Color Coherence and Color Entanglement

Recent Results from the PHENIX Experiment at RHIC

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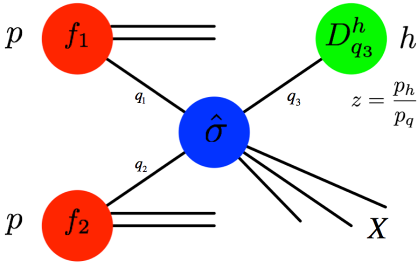
Motivation

- Understanding QCD as a non-Abelian gauge theory: what role does color and color flow play?
- Recent papers from the nucleon structure community studying "color entanglement"
- Studies from the Tevatron and, more recently, CMS on "color coherence"
- Are these related in any way?? If at all??
- Note that this talk is based off of the following publications, and references therein (additional refs. in backups):
    - Color entanglement
        - T.C. Rogers and P. J. Mulders: Phys. Rev. D 81, 094006 (2010)
        - PHENIX Collaboration: arXiv:1609.04769 (submitted to Phys. Rev. D)
    - Color coherence
        - Y. Dokshitzer et. al: Rev. Mod. Phys., 60:373 (1988)
        - CMS Collaboration: Eur. Phys. J. C (2014) 74: 2901

QCD Factorization

- QCD factorization theorem - a corner stone of perturbative calculations
- Separate initial-state and final-state nonperturbative behavior from a perturbatively calculable hard function
- Nonperturbative functions historically approximated as a function of x and Q^2 only



$$\sigma = f_{q_1}(x, Q^2) \otimes f_{q_2}(x, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D^h_{q_3}(z, Q^2)$$

Transverse-Momentum-Dependence (TMD)

- There must be transverse motion of partons due to confined nature of partons, as well as NLO radiation
- For a multidimensional description of nucleon structure, can also include transverse-momentum-dependence of partons within a nucleon

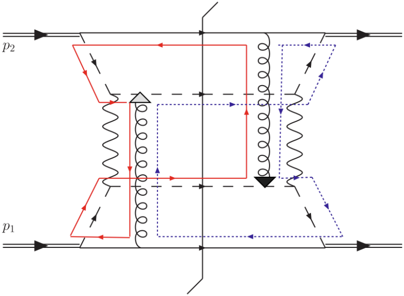
$$\text{Parton Distribution Functions (PDFs): } f(x, Q^2) \rightarrow f(x, k_T, Q^2)$$

$$\text{Fragmentation Functions (FFs): } D(z, Q^2) \rightarrow D(z, j_T, Q^2)$$

- Small transverse momentum scale introduces a two-scale problem: $\Lambda_{QCD} \lesssim k_T \ll Q^2$

Color Entanglement

- Factorization breaking (color entanglement) predicted in a transverse-momentum-dependent framework for $p + p \to h_1 + h_2$ (Phys. Rev. D 81, 094006 (2010))
- Individual nonperturbative functions no longer defined - partons are quantum mechanically entangled via color across hadrons
- Novel color flow paths through entire hard scattering possible from soft gluon exchanges with hadron remnants in both the initial and final state



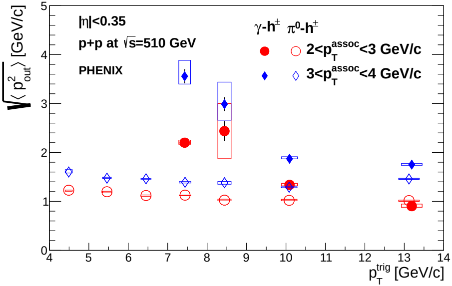
- Consequence of QCD as a non-Abelian gauge theory

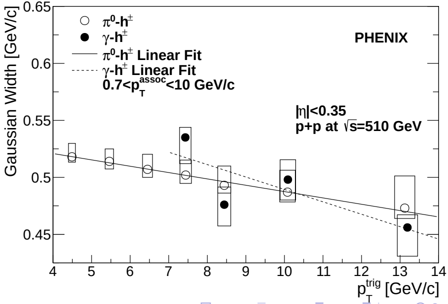
Color Entanglement

- Entanglement arises from interference between soft gluons in the strong coupling regime
- Requires colored objects in both the initial and final states, i.e. $\geq$3 partons in hard scattering
  - Gluon exchanges in the initial and final states necessary
  - NOT predicted in $e^+e^- \rightarrow$ jets, Drell-Yan, Semi-Inclusive DIS
- Color flow connects partons in the hard scattering with remnants of the collision
- Requires explicit transverse-momentum-dependence in the PDFs and FFs - in the strictly collinear factorization framework the graphs leading to the entanglement cancel *after* integration over transverse momentum

