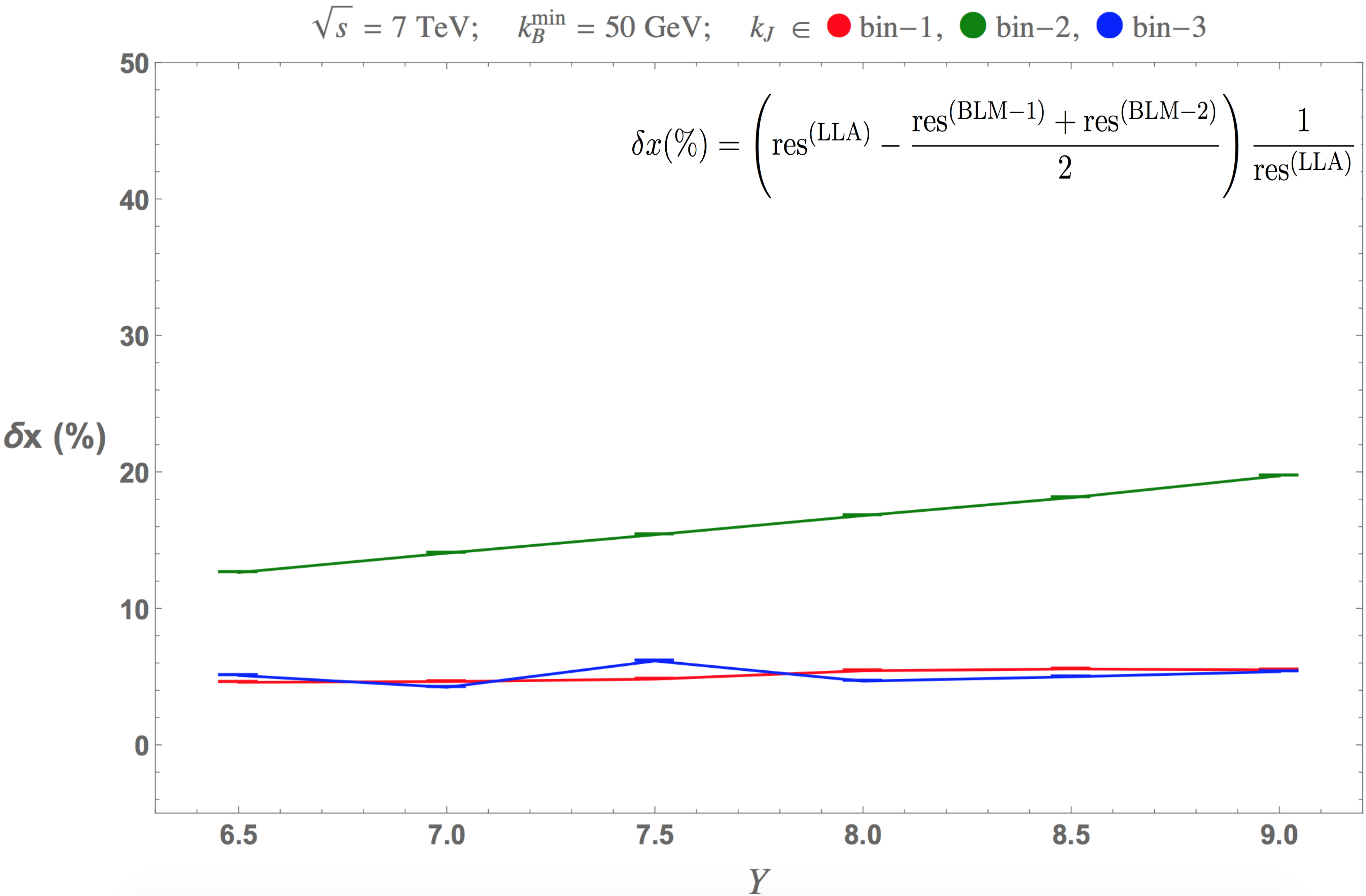
$$60\,\mathrm{GeV} < k_J < 120\,\mathrm{GeV} \;\; (\mathrm{bin}\text{-}3)$$

