Probing effects from QCD color with γ-h$^{\pm}$/jet and dihadron/jet correlations

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Color in QCD

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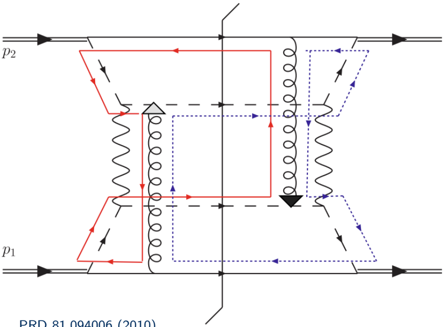
- QCD is a non-Abelian quantum field theory
- Fermions and bosons in QCD have color charge
- Color has always been an integral part of the theory
- However the last several decades have illuminated some of the specific consequences that color can have within QCD!

Example 1: Color Entanglement



PRD 81,094006 (2010)

- Example: color entanglement
- When explicitly considering the transverse motion of partons in a nucleon, color entanglement predicted

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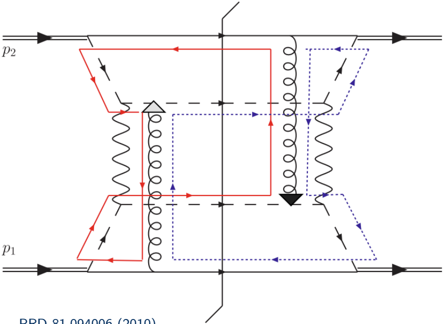

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- When explicitly considering the transverse motion of partons in a nucleon, color entanglement predicted
- Corresponds to break down of factorization in a transverse-momentum-dependent (TMD) framework

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

$$\downarrow$$

$$\sigma \stackrel{?}{=} CF(x_1, x_2, k_{T_1}, k_{T_2}, z_1, z_2, j_{T_1}, j_{T_2}) \otimes \frac{d\hat{\sigma}}{dt}$$

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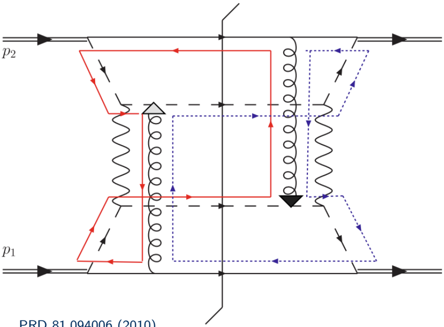
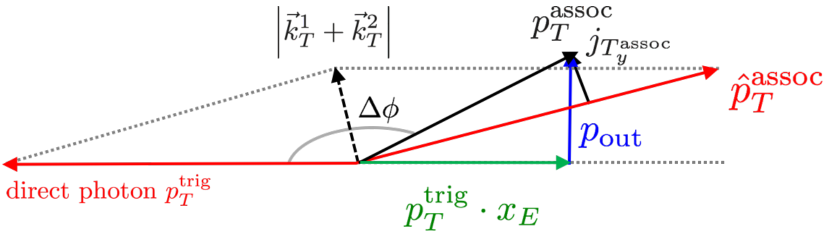


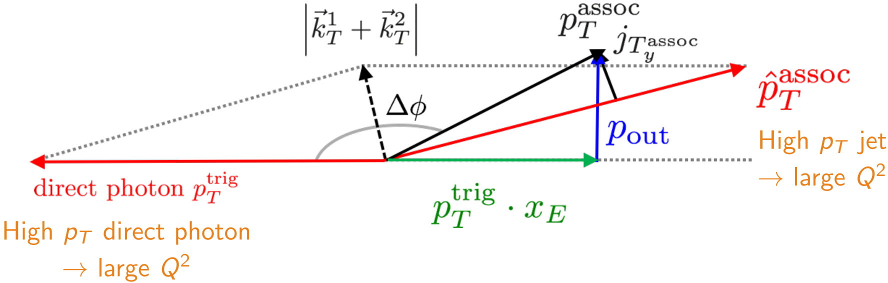
PRD 81,094006 (2010)

- Example: color entanglement
- When explicitly considering the transverse motion of partons in a nucleon, color entanglement predicted
- Corresponds to break down of factorization in a transverse-momentum-dependent (TMD) framework
- Specifically a non-Abelian effect



- To probe transverse-momentum-dependent physics, an observable must be sensitive to two scales: $\Lambda_{QCD} \lesssim k_T \ll Q$