First Measurement

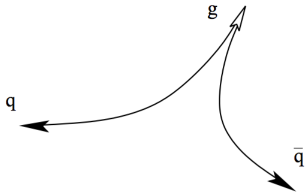
- First measurement searching for predicted color entanglement effects from the PHENIX experiment at RHIC
- Perturbative transverse momentum dependent evolution, which comes directly from the generalized TMD QCD factorization theorem, predicts increasing momentum widths with hard scale of interaction
- PHENIX measured opposite: decreasing widths in $p+p \rightarrow \pi^0 + h^\pm$ and $p+p \rightarrow \gamma + h^\pm$





Color Coherence

- Color coherence predicted 30 years ago in a perturbative framework
- Predicted due to color interference effects in multiple-jet final states
- Originally predicted for $e^+e^- \rightarrow$3 jets in final state, but effects can be present connecting initial to final states in $p + p \rightarrow$jets



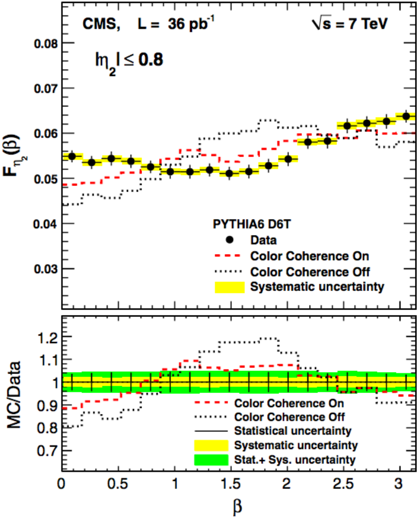
- Also known as the drag effect - radiation of gluon "drags" color away from vertex
- Destructive interference inhibits particle production in certain regions of phase space

Color Coherence

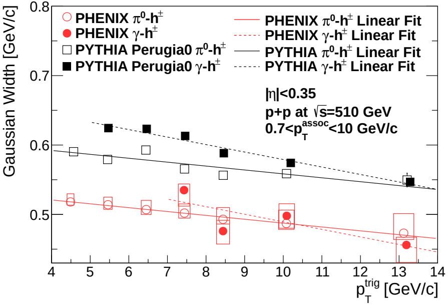
- Coherence arises from destructive interference of gluons in the final-state
- Results in a suppression of hadrons opposite the radiated gluon (where the destructive interference occurs)
  - i.e. there is an angular dependence to the final-state hadron/jet production
- Predicted in perturbative modified leading logarithmic approximation
- Color topology of hard process affects jet evolution in processes with $\geq$3 partons
- Alters soft particle production accompanying high p_T jets

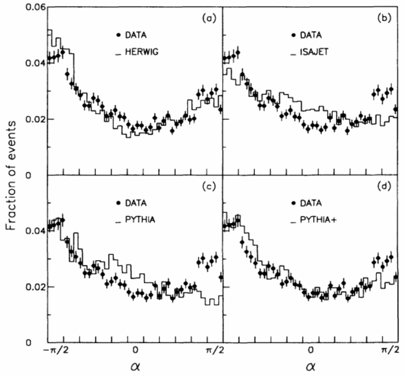
Color Coherence

- Measurements first in $e^+e^- \to 3$ jets observed coherence effects
- Measurements at D0 and CDF first to study coherence effects in hadronic collisions
- Recently CMS published new coherence results in $pp \to$jets



PYTHIA Reproduction of Effects





Phys. Rev. D 50, 5562 (1994)

- PYTHIA reproduces color coherence effects reasonably and (possible) color entanglement effects quite well
- PYTHIA includes angular ordering effects and color interactions with remnants
- Traditional pQCD calculations don't include any interactions with remnants, i.e. $p+p \rightarrow$h+X

Similarities Between Entanglement and Coherence

- Gluon interference is the underlying physical process driving effects
- Color topology throughout entire hard process important - Color connection between incoming and outgoing partons
- Angular dependence of measured hadrons modified
- Initial and final-state interactions important
- PYTHIA reproduces effects reasonably well
- From what I have found, there are no strictly perturbative calculations compared to data - only Monte Carlo showering/event generators
- One ideal measurement: Prompt photon+jet? Limits potential color paths/flows

