Experimental perspectives on factorization breaking and color entanglement

Part 2 - New LHCb jet hadronization results
on behalf of the LHCb collaboration

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FF2019, March 16, 2019
Example 1: Color Entanglement

- Many recent examples within QCD of processes sensitive to color flow
- In a transverse-momentum-dependent (TMD) framework, color entanglement predicted in $p + p \rightarrow$ dihadrons

PRD 81,094006 (2010)

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Example 1: Color Entanglement

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In a transverse-momentum-dependent (TMD) framework, color entanglement predicted in $p + p \rightarrow$ dihadrons

Corresponds to break down of factorization in a TMD framework

$\sigma = f_1(x, k_T) \otimes f_2(x, k_T) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_1(z, j_T) \otimes D_2(z, j_T)$

$\downarrow$

$\sigma \overset{?}{=} CF(x_1, x_2, k_{T_1}, k_{T_2}, z_1, z_2, j_{T_1}, j_{T_2}) \otimes \frac{d\hat{\sigma}}{dt}$
Example 1: Color Entanglement

- Many recent examples within QCD of processes sensitive to color flow
- In a transverse-momentum-dependent (TMD) framework, color entanglement predicted in $p + p \rightarrow$ dihadrons
- Corresponds to break down of factorization in a TMD framework
- Specifically a non-Abelian effect
To probe TMD physics, an observable must be sensitive to two scales: \( \Lambda_{QCD} \lesssim k_T \ll Q \)
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High $p_T$ direct photon $\rightarrow$ large $Q^2$
Observables To Probe Entanglement

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High \( p_T \) direct photon
\( \rightarrow \) large \( Q^2 \)

- Nearly back-to-back
- \( \Delta \phi \sim \pi \rightarrow \) small \( p_{out} \)

High \( p_T \) jet
\( \rightarrow \) large \( Q^2 \)
Observables To Probe Entanglement

\[ |\vec{k}^1_T + \vec{k}^2_T| \]

\[ \hat{p}_T^{\text{assoc}} \]

\[ \hat{j}_{T_y}^{\text{assoc}} \]

\[ p_{\text{out}} \]

\[ \Delta \phi \]

\[ \Delta \phi \]

\[ p_T \cdot x_E \]

\[ \hat{p}_T \]

\[ \hat{p}_T \]

\[ j_{T_y}^{\text{trig}} \]

\[ \hat{j}_{T_y}^{\text{trig}} \]

\[ \hat{p}_T^{\text{trig}} \]

\[ p_{\text{trig}} \]

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Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow qualitative expectations from CSS evolution. The evolution prediction comes directly out of the derivation for TMD factorization. If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!
Measurements of $p_{\text{out}}$ Distributions in $p+p \rightarrow \text{hadrons}$

Phys. Rev. D 98, 072004

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Measurements of $p_{out}$ Distributions in $p+p \rightarrow$ hadrons

- Two distinct regions:
  - Gaussian at small $p_{out}$
  - Power law at large $p_{out}$

PHENIX
p+p $\sqrt{s}=200$ GeV
$0.1<x_E<0.5$
$|\eta|<0.35$

$\frac{dN}{dp_{out}} [\text{GeV/c}]$

Phys. Rev. D 98, 072004
Measurements of $p_{out}$ Distributions in $p+p \rightarrow$ hadrons

- Two distinct regions:
  - Gaussian at small $p_{out}$
  - Power law at large $p_{out}$
- Indicates TMD observable - $\Lambda_{QCD} \lesssim p_{out} \ll p_T^{\text{trig}}$
- Can characterize any potential differences from CSS by studying width evolution
Away-side Gaussian widths shown as a function of $p_T^{\text{trig}}$ (top) and $x_T$ (bottom) at $\sqrt{s} = 200$ and 510 GeV.
Away-side Gaussian widths shown as a function of $p_T^{\text{trig}}$ (top) and $x_T$ (bottom) at $\sqrt{s} = 200$ and 510 GeV

- Qualitatively similar behavior to Drell-Yan and semi-inclusive DIS interactions where color entanglement is not predicted

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Comparing Drell-Yan and $p+p \rightarrow$ hadrons

- Since qualitative behavior is similar, calculations needed to compare TMD evolution rates in different processes
- Drell-Yan (no color entanglement predicted) and $p+p \rightarrow$ hadrons (color entanglement predicted) may exhibit different magnitudes, evolution rates, etc.

