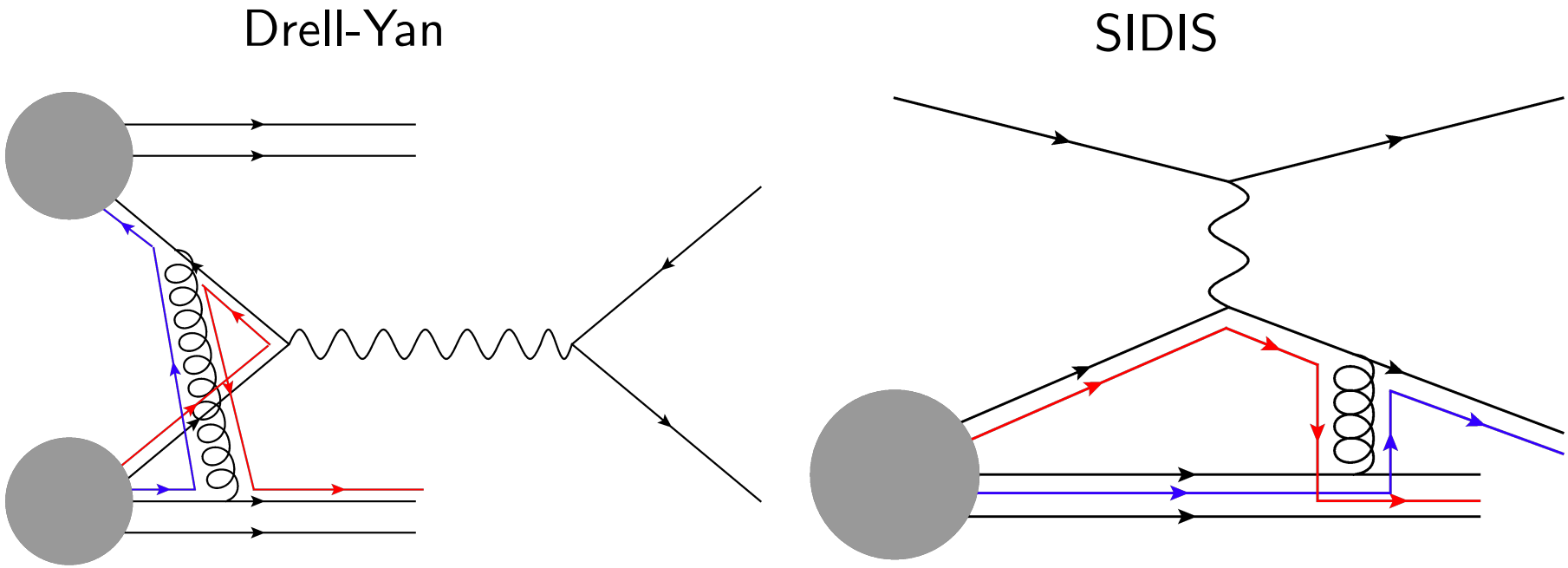
Nonperturbative Transverse Momentum Effects in Dihadron and Direct Photon-Hadron Angular Correlations

Joe Osborn for the PHENIX Collaboration

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

SPIN 2016

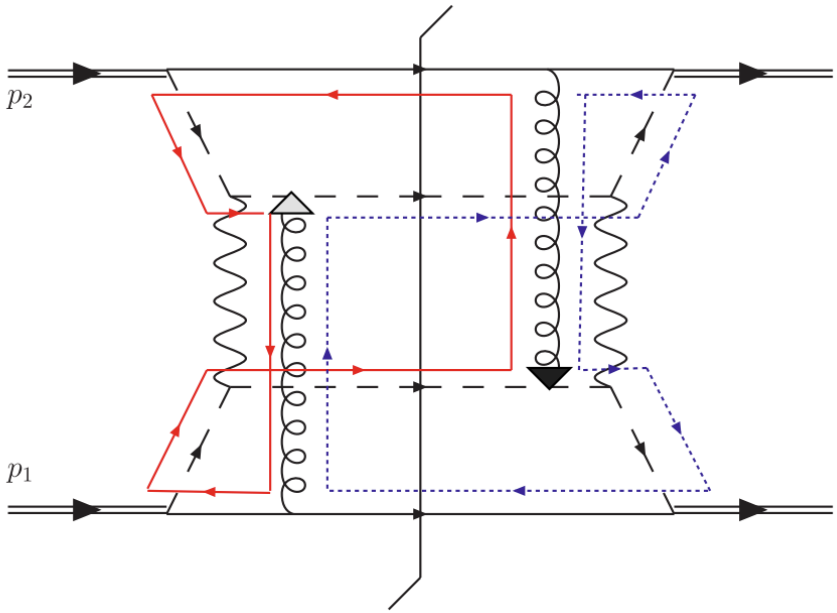
Universality and Factorization in TMDs



- 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 $p+p \to h_1 h_2$ 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

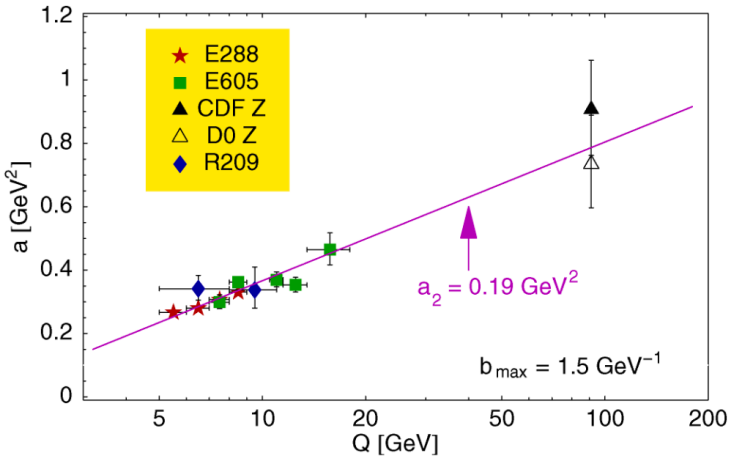


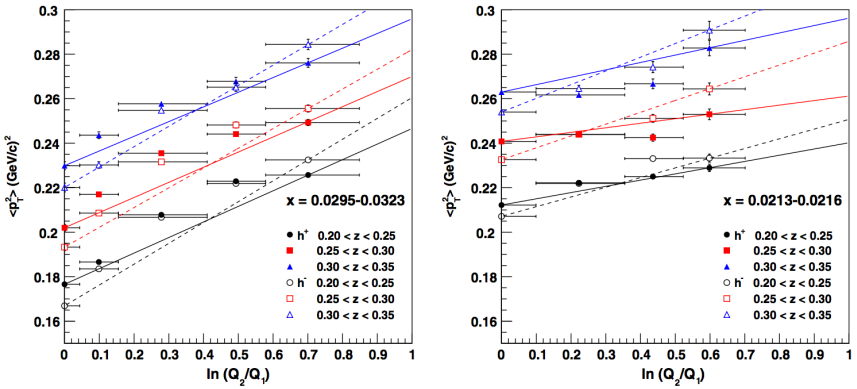
- $\geq$2 gluons exchanged with proton remnants leads to predicted breakdown

