Rapidity and Angular correlations in multi-Regge kinematics

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Outline

- Multiparticle production in the last 50-60 years
- An important tool that comes from the past: two particle correlations
- The emergence of the so-called multiperipheral models and the concept of clusters in the 60s and 70s
- How do these old ideas fare in the QCD era and are there useful at all?
- To answer that, go to a certain kinematical limit (multi-Regge kinematics) and use Monte Carlo techniques (**BFKLex**)
- Results and outlook

~70 years ago

Progress of Theoretical Physics, Vol. 5, No. 4, July~August, 1950

High Energy Nuclear Events

Enrico FERMI

Institute for Nuclear Studies
University of Chicago
Chicago, Illinois

(Received June 30, 1950)

Abstract

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possible numbers of particles are determined essentially by the statistical weights of the various possibilities.

~50 years ago

CORRELATIONS AND MULTIPLICITY DISTRIBUTIONS IN MULTIPARTICLE PRODUCTION

BY M. LE BELLAC

University of Nice*

(Presented at the XIII Cracow School of Theoretical Physics, Zakopane, June 1–12, 1973)

A general discussion of Short Range Order hypothesis and its comparison with experimental data on correlations in inclusive spectra is given.

1. Introduction

In the absence of a theory of strong interactions, one of the main purposes of the present experiments on multiparticle production is to discover empirical regularities in the experimental data, in the hope that these regularities will be useful later for a more fundamental understanding of hadrodynamics. Some of these empirical regularities have

Chew, G. F., 'Multiperipheralism and the Bootstrap,' Comments on Nuclear and Particle Physics 2 (1968), 163–168.

Multiperipheralism and the Bootstrap

The adjective "peripheral", when applied to hadronic reactions, characterizes a correlation between large angular-momentum values that produces a smooth and persistent momentum-transfer dependence favoring small angles. The best-known example is the so called "forward diffraction peak" in elastic scattering, but almost all two-hadron reactions have exhibited similar forward peaking, with widths in momentum transfer that change only slowly with energy. The widths vary from one reaction to another but usually are well below 0.5 GeV. Although "peripheralism" at first sight may seem an unsurprising phenomenon, close study has revealed profound theoretical implications that touch on the very origin of the hadrons. One crucial inference is that multiple-production reactions should be "multiply-peripheral". This note proposes briefly to survey multiperipheralism, together with the related hypothesis of multi-Regge-poles. It will be seen that a new class of bootstrap constraints is implied.

Sergio Fubini
Comments Nucl.Part.Phys. 4 (1970) 3, 102-106

Multiperipheral Model

Work in the multiperipheral model was started almost ten years ago. It is pleasant to realize that the model in its different forms retains the attention of many physicists and that some of its general predictions seem to be in good agreement with experiment.[1]

Although a detailed study of the model requires a rather involved mathematical apparatus, most of the main results can be understood in a simple intuitive way.

The multiperipheral model is based on the idea that multiple production at high energy is dominated by the graphs shown in Fig. 1.

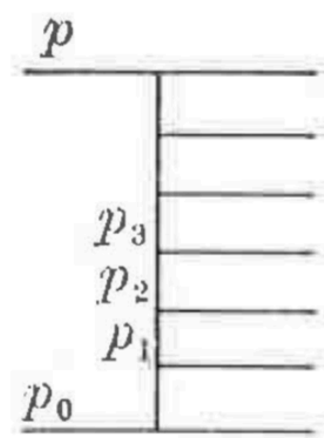


FIGURE 1

The different versions of the model differ in the choice of what object (particle, Regge poles $\cdots$) corresponds to the peripheral lines of momentum $p_1, p_2 \cdots$.

Notion of Clusters (70s)

Progress of Theoretical Physics, Vol. 53, No. 3, March 1975

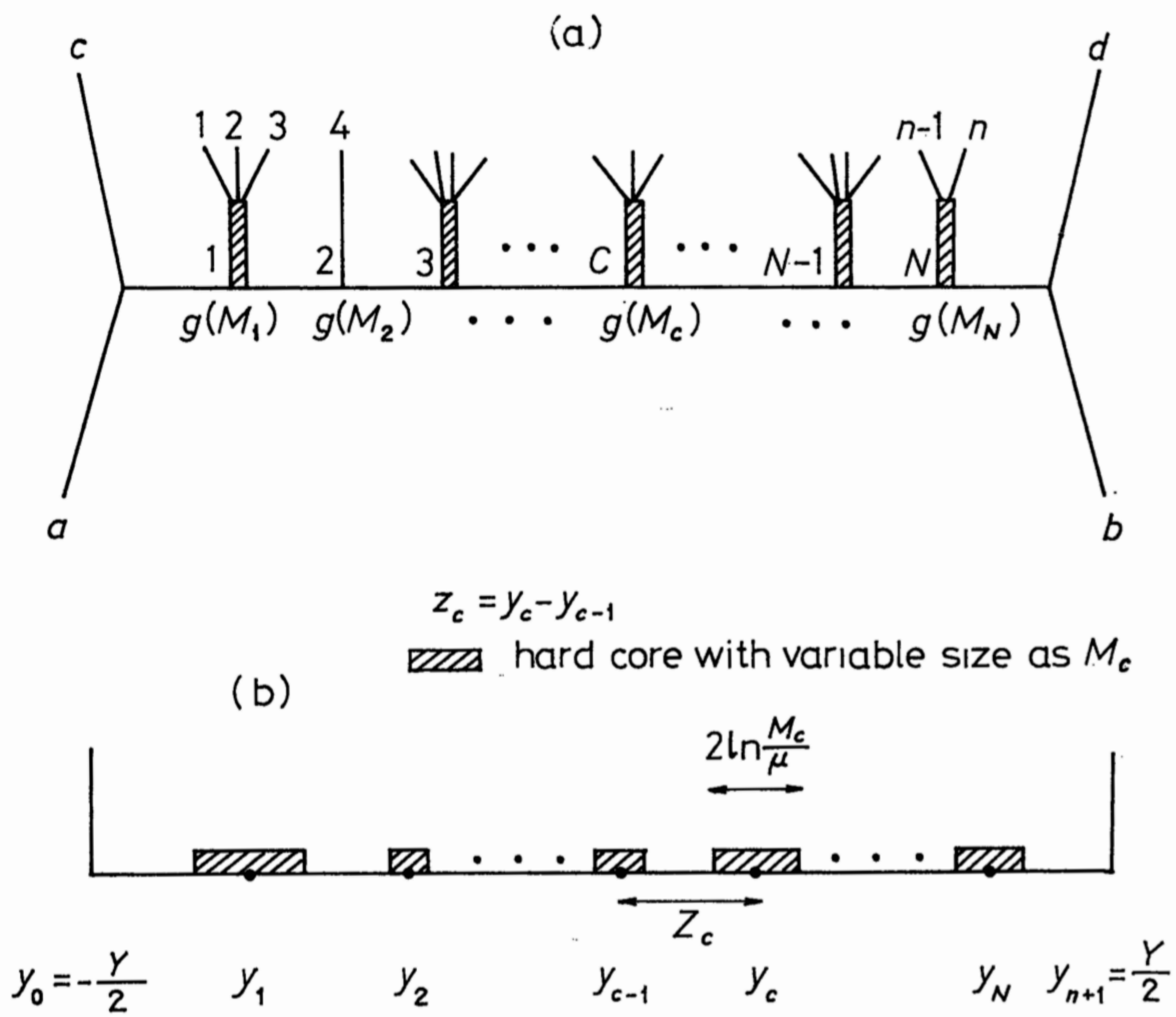


Fig. 1 (a) Multiperipheral chain of our cluster emission model. (b) Rapidity space configuration of clusters with variable mass M_c. Each cluster has a hard core of length $2\ \ln(M_c/\mu)$.