Observables To Probe Entanglement



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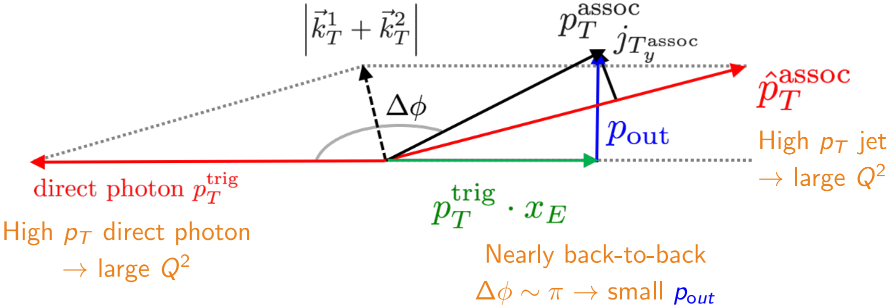

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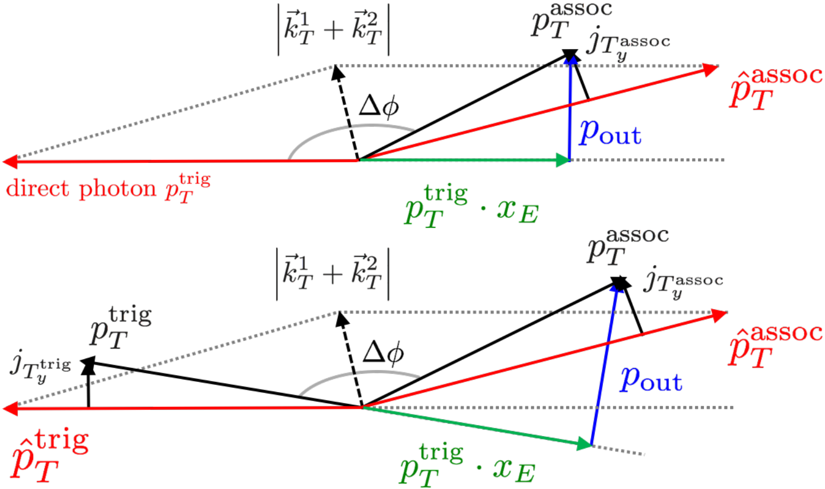
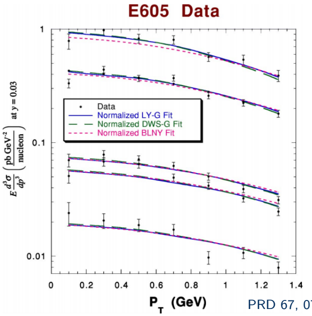
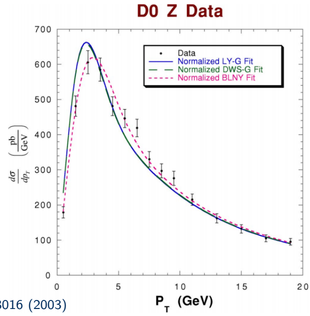


- CSS evolution first published in 1985. Similar to DGLAP evolution equation, but includes small transverse momentum scale
- Has been used to successfully describe global Drell-Yan and Tevatron Z^0 cross sections

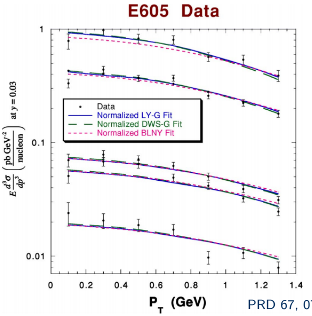


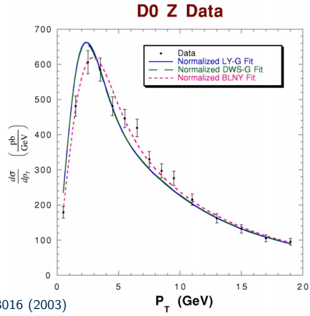


PRD 67, 073016 (2003)

Collins-Soper-Sterman (CSS) Evolution with Q^2

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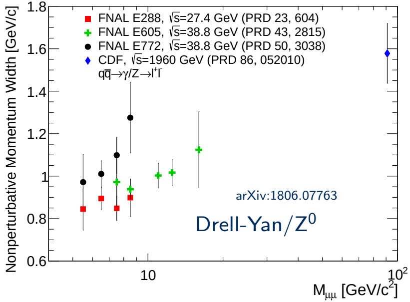
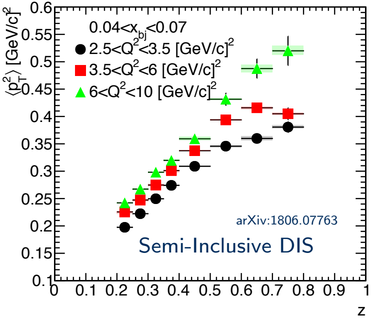
Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow theoretical prediction