Integrate over a central rapidity bin

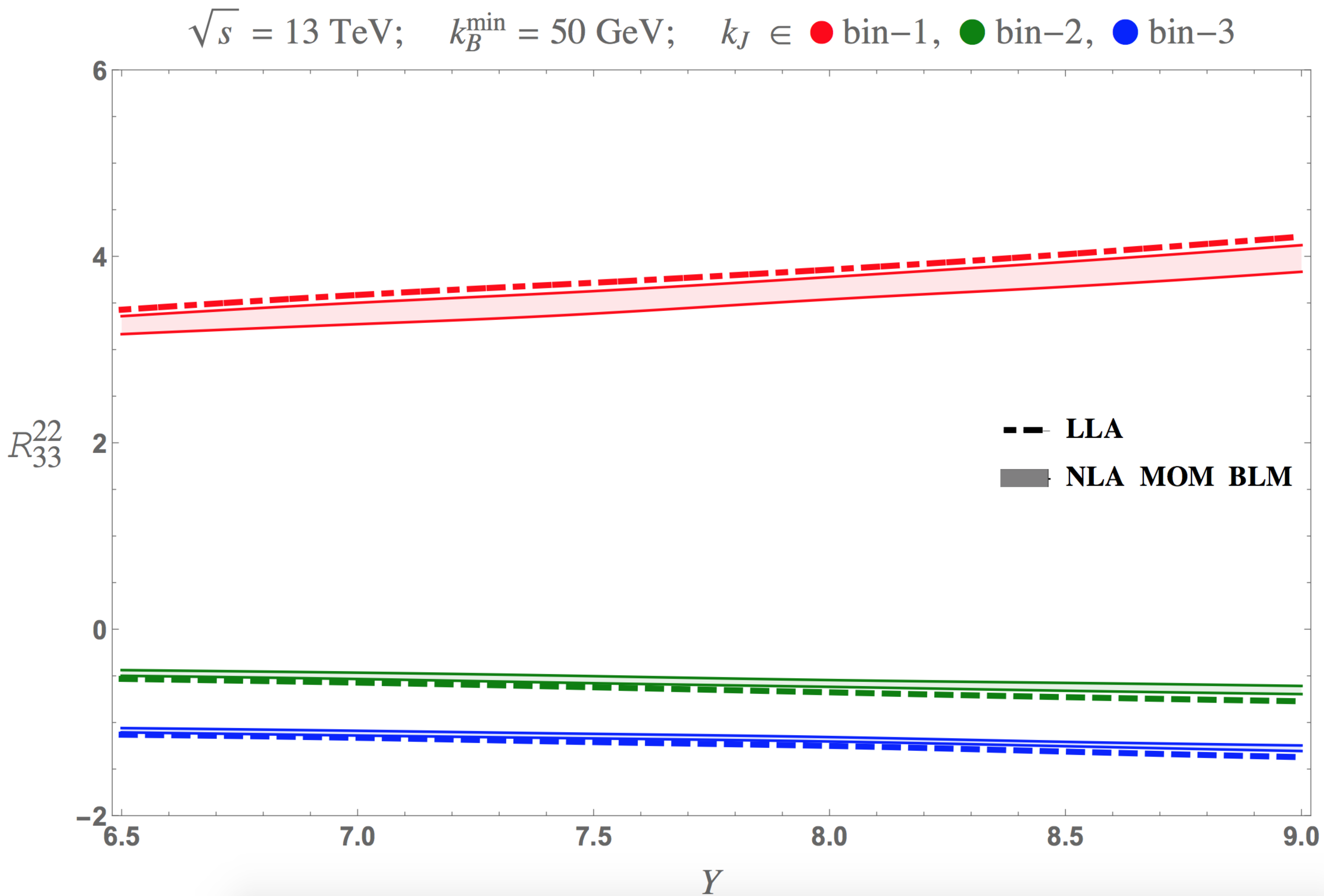




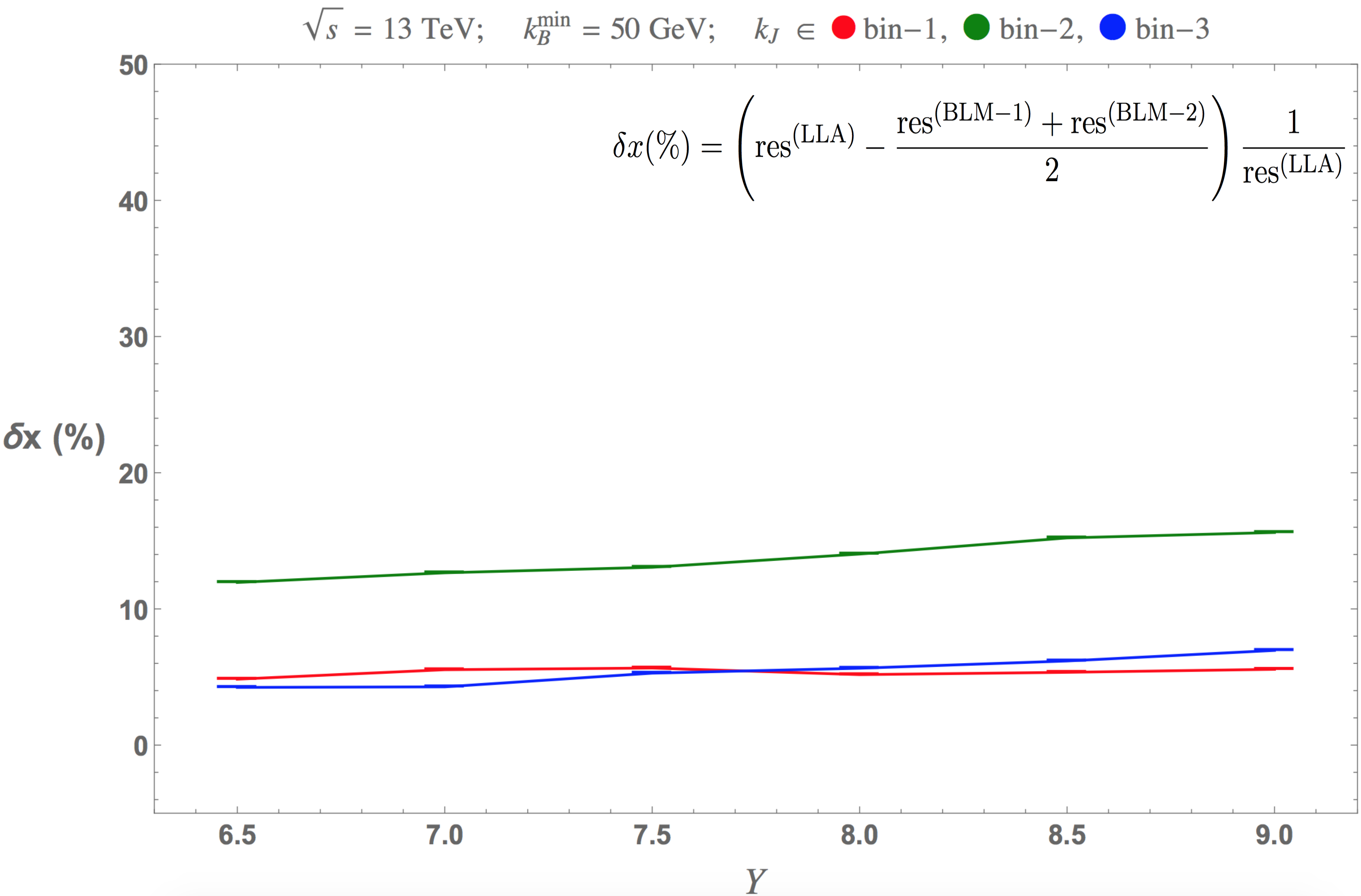
$\sqrt{s}$ = 7 TeV; $k_B^{\min}$ = 50 GeV; $k_J \in$ bin−1, bin−2, bin−3
R_{33}^{22}
Y
LLA
NLA MOM BLM
6
4
2
0
−2
6.5
7.0
7.5
8.0
8.5
9.0



