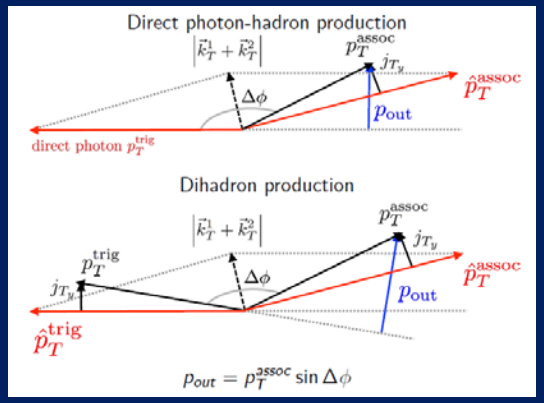
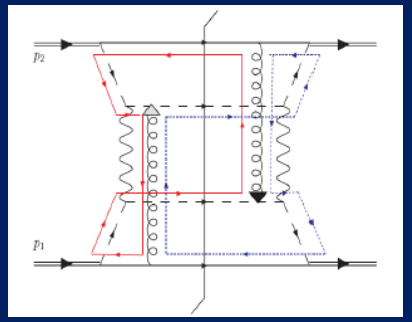
Searching for Factorization-Breaking Effects via Two-Particle Correlation Measurements in Hadronic Collisions



Christine A. Aidala
University of Michigan



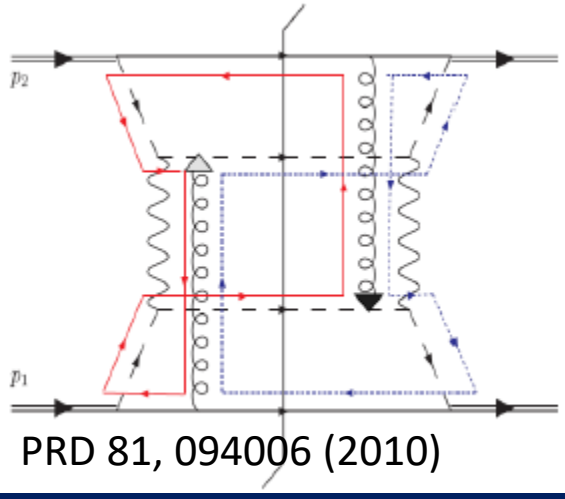
APS April Meeting
January 29, 2017

Transverse-momentum-dependent (TMD) factorization breaking and color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons if parton transverse momentum taken into account
- Due to gluon exchange between scattering parton and proton remnant in *both* initial and final state

- Partons become correlated *across* the two colliding protons
  - Can no longer factorize the nonperturbative functions into independent pdfs and fragmentation functions
  - Will need new (unknown) nonperturbative functions describing quantum-correlated partons across bound states

- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!



PRD 81, 094006 (2010)

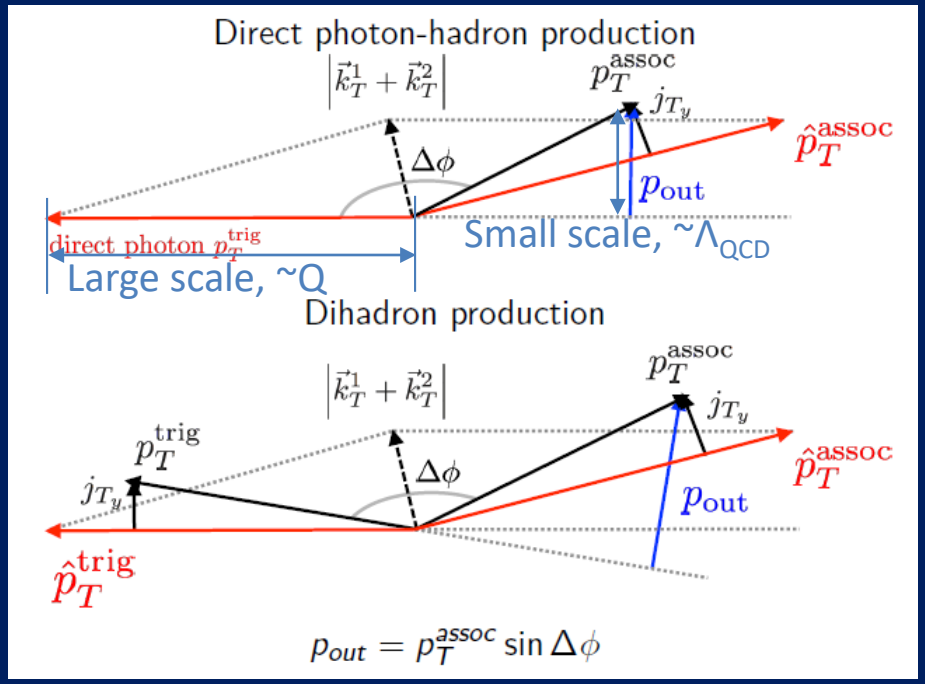
$$p + p \rightarrow h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires simultaneous presence of both.

