Long-range angular correlations by strong color fields in hadronic collisions

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First LHC Discovery! (Sept. 2010)

(b) CMS MinBias, 1.0GeV/c<\(p_T\)<3.0GeV/c

(d) CMS N ≥ 110, 1.0GeV/c<\(p_T\)<3.0GeV/c

CMS Collaboration (Khachatryan, Vardan et al.)
JHEP 1009 (2010) 091
arXiv:1009.4122 [hep-ex]
HERA's view of the proton

\[ Q^2 = 10 \text{ GeV}^2 \]

valence quarks \[ = \int u_v + d_v \, dx = 3 \]

 gluons \[ = \int g \, dx \gtrless 30 \]
The rise at small $x$

This cannot continue to rise like this forever!
Criteria for Gluon Saturation

1. Transverse gluon density: \( \rho \sim \frac{xG A}{S_\perp} \sim \frac{A xG}{A^{2/3}} \sim A^{1/3} xG \)

2. Recombination cross-section: \( \sigma_{gg \rightarrow g} \sim \frac{\alpha_s}{Q^2} \)

3. Saturation Criteria: \( \rho \sigma_{gg \rightarrow g} \gtrsim 1 \)

\[ Q_s^2 \sim A^{1/3} xG \sim A^{1/3} x^{-0.3} \]

Saturation scale is a new momentum scale in problem

Gribov, Levin, Ryskin (1983)
Power counting in QCD: multiparticle production

Low color charge density (min bias):

Jet graph:

\[ g \]

\[ \mathcal{O} \left( \alpha_s^4 \right) \]

Glasma graph:

\[ F \]

\[ \mathcal{O} \left( \alpha_s^6 \right) \]
Power counting in QCD: multiparticle production

Low color charge density (min bias):
Jet graph: \( g \)
\[
\mathcal{O} \left( \alpha_s^4 \right)
\]
Glasma graph:
\[
\mathcal{O} \left( \alpha_s^6 \right)
\]

High color charge density (central):
Jet graph: \( g \rightarrow 1/g \)
\[
\mathcal{O} \left( 1 \right)
\]
Glasma graph:
\[
\mathcal{O} \left( \alpha_s^{-2} \right)
\]

Expect \( \alpha_s^8 \) enhancement of “Glasma” graph! Is this seen in the data?
Anatomy of a proton-proton collision

Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
Anatomy of a proton-proton collision

Jet graph:

Glasma graph:

pp $\sqrt{s} = 7$ TeV, $N \geq 110$
$2 < p_T^{\text{trig}} < 3$ GeV/c
$1 < p_T^{\text{assoc}} < 2$ GeV/c

Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
Systematics of the p+p ridge

Ridge persists to large rapidity separations:

Evidence for a semi-hard scale!

CMS Preliminary

N ≥ 110

2<p_T^{trig}<3 GeV/c
1<p_T^{assoc}<2 GeV/c

Low Multiplicity → High Multiplicity

Associated Yield

N < 35
35 ≤ N < 90
N ≥ 90
N ≥ 110
N ≥ 130

CMS Preliminary

2<|Δη|<4
1<p_T^{assoc}<2 GeV/c

Evidence for a semi-hard scale!
Both Jet and Ridge understood!

Description requires both saturation and non-linear BFKL gluon dynamics

Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
Factorization in the dense-dense limit

\[ d^2 N \propto \frac{S_\perp}{p_\perp^2 q_\perp^2} \int_{k_\perp} \Phi_A^2(x_1, k_\perp) \Phi_B(x_1, p_\perp - k_\perp) \Phi_B(x_2, q_\perp - k_\perp) + \cdots \]

Many-body high energy QCD: The Color Glass Condensate

Observables must be independent from how the large-$x$ and small-$x$ degrees of freedom are separated: Functional Renormalization Group equation (JIMWLK).


\[ l_\perp \sim Q_0 \]

\[ Q_0 \text{(projectile), } Q_0 \text{(target)} \text{ chosen to match multipliicty / centrality} \]
Understanding the Ridge

The origin of the ridge is a subtle form of quantum interference:

\[ \propto \frac{S_\perp}{p_\perp^2 q_\perp^2} \int d^2 k_\perp \Phi_A^2(k_\perp) \Phi_B(|p_\perp - k_\perp|) \Phi_B(|q_\perp - k_\perp|) \]

Cauchy-Schwarz Inequality:

\[ \int d^2 k_\perp \Phi_A^2(k_T) \Phi_B(|p_T - k_T|) \Phi_B(|q_T - k_T|) \leq \int d^2 k_\perp \Phi_A^2(k_T) \Phi_B^2(|p_T - k_T|) \]

Equality satisfied if and only if: \[ \Phi(|p_T + k_T|) \propto \Phi(|q_T + k_T|) \]

Expect collimation on very general grounds
Understanding the Ridge

Ratio of Peak to Pedestal: \[ CY \propto \frac{\int d^2 k^2 \Phi^2_A(k_T) \Phi^2_B(|p_T - k_T|)}{\int d^2 k^2 \Phi^2_A(k_T) \Phi_B(|p_T - k_T|) \Phi_B(|p_T + k_T|)} \]

Collimation sensitive to detailed structure of nuclear wavefunction
CMS Collaboration (Chatrchyan, Serguei et al.)
Submitted to Physics Letters B
arXiv:1210.5482 [nucl-ex]
Similar systematics BUT factor of 4 larger for same \( N_{\text{trk}} \) (i.e. density)
Understanding the Ridge

\[ Q_0^2(\text{lead}) = N_{\text{part}}^{\text{Pb}} \cdot 0.168 \text{ GeV}^2 \]

New High-Multiplicity Predictions!
p+Pb CMS Systematics

Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
ALICE systematics

ALICE managed to subtract away-side jet and observes both the near and away-side ridge!

Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
ATLAS systematics

Data: Extracted from ATLAS Data of e-Print: arXiv:1212.5198 [hep-ex]
Dusling, Venugopalan, arXiv:1302.7018, submitted to PRD.
Summary

The LHC has made a remarkable discovery of a novel collimation between two particles flying in opposite directions in ultra-rare high multiplicity events.

1. Unified description of p+p and p+Pb data across all experiments
2. High gluon densities are essential
3. Possible smoking gun for gluon saturation
Backup
Final-State effects?

1. Why is jet unmodified?
   - A 1-2 GeV mini-jet escapes unmodified yet interactions are strong enough to produce a large flow of the underlying event?
   - This would be a peculiar paradigm much different from A+A

2. Is there a consistent hydrodynamic picture of BOTH p+p and p+Pb?
   - Why is the signal 4 times larger in p+Pb for the same multiplicity?
   - Considering that the p+Pb and p+p areas are comparable?
RHIC d+Au predictions

ALICE Result ($\sqrt{s}=5.02$ TeV)

\[ Q_{0,\text{proton}}^2 = 0.336 \text{ GeV}^2 \ (\sqrt{s}=200 \text{ GeV}) \]

bottom to top: \( N_{\text{Part}}^{\text{Pb}} = 3, 6, 10, 14, 22 \)

\[ 2 < p_T^{\text{trig}} < 4 \text{ GeV}; \ 1 < p_T^{\text{asc}} < 2 \text{ GeV} \]

\[ Q_{0,\text{proton}}^2 = 0.336 \text{ GeV}^2; \ N_{\text{Part}}^{\text{Pb}} = 18 \]

\[ 0.5 < p_T^{\text{asc}} [\text{GeV}] < 0.75 \]
The ridge phenomenon was first discovered in heavy-ion collisions.

Dan Magestro, STAR, Hard Probes 2004
Jorn Putschke, STAR, Quark Matter 2006
In p+p we are seeing the intrinsic collimation from a single flux tube. Increasing transverse flow in p+p creates a discrepancy with data. Are we sure the A+A ridge is probing the nuclear wavefunction?

In A+A there are many such tubes each with an intrinsic correlation enhanced by flow. Yet, transverse flow is needed to explain identical measurements in Pb+Pb.

The correlation is long range in rapidity.
Causality dictates the correlation formed early.