$\sqrt{s}$ = 7 TeV; $k_B^{\rm min}$ = 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
LLA
NLA MOM BLM
R_{33}^{22}
Y
6
4
2
0
−2
6.5
7.0
7.5
8.0
8.5
9.0



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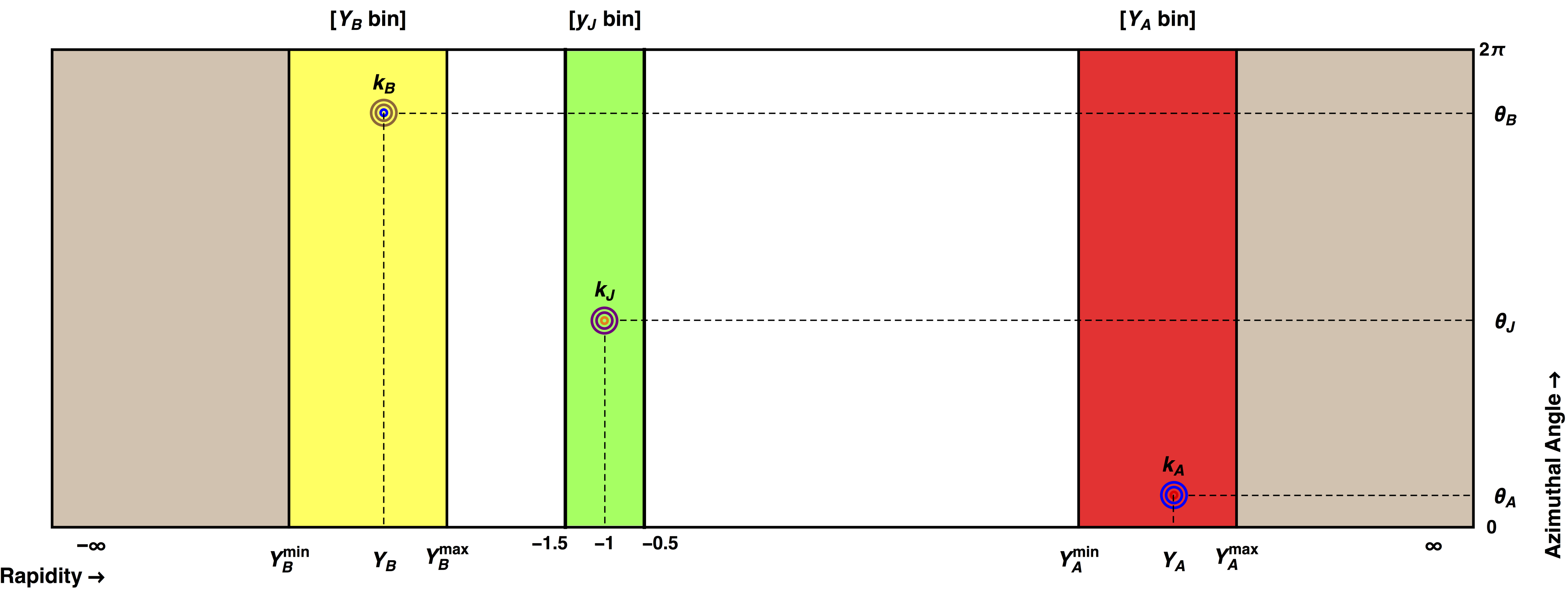
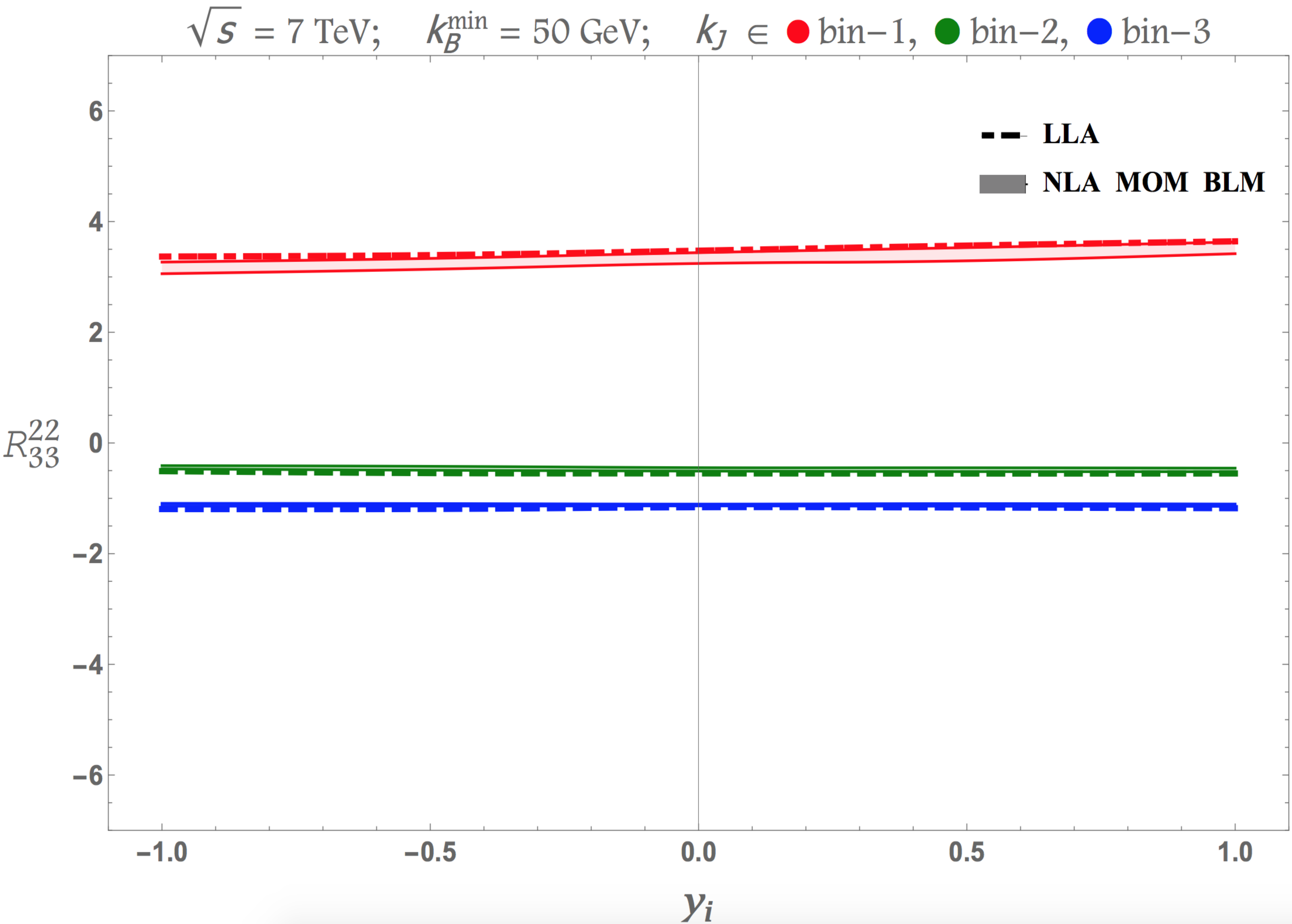
δx (%)
50
40
30
20
10
0
6.5
7.0
7.5
8.0
8.5
9.0
Y