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Nonperturbative Transverse Momentum Broadening in $p+A$

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- No significant near-side transverse momentum broadening.

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Nonperturbative Transverse Momentum Broadening in $p+A$

- Can also extend Gaussian width studies to compare between $p+A$ and $p+p$
- No significant near-side transverse momentum broadening
- Nonzero away-side nonperturbative transverse momentum broadening in $p+A$

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- Stronger color fields in nuclear interactions?
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Physical effects that contribute?

- Stronger color fields in nuclear interactions?
- Additional initial-state $k_T$ in nucleus?
- Energy loss?
- Physical effects behind “Cronin” mechanisms?
- ...
Example 2: Color Coherence

- Another example: color coherence
- Color flow through hard processes leads to certain regions of particle production in hadronic collisions

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- Another example: color coherence
- Color flow through hard processes leads to certain regions of particle production in hadronic collisions
- Color connects hard scattered partons with remnants of other proton

\( p + p \rightarrow \text{dijet} + \text{jet} + X \)
\( p + p \rightarrow \gamma + \text{jet} + \text{jet} + X \)

- \( \beta \) is angle in \((\phi, \eta)\) space between sub-leading hard-scattered jet and third jet
Color Coherence Measurements

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- Third jet more likely to be found at $\beta = 0$, $\beta = \pi$, i.e. similar $\phi$ but large $\eta$ gap
Color Coherence Measurements

- Even stronger correlation to opposite beam at forward rapidities!
Color Coherence Measurements

Even stronger correlation to opposite beam when using $\gamma-$jet!

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Z-tagged jet hadronization at LHCb
Hadronization Studies at the LHC

- Several measurements of jet substructure at midrapidity from ATLAS, CMS, ALICE
- Wide range of physics interests and effects probed

![Graph showing data and theoretical predictions for jet substructure at the LHC](image)

PRL 121, 092001 (2018)

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- Uniform coverage tracking, PID, and calorimetry
- Can identify nearly all particles within a high $p_T$ jet
- Also occupy a unique region in $(x, Q^2)$
**Z+jet at LHCb**

- **Z+jet cross section published at** $\sqrt{s} = 8$ TeV
- **High signal-to-background, established analysis techniques**

![Graph showing the ratio of $\sigma(Z+jet)/d^2p_T$](image)

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- Preferentially selects light quarks (!)
- Starkly in contrast from midrapidity inclusive jet results from CMS/ATLAS/ALICE which are gluon dominated until very high $p_T$ ($p_T > \mathcal{O}(400)$ GeV)
- Very recent ATLAS $\gamma$–tagged jets complementary (arXiv:1902.10007)

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  - **First LHC measurement of charged hadrons within \( Z \) tagged jets**
  - **First LHC measurement of charged hadrons-in-jets at forward rapidity**

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Observables

- Measure hadronization observables in two dimensions
  - Longitudinal momentum fraction $z$
  - Transverse momentum $j_T$
  - Radial profile $r$

\[ z = \frac{p_{\text{jet}} \cdot p_h}{|p_{\text{jet}}|^2} \]

\[ j_T = \frac{|p_h \times p_{\text{jet}}|}{|p_{\text{jet}}|} \]

\[ r = \sqrt{(\phi_h - \phi_{\text{jet}})^2 + (y_h - y_{\text{jet}})^2} \]
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- Intended to lay the foundation for a broader hadronization program at LHCb utilizing
  - Particle ID (tracking, RICH, calorimetry)
  - Heavy flavor jet tagging
  - Resonance production within jets \((\phi, J/\psi, \Upsilon)\)
  - Correlations with flavor ID within jets