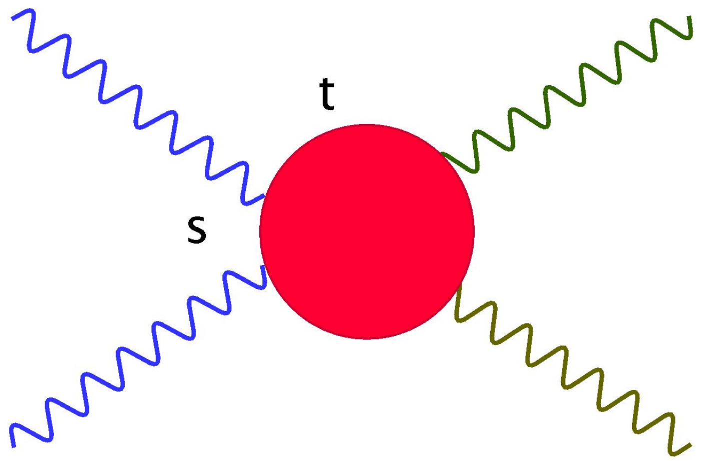
Hadron Colliders

- The first hadron collider was the 1-km-circumference proton–proton (pp) **Intersecting Storage Rings (ISR)**,1 commissioned at CERN in 1971. Its beam energies ranged from 12 to 31 GeV. Experiments at the ISR revealed the logarithmic rise of the pp total scattering cross section at energies where it was expected to have leveled off.
- Ten years later, CERN's **Super Proton Synchrotron (SPS)**, until then a fixed-target accelerator, became the SppS, a proton–antiproton collider with Ecm up to 630 GeV. By the end of 1983, the collaborations that ran the large UA1 and UA2 detectors at the collider's beam-crossing points had discovered the heavy W± and Z0 bosons that mediate the weak interactions
- Next, Fermilab's pp Tevatron collider had a Ecm of 1.8 TeV; eventually it reached 2 TeV. 1995 top quark discovery
- Currently: LHC era

https://physicstoday.scitation.org/doi/10.1063/PT.3.2010

The high energy or *Regge* limit

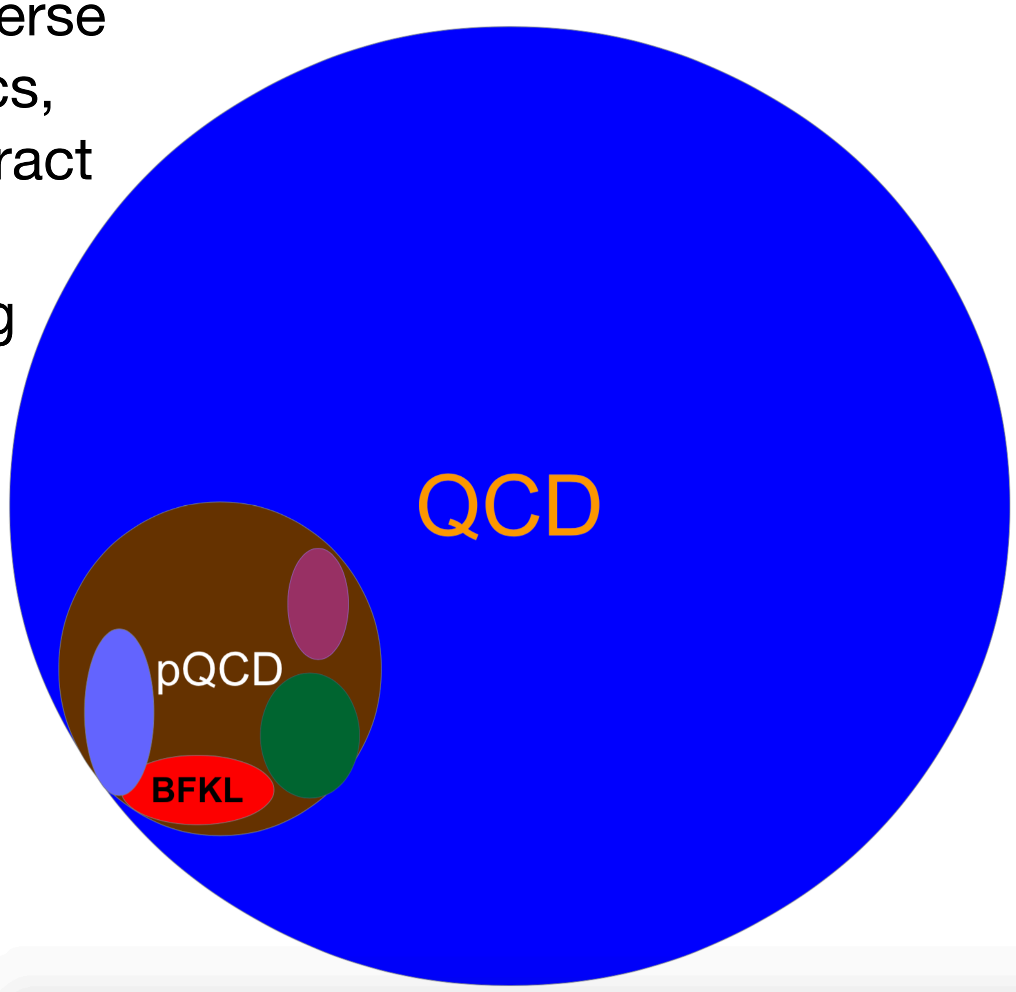
$$s \gg -t \gg m^2$$



There is a plethora or things we access by studying that limit: **Theory**: Integrability, gravity, black holes, AdS/CFT, Bern-Dixon-Smirnov amplitudes, factorization, separation between transverse and longitudinal d.o.f, transition from hard to soft scale physics, glueballs. Furthermore, in **Mathematics**: number theory, abstract algebra, special functions, …

We are here interested in **Phenomenology** and understanding **QCD** better.

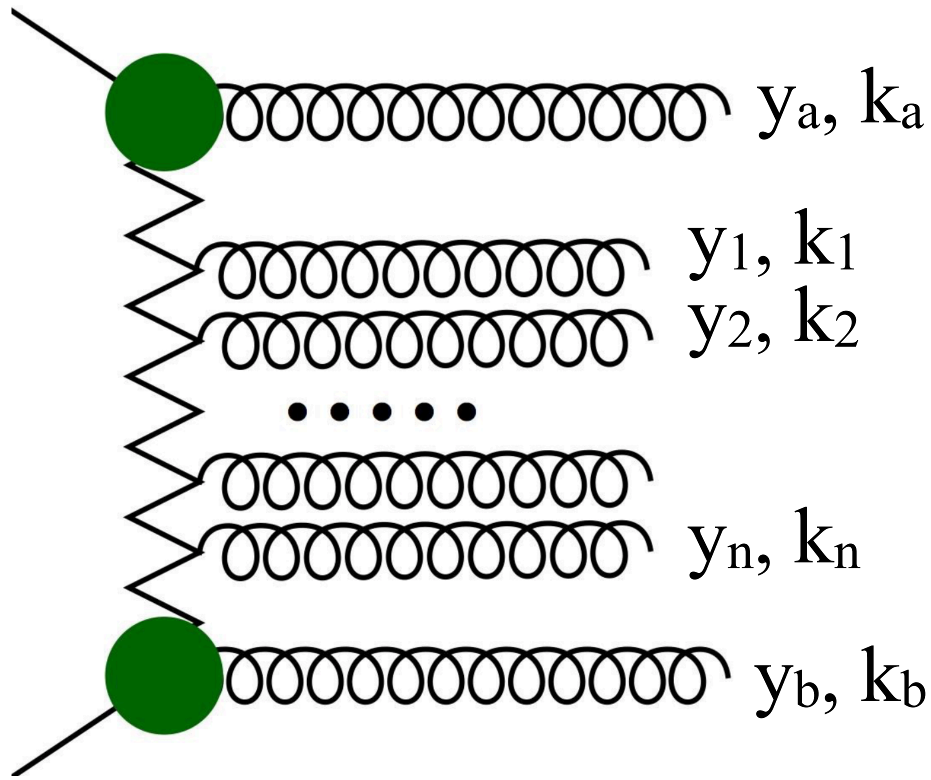
A crucial tool to study the *Regge* limit in QCD is ***Balitsky-Fadin-Kuraev-Lipatov*** **(BFKL)** dynamics. In its essence, BFKL resums to all orders diagrams that carry **large logarithms** in energy.
It goes beyond fixed order.