Integrate over a forward, backward and central rapidity bin

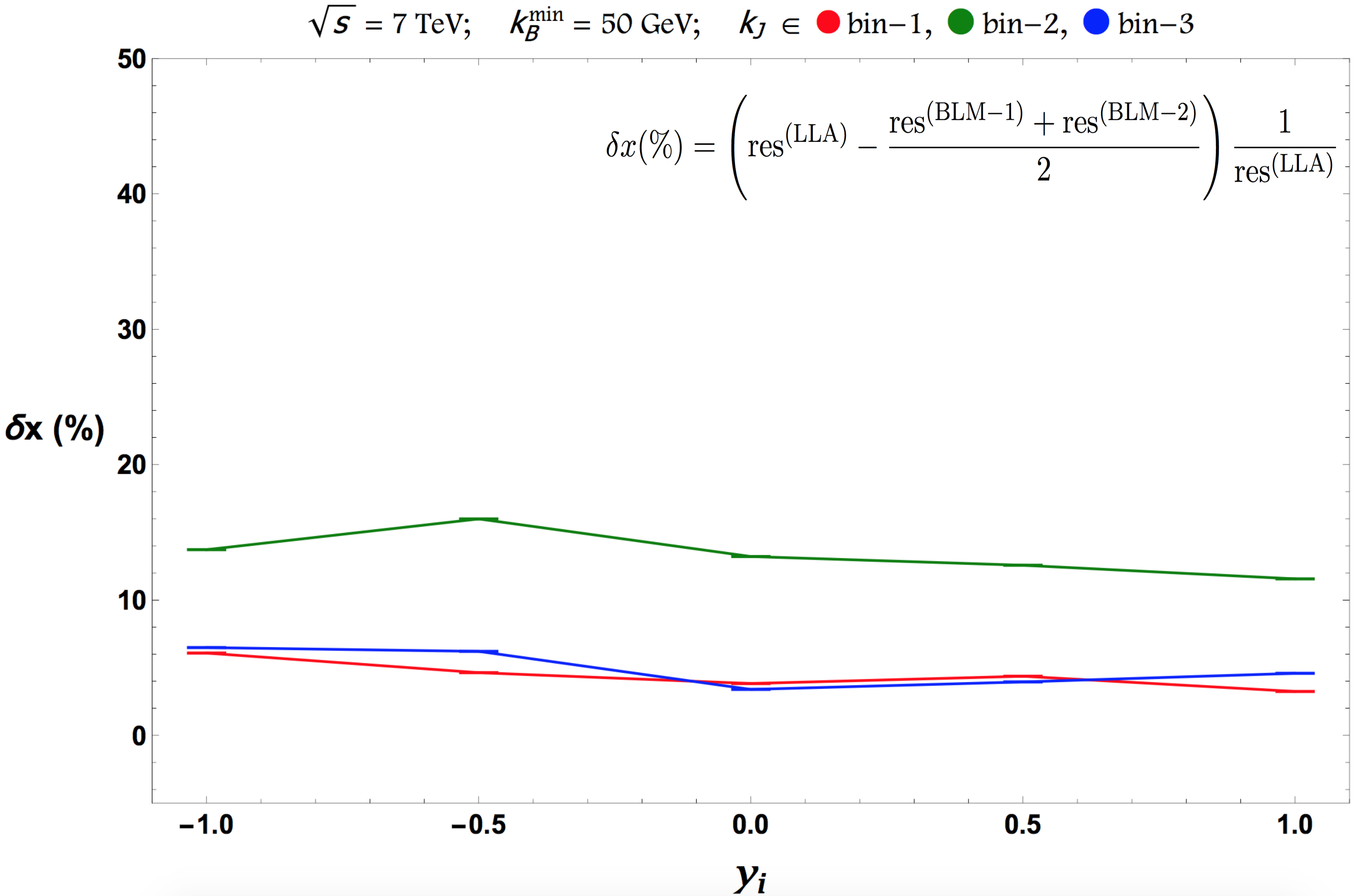


$$(Y_A^{\rm min} = 3) < Y_A < (Y_A^{\rm max} = 4.7)$$

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