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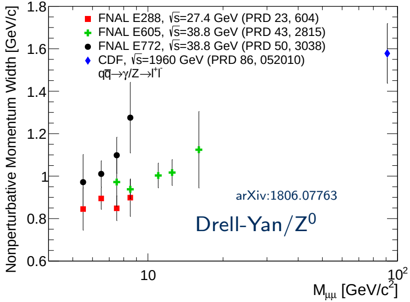
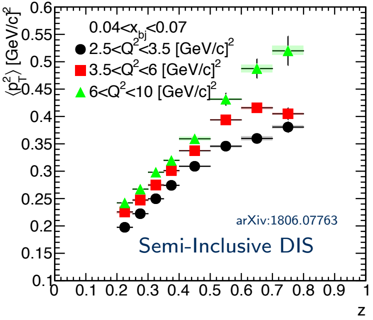
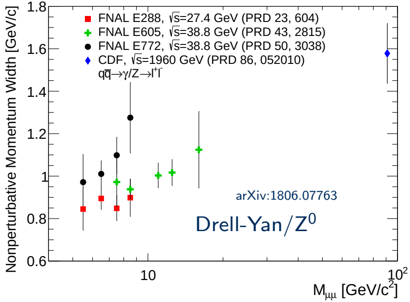
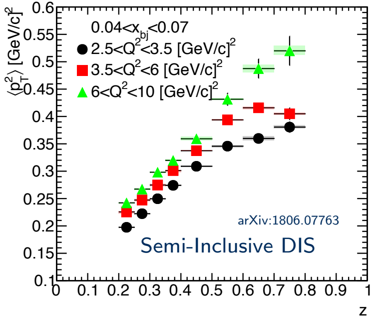




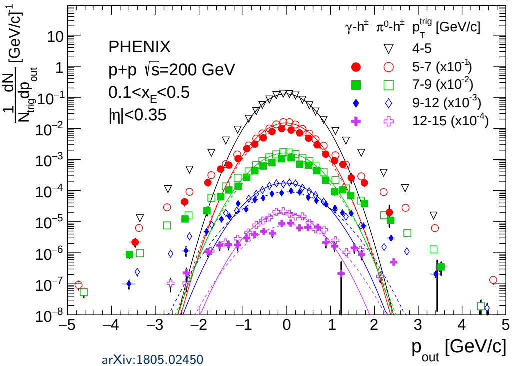
Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- 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!





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



arXiv:1805.02450

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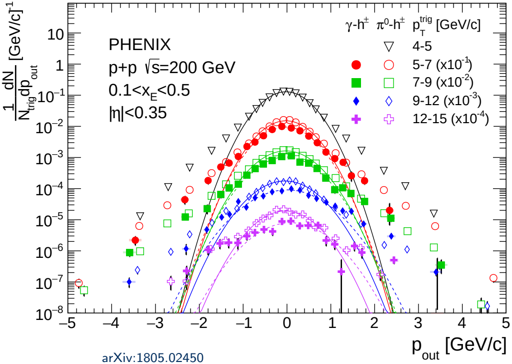

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- Two distinct regions:
  - Gaussian at small p_{out}
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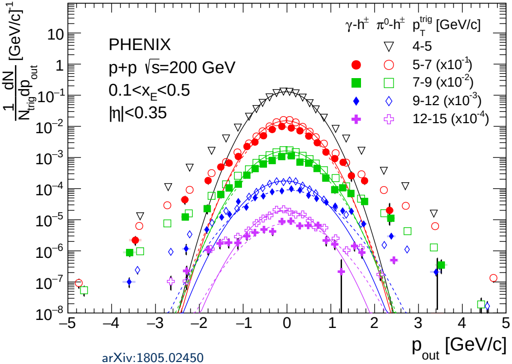

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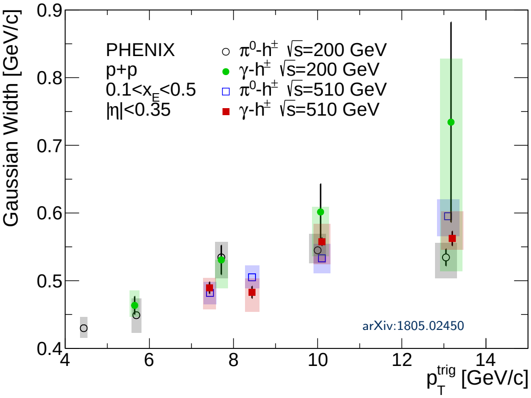
- Two distinct regions:
  - Gaussian at small p_{out}
  - Power law at large p_{out}
- Indicates TMD observable - $\Lambda_{QCD} \lesssim p_{out} \ll p_T^{\rm trig}$
- Can characterize any potential color effects by studying width evolution