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

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

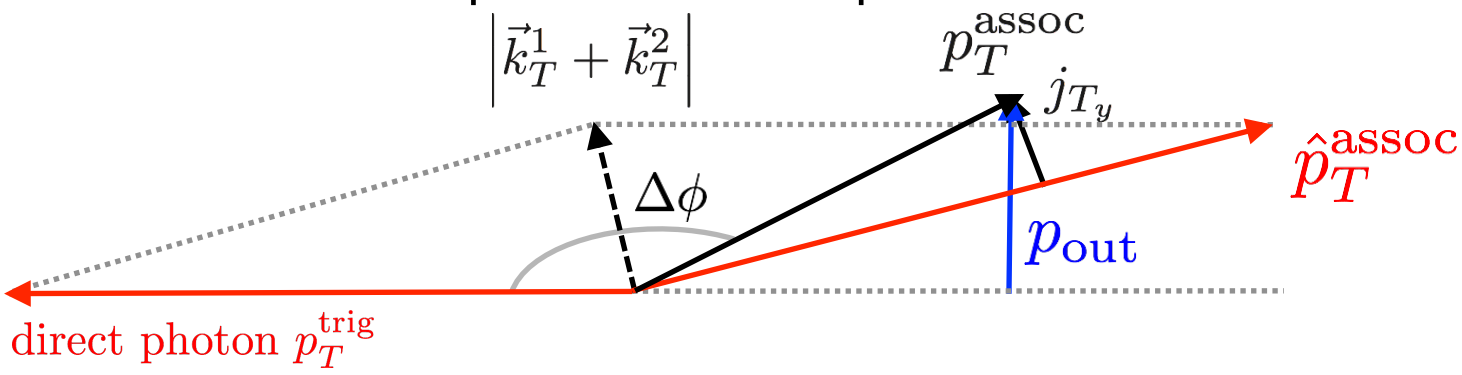




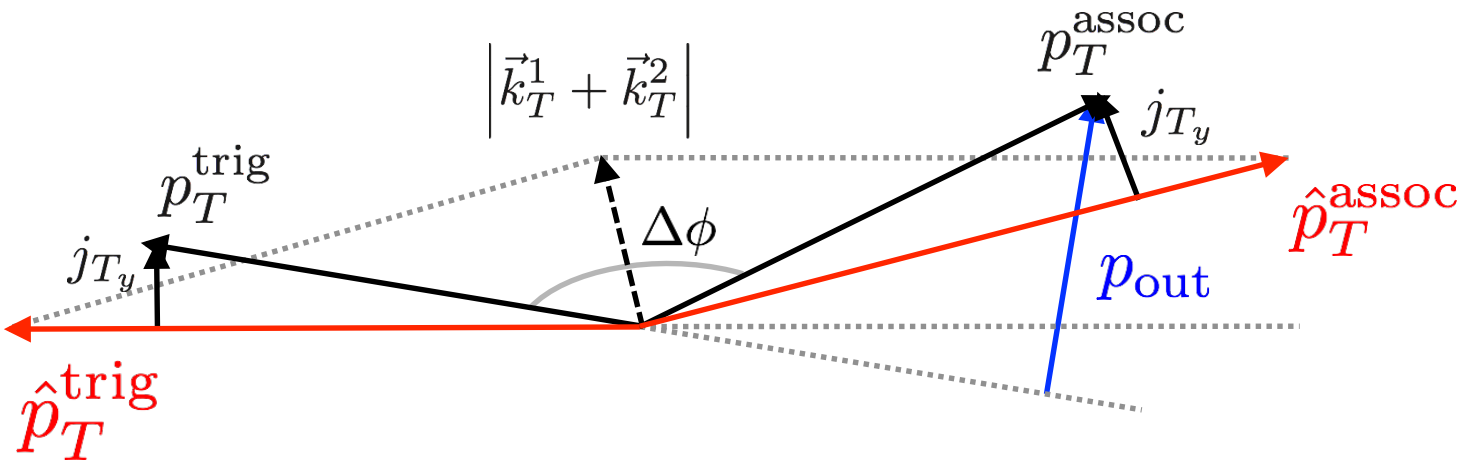
Phys. Rev. D 89, 094002 (2014)
(SIDIS)

