

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

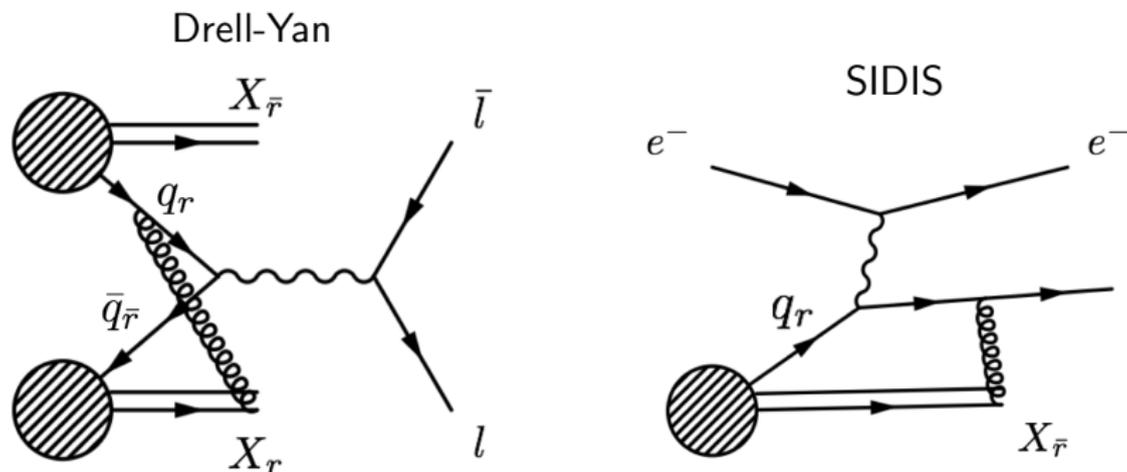
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QCD-N'16, July 12, 2016



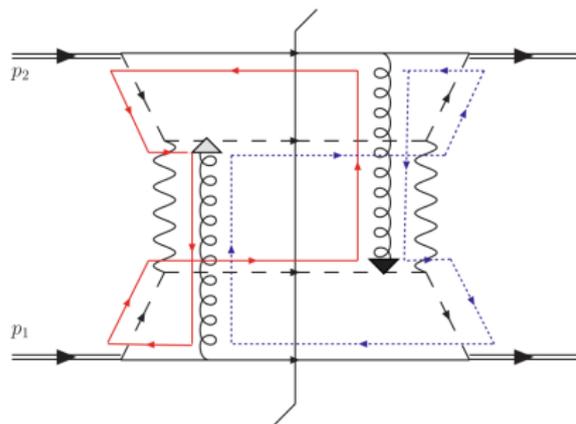
Universality and Factorization in TMDs



- 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

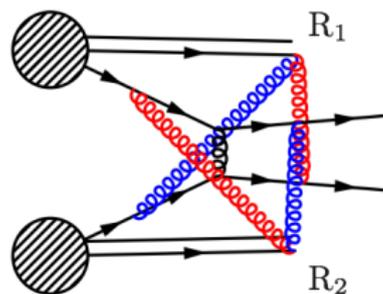
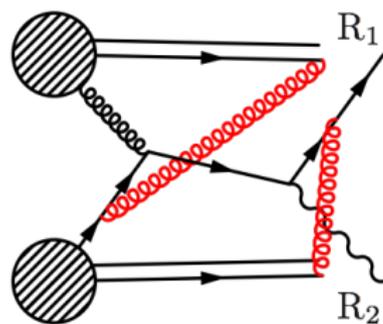
- Rogers and Mulders paper predicts QCD factorization breaking in dihadron production from $p+p$ collisions in a TMD framework (Phys. Rev. D 81,094006 (2010))
- Back-to-back two particle angular correlations give sensitivity to initial- and final-state transverse momentum k_T and j_T



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

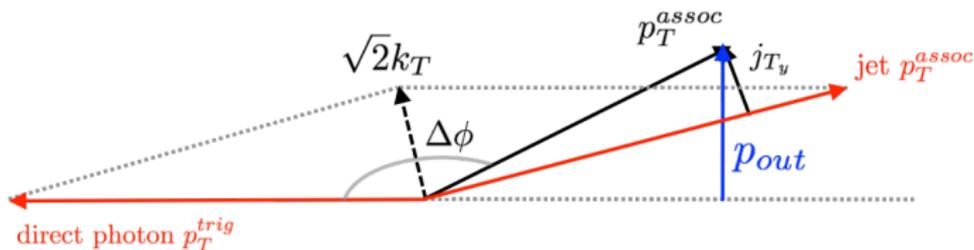
Direct Photons and Dihadrons

- 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?

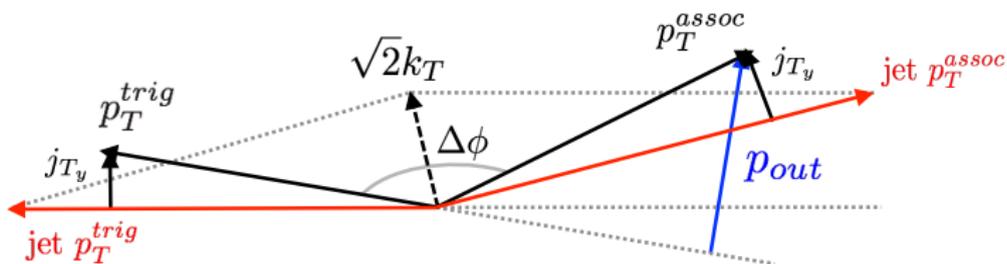


Angular Correlation Observables

Direct photon-hadron production



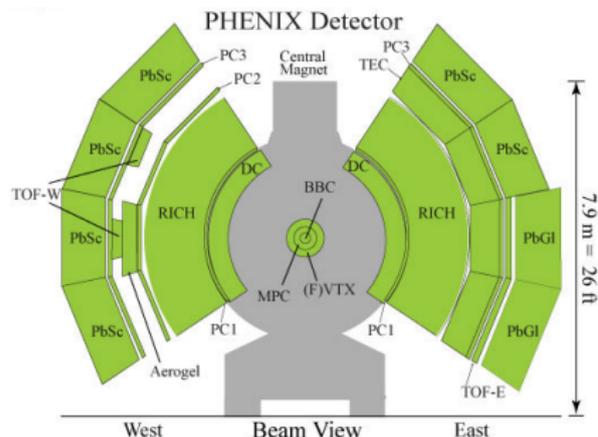
Dihadron production



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

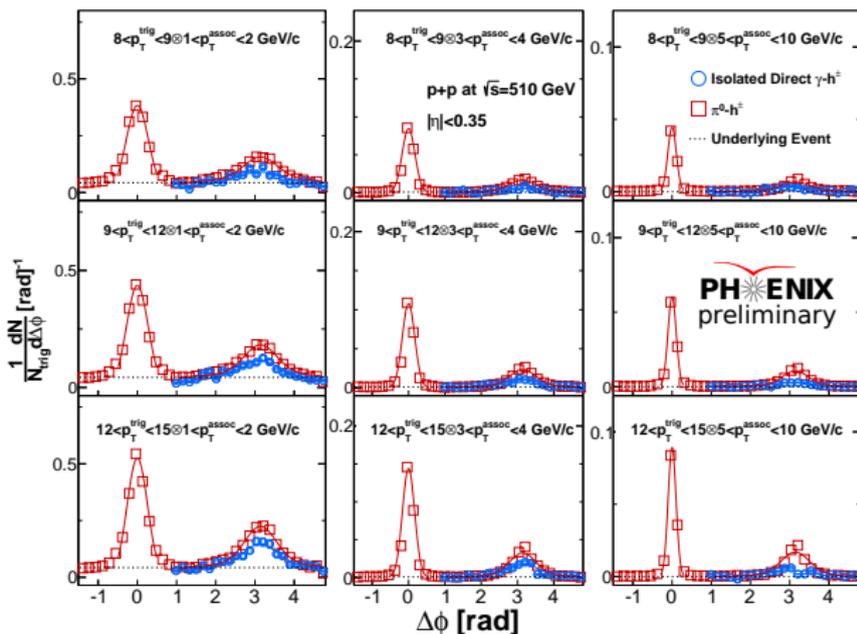
PHENIX Detector

- 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



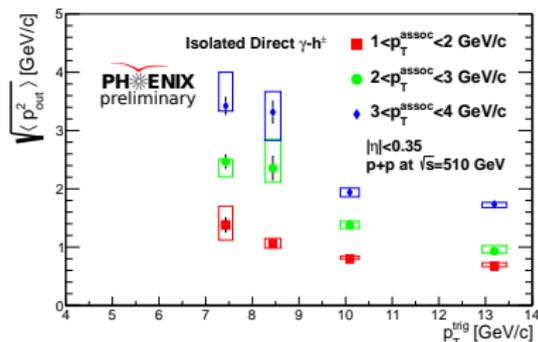
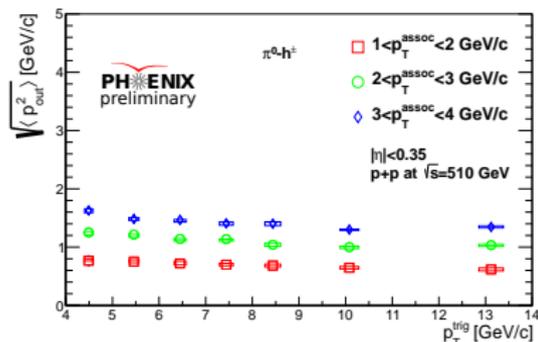
- New results from 2012/2013 $\sqrt{s}=510$ GeV $p+p$ runs

$\Delta\phi$ 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

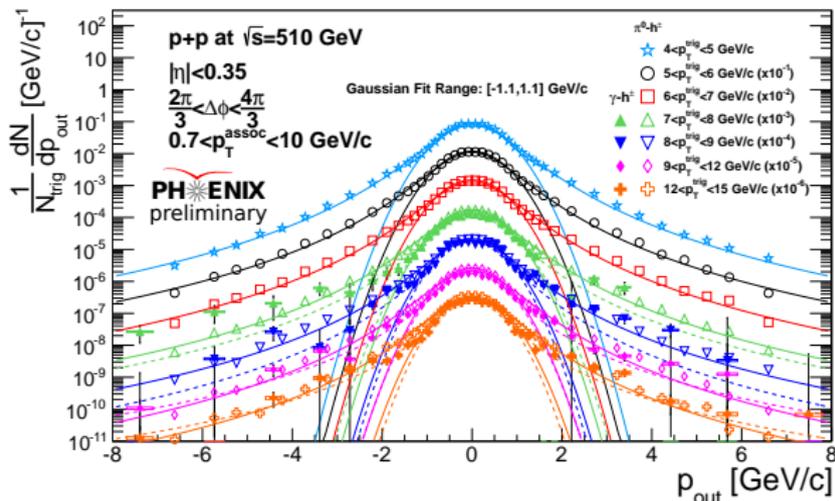
$\sqrt{\langle p_{out}^2 \rangle}$ Extracted from Fits to $\Delta\phi$ Correlations



- $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width and decreases with hard scale p_T^{trig}
- Sensitive to perturbative and nonperturbative k_T and j_T

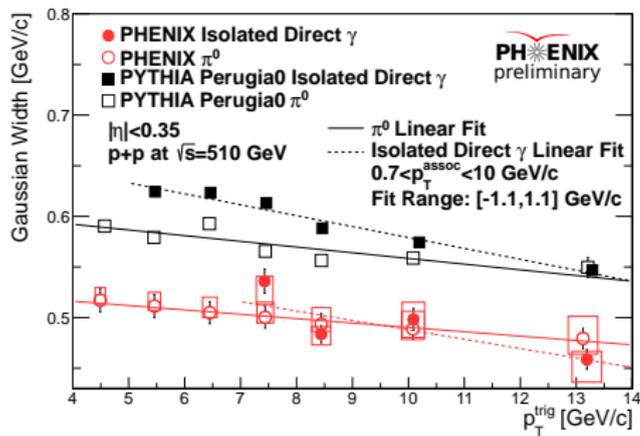
p_{out} Distributions

- 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!!

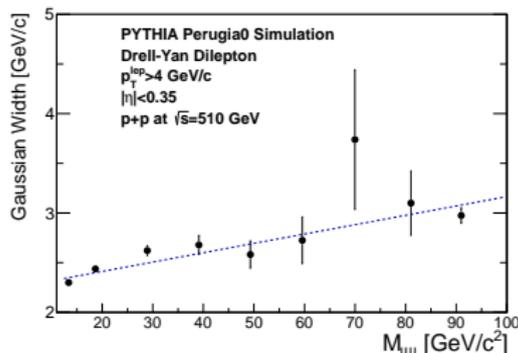
Gaussian Widths of p_{out}



- Gaussian widths of p_{out} distributions 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

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

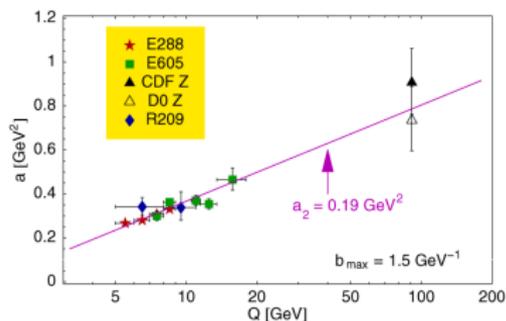


- PYTHIA confirms expectation from CSS evolution for same observable

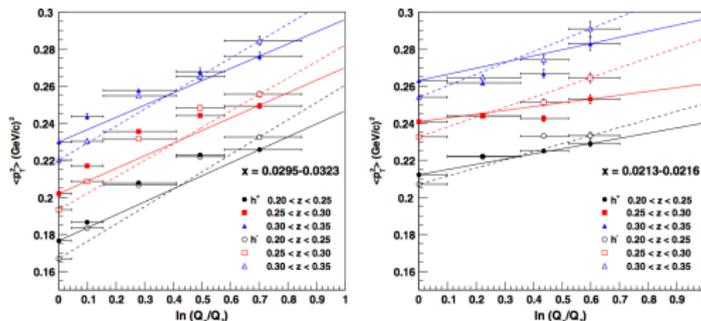
SIDIS and DY/Z Measurements

- DY/Z and SIDIS, where factorization is predicted to hold, have been shown to follow CSS evolution
- Phenomenological studies in both interactions show increasing momentum widths when sensitive to small k_T scale

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



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



Conclusions

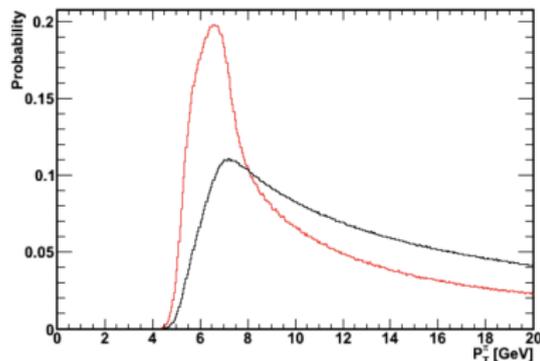
- Factorization breaking has been predicted in $p+p \rightarrow h + X$ collisions for observables sensitive to nonperturbative transverse momentum
- New measurements from PHENIX of nearly back-to-back dihadron and isolated direct photon-hadron correlations at $\sqrt{s}=510$ GeV
- Angular correlations 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 draft undergoing internal review process!

Back Up

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

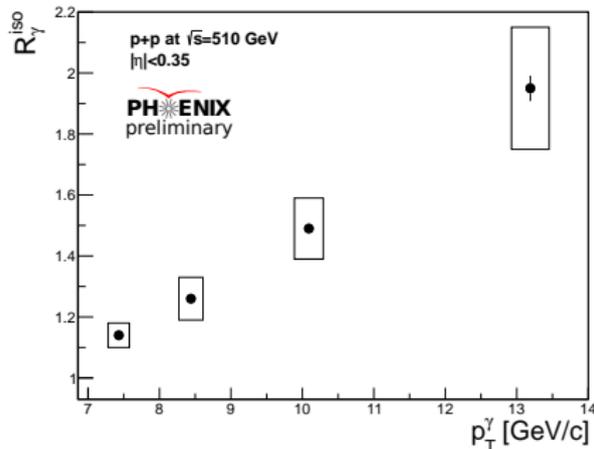
Probability for a π^0 to decay to a photon which could not be tagged with $5 < p_T < 7$ GeV/c in PHENIX



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

R_γ^{iso} Measurement at $\sqrt{s}=510$ GeV

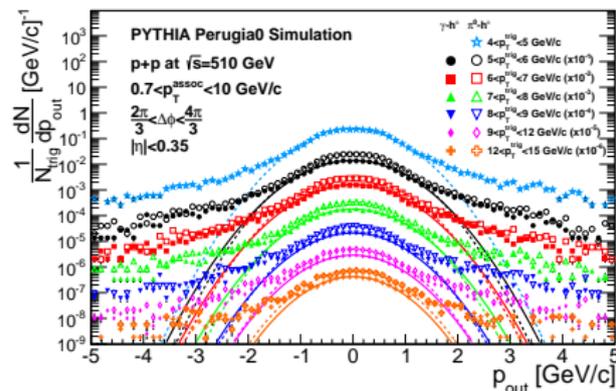
- R_γ^{iso} measured for statistical subtraction of isolated decay photon contribution
- R_γ measured in PHENIX and corrected by tagging and isolation efficiencies
- $R_\gamma^{iso} > 1$ indicates isolated direct photon production



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

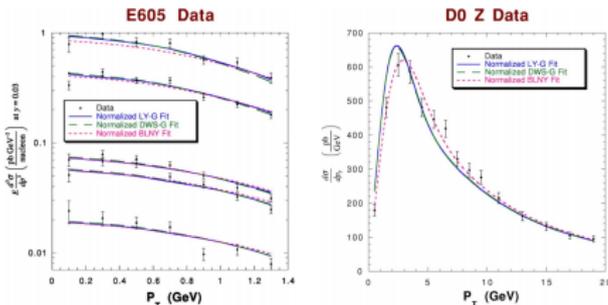
PYTHIA p_{out} Distributions

- 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

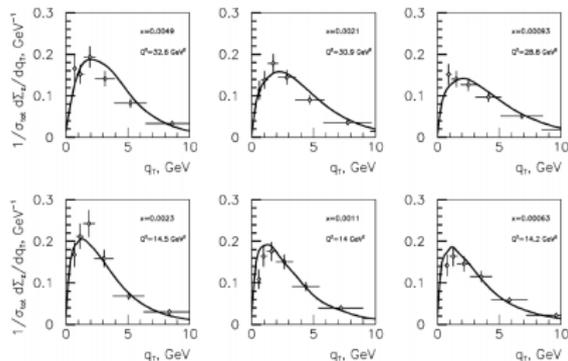
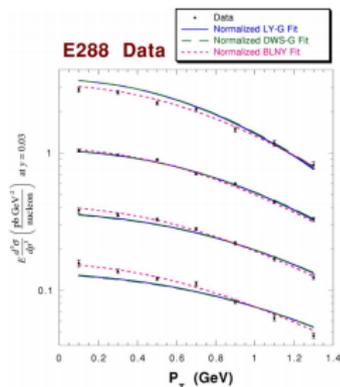


Other DY/Z and SIDIS Refs.

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

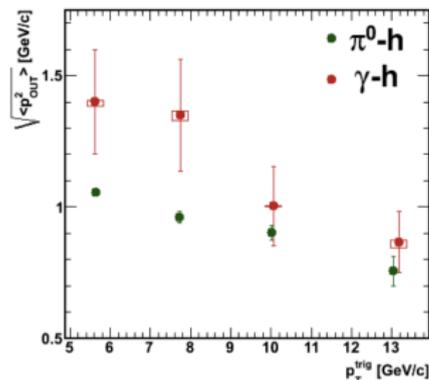
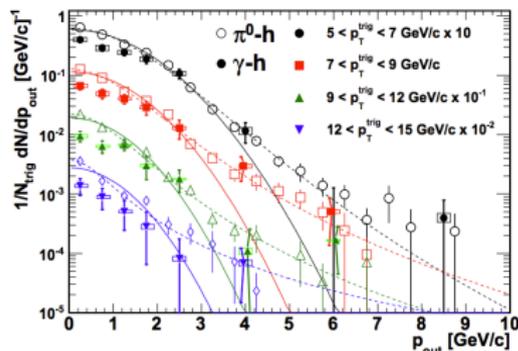


Phys. Rev. D 61, 014003 (2000)
(SIDIS)



$\sqrt{s}=200$ GeV Results

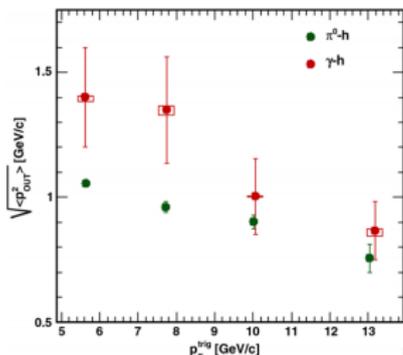
- Previous PHENIX result at $\sqrt{s}=200$ GeV with larger errors (Phys. Rev. D 82, 072001 (2010))
- Next step: analyze recent Run 15 $\sqrt{s}=200$ GeV $p+p$ and $p+A$ data from RHIC!
- 6x luminosity in Run 15 $p+p$, as well as first result from $p+A$



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

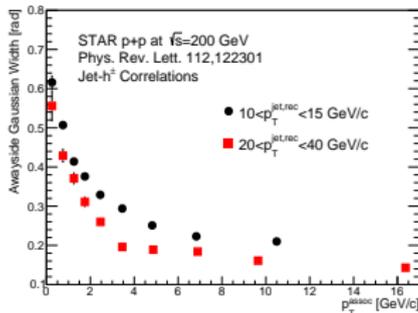
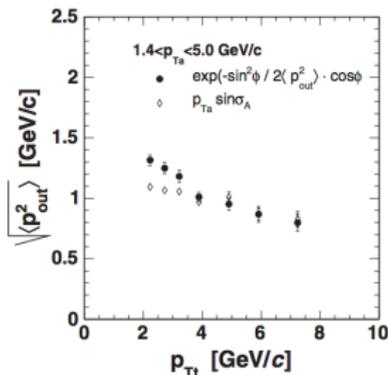
Other Measurements in Literature

- 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)



PRL 112,122301 (2014) (STAR)

Possible Links to Color Coherence Effects?

- D0, CDF, CMS have all published papers on evidence for "color coherence effects"
- Color flow and "antenna" traced through hard scatter with gluon radiation
- 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)