Relevant considerations for the *Regge* limit

- Q: Is a fixed order calculation enough?
- A: It depends on the energy and the order, for asymptotic energies, no
- Q: What is the most relevant scale in high energy scattering?
- A: The center-of-mass energy squared s, t has also to be small though
- Q: In which functional form does s appear in the Feynman diagrams?
- A: $\alpha_s^m \ln(s)^n$ (for this talk, it is actually $\alpha_s^n \ln(s)^n$)
- Q: Can one isolate those Feynman diagrams that come with a numerically important [$\alpha_s^m \ln(s)^n \sim 1$] contribution?
- A: It depends (for this talk the answer is yes)
- Q: Can one resum all these diagrams with important $\alpha_s^m \ln(s)^n$ contributions to all orders in α_s?
- A: It depends (for this talk the answer is yes)

The multi-*Regge* kinematics



$$y_b \ll y_n \ll \cdots \ll y_2 \ll y_1 \ll y_a$$

$$|k_{b\perp}| \simeq |k_{n\perp}| \simeq \cdots \simeq |k_{2\perp}| \simeq |k_{1\perp}| \simeq |k_{a\perp}|$$

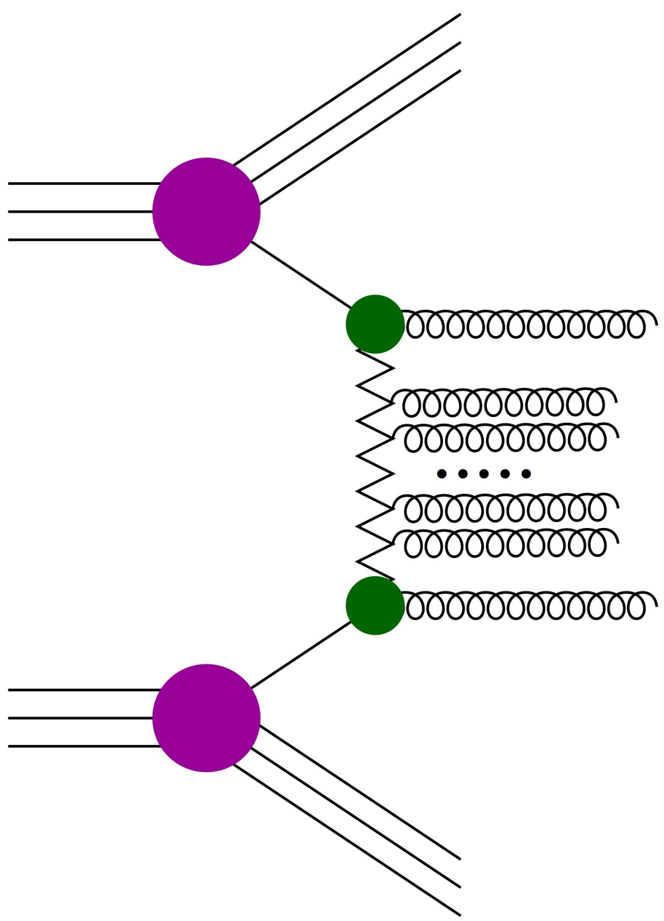
In n+2 particle production, the requirements are:

- Strong ordering in rapidity
- similar transverse momenta

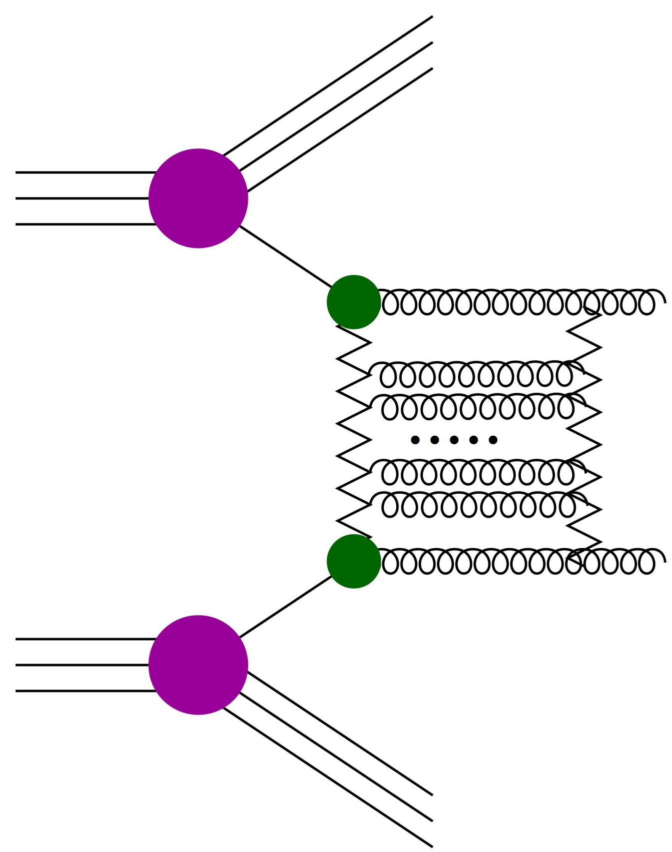
High energy scattering QCD

Rich phenomenology, e.g.