Searching for evidence of predicted TMD-factorization breaking at RHIC

- Need observable sensitive to a nonperturbative momentum scale
  - Nearly back-to-back particle production
- Need 2 initial-state hadrons
  - color exchange between a scattering parton and remnant of other proton
- And at least 1 final-state hadron
  - exchange between scattered parton and either remnant

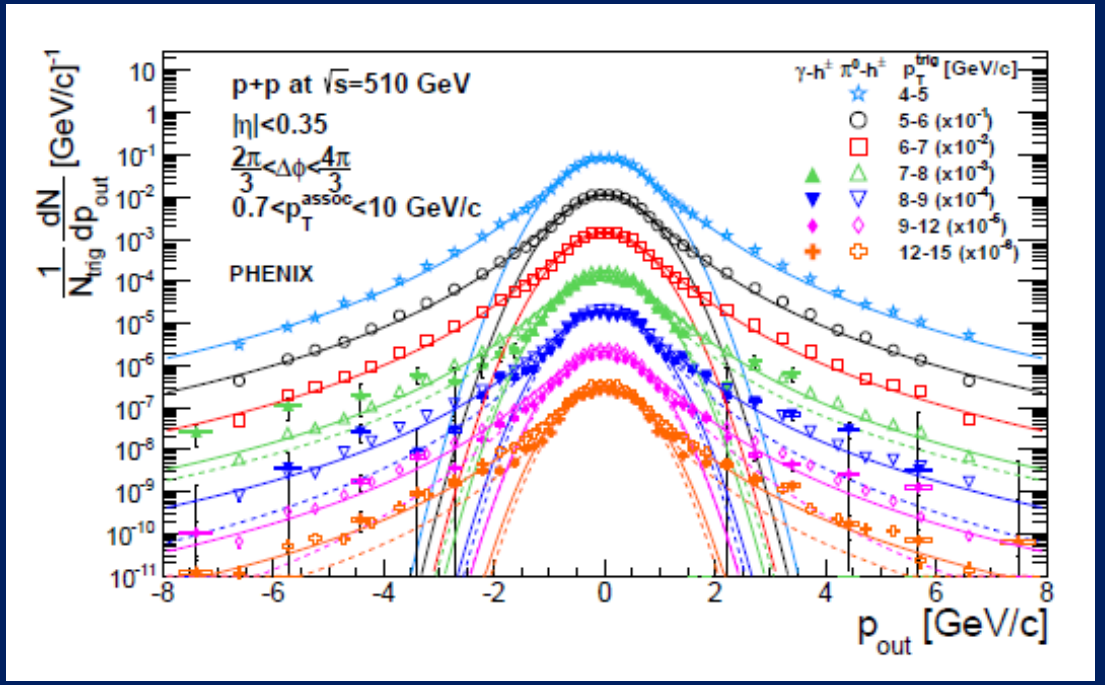
→ In p+p collisions, measure out-of-plane momentum component in nearly back-to-back photon-hadron and hadron-hadron production



Out-of-plane momentum component distributions

- Clear two-component distribution
  - Gaussian near zero—nonperturbative transverse momentum
  - Power-law at large p_{out}—kicks from hard (perturbative) gluon radiation
- Different colors → different bins of trigger particle p_T, proxy for hard interaction scale