Differences Between Entanglement and Coherence

Entanglement	Coherence
Predicted in a transverse-momentum-dependent framework	No explicit transverse-momentum-dependence necessary (although two leading jets are nearly back-to-back!)
Nonperturbative effect with PDFs and FFs no longer factorizing from each other	Perturbatively generated gluon jets result in measured effects
Requires initial and final state interactions with hard process	Measured in $e^+e^- \rightarrow$3 jet events
Color flow explicitly includes remnants	Color flow doesn't explicitly require remnants (?) although measurements show "remnants" (forward rapidities) are preferred

Conclusions

- Many recent experimental studies emphasizing the role that color flow plays in hard QCD processes
- Color entanglement and color coherence both predicted in hadronic collisions with final-state colored partons
- Both result from interference of gluon radiation between initial and final-state partons involved in the hard process
- Some noticeable differences though: Are these phenomena related and if so, how?
- What can we learn from different communities studying (seemingly) similar phenomena specific to non-Abelian QCD?

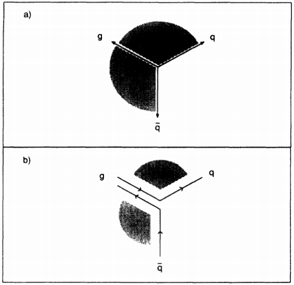
Back Up

Additional Color Coherence References

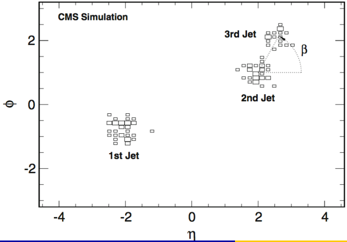
- "Basics of Perturbative QCD." Y. Dokshitzer et al., Editions Frontieres (1991).
- CDF: Phys. Rev. D 50, 5562 (1994)
- D0: Phys. Lett. B 414, 419 (1997)
- Additional references within above sources

Color Coherence Diagrams

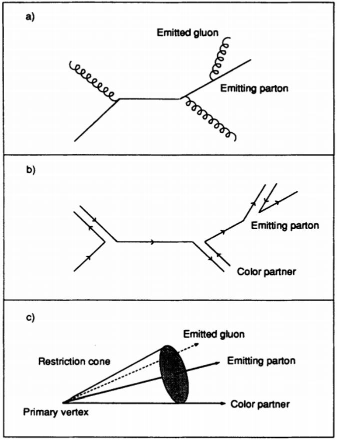
e^+e^- color coherence



CMS definition of β



Angular ordering



Color Coherence in $p + p \rightarrow$jets

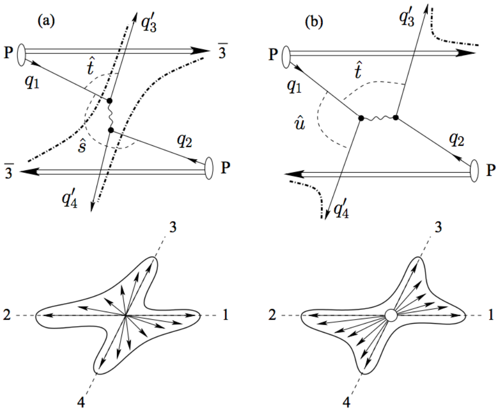


Figure 10.3: Color antennae for two crossing high-$p_\perp$ qq scattering processes and the drawings of the corresponding particle flows.

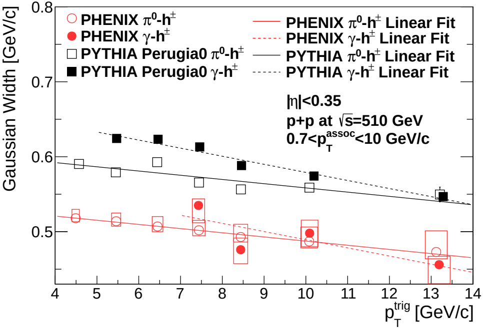
- Particle flows in high p_T scattering processes
- Color coherence constructive interference occurs between seemingly "independent" partons

Additional Color Entanglement References

- M. G. A. Buffing and P. J. Mulders, Phys. Rev. Lett. 112, 092002 (2014)
- T.C. Rogers, Phys. Rev. D 88, 014002 (2013)
- S. M. Aybat and T. C. Rogers, Phys. Rev. D 83, 114042 (2011)
- Additional references within above sources

