Nonperturbative Transverse Momentum Effects in p+p and p+A Collisions at PHENIX

Mike Skoby
University of Michigan
Quarks can become correlated across colliding protons in hadron production processes sensitive to nonperturbative transverse momentum effects (Rogers and Mulders, Phys. Rev. D 81 (2010) 094006).

Correlated partons across protons would be described by a single nonperturbative correlation function.

Nonperturbative transverse momentum widths as a function of the hard interaction scale can help distinguish these effects from other possibilities (Collins-Soper-Sterman).
Collins-Soper-Sterman

- CSS Evolution comes directly from proof of TMD factorization
- Predicts nonperturbative momentum widths to increase with hard scale
- Experimental and phenomenological confirmation

Observables

- $\pi^0$-hadron and $\gamma$-hadron correlations
- Sensitive to nonperturbative transverse momentum in the initial state (in the proton) and final state (hadronization)

Per trigger yield:

$$\frac{1}{N_{\text{trig}} d\Delta \phi} \frac{dN}{d\Delta \phi_{\text{raw}}} = \frac{1}{N_{\text{trig}} dN/d\Delta \phi_{\text{mixed}} \epsilon(p_T)}$$
Azimuthal coverage: $2 \times \pi/2$

Psuedo-rapidity coverage: $+/-.35$

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
Near-side peak $\Delta\phi=0$, away-side charged hadrons $\Delta\phi=\pi$
RMS of $p_{\text{out}}$

- Extracted from fit to away-side $\Delta\phi$ correlations
- Width of away-side jet decreases with hard scale
- Measured in $p+p$ at 2 energies and $p+A$ at 200 GeV
\( p_{\text{out}} \) Distributions

- Gaussian fit region \([-1.1, 1.1]\) \(\rightarrow\) nonperturbative
- At large \( p_{\text{out}} \) \(\rightarrow\) perturbative (hard gluon radiation)
Evolution with Hard Scale

- Extracted from Gaussian fits to $p_{out}$ distributions
- Gaussian widths sensitive only to nonperturbative contributions
- Decrease with $p_T^{\text{trig}}$ → Qualitatively opposite of SIDIS, DY
**$x_T$ Scaling**

- Nonperturbative momentum widths do not exhibit $x_T$ scaling.
- RMS of $p_{out}$ nearly scales with $x_T$.
- Insight into nonperturbative vs perturbative effects?
Factorization breaking is predicted in processes sensitive to nonperturbative transverse momentum effects such as $\pi^0$-hadron and $\gamma$-hadron correlations in hadronic collisions.

Widths decrease with hard scale $\rightarrow$ opposite behavior of CSS

Examining effects sensitive to color interactions in PYTHIA could potentially further our understanding of these results.
Backup
C. A. Aidala, B. Field, L. P. Gamberg, and T. C. Rogers
PRD 89, 094002 with COMPASS, EPJ C73, 2531 (2013)
Extract RMS of $p_{out}$ from away-side charged hadrons

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

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

$p_{out}$ yields

Hadrons: $2\pi/3 < \Delta \phi < 4\pi/3$
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)
**PHENIX PRD 95, 072002 (2017), \(\sqrt{s}=510\) GeV**

**PHENIX Preliminary, \(\sqrt{s}=200\) GeV**

**p+p**

**Isolated Direct \(\gamma-h^+\)**

\[2\pi < \Delta \phi < \frac{4\pi}{3}\]

\[0.7 < p_T^{assoc} < 6\text{ GeV/c}\]

**Fit Range [-1.1, 1.1] GeV/c**

\[x_T = 2p_T/\sqrt{s}\]