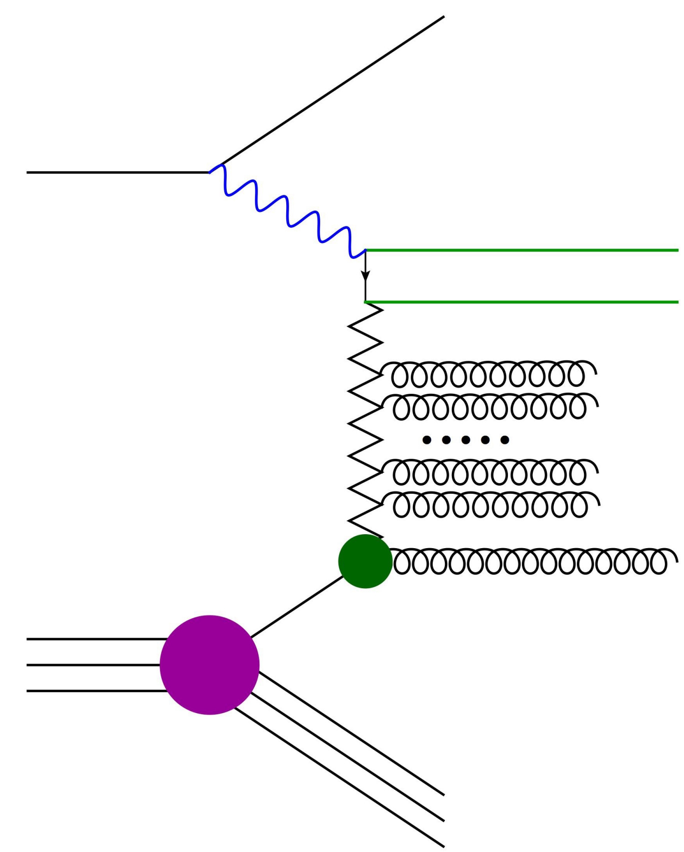
Mueller-Navelet jets



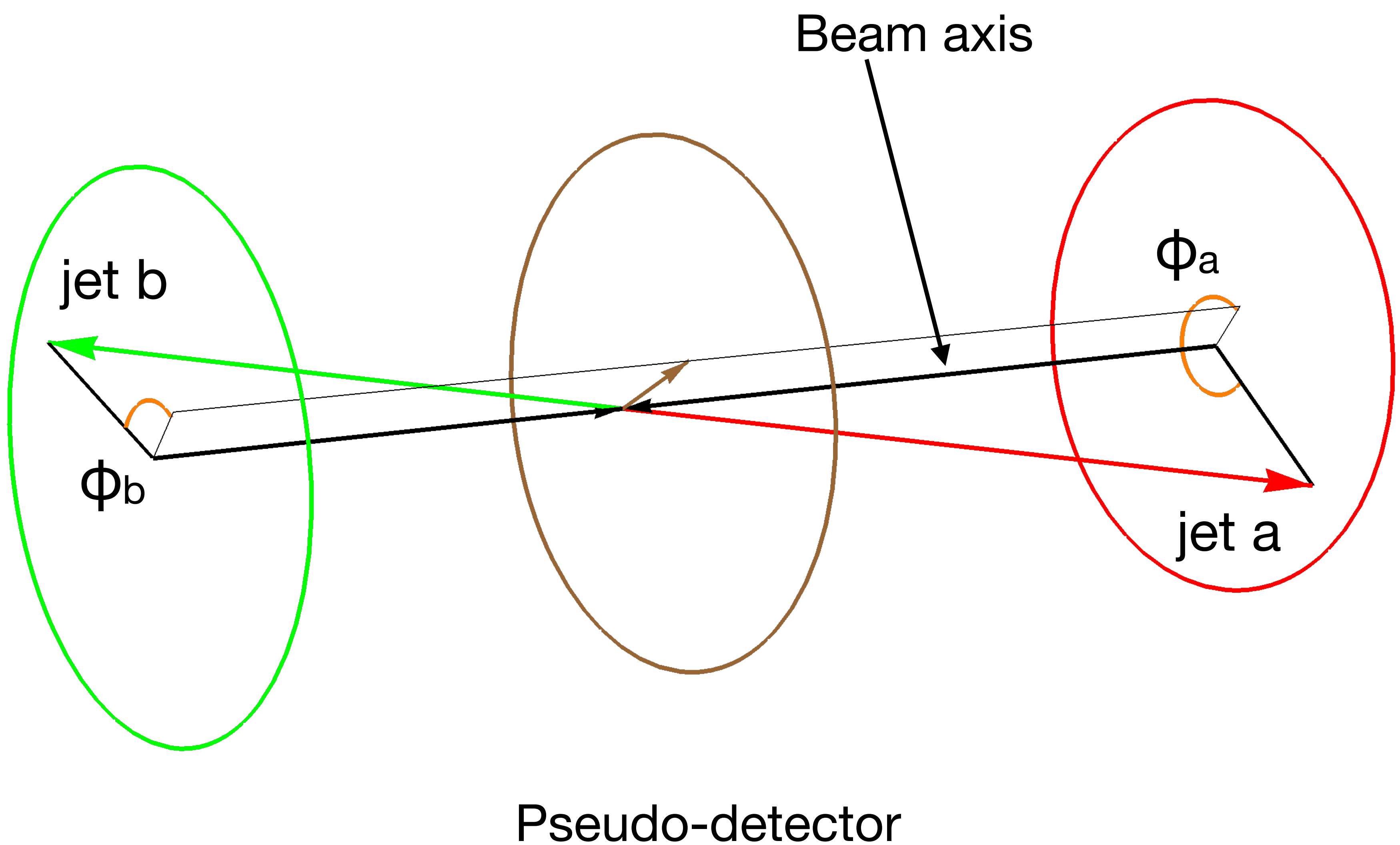
rapidity gaps



DIS

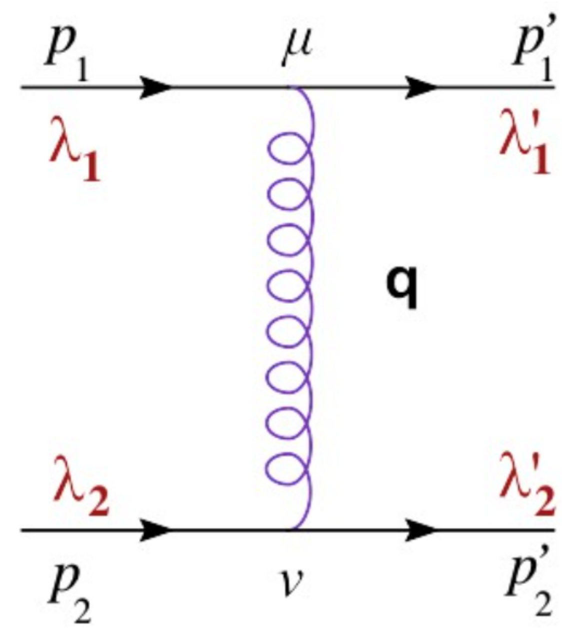


A MN jets example



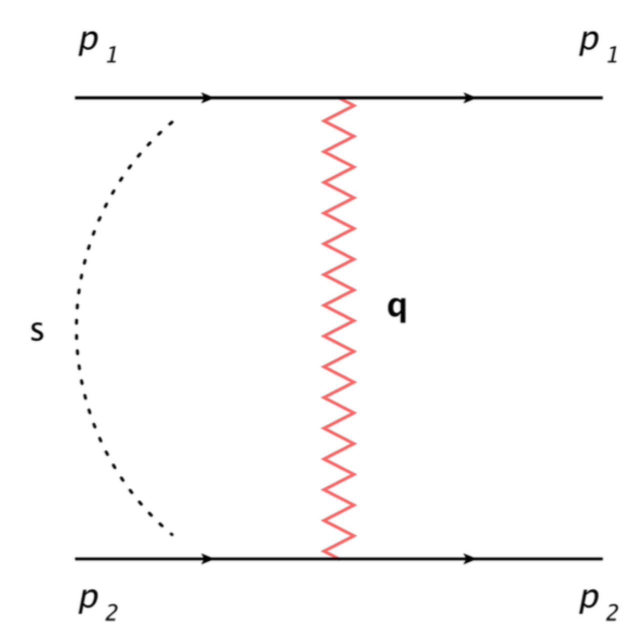
Large logs from virtual corrections

A normal gluon propagator: $D_{\mu\nu}(s, q^2) = -i\frac{g_{\mu\nu}}{q^2}$

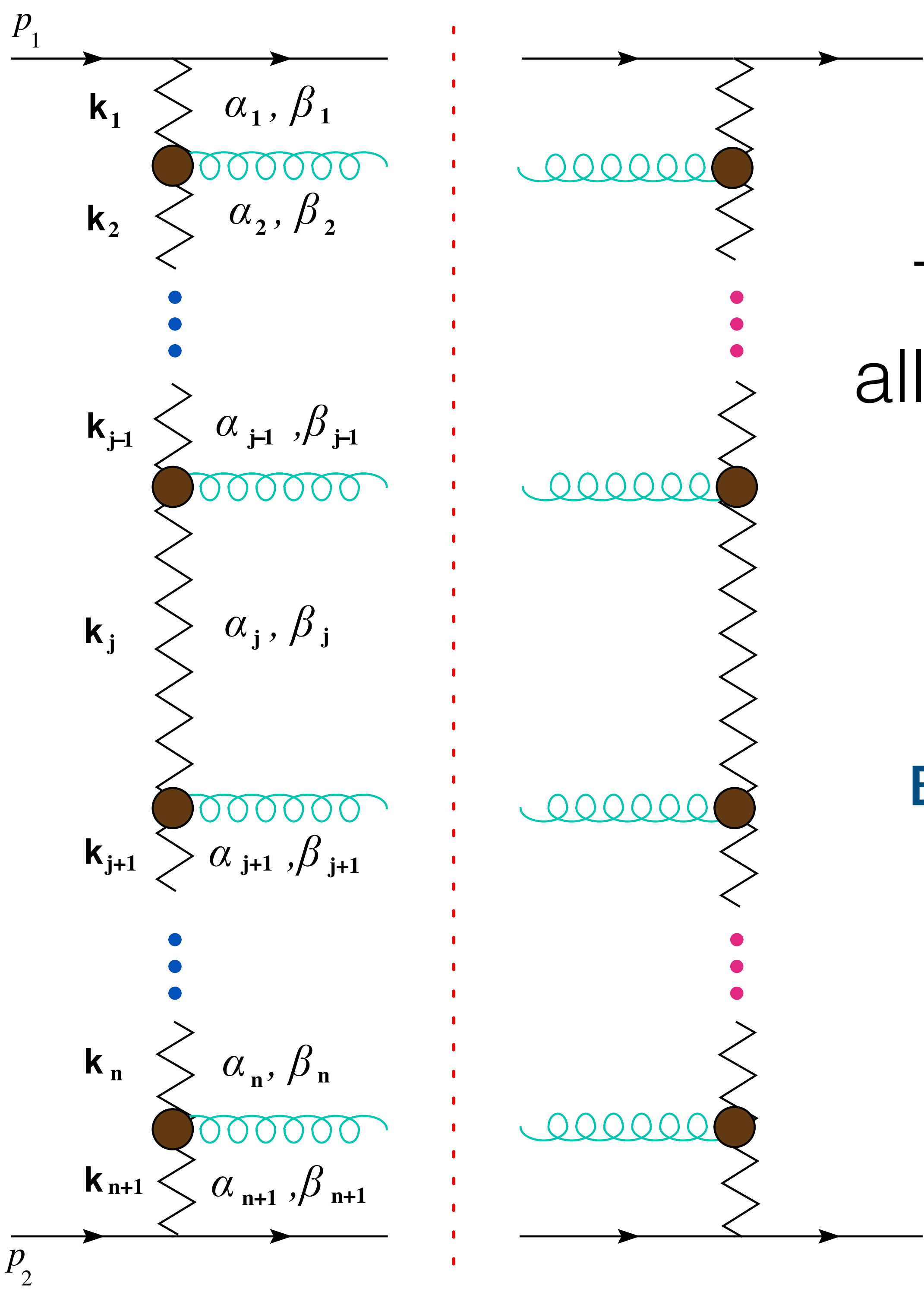


The reggeized gluon is a gluon with modified propagator:

$$D_{\mu\nu}(s, q^2) = -i\frac{g_{\mu\nu}}{q^2}\left(\frac{s}{\mathbf{k}^2}\right)^{\omega(q^2)}$$

