Nonperturbative Transverse Momentum Effects in Dihadron and Direct Photon-Hadron Angular Correlations

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Universality and Factorization in TMDs

- Sign change in Sivers TMD PDF predicted due to initial-state vs. final-state gluon exchange with proton remnants between DY and SIDIS: modified universality!

- What about $p+p \rightarrow h_1 h_2$ where both initial- and final-state interactions are possible?
TMD Factorization Breaking

- Rogers and Mulders paper predicts QCD factorization breaking in dihadron production from $p+p$ collisions in a TMD framework (Phys. Rev. D 81, 094006 (2010))
- Back-to-back two particle angular correlations give sensitivity to initial- and final-state transverse momentum $k_T$ and $j_T$
- $\geq 2$ gluons exchanged with proton remnants leads to predicted breakdown
Expectations from Collins-Soper-Sterman (CSS) Evolution

- Expectation from CSS evolution is that any momentum width sensitive to nonperturbative $k_T$ grows with the hard scale.
- Broadening due to increased phase space for hard gluon radiation.
- Note that the CSS evolution equation comes directly out of the derivation for TMD factorization.
- Phenomenological studies have shown that DY/Z and SIDIS follow this expectation.


Direct photon-hadron production

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

Direct photon \( p_T^{\text{trig}} \)

Dihadron production

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

Dihadron production \( p_T^{\text{assoc}} \)

\[ p_{out} = p_T^{\text{assoc}} \sin \Delta \phi \]
PHENIX central arms
- $\Delta \phi \sim \pi$
- $|\eta| < 0.35$

Electromagnetic Calorimeter (PbSc/PbGl) provides isolated direct photon and $\pi^0 \rightarrow \gamma\gamma$ detection

Drift Chamber (DC) and Pad Chambers (PC) provide nonidentified charged hadron detection

New results from 2012/2013 $\sqrt{s} = 510$ GeV $p+p$ runs
Two jet structure visible for $\pi^0$-$h^\pm$, isolation cut on near side for direct $\gamma$-$h^\pm$

Direct $\gamma$-$h^\pm$ probes smaller jet energy due to emerging from hard scattering at LO
$\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width in momentum space

- Decreases with hard scale, opposite of SIDIS and DY!
- Sensitive to perturbative and nonperturbative $k_T$ and $j_T$
$p_{\text{out}}$ Distributions

- $p_{\text{out}}$ shows two distinct regions: gaussian and power law
- Gaussian fits clearly fail past $\sim 1.3$ GeV/c
- Indicates transition from nonperturbative to perturbative $k_T$ and $j_T$

Note: Curves are Kaplan and Gaussian fits, not calculations!!
Gaussian Widths of $p_{out}$

- Gaussian widths of $p_{out}$ distributions also decrease with hard scale $p_T^{trig}$
- Sensitive to only nonperturbative $k_T$ and $j_T$ in the nearly back-to-back region $\Delta \phi \sim \pi$
- PYTHIA replicates slope almost exactly, but shows 15% difference in magnitude of widths
Conclusions

- Factorization breaking has been predicted in $p + p \rightarrow h + X$ collisions for observables sensitive to nonperturbative transverse momentum
- New measurements from PHENIX of nearly back-to-back dihadron and isolated direct photon-hadron correlations at $\sqrt{s}=510$ GeV
- Angular correlations sensitive to initial-state $k_T$ and final-state $j_T$ show decreasing momentum widths with hard scale in $p + p \rightarrow h + X$
- Literature shows that Drell-Yan/Z and SIDIS interactions, which CSS evolution describes, exhibit increasing momentum widths with hard scale
Back Up
Direct Photons and Dihadrons

- Direct photon-hadron and dihadron correlations both predicted to be sensitive to factorization breaking effects in PHENIX
- Assuming factorization, direct photon-hadrons probe three nonperturbative functions, while dihadrons probe four
- Direct photons offer one less avenue for gluon exchange in the final-state: fewer/different effects?
\( R_{iso}^{\gamma} \) measured for statistical subtraction of isolated decay photon contribution