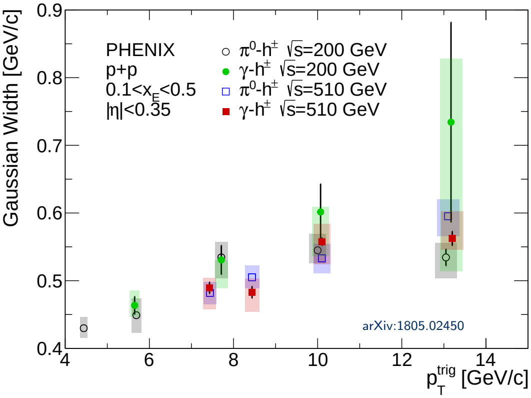
Gaussian Width of p_{out} Evolution in $p+p \rightarrow$ hadrons

- Away-side Gaussian widths shown as a function of p_T^{trig} at $\sqrt{s} = 200$ and 510 GeV



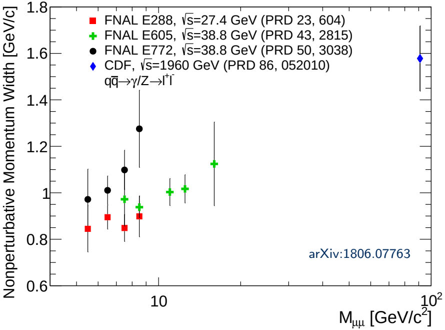
Gaussian Width of p_{out} Evolution in $p+p \rightarrow$ hadrons

- Away-side Gaussian widths shown as a function of p_T^{trig} at $\sqrt{s} = 200$ and 510 GeV
- Qualitatively similar behavior to Drell-Yan and semi-inclusive DIS interactions where color entanglement is not predicted

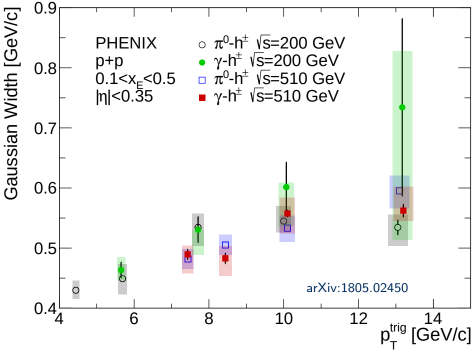


Comparing Drell-Yan and $p+p \to$ hadrons

Drell-Yan

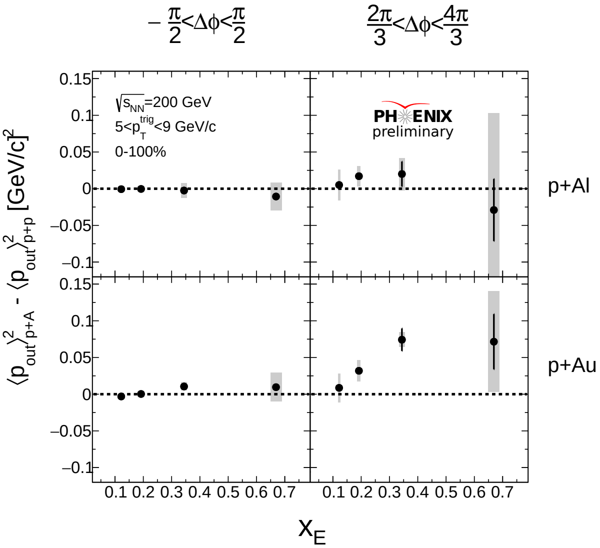


$p+p \to$ hadrons



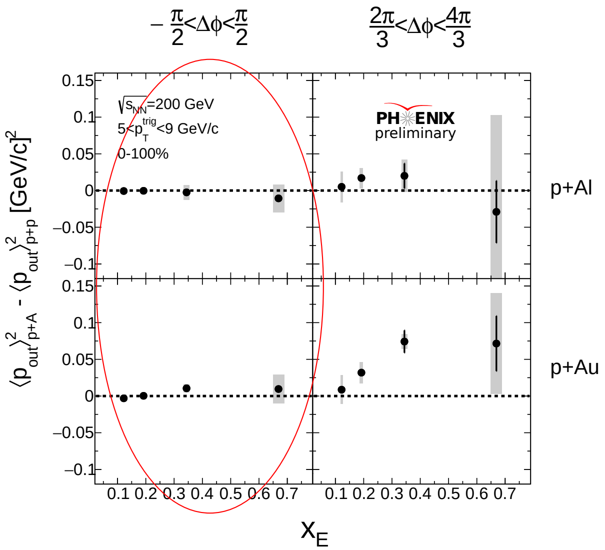
- Since qualitative behavior is similar, calculations needed to compare transverse-momentum-dependent evolution rates in different processes
- Drell-Yan (no color entanglement predicted) and $p+p \to$ hadrons (color entanglement predicted) may exhibit different magnitudes, evolution rates, etc.

Extending Color Studies to p+A



- Can also extend Gaussian width studies to compare between p+A and p+p

Nonperturbative Transverse Momentum Broadening in p+A



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- No significant near-side transverse momentum broadening

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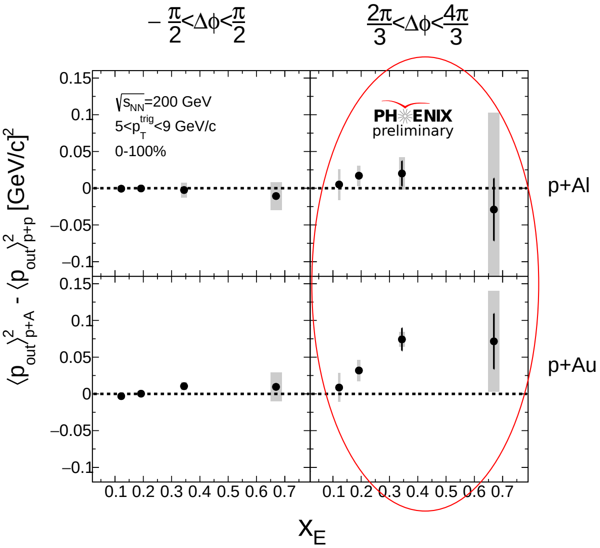
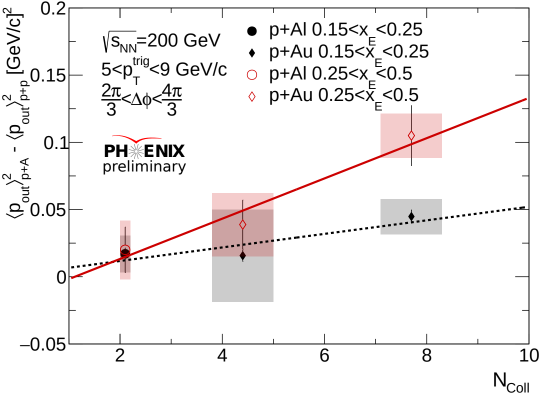


- Can also extend Gaussian width studies to compare between p+A and p+p
- No significant near-side transverse momentum broadening
- Nonzero away-side nonperturbative transverse momentum broadening in p+A

Broadening as a Function of N_{coll}



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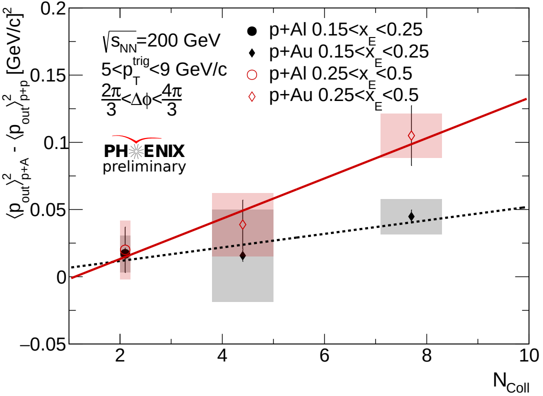

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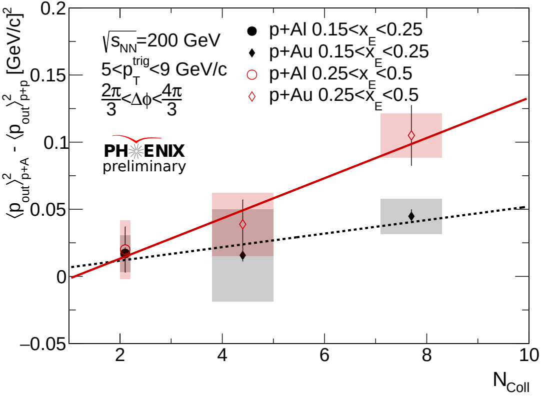
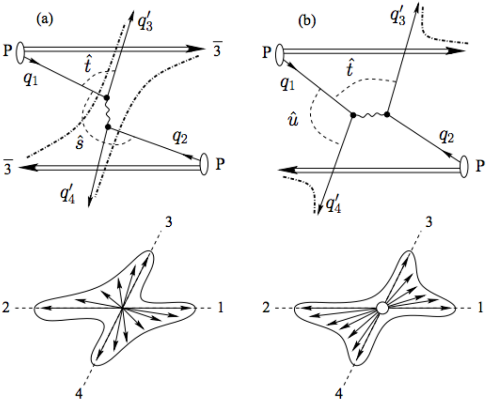


- Away-side transverse momentum broadening is clearly a function of N_{coll} for two x_E bins
- Physical effects that contribute?
  - Stronger color fields in nucleus?
  - Additional initial-state k_T in nucleus?
  - Energy loss?
  - Physical effects behind "Cronin" mechanisms?

Example 2: Color Coherence

- Another example: color coherence



Y. Dokshitzer. Basics of Perturbative QCD, 1991

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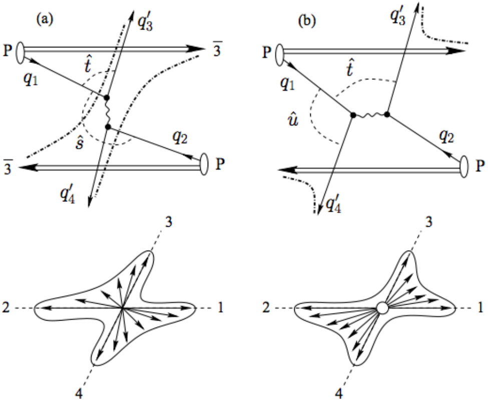

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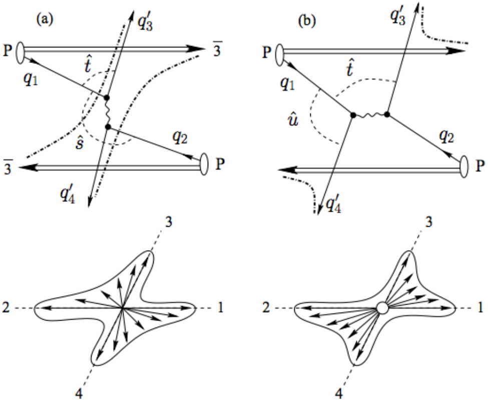
- Color connects hard scattered partons with remnants of other proton



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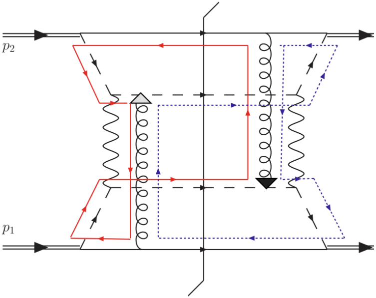
Color entanglement



PRD 81, 094006 (2010)

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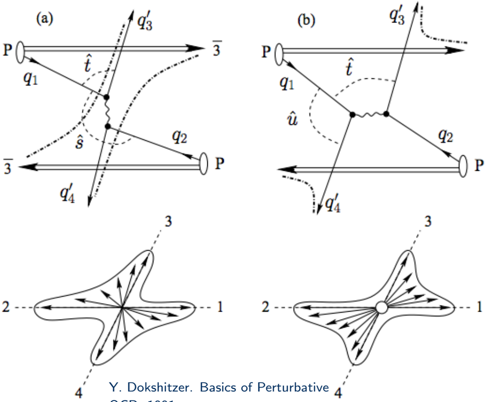
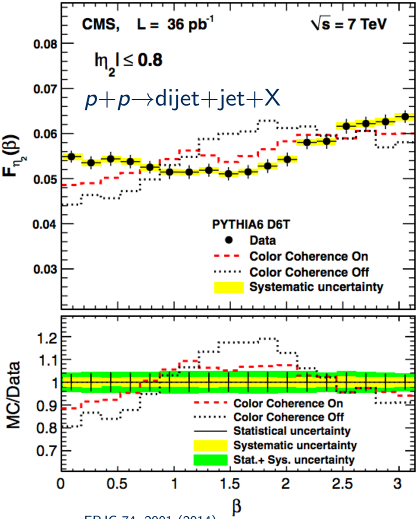


Y. Dokshitzer. Basics of Perturbative QCD, 1991

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

Color Coherence Measurements



EPJC 74, 2901 (2014)

- β is angle in (ϕ, η) space between sub-leading hard-scattered jet and gluon initiated jet

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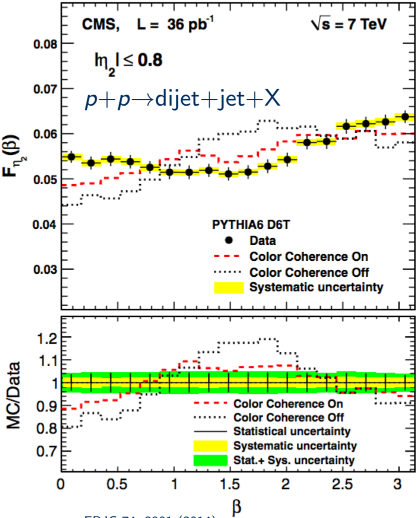

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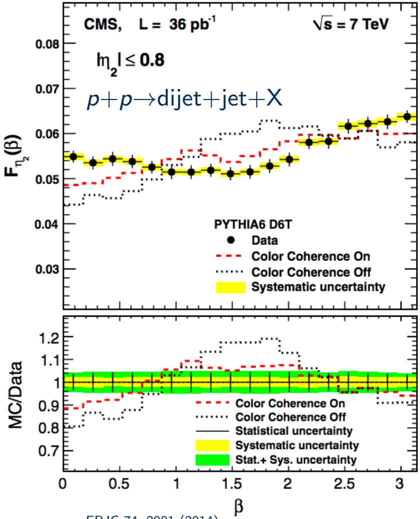