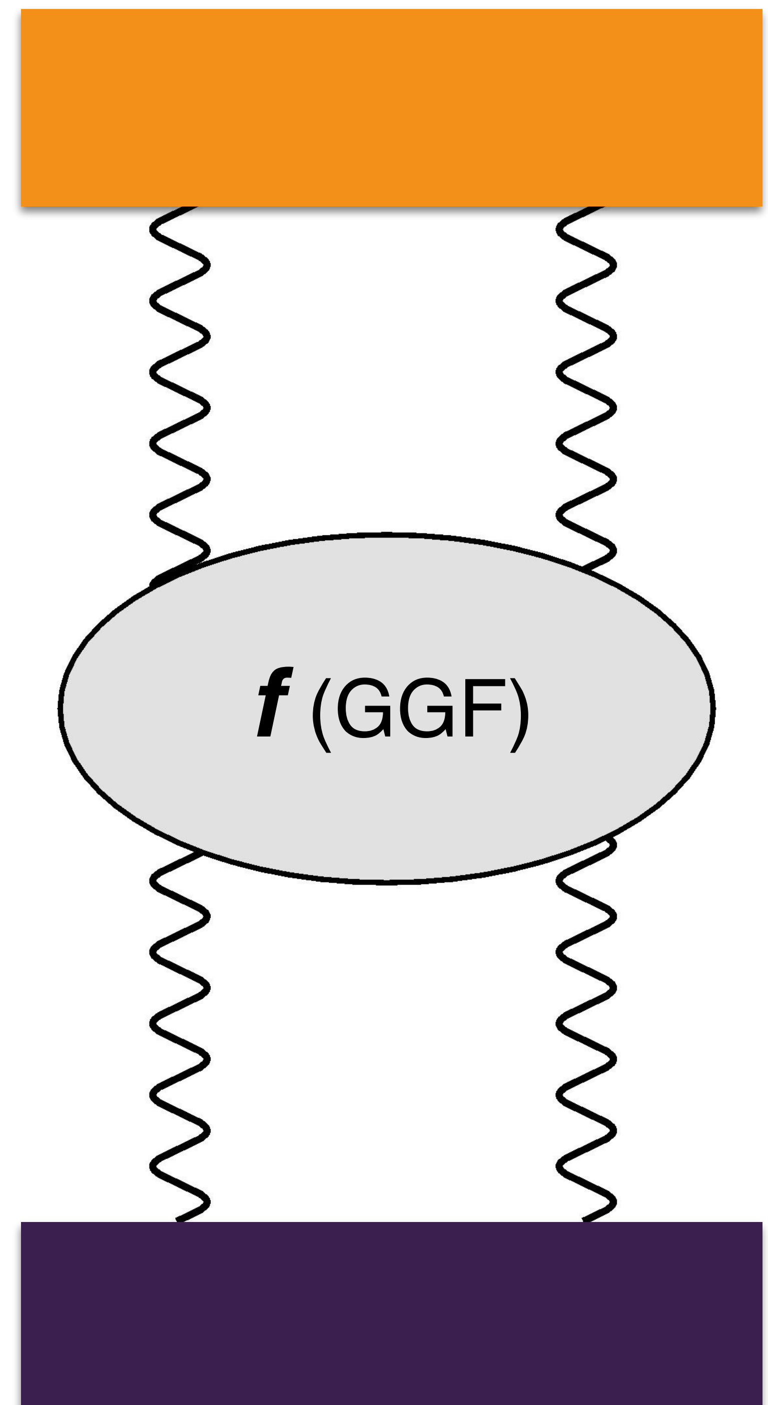


Large logs from real emission corrections

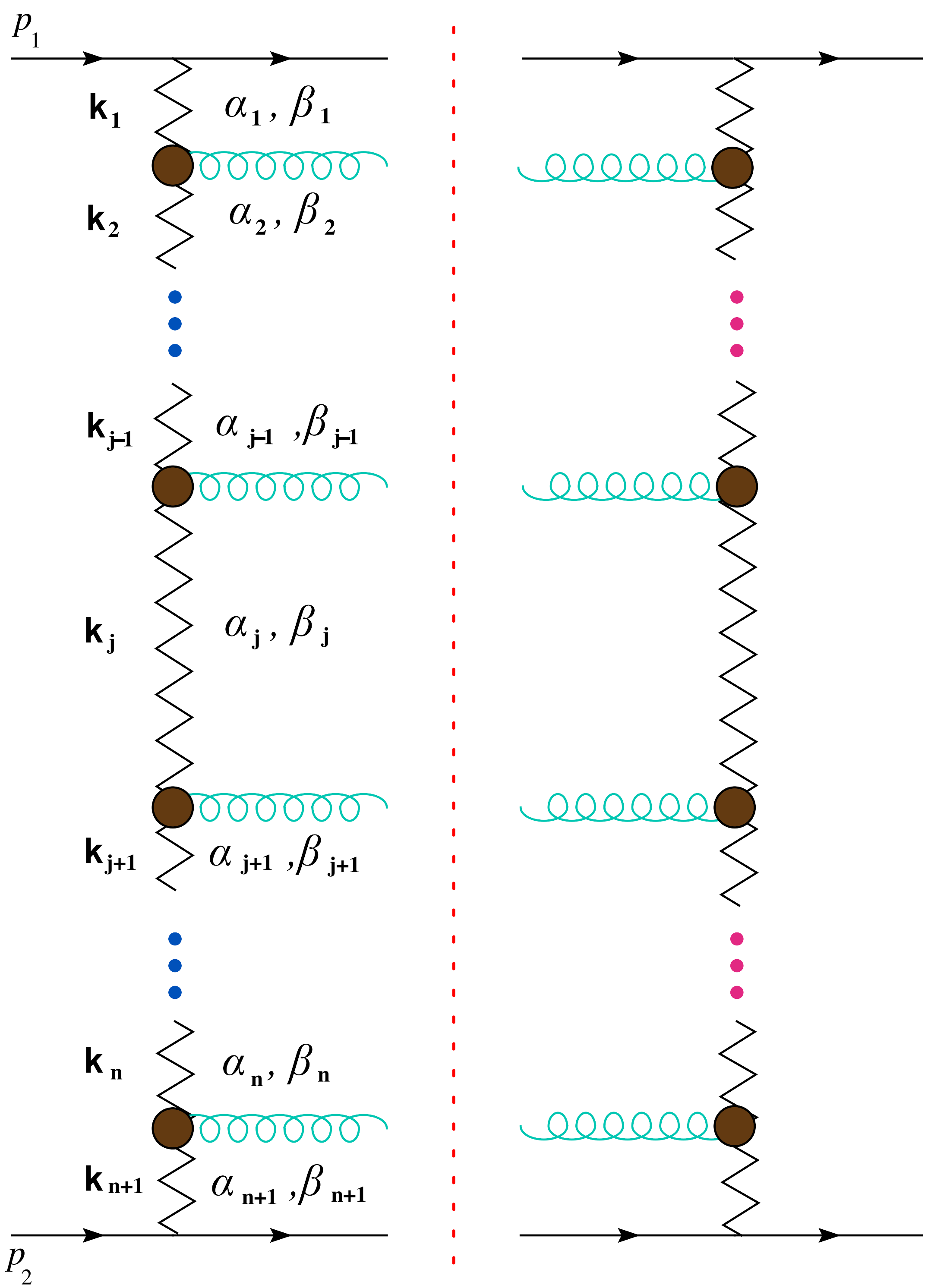


To resum to all n, use BFKL

BFKL Pomeron



Large logs from real emission corrections



- Assume Reggeons in the t-channel
- Assume you have only one real emission
- Do the phase-space integration —> res1
- Now assume you have two real emissions
- Do the phase-space integration —> res2
- Add the results: RES = res1+res2
- Now assume you have three real emissions
- Do the phase-space integration —> res3
- Add the results: RES = RES + res3
- Repeat until you have N real emissions with resN so tiny compared to RES such that you are allowed to claim convergence

NOTE: The phase-space integration is over rapidity and transverse momenta.