Angular Correlation Observables

Direct photon-hadron production



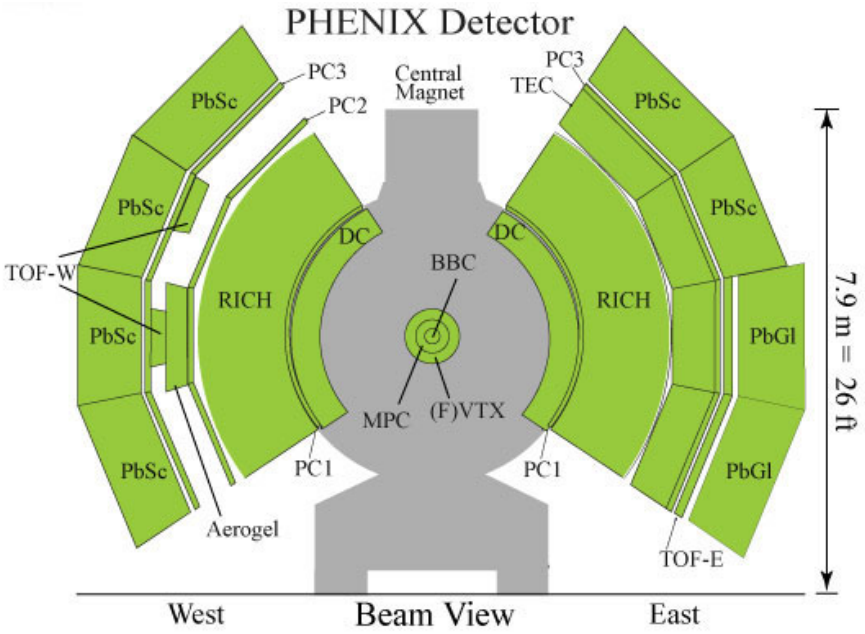
Dihadron production



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

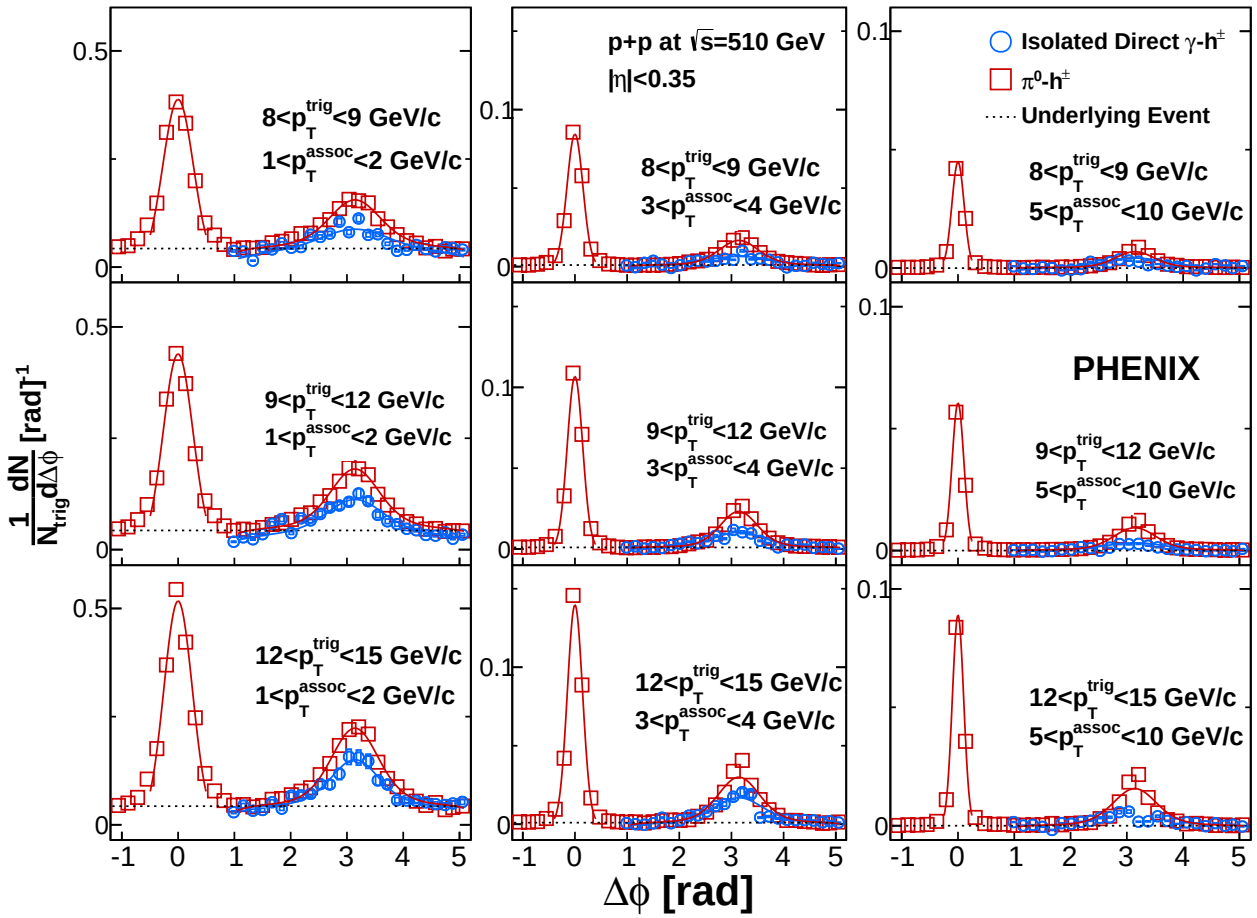
PHENIX Detector

- 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



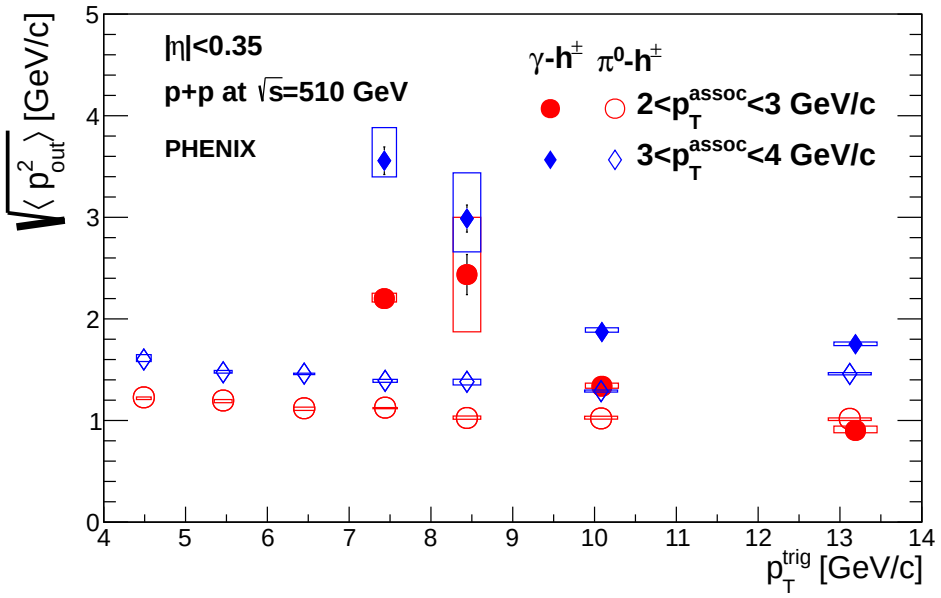
- New results from 2012/2013 $\sqrt{s}$=510 GeV p+p runs

$\Delta\phi$ 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

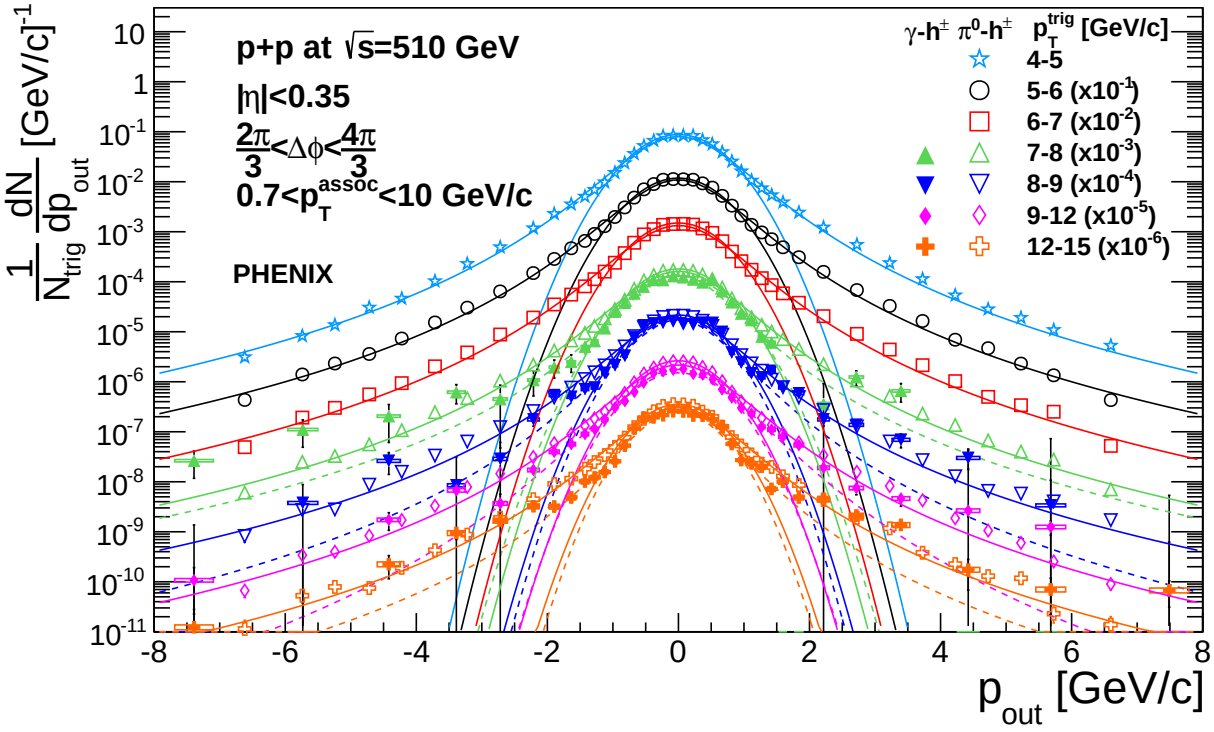
$\sqrt{\langle p_{out}^2 \rangle}$ Extracted from Fits to $\Delta\phi$ Correlations



- $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width in momentum space
- Decreases with hard scale, opposite of SIDIS and DY!
- Sensitive to perturbative and nonperturbative k_T and j_T

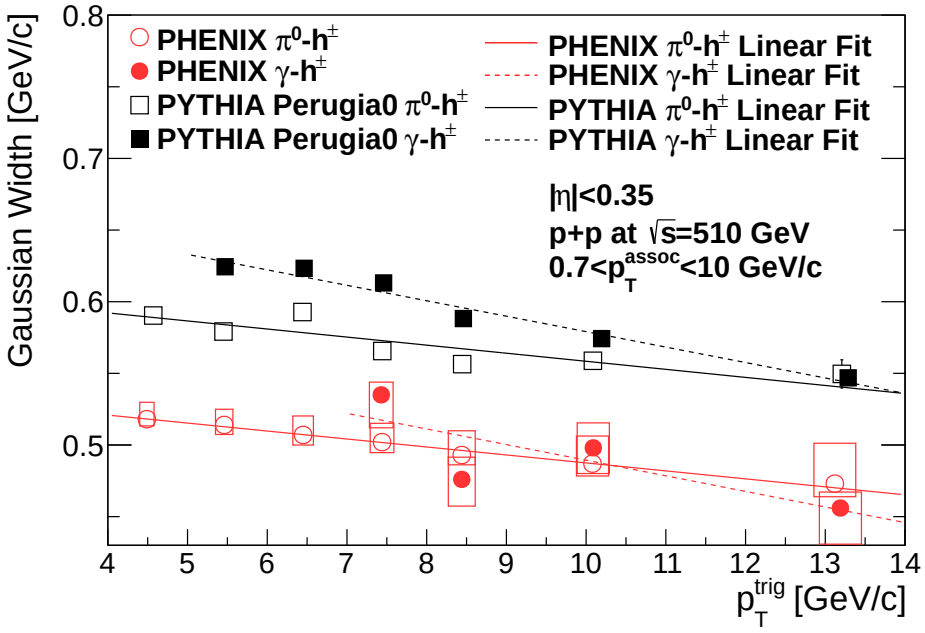
p_{out} Distributions

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

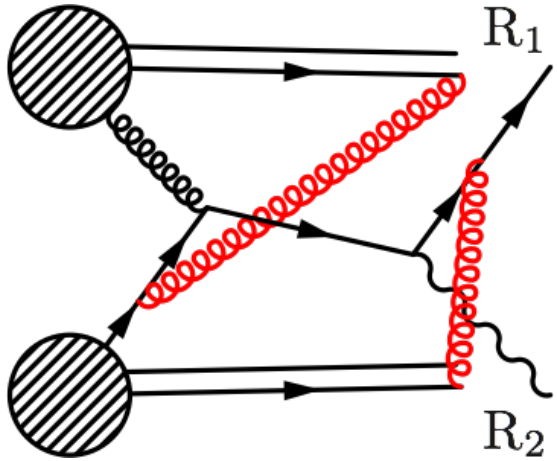
Conclusions

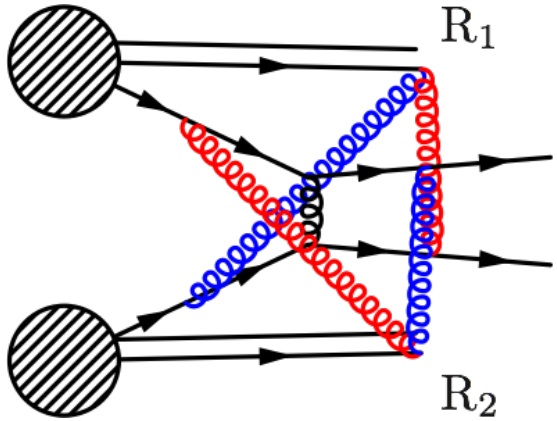
- Factorization breaking has been predicted in $p + p \rightarrow h + X$ collisions for observables sensitive to nonperturbative transverse momentum
- New measurements from PHENIX of nearly back-to-back dihadron and isolated direct photon-hadron correlations at $\sqrt{s}$=510 GeV
- Angular correlations 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
- Paper submitted to Phys. Rev. D, arXiv:1609.04769

Back Up

Direct Photons and Dihadrons

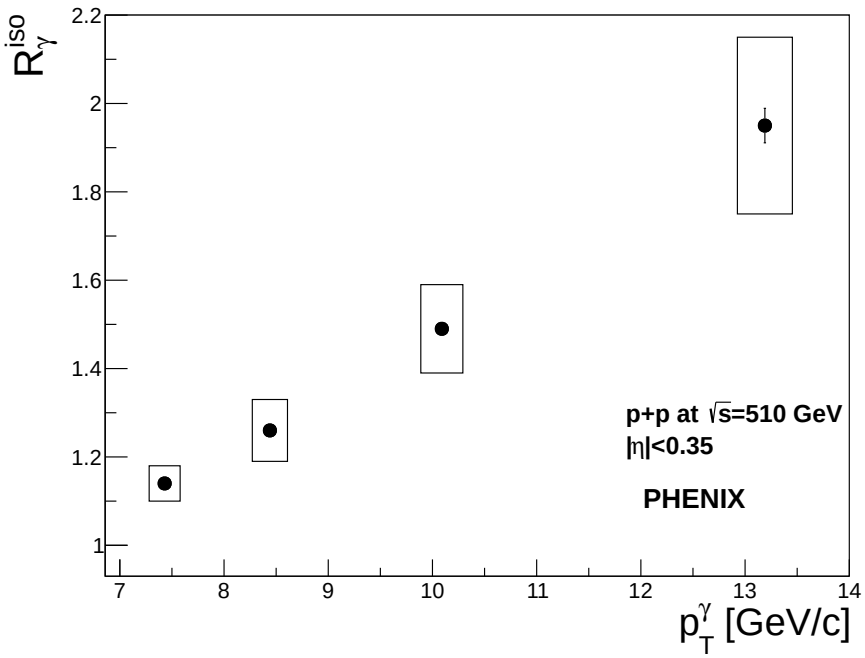
- Direct photon-hadron and dihadron correlations both predicted to be sensitive to factorization breaking effects in PHENIX
- Assuming factorization, direct photon-hadrons probe three nonperturbative functions, while dihadrons probe four
- Direct photons offer one less avenue for gluon exchange in the final-state: fewer/different effects?





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

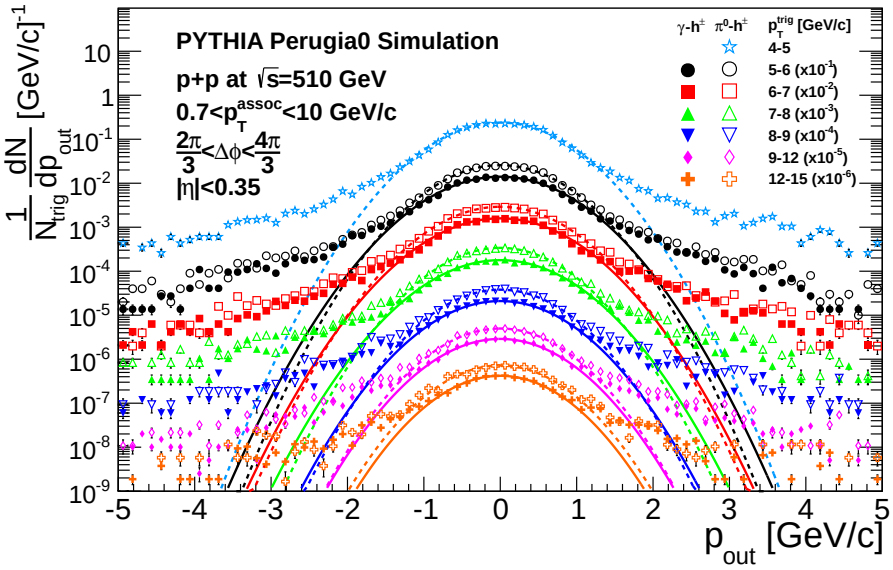
- R_γ^{iso} measured for statistical subtraction of isolated decay photon contribution
- R_γ measured in PHENIX and corrected by tagging and isolation efficiencies
- $R_\gamma^{iso} > 1$ indicates isolated direct photon production