PHENIX Collab., arXiv:1609.04769



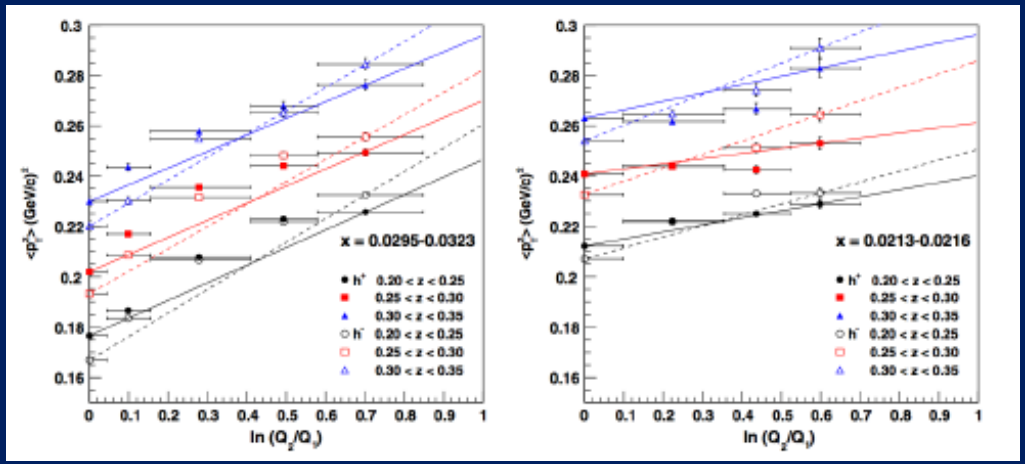
Curves are fits to Gaussian and Kaplan functions, not calculations!

*Look at **evolution** of nonperturbative transverse momentum widths with hard scale (Q^2)*

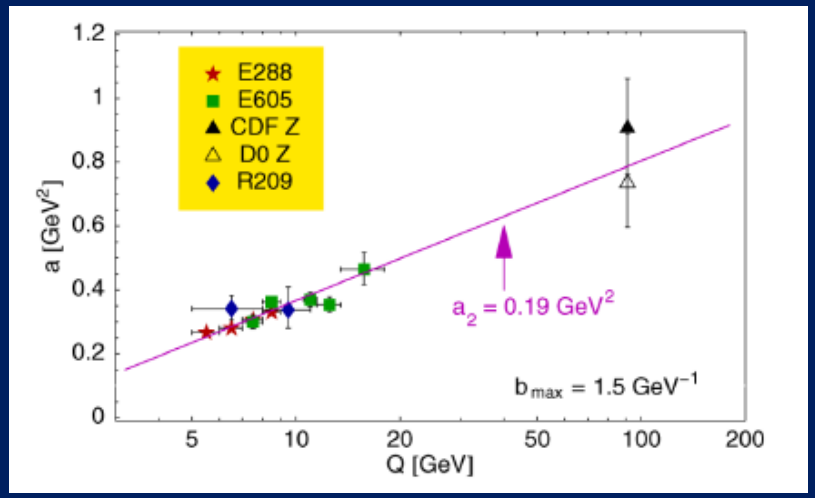
- Theoretical proof of factorization within transverse-momentum-dependent framework directly predicts that nonpertubative transverse momentum widths *increase* as a function of the hard scattering energy scale (Collins-Soper-Sterman evolution)
  - Increased phase space for gluon radiation

*Look at **evolution** of nonperturbative transverse momentum widths with hard scale (Q^2)*

- Theoretical proof of factorization within transverse-momentum-dependent framework directly predicts that nonpertubative transverse momentum widths *increase* as a function of the hard scattering energy scale (Collins-Soper-Sterman evolution)
  - Increased phase space for gluon radiation
- Confirmed experimentally in semi-inclusive deep-inelastic lepton-nucleon scattering (left) and quark-antiquark annihilation to leptons (right)