BFKLex

- A Monte Carlo code for the iterative solution of the BFKL equation
- The big advantage of a MC code is that differential information regarding the rapidities and momenta of the final state gluons can be booked and differential distributions for a large number of observables can be produced.
- Already, BFKLex was used to propose new observables in order to search for BFKL related effects at the LHC.

Multiperipheral models vs perturbative QCD

- The key idea is to use an old multiperipheral model (the Chew-Pignotti model) for Mueller-Navelet jet final states at the LHC assuming that the jet multiplicity is fixed and rather large
- By jets in this context we really mean final state gluons before parton shower and before hadronization
- We want to study gluon rapidity distributions and two-gluon rapidity correlations
- We then want to produce the same distributions with BFKLex and compare the two approaches

A first comparison between the Chew-Pignotti model and simplified BFKL results can be found in **Nucl.Phys.B 971 (2021) 115518** by N. Bethencourt de León, GC and A. Sabio Vera

Definition of the two-particle rapidity-rapidity correlation function

$$C_2(y_1,p_{\perp 1},y_2,p_{\perp 2}) = \frac{1}{\sigma_{in}}\frac{d^6\sigma}{dy_1 d^2p_{\perp 1} dy_2 d^2p_{\perp 2}} - \frac{1}{\sigma_{in}^2}\frac{d^3\sigma}{dy_1 d^2p_{\perp 1}}\frac{d^3\sigma}{dy_2 d^2p_{\perp 2}}$$

$$\rho_1(y) = \frac{1}{\sigma_{in}}\int d^2p_\perp \frac{d^3\sigma}{dy d^2p_\perp}$$

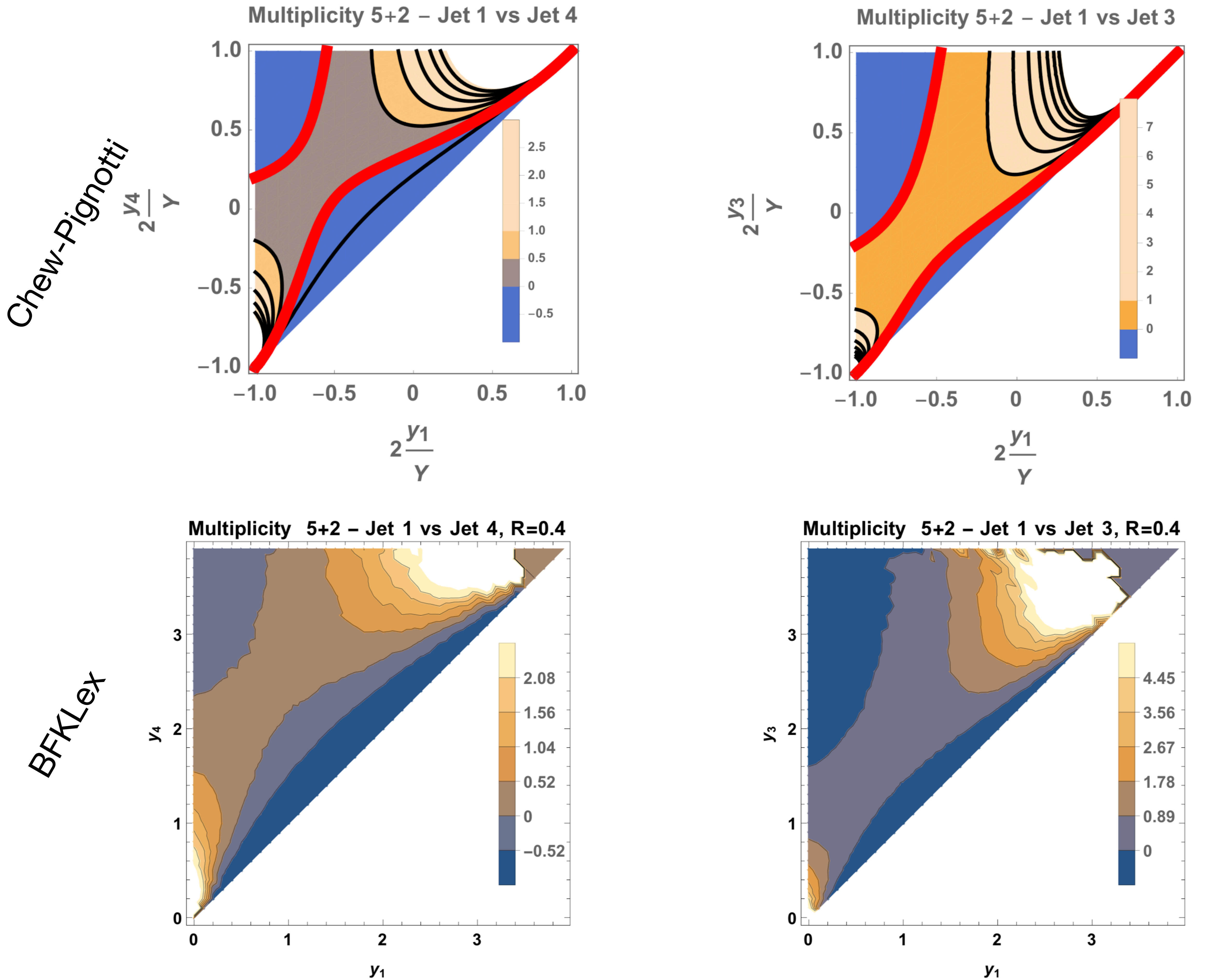
$$\rho_2(y_1,y_2) = \frac{1}{\sigma_{in}}\int d^2p_{\perp 1} d^2p_{\perp 2}\, \frac{d^6\sigma}{dy_1 d^2p_{\perp 1} dy_2 d^2p_{\perp 2}}$$

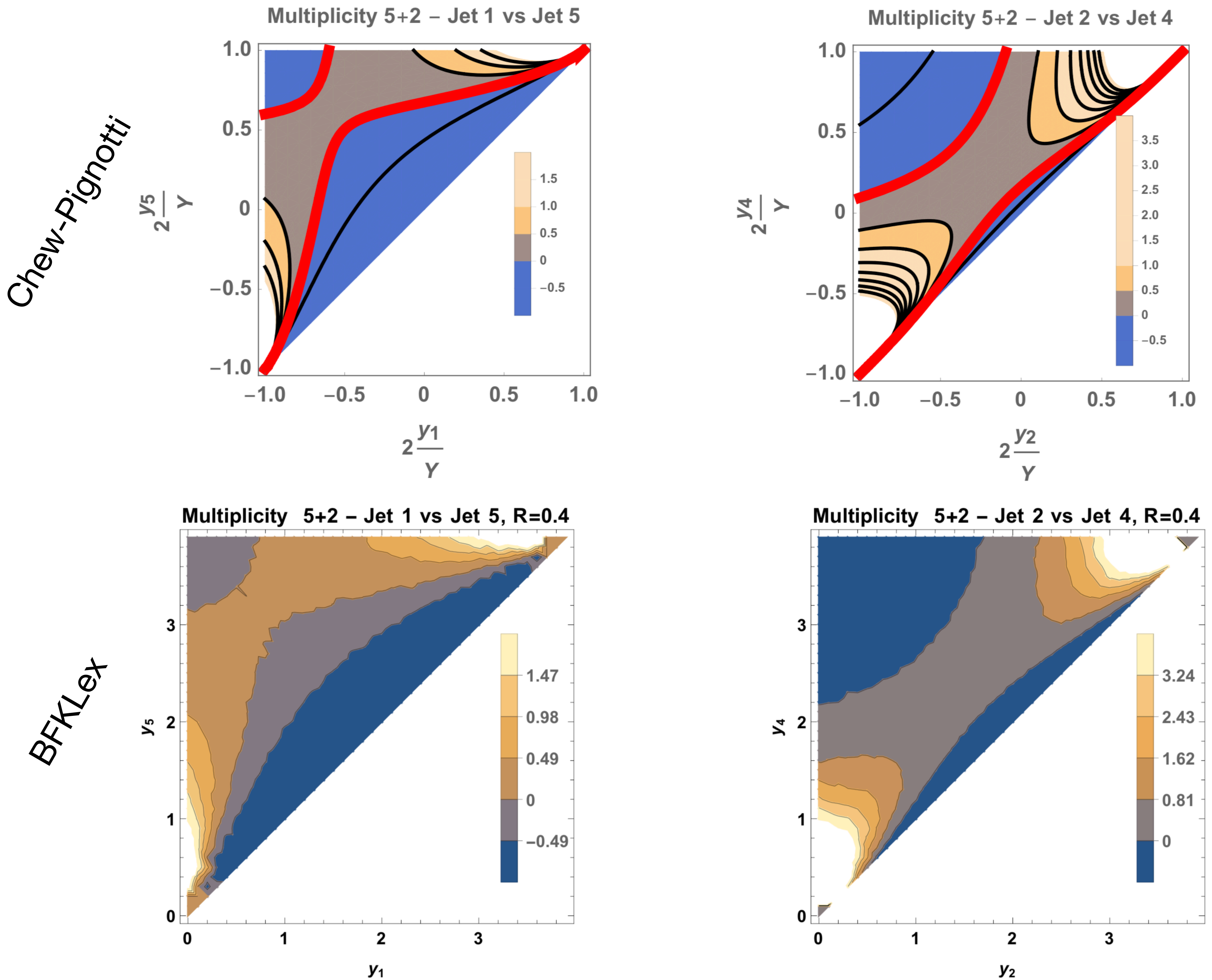
$$C_2(y_1,y_2) = \frac{1}{\sigma_{in}}\frac{d^2\sigma}{dy_1 dy_2} - \frac{1}{\sigma_{in}^2}\frac{d\sigma}{dy_1}\frac{d\sigma}{dy_2} \equiv \rho_2(y_1,y_2) - \rho_1(y_1)\rho_1(y_2)$$