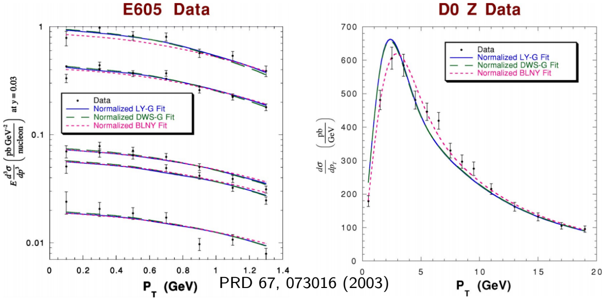
PHENIX Data Comparison with PYTHIA

- PYTHIA reproduces (surprising) negative slope of data
- PYTHIA magnitude differs by ∼15%
- Likely due to PYTHIAs handling of nonperturbative gluon radiation



Collins-Soper-Sterman (CSS) Evolution

- 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 hard gluon radiation

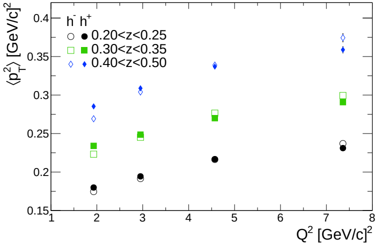


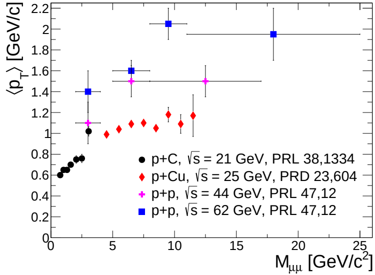
PRD 67, 073016 (2003)

Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Measurements show that Drell-Yan and semi-inclusive DIS follow theoretical prediction - widths rise with hard scattering scale
- The theoretical evolution prediction comes directly out of the derivation for transverse-momentum-dependent factorization

SIDIS - Eur. Phys. J. C(2013) 73,2531



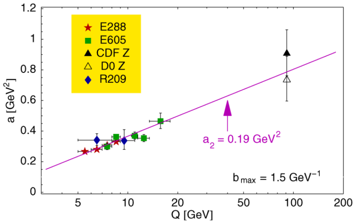


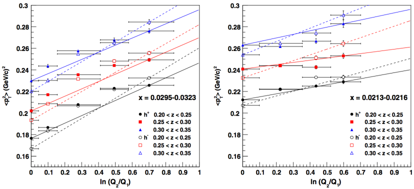
FNAL fixed target DY

Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow theoretical prediction
- The evolution prediction comes directly out of the derivation for transverse-momentum-dependent (TMD) factorization
  - If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!
- Drell-Yan and semi-inclusive DIS clearly follow theoretical prediction

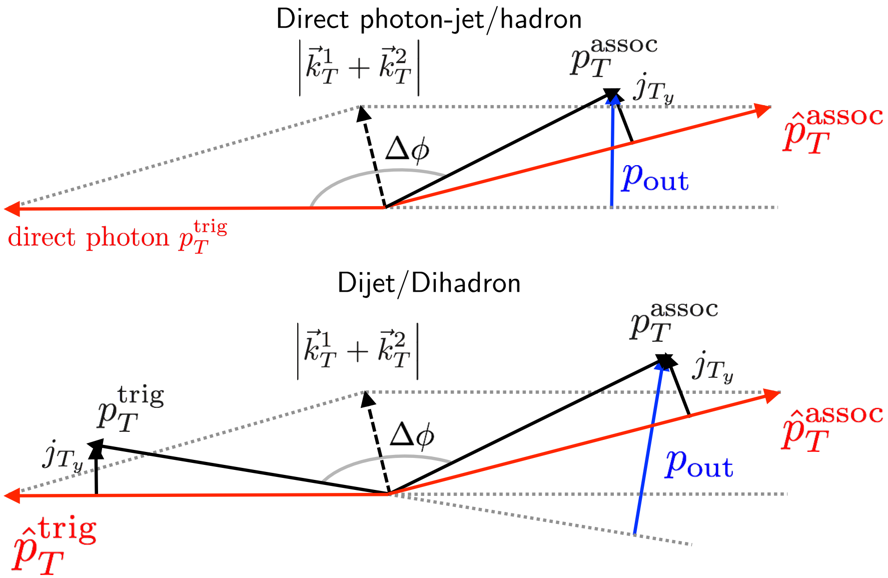
DY/Z - PLB 633, 710 (2006)





SIDIS - PRD 89, 094002 (2014)

Definition of PHENIX Observables



p_{out} Measurements

- p_{out} distributions show Gaussian transition to Power law
- Indicates transition from nonperturbative gluon to perturbative gluon sensitivity
- Nearly back-to-back hadrons around $p_{out} \sim 0$ sensitive to only soft k_T and j_T