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



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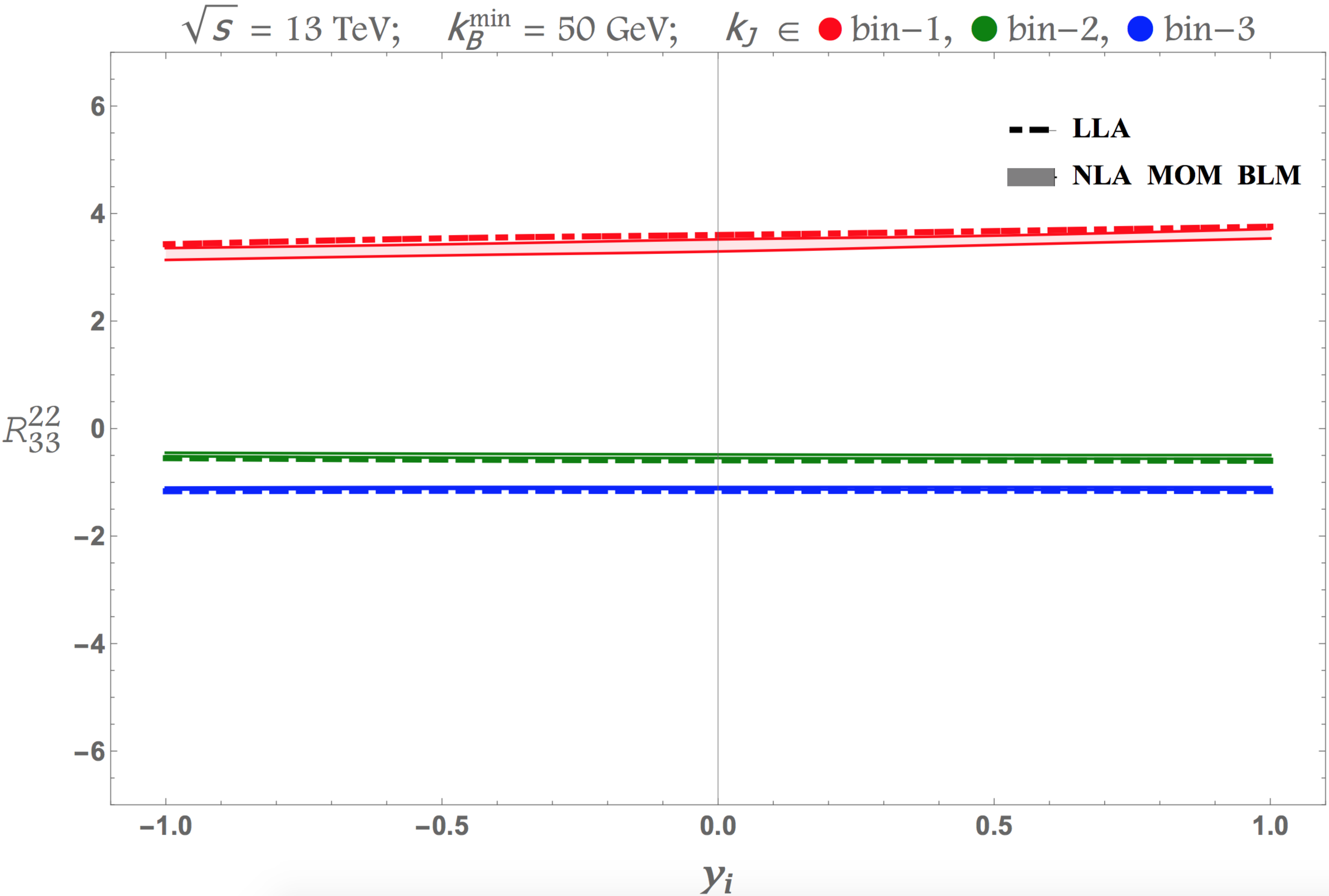
δx (%)
y_i
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0