$$R_2(y_1,y_2) = \frac{C_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} = \frac{\rho_2(y_1,y_2)}{\rho_1(y_1)\rho_1(y_2)} - 1$$

Signal

Background


Chew-Pignotti
BFKLex
Multiplicity 5+2 – Jet 1 vs Jet 4
Multiplicity 5+2 – Jet 1 vs Jet 3
$2\frac{y_4}{Y}$
$2\frac{y_3}{Y}$
$2\frac{y_1}{Y}$
2.5
2.0
1.5
1.0
0.5
0
−0.5
7
6
5
4
3
2
1
0
Multiplicity 5+2 – Jet 1 vs Jet 4, R=0.4
Multiplicity 5+2 – Jet 1 vs Jet 3, R=0.4
y_4
y_3
y_1
2.08
1.56
1.04
0.52
0
−0.52
4.45
3.56
2.67
1.78
0.89
0



Chew-Pignotti
Multiplicity 5+2 − Jet 1 vs Jet 5
Multiplicity 5+2 − Jet 2 vs Jet 4
$2\frac{y_5}{Y}$
$2\frac{y_1}{Y}$
$2\frac{y_4}{Y}$
$2\frac{y_2}{Y}$
BFKLex
Multiplicity 5+2 − Jet 1 vs Jet 5, R=0.4
Multiplicity 5+2 − Jet 2 vs Jet 4, R=0.4
y_5
y_1
y_4
y_2
1.47
0.98
0.49
0
−0.49
3.24
2.43
1.62
0.81
0

Definition of the two-particle azimuthal angle-rapidity correlation function

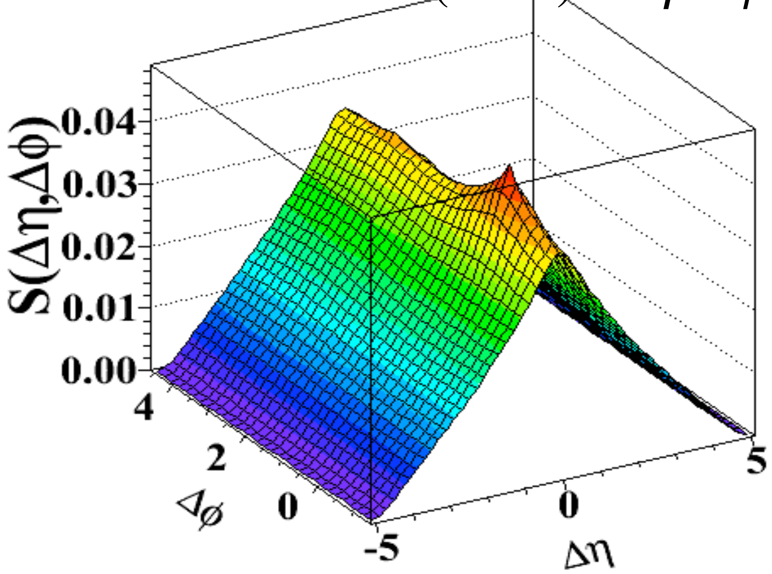
Rapidity (Δy)-azimuthal angle ($\Delta \phi$) two particle correlations are of great importance as they revealed the famous ridge effect in proton-proton collisions

To date, there is not a Monte Carlo based study of Δy-$\Delta \phi$ correlations in multi-Regge kinematics

Definition of the two-particle azimuthal angle-rapidity correlation function

Signal distribution:

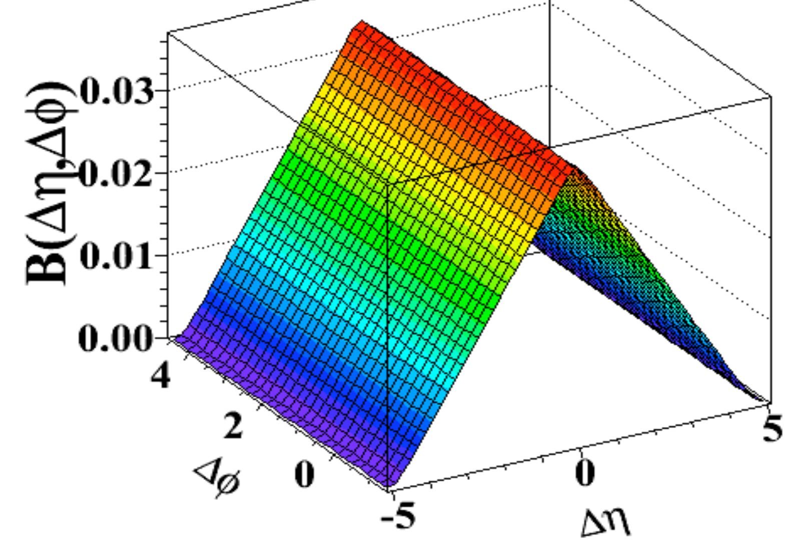
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\varphi}$$



Same event pairs

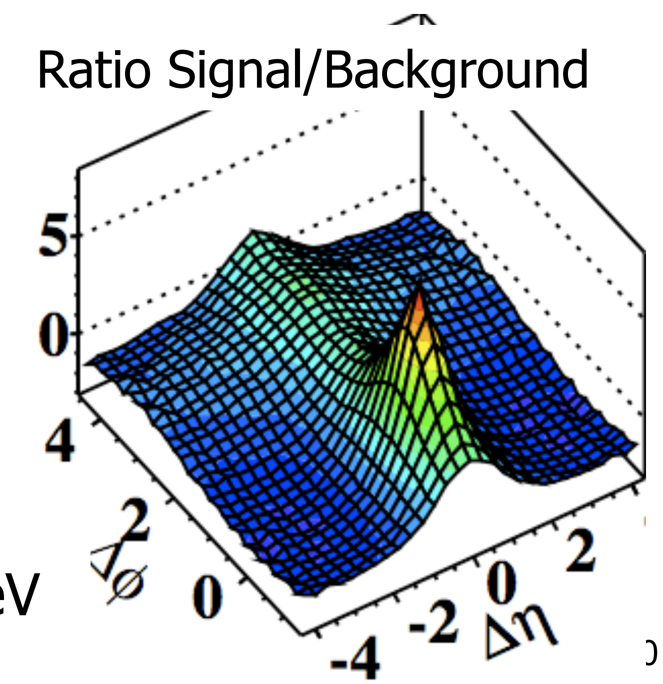
Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2} \frac{d^2 N^{bkg}}{d\Delta\eta d\Delta\varphi}$$



