

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

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Based on work in arXiv:1609.04769, submitted to Phys. Rev. D

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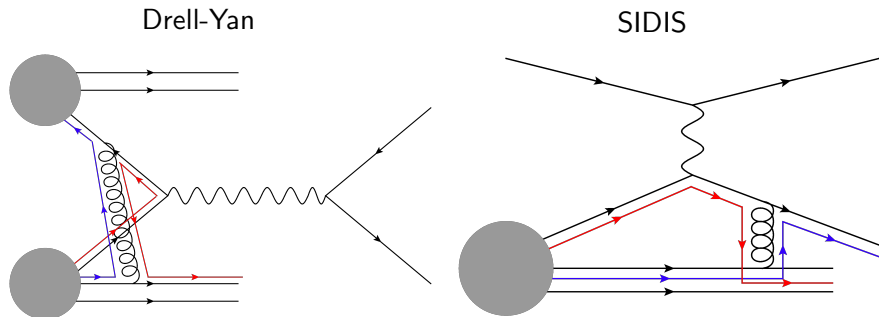


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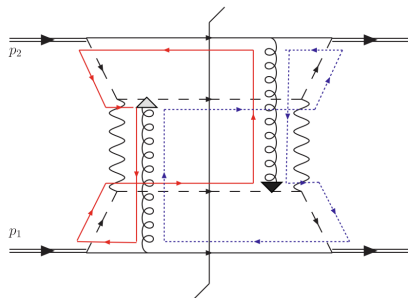
Universality and Factorization in TMDs



- 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

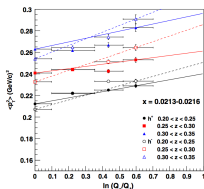
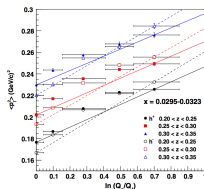
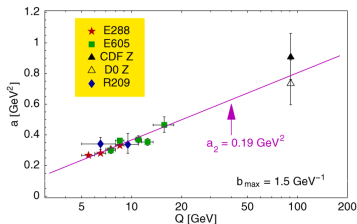


- ≥ 2 gluons exchanged with proton remnants leads to predicted breakdown

Expectations from Collins-Soper-Sterman (CSS) Evolution

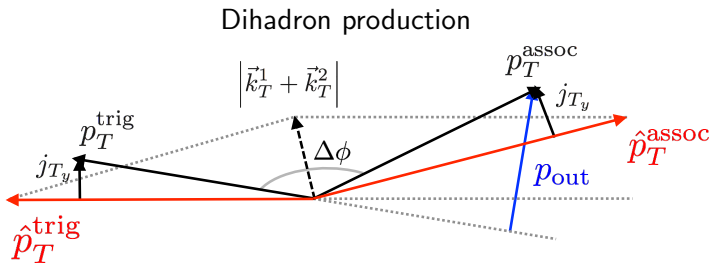
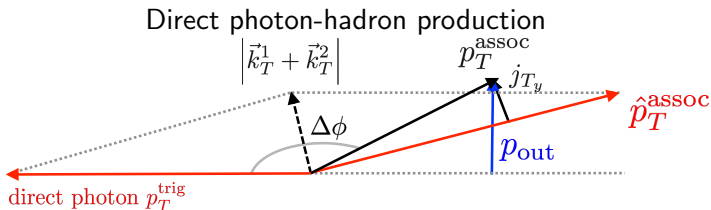
- Expectation from CSS evolution is that any momentum width sensitive to nonperturbative k_T grows with the hard scale
 - Broadening due to increased phase space for hard gluon radiation
- Note that the CSS evolution equation comes directly out of the derivation for TMD factorization
- Phenomenological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

Phys. Lett. B 633, 710 (2006)
(DY/Z)



Phys. Rev. D 89, 094002 (2014)
(SIDIS)

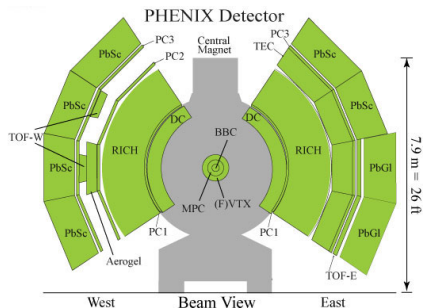
Angular Correlation Observables



$$p_{\text{out}} = p_T^{\text{assoc}} \sin \Delta\phi$$

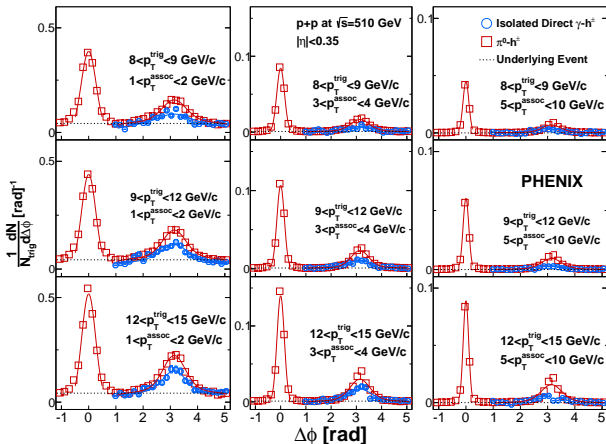
PHENIX Detector

- 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



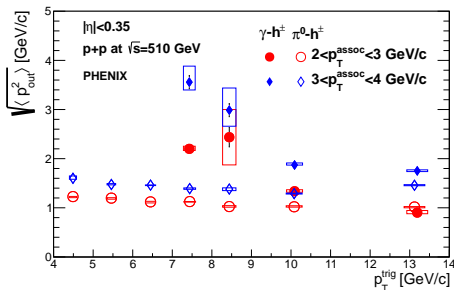
- New results from 2012/2013 $\sqrt{s}=510$ GeV $p+p$ runs

$\Delta\phi$ Correlations for π^0 - h^\pm and Direct γ - h^\pm



- Two jet structure visible for π^0 - h^\pm , isolation cut on near side for direct γ - h^\pm
- Direct γ - h^\pm probes smaller jet energy due to emerging from hard scattering at LO

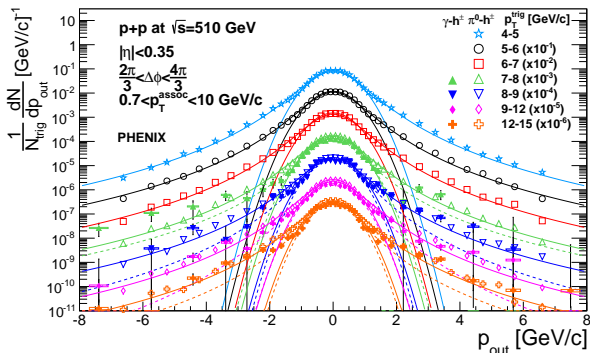
$\sqrt{\langle p_{out}^2 \rangle}$ Extracted from Fits to $\Delta\phi$ Correlations



- $\sqrt{\langle p_{out}^2 \rangle}$ 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

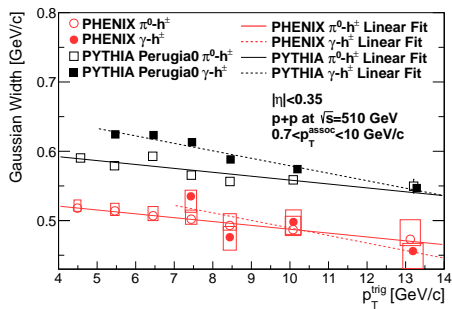
p_{out} Distributions

- p_{out} shows two distinct regions: gaussian and power law
- Gaussian fits clearly fail past ~ 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

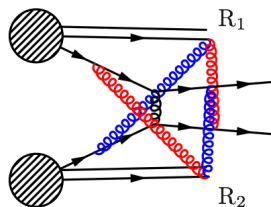
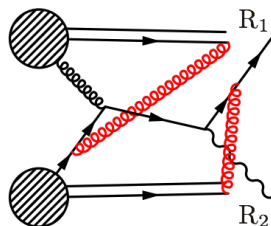
Conclusions

- 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
- Paper submitted to Phys. Rev. D, arXiv:1609.04769

Back Up

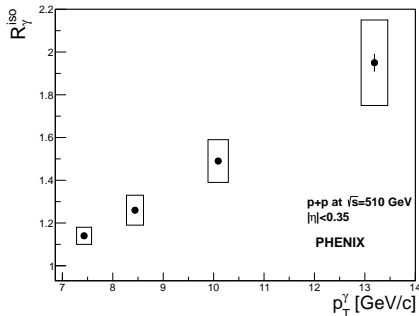
Direct Photons and Dihadrons

- 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_{γ}^{iso} Measurement at $\sqrt{s}=510$ GeV

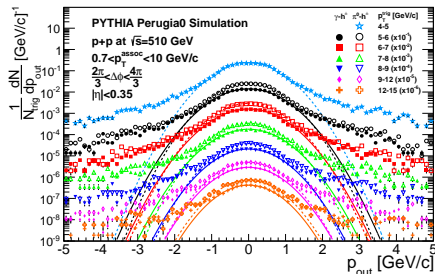
- R_{γ}^{iso} measured for statistical subtraction of isolated decay photon contribution
- R_{γ} measured in PHENIX and corrected by tagging and isolation efficiencies
- $R_{\gamma}^{iso} > 1$ indicates isolated direct photon production



$$R_{\gamma}^{iso} = \frac{R_{\gamma}}{(1 - \epsilon_{dec}^{tag})(1 - \epsilon_{dec}^{niso})} \frac{N_{inc}^{iso}}{N_{inc}}$$

PYTHIA p_{out} Distributions

- PYTHIA π^0 - h^\pm and isolated γ - 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



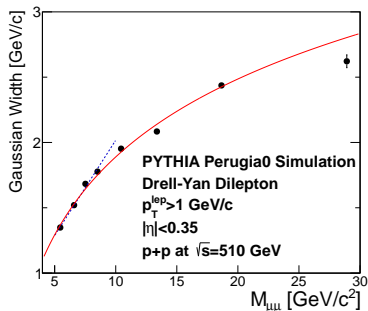
PYTHIA Reproduces CSS Evolution

- Can check if PYTHIA also reproduces CSS evolution with DY dimuon production

- Construct same observable

$p_{out} = p_T^{lep} \sin \Delta\phi$
between two nearly
back-to-back leptons

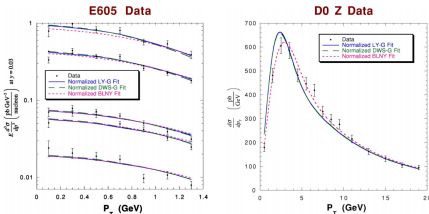
- PYTHIA confirms expectation from CSS evolution for same observable



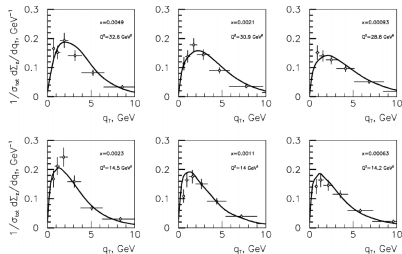
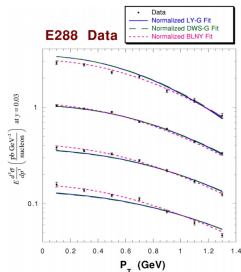
- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

Other DY/Z and SIDIS Refs.

Phys. Rev. D 67, 073016 (2003)
(DY/Z)

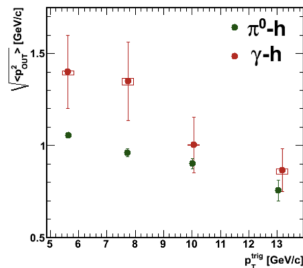
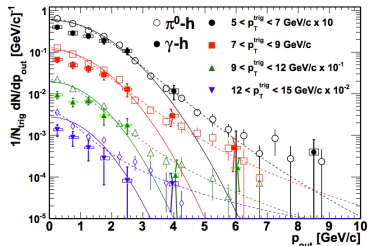


Phys. Rev. D 61, 014003 (2000)
(SIDIS)



$\sqrt{s}=200$ GeV Results

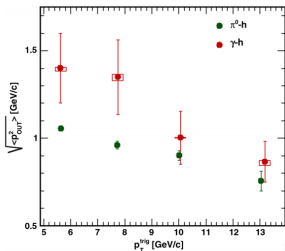
- Previous PHENIX result at $\sqrt{s}=200$ GeV with larger errors (Phys. Rev. D 82, 072001 (2010))
- Next step: analyze recent Run 15 $\sqrt{s}=200$ GeV $p+p$ and $p+A$ data from RHIC!
- 6x luminosity in Run 15 $p+p$, as well as first result from $p+A$
- Can also look at transverse spin dependence in Run 15!



$$2 < p_T^{assoc} < 5$$

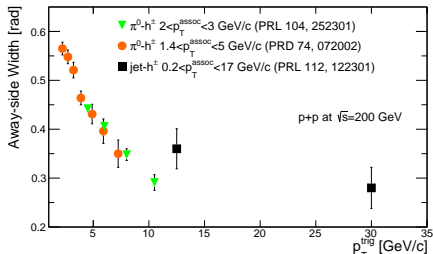
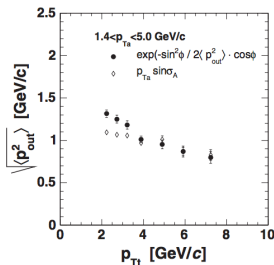
Other Measurements in Literature

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



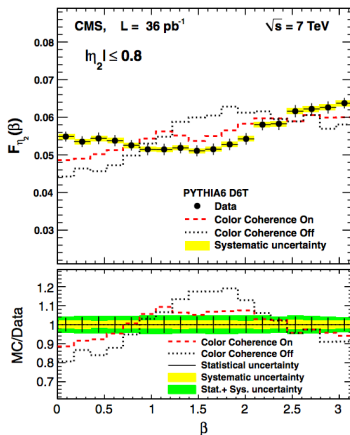
PRD 82, 072001 (2010) (PHENIX)

PRD 74, 072002 (2006) (PHENIX)



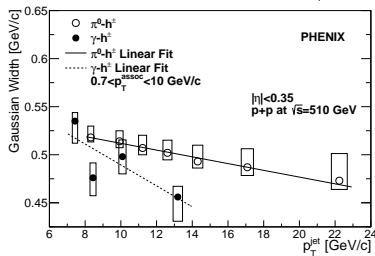
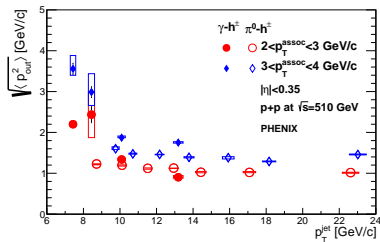
Possible Links to Color Coherence Effects?

- 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!
- CMS: Eur.Phys.J. C74 (2014) no.6, 2901
- CDF: Phys. Rev. D 50, 5562 (1994)
- D0: Phys. Lett. B 414, 419 (1997)



PYTHIA $\langle z_T \rangle$ Correction

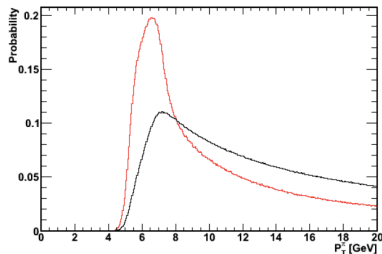
- Direct photons emerge directly from hard scattering, π^0 s are a fragment
- Thus a more direct comparison is between p_T^{trig} for direct photon and jet p_T^{trig} for π^0
- Determine $\langle z_T \rangle = p_T^{\pi^0} / \hat{p}_T^{parton}$ using PYTHIA, "correct" π^0 p_T^{trig} to get $p_T^{jet} = p_T^{trig, \pi^0} / \langle z_T \rangle$



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



$$Y_{dir}^{iso} = \frac{1}{R_\gamma^{iso} - 1} \left(R_\gamma^{iso} Y_{inc}^{iso} - Y_{dec}^{iso} \right)$$

DY and SIDIS Measurements

- 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)