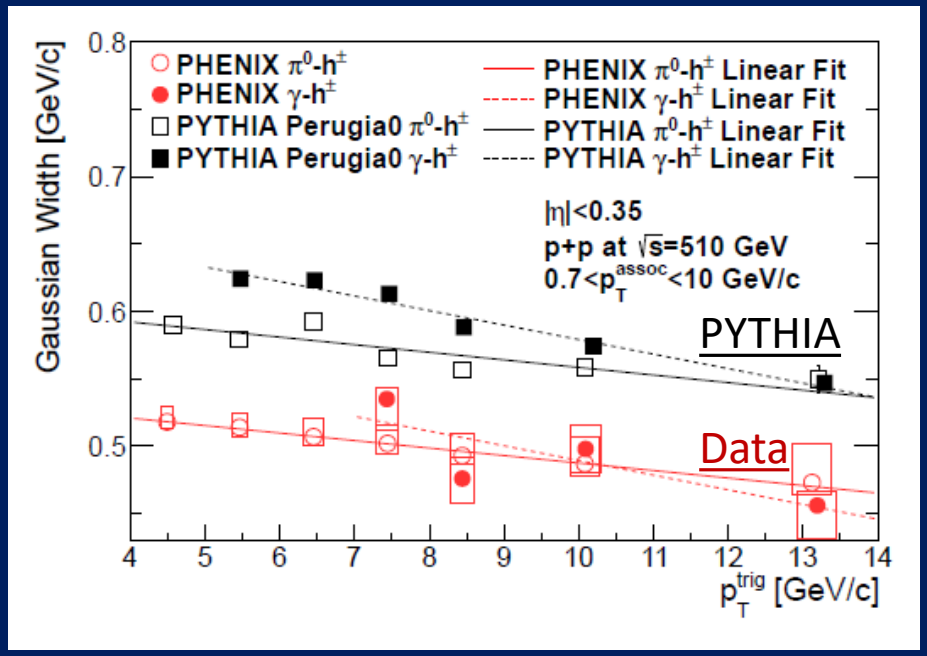


Aidala, Field, Gamberg, Rogers, Phys. Rev. D89, 094002 (2014)



Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)

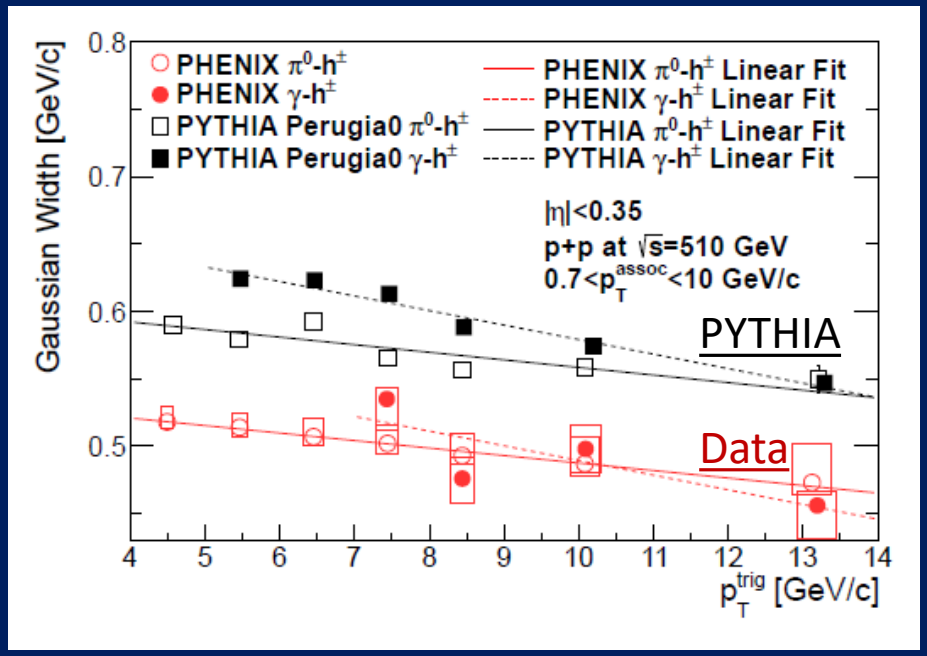
*Nonperturbative momentum widths observed to **decrease** in processes where factorization breaking predicted*



PHENIX Collab., arXiv:1609.04769

- Suggestive of TMD-factorization breaking effects?
- Have not yet completely ruled out a "trivial" nonperturbative correlation between partonic longitudinal momentum fraction *x* and partonic transverse momentum k_T
- Steeper negative slope for photon-hadron than dihadron correlations—counterintuitive?
  - