Possible Color Entanglement Effects in $p+p$ and $p+A$ Collisions
Overview

- Color entanglement and factorization breaking
- Observables at PHENIX

Results
- $\Delta \phi$ correlations
- Transverse momentum dependent widths
- Comparison to PYTHIA

Conclusions
Color Entanglement and Factorization Breaking

- Due to the non-Abelian nature of QCD, Rogers and Mulders (2010) predicted that quarks can become correlated across colliding protons in hadron production processes sensitive to nonperturbative transverse momentum effects.

- Rather than two factorized parton distribution functions, correlated partons across protons would be described by a single nonperturbative correlation function.

- Measuring the evolution of nonperturbative transverse momentum widths as a function of the hard interaction scale can help distinguish these effects from other possibilities (Collins-Soper-Sterman predicts the widths to increase with hard scale).
Collins-Soper-Sterman Evolution

- Comes directly from proof of TMD factorization
- Drell-Yan, SIDIS, e+e- annihilation
- Predicts nonperturbative momentum widths to increase with hard scale
- Experimental and phenomenological confirmation


C. A. Aidala, B. Field, L. P. Gamberg, and T. C. Rogers
PRD 89, 094002 with COMPASS, EPJ C73, 2531 (2013)
Look at $\pi^0$-hadron and $\gamma$-hadron correlations, which are sensitive to nonperturbative transverse momentum in the initial state (in the proton) and final state (hadronization).
Azimuthal coverage: $2 \times \frac{\pi}{2}$

Pseudo-rapidity coverage: $\pm 0.35$

Isolated direct photons and $\pi^0 \rightarrow \gamma \gamma$ detected by electromagnetic calorimeter

Charged hadrons detected by Drift and Pad Chambers

Centrality in $p+A$:
- Integrated charge in beam-beam counters
- Proxy for impact parameter
**Δφ Correlations**

- **Near-side peak** \( Δφ = 0 \)
- **Isolation cut for** \( γ-h \rightarrow \) **no near-side peak**
- **Away-side charged hadrons** \( Δφ = π \)
- **Per trigger yield:**

\[
\frac{1}{N_{trig}} \frac{dN}{dΔφ} = \frac{1}{N_{trig}} \frac{dN/dΔφ_{raw}}{dN/dΔφ_{mixed} \epsilon(p_T)}
\]

Accepted by PRD
RMS of $p_{\text{out}}$

- Extracted from fit to away-side $\Delta\phi$ correlations
- Width of away-side jet decreases with hard scale

Decrease for $\gamma$-hadron is large compared to $\pi^0$-hadron

$\pi^0$-hadron has fragmentation function dependence

Accepted by PRD
$p_{\text{out}}$ Distributions

- Gaussian fit region $[-1.1, 1.1]$ → nonperturbative (soft gluon radiation)
- Power law behavior → perturbative (hard gluon radiation)
- Kaplan function fits entire range for $p+p$ data

Accepted by PRD
Evolution with Hard Scale

- Extracted from Gaussian fits to $p_{\text{out}}$ distributions
- Gaussian widths sensitive only to nonperturbative contributions
- Decrease with $p_T^{\text{trig}}$ 
  - Qualitatively opposite of SIDIS, DY
System Size and Centrality Dependence

Hint that possible factorization-breaking effects stronger in p+A than p+p

Centrality dependence could be due to multiple scattering interactions
PYTHIA Simulations

- PYTHIA-generated slopes show almost perfect agreement with data.
- Widths differ by about 15%.
- PYTHIA possibly sensitive to factorization breaking effects? (gluon exchange between partons in hard scatter and remnants.)

Accepted by PRD
**Conclusions**

- Factorization breaking is predicted in processes sensitive to nonperturbative transverse momentum effects such as \( \pi^0 \)-hadron and \( \gamma \)-hadron correlations in hadronic collisions.

- These results show widths decrease with hard scale, suggesting possible TMD factorization breaking and color entanglement of partons across colliding protons.

- Examining color interactions in PYTHIA could potentially further our understanding of these results.

- Results from \( p+p \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) coming soon! → Look at \( x_T \) scaling.

STAR p+p at $\sqrt{s}=200$ GeV
Phys. Rev. Lett. 112, 122301
Jet-h$^\pm$ Correlations

10<p$_T^{\text{jet,rec}}$<15 GeV/c
20<p$_T^{\text{jet,rec}}$<40 GeV/c
**Extract RMS of $p_{out}$ from away-side charged hadrons**

\[
\frac{dN}{d\Delta \phi} = C_0 + C_1 \cdot \frac{dN_{\text{far}}}{d\Delta \phi}
\]

\[
\frac{dN_{\text{far}}}{d\Delta \phi} = \begin{cases} 
0 & |\Delta \phi - \pi| > \frac{\pi}{2} \\
\sqrt{2\pi}(p_{out}^2) \frac{-p_{T,\text{assoc}} \cos \Delta \phi}{\sqrt{2}(p_{out}^2)} \times \exp \left( -\frac{|p_{T,\text{assoc}}^2 \sin^2 \Delta \phi}{2(p_{out}^2)} \right) & |\Delta \phi - \pi| \leq \frac{\pi}{2}
\end{cases}
\]

**$p_{out}$ yields**

- Hadrons: $2\pi/3 < \Delta \phi < 4\pi/3$