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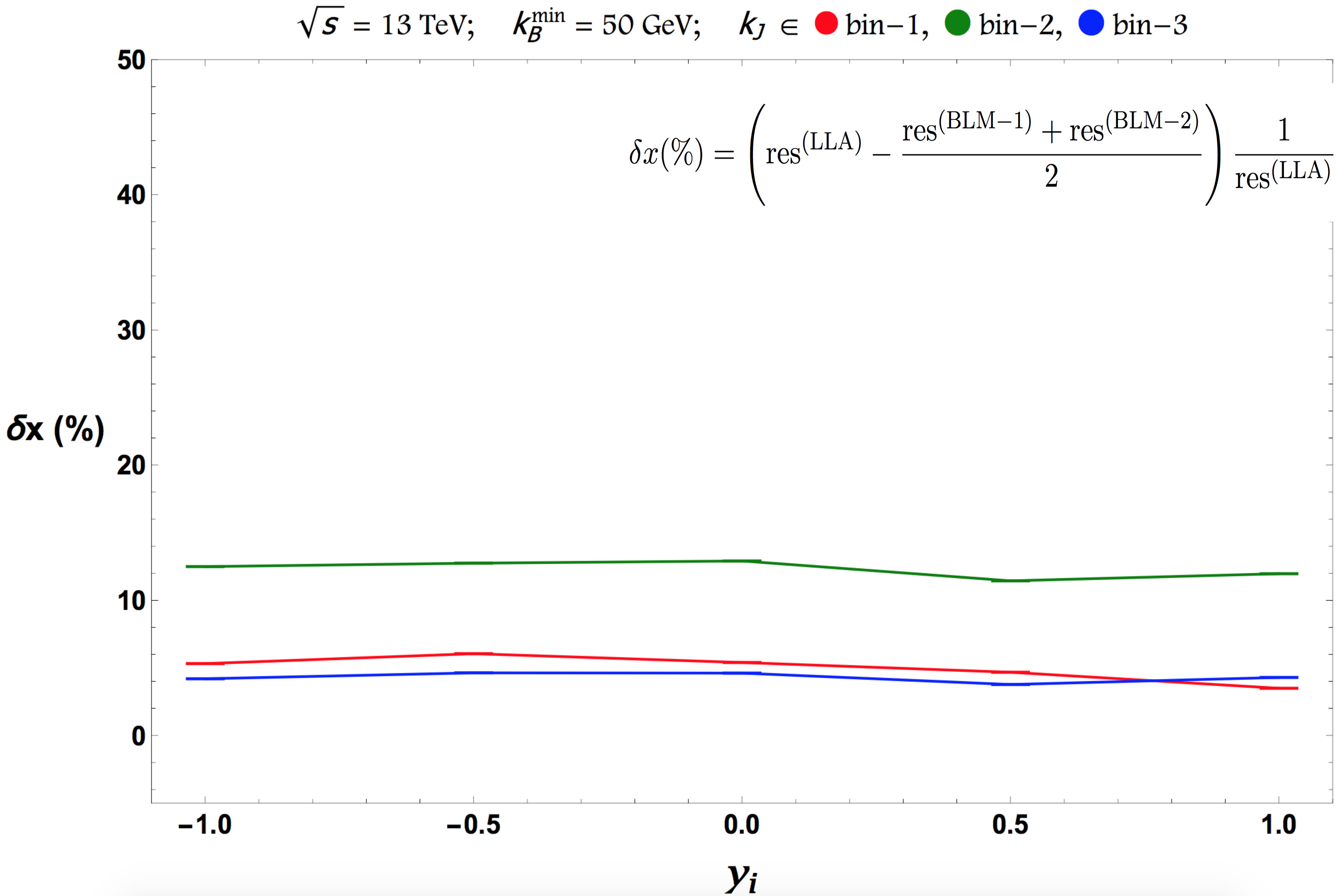
LLA
NLA MOM BLM
6
4
2
0
−2
−4
−6
R_{33}^{22}
−1.0
−0.5
0.0
0.5
1.0
y_i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δx (%)
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0
y_i

Conclusions

- We use events with three tagged jets to propose **new observables** aiming at disentangling a distinct signal of BFKL dynamics.
- The observables are defined as **ratios** of correlation functions to **minimize the influence of higher order effects**.
- The **stability** of the azimuthal observables after introducing higher order corrections is good.
- The measurement of the observables proposed here **poses no intricacies** in the analysis of the data.

Input from the experimental side is highly anticipated...