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

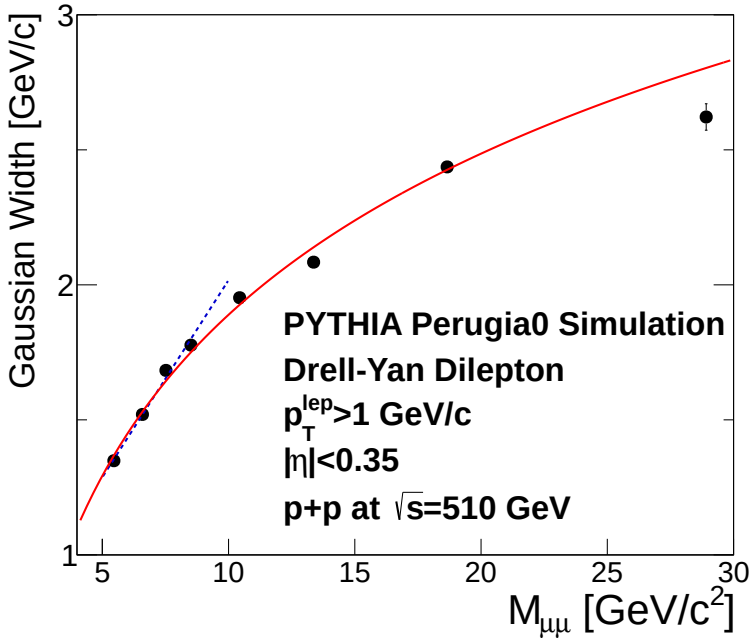
PYTHIA p_{out} Distributions

- 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

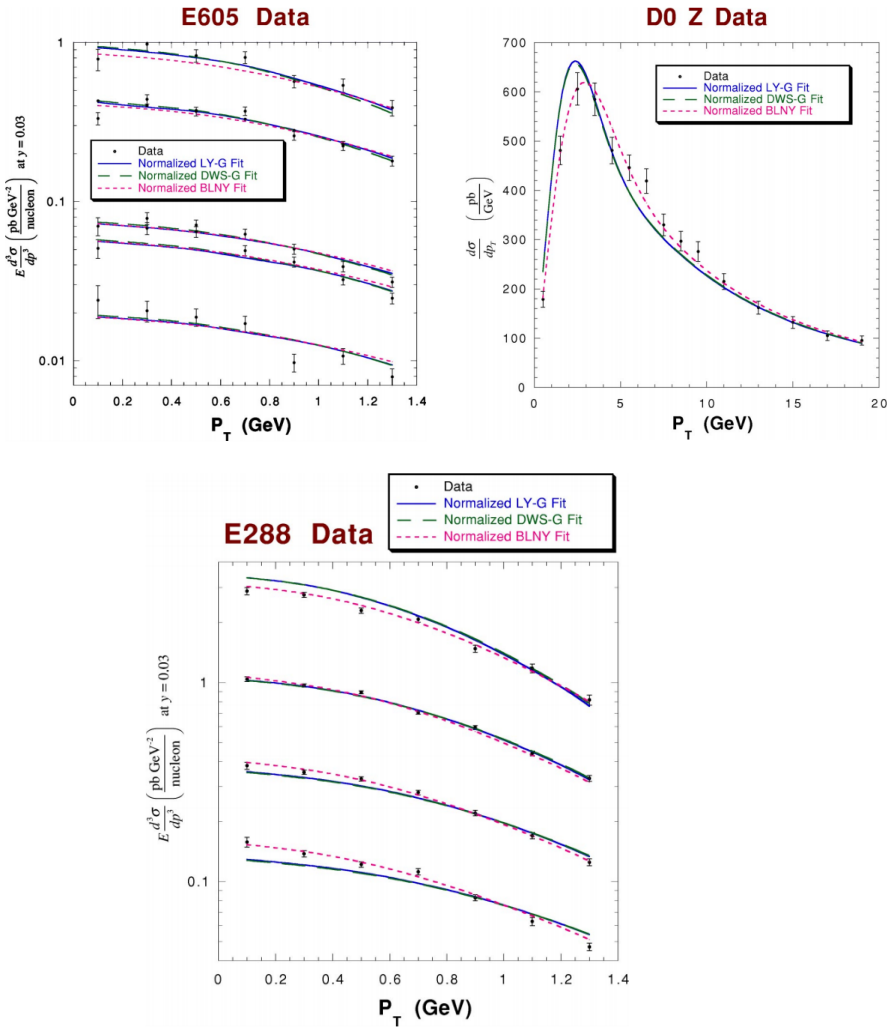
- Can check if PYTHIA also reproduces CSS evolution with DY dimuon production
- Construct same observable $p_{out} = p_T^{lep} \sin \Delta\phi$ between two nearly back-to-back leptons
- PYTHIA confirms expectation from CSS evolution for same observable



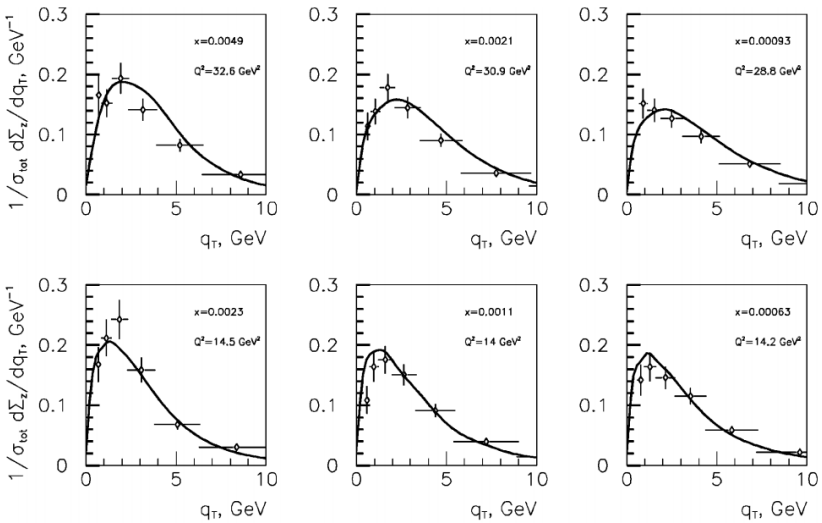
- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

Other DY/Z and SIDIS Refs.

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

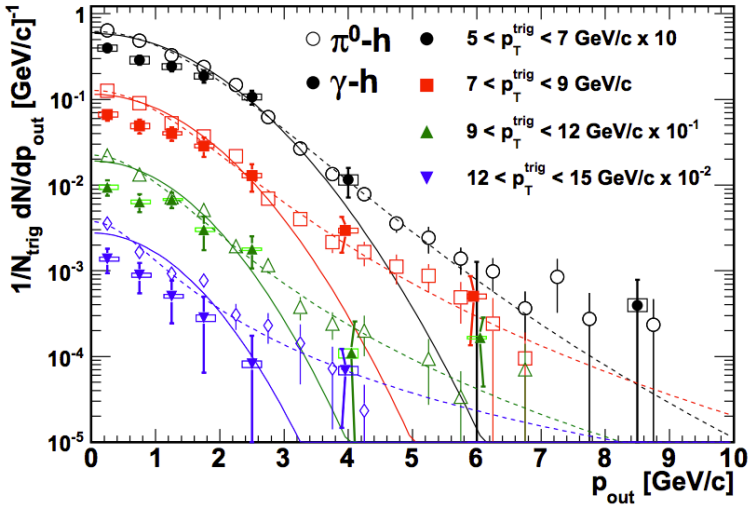


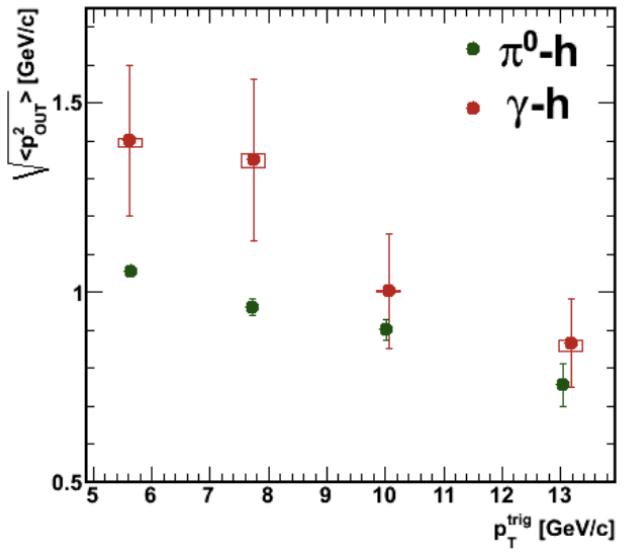
Phys. Rev. D 61, 014003 (2000)
(SIDIS)



$\sqrt{s}$=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!



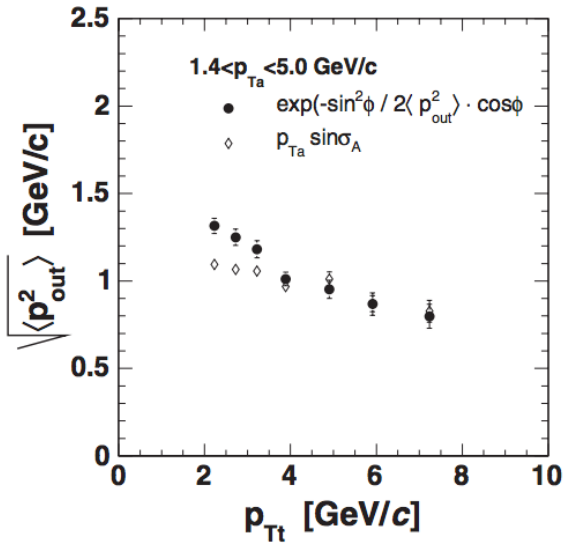


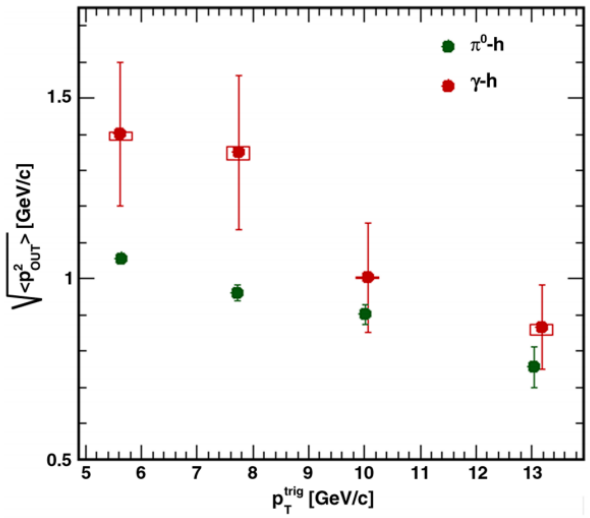
$$2 < p_T^{assoc} < 5$$

Other Measurements in Literature

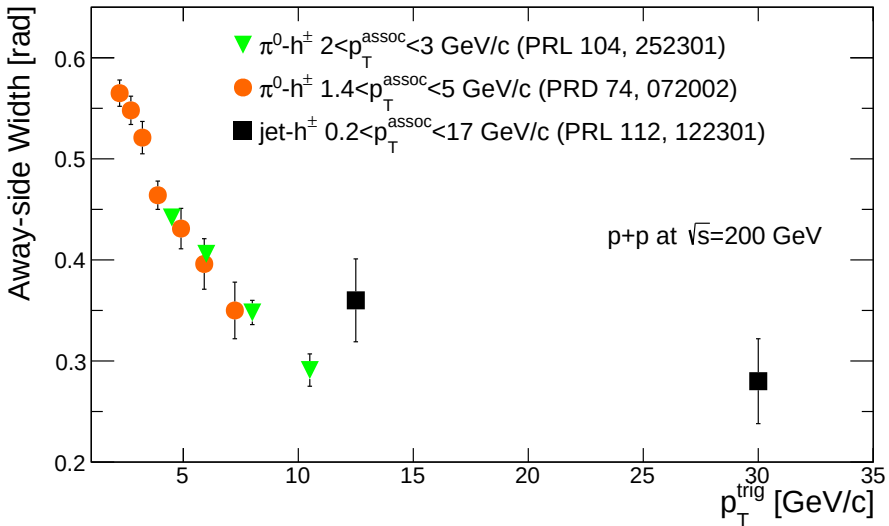
- Other RHIC publications show the same effect in $\sqrt{\langle p_{out}^2 \rangle}$ and away-side width
- All previous analyses motivated by different physics goals: fragmentation functions, partonic energy loss in QGP, etc.

PRD 74, 072002 (2006) (PHENIX)



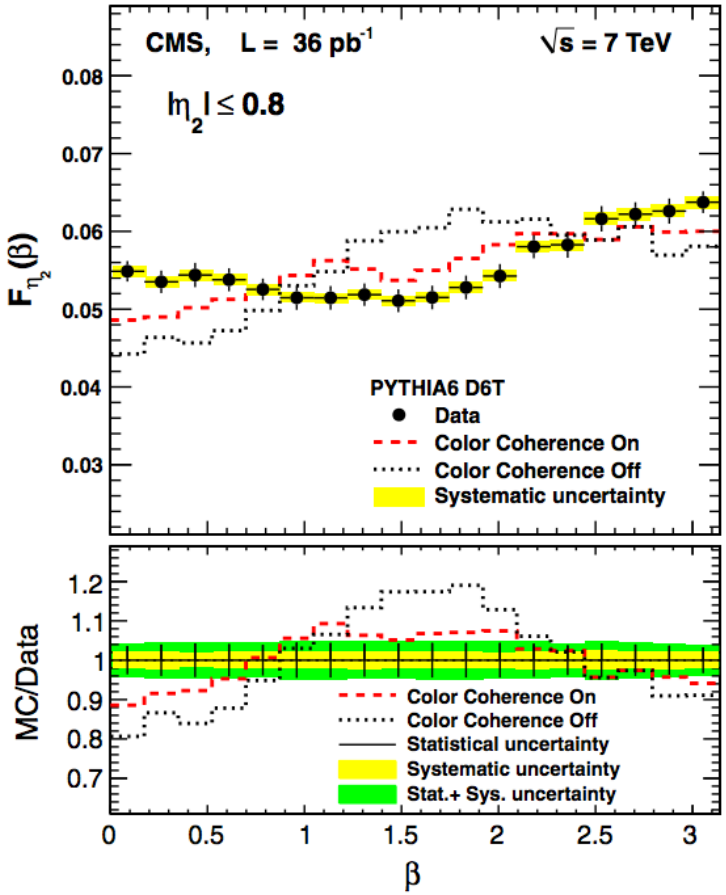


PRD 82, 072001 (2010) (PHENIX)



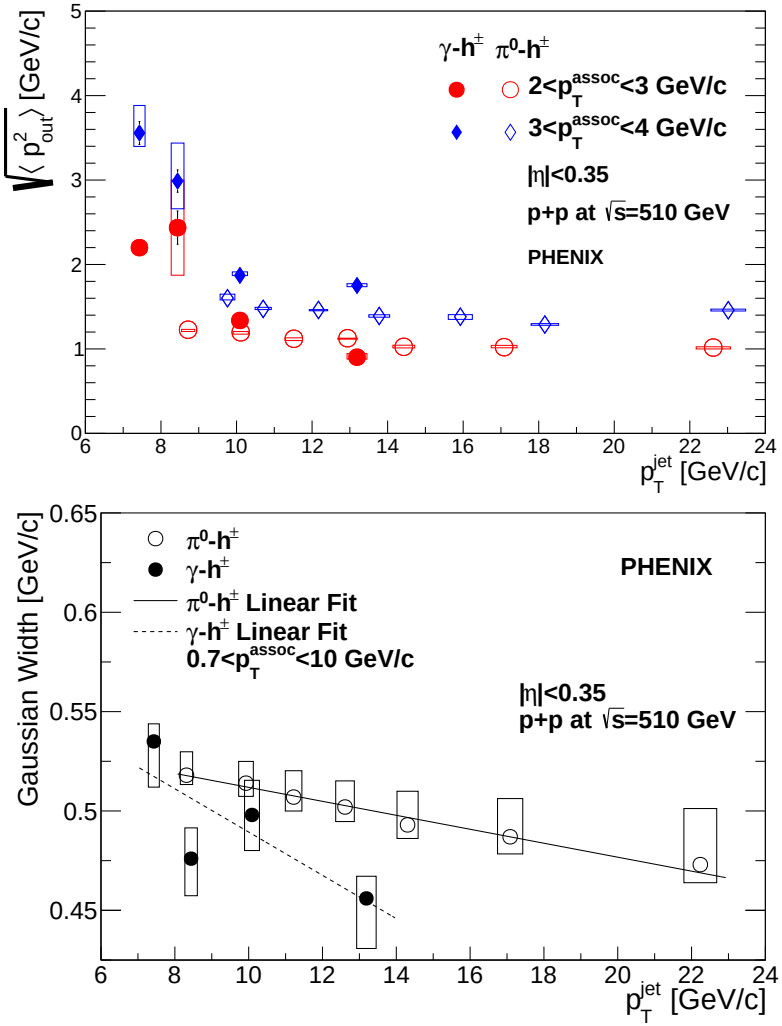
Possible Links to Color Coherence Effects?

- 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

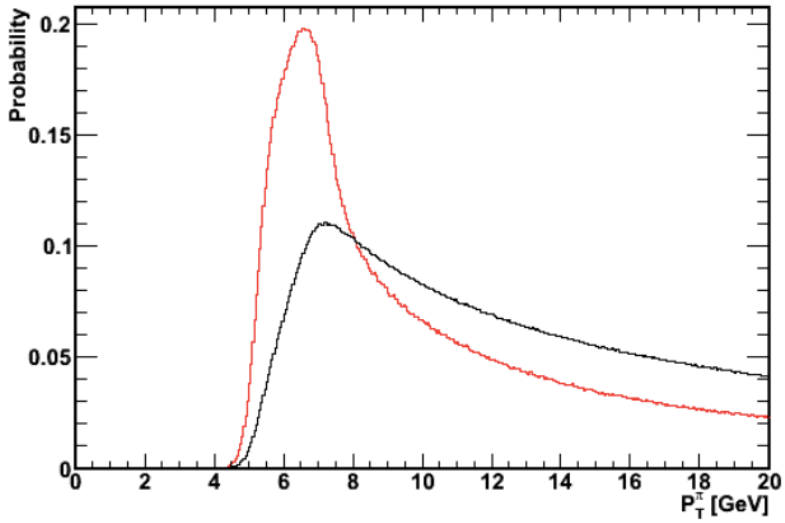
- Direct photons emerge directly from hard scattering, π^0s are a fragment
- Thus a more direct comparison is between p_T^{trig} for direct photon and jet p_T^{trig} for π^0
- Determine $\langle z_T \rangle = p_T^{\pi^0} / \hat{p}_T^{parton}$ using PYTHIA, "correct" π^0 p_T^{trig} to get $p_T^{jet} =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



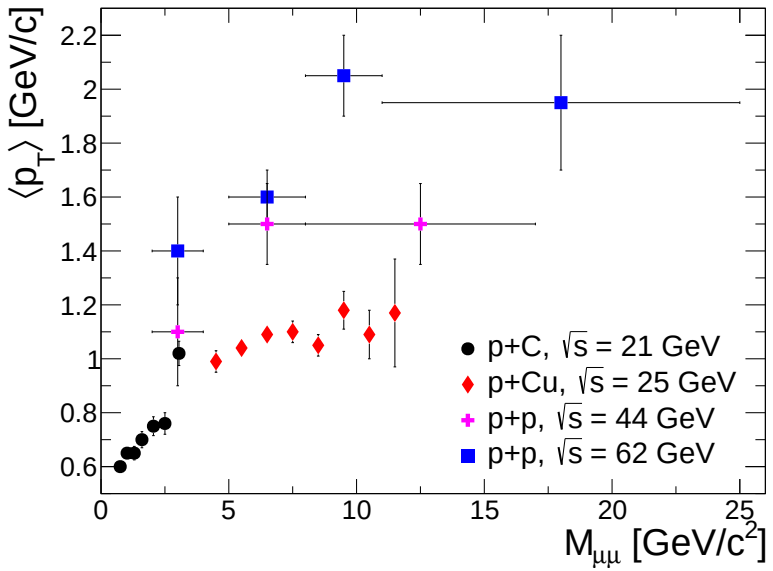
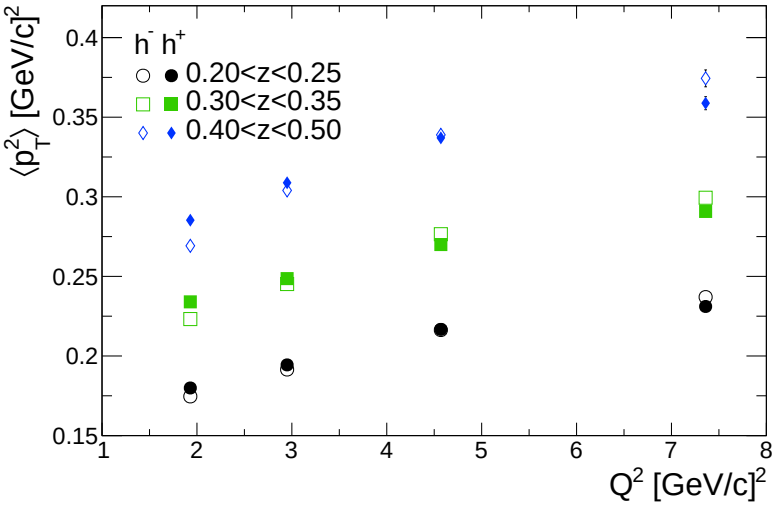
Analysis Methods

- 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)