Mixed event pairs

Ratio Signal/Background



CMS pp 7TeV

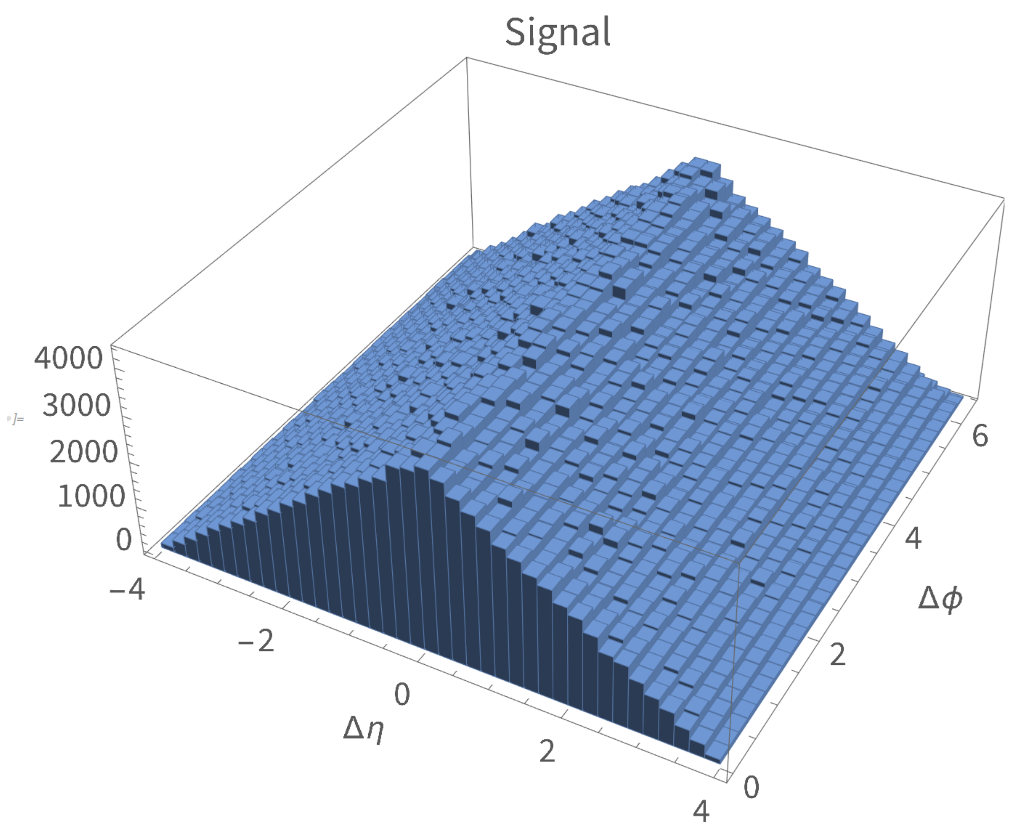
$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

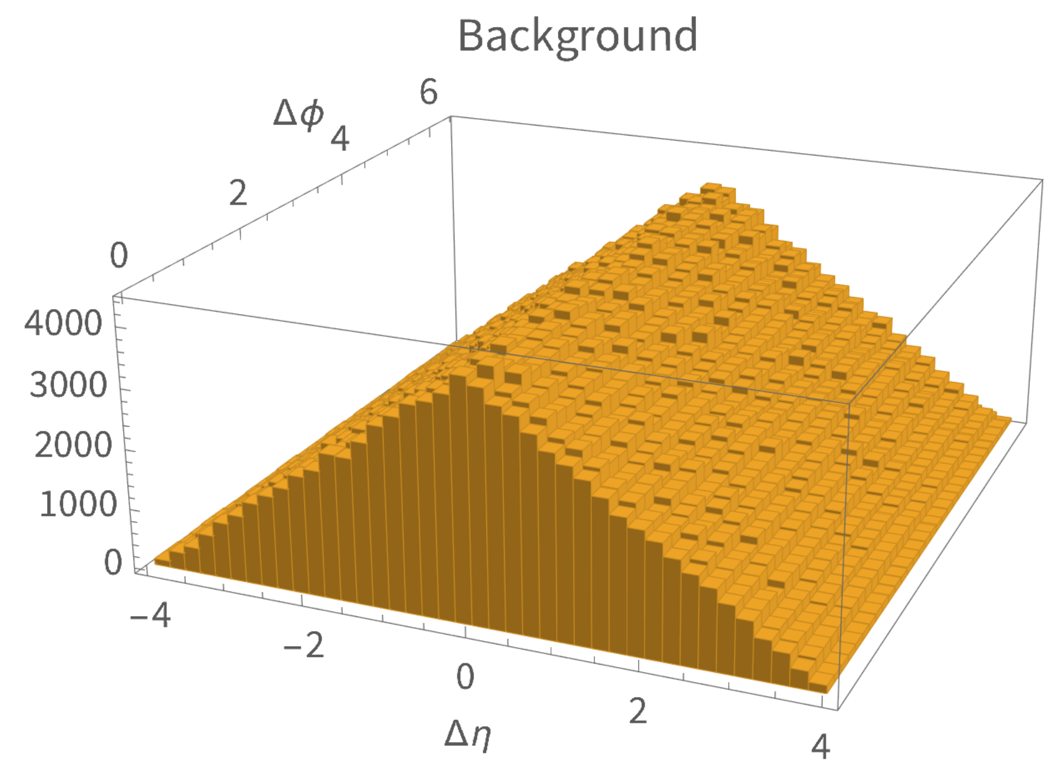
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

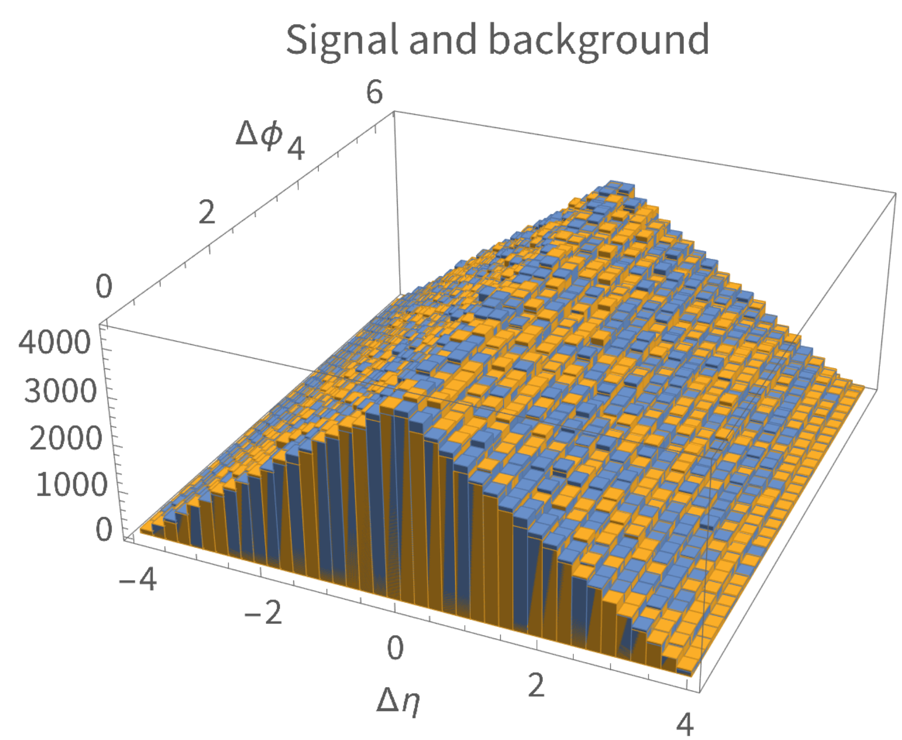
p_T-inclusive two-particle angular correlations in min bias collisions

From a talk by Gunther Roland/MIT at CERN Seminar, September 21, 2010

Naive (toy) MC


Signal
4000
3000
2000
1000
0
−4
−2
0
2
4
Δη
0
2
4
6
Δϕ


Background
Δϕ
6
4
2
0
4000
3000
2000
1000
0
−4
−2
0
2
4
Δη


Signal and background
Δϕ
6
4
2
0
4000
3000
2000
1000
0
−4
−2
0
2
4
Δη

The “BFKL ridge”