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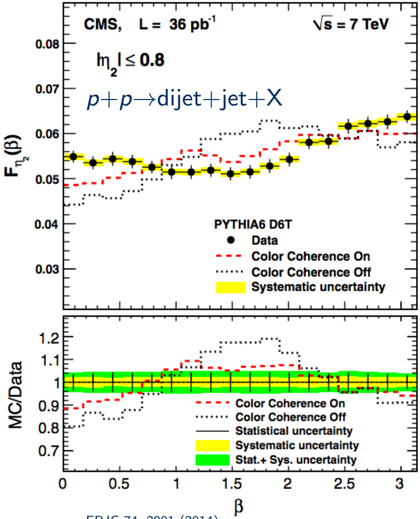

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- $\beta = 0$ points to the beam closer to sub-leading jet in (ϕ, η) space
- $\beta = \pi$ points to the beam farther from sub-leading jet in (ϕ, η) space
- Third jet more likely to be found at $\beta = 0$, $\beta = \pi$, i.e. similar ϕ but large η gap

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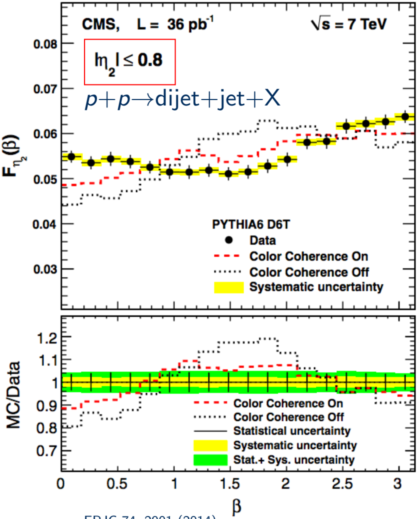

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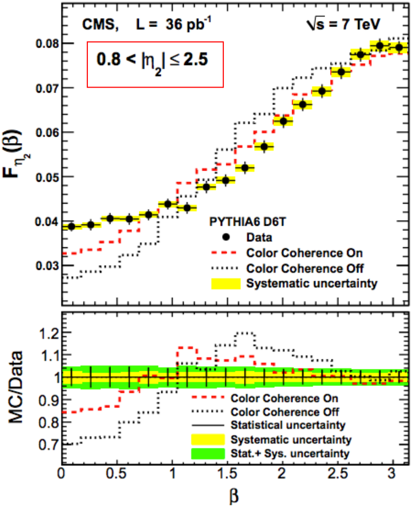
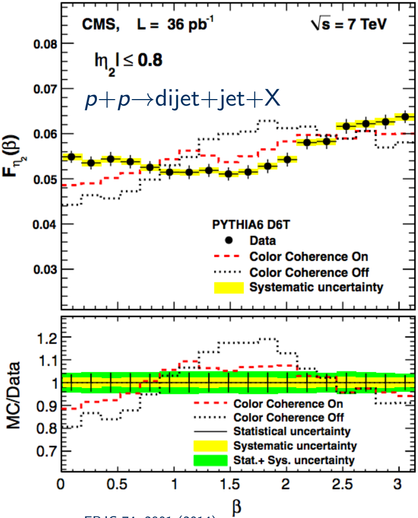


Nucl. Phys. B 918, 257 (2017)

- Even stronger correlation to opposite beam at forward rapidities!

Color Coherence Measurements



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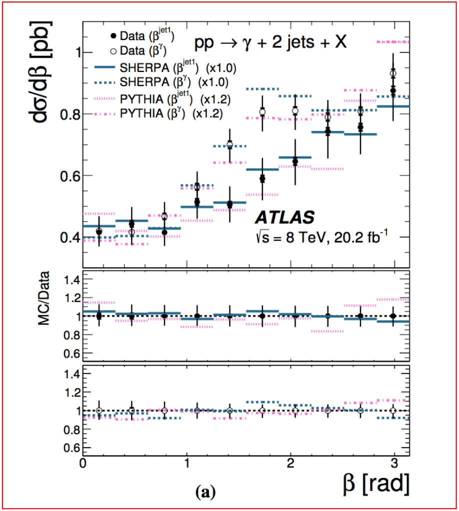
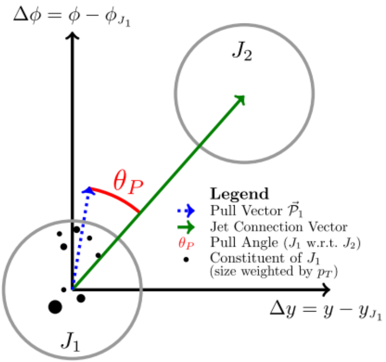
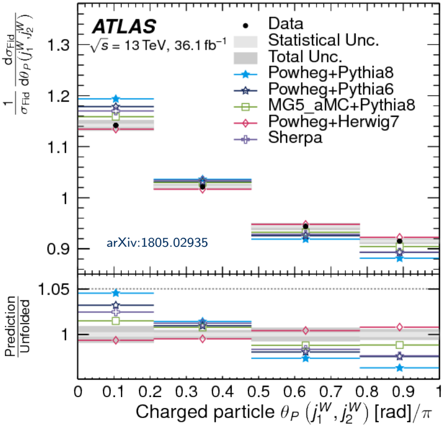


Nucl. Phys. B 918, 257 (2017)

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

Example 3: Jet Substructure





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

What is the relation to jet backgrounds??

The Role of Color in Jet Observables

- Color has been shown to modify e.g. event and/or jet topologies in a variety of ways
- Therefore, it may be essential to consider these effects when studying new observables!

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The Role of Color in Jet Observables

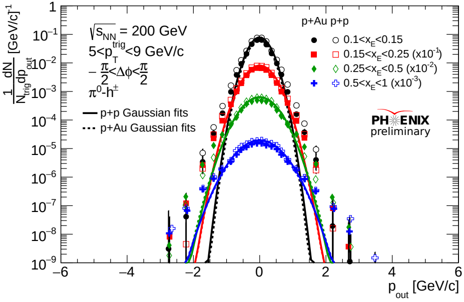
- Color has been shown to modify e.g. event and/or jet topologies in a variety of ways
- Therefore, it may be essential to consider these effects when studying new observables!
- This may be especially important for jet substructure studies, observables which are sensitive to global event characteristics, multiscale problems...
- It is also especially important for interpretation of future EIC data, where complex color flows may be more difficult to study due to differences in $\ell + p(A) \rightarrow \ell + h + X$ vs. $p+p(A) \rightarrow h/jet + X$

“Backgrounds” in jet observables can actually carry important information about fundamental aspects of QCD!

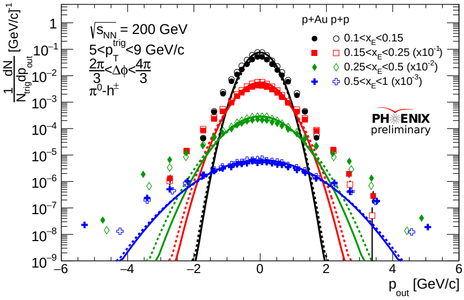
Back Up

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

Color Coherence Measurements

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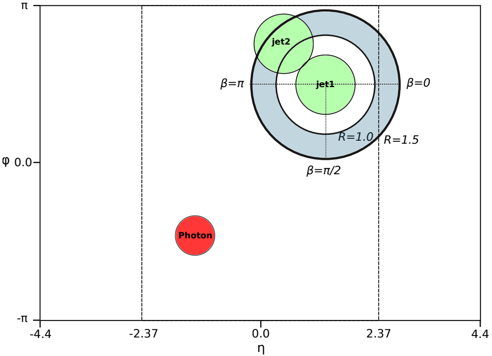
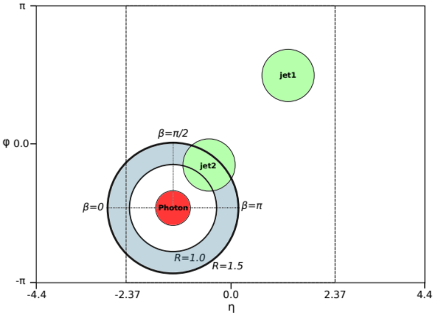


- Color coherence measurements study:

$$\beta = \tan^{-1} \frac{\Delta\phi_{21}}{\mathrm{sign}(\eta_1)\Delta\eta_{21}}$$

- 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 (ϕ, η) space
- $\beta = \pi$ points to the beam farther from jet 1 in (ϕ, η) space

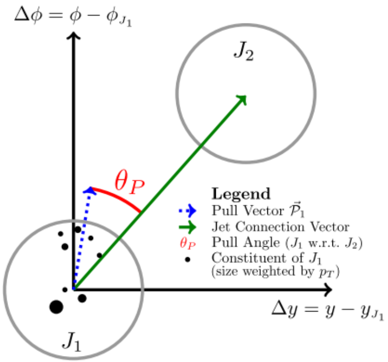
β_γ Definition



- ATLAS collaboration also measures β_γ, defined in a similar way to β_{jet}

$$\beta^\gamma = \tan^{-1}\frac{|\phi^{jet2} - \phi^\gamma|}{\mathrm{sign}(\eta^\gamma)\cdot(\eta^{jet2} - \eta^\gamma)}$$

Example 3: Jet Substructure



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

$$\vec{\mathcal{P}}(j) = \sum_{i \epsilon j} \frac{\left|\vec{\Delta r}_i\right| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$

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

$t\bar{t}$ Color Topology

- 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