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Analysis Details

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- $Z \rightarrow \mu^+\mu^-$ identified with $60 < M_{\mu\mu} < 120$ GeV, in $2 < \eta < 4.5$
- Anti-$k_T$ jets are measured with $R = 0.5$, $p_T^{\text{jet}} > 20$ GeV, in $2.5 < \eta < 4$
- $|\Delta \phi_{Z+\text{jet}}| > 7\pi/8$ selects $2 \rightarrow 2$ event topology
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- Charged hadrons identified with $p_T > 0.25$ GeV, $p > 4$ GeV, $\Delta R < 0.5$
- Results efficiency corrected and 2D Bayesian unfolded
• Measurements in three $p_T^{jet}$ bins, integrated over $Z$ kinematics

• Longitudinal hadron-in-jet distributions independent of jet $p_T$ at high $z$

• Distributions diverge at low $z$ due to kinematic phase space available
Comparing ATLAS midrapidity inclusive jets to LHCb forward $Z+\text{jet}$ shows longitudinal FFs “flatter” as a function of $z$
Comparing ATLAS midrapidity inclusive jets to LHCb forward $Z+$jet shows longitudinal FFs “flatter” as a function of $z$

Caveats - ATLAS/LHCb measurements can only be compared qualitatively due to different kinematics
• Transverse momentum shows nonperturbative to perturbative transition

• Shapes very similar as a function of $p_T^{jet}$ - slight increase of $\langle j_T \rangle$ with $p_T^{jet}$
ATLAS and LHCb Comparisons

- Transverse momentum distributions show slightly smaller $\langle j_T \rangle$ in $Z+\text{jet}$ vs. inclusive jet at small $j_T$
Results

- Radial profiles largely independent of jet $p_T$ away from jet axis
  - Indication of independence of nonperturbative contributions?
- Multiplicity of hadrons along jet axis rises sharply with jet $p_T$
Comparing ATLAS midrapidity inclusive jets to LHCb forward $Z$+jet shows jets are more collimated when tagged with a $Z$. 

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Conclusions

- Color entanglement and TMD factorization breaking
  - Results from PHENIX experiment comparing evolution of TMD observables to expectations from CSS
  - Recent LHC results studying color coherence
  - Other measurements I haven’t touched on sensitive to color flow (e.g. jet substructure observables)
  - A large amount of data now exists, perhaps not with enough TMD sensitivity, but is worth looking into (e.g. arXiv:1902.04374)
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• New results on hadronization in $Z$-tagged jets at LHCb
  • Select events that better correspond to a $2 \rightarrow 2$ hard scattering
  • Measure longitudinal and transverse charged hadron-in-jet observables with respect to jet axis
  • Preferentially selects light quark jets vs. gluon jets - opportunity for understanding nonperturbative hadronization differences
Conclusions

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• More results to come from LHCb utilizing PID, heavy flavor ID, and calorimetry
Discussions and/or ideas about observables of interest are more than welcome!
Back Up
• QCD is a non-Abelian quantum field theory
• Fermions and bosons in QCD have color charge
• Color has always been an integral part of the theory
• However the last several decades have illuminated some of the specific consequences that color can have within QCD!
CSS evolution first published in 1985. Similar to DGLAP evolution equation, but includes small transverse momentum scale

Has been used to successfully describe global Drell-Yan and Tevatron $Z^0$ cross sections

Clear qualitative prediction - momentum widths sensitive to nonperturbative transverse momentum increase with increasing hard scale

Due to increased phase space for gluon radiation

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Extending Color Studies to $p+A$

- Dihadrons give additional QCD interactions in $p+A$ collisions compared to direct photon-hadrons
- Measure the $p_{out}$ distributions on both the near-side and away-side in $p+p$ and $p+A$ to compare

**Near-side**

**Far-side**

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Broadening as a Function of Nucleus Size

- Interesting to compare to other collision systems, e.g. HERMES $e + A$ data
- Caveats - kinematics...
Example 2: Color Coherence

- The same underlying QCD phenomena at play - color leads to nonperturbative consequences

Color entanglement

Color coherence

PRD 81, 094006 (2010)

- **Color coherence measurements study:**
  \[ \beta = \tan^{-1} \frac{\Delta \phi_{21}}{\text{sign}(\eta_1) \Delta \eta_{21}} \]

- Angle in \((\phi, \eta)\) space between sub-leading hard-scattered jet and gluon initiated jet
- \(\beta = 0\) points to the beam closer to jet 1 in \((\phi, \eta)\) space
- \(\beta = \pi\) points to the beam farther from jet 1 in \((\phi, \eta)\) space
ATLAS collaboration also measures $\beta_\gamma$, defined in a similar way to $\beta_{\text{jet}}$

$$\beta_\gamma = \tan^{-1} \frac{|\phi_{\text{jet}2} - \phi_\gamma|}{\text{sign}(\eta_\gamma) \cdot (\eta_{\text{jet}2} - \eta_\gamma)}$$
Example 3: Jet Substructure

Jet-pull vector predicted to be sensitive to color connections (PRL 105, 022001 (2010))

\[ \vec{P}(j) = \sum_{i \in j} \left( \frac{\Delta r_i}{p^j_T} \right) \hat{r}_i \]

- Absence of color connection - \( \theta_p \) expected to be distributed uniformly
- Color connection - \( \theta_p \) expected to preferentially lie along jet connection vector \( \theta_p \sim 0 \)

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Example 3: Jet Substructure

- Jet pull angle preferentially $\sim 0 \rightarrow \text{color connections}$
- Color affects radiation patterns within jets

Legend
- Pull Vector $\vec{P}_1$
- Jet Connection Vector $\theta_P$
- Pull Angle ($J_1$ w.r.t. $J_2$)
- Constituent of $J_1$ (size weighted by $p_T$)

\[
\Delta \phi = \phi - \phi_{J_1}
\]

\[
\Delta y = y - y_{J_1}
\]

\[\text{ATLAS} \quad \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}\]

- Data
- Statistical Unc.
- Total Unc.
- Powheg+Pythia8
- Powheg+Pythia6
- MG5 aMC+Pythia8
- Powheg+Herwig7
- Sherpa

arXiv:1805.02935
Example $t\bar{t}$ color topology

$t\bar{t}$ are color connected via gluon splitting

Hadronizing quarks from $W$ decays can also be color connected
“Global Fits”??

- A wealth of data that should be sensitive to TMD color entanglement effects now exists from RHIC and the LHC
- At least $\Delta \phi$ correlations exist in all of these publications
- Are “phenomenological” studies now possible? Need to also encourage experimental colleagues to measure additional observables (not only $\Delta \phi$)

**Dihadron/$\gamma$-hadron**
- Phys. Rev. D 95, 072002 (2017)
- arXiv:1809.09045

**Dijet/$\gamma(W^\pm, Z)$-jet**
- JHEP 1704, 022 (2017)
- Phys. Rev. D 95, 052002 (2017)
- arXiv:1901.10440
- arXiv:1902.04374
- ...
Jet physics is a broad experimental endeavor at LHC

Enabled by more robust comparisons that can be made between theory and experiment with e.g. anti-\(k_T\) algorithm

plot by G. Salam
Jet Hadronization

- Jet physics is a broad experimental endeavor at LHC
- Enabled by more robust comparisons that can be made between theory and experiment with e.g. anti-\(k_T\) algorithm
- Jets are a proxy for partons, and thus provide a way to have sensitivity to the underlying partonic dynamics
Comparisons with PYTHIA ($z$)

- PYTHIA generally underpredicts the number of high $z$ hadrons.
Comparisons with PYTHIA ($j_T$)

- PYTHIA generally gets $j_T$ shape, with about a 20% difference in normalization.
Comparisons with PYTHIA ($r$)

PYTHIA generally underpredicts the number of small $r$ hadrons.

- LHCb preliminary
- $20<p_T^{jet}<30$ GeV
- $30<p_T^{jet}<50$ GeV
- $50<p_T^{jet}<100$ GeV

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Comparison to ATLAS $\gamma$-jet

- ATLAS midrapidity $\gamma$-jet and LHCb $Z$-jet longitudinal fragmentation function are very similar in the comparable jet $p_T$ bin
- Kinematic fiducial space similar but not exactly the same

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Parton shower: in theory...

First splitting

direction of shower

direction of clustering
Parton shower: in practice

First splitting

direction of shower

Direction of clustering
Jet Formation

Parton shower: in theory....

Direction of shower

Fragmentation

First splitting

Direction of clustering

Hadronization