\( R_{\gamma} \) measured in PHENIX and corrected by tagging and isolation efficiencies

\( R_{iso}^{\gamma} > 1 \) indicates isolated direct photon production

\[
R_{iso}^{\gamma} = \frac{R_{\gamma}}{(1 - \epsilon_{tag}^{dec})(1 - \epsilon_{niso}^{dec})} \frac{N_{iso}^{inc}}{N_{inc}}
\]
PYTHIA $p_{out}$ Distributions

- PYTHIA $\pi^0$-h$^\pm$ and isolated $\gamma$-h$^\pm$ correlations analyzed similarly to data.
- PYTHIA exhibits similar characteristics to data: nonperturbative transitioning to perturbative region.
- Initial and final state interactions possible in PYTHIA: all particles are forced to color neutralize.
Can check if PYTHIA also reproduces CSS evolution with DY dimuon production

Construct same observable

\[ p_{\text{out}} = p_{\text{lep}}^T \sin \Delta \phi \]

between two nearly back-to-back leptons

PYTHIA confirms expectation from CSS evolution for same observable

Note rate of increase is significantly larger in magnitude also

Red solid line shows log fit, blue dotted line shows linear fit
Other DY/Z and SIDIS Refs.

(DY/Z)

(SIDIS)
Previous PHENIX result at $\sqrt{s}=200$ GeV with larger errors (Phys. Rev. D 82, 072001 (2010))

Next step: analyze recent Run 15 $\sqrt{s}=200$ GeV $p+p$ and $p+A$ data from RHIC!

6x luminosity in Run 15 $p+p$, as well as first result from $p+A$

Can also look at transverse spin dependence in Run 15!
Other Measurements in Literature

- Other RHIC publications show the same effect in $\sqrt{\langle p_{\text{out}}^2 \rangle}$ and away-side width.
- All previous analyses motivated by different physics goals: fragmentation functions, partonic energy loss in QGP, etc.

PRD 82, 072001 (2010) (PHENIX)

PRD 74, 072002 (2006) (PHENIX)
Possible Links to Color Coherence Effects?

- D0, CDF, CMS have all published papers on evidence for "color coherence effects"
- Color flow gives rise to areas in phase space where gluons destructively interfere
- Few citations though, relatively unknown work!
Direct photons emerge directly from hard scattering, $\pi^0$s are a fragment.

Thus a more direct comparison is between $p_T^{\text{trig}}$ for direct photon and jet $p_T^{\text{jet}}$ for $\pi^0$.

Determine $\langle z_T \rangle = p_T^{\pi^0} / \hat{p}_T^{\text{parton}}$ using PYTHIA, ”correct” $\pi^0$ $p_T^{\text{trig}}$ to get $p_T^{\text{jet}} = p_T^{\text{trig},\pi^0} / \langle z_T \rangle$.
Analysis Methods

- Correlated $\pi^0 - h^\pm$ or isolated $\gamma - h^\pm$ are collected and corrected with:
  - Charged hadron efficiency
  - Acceptance correction

- Direct photons undergo additional statistical subtraction to remove decay photon background, estimated with Monte Carlo probability functions

- Isolation and tagging cuts remove decay photon background and NLO fragmentation photons

Probability for a $\pi^0$ to decay to a photon which could not be tagged with $5 < p_T < 7$ GeV/c in PHENIX

\[
Y_{iso}^{dir} = \frac{1}{R_{iso}^{\gamma}} - 1 \left( R_{iso}^{\gamma} Y_{iso}^{inc} - Y_{iso}^{dec} \right)
\]
A few examples of DY and SIDIS TMD measurements shown here.

Both show increasing trends with the hard scale.

Phys. Rev. Lett. 38, 1334 (DY)

Phys. Rev. Lett. 47, 12 (DY)

Phys. Rev. D 23, 604 (DY)

Eur. Phys. J. C73, 2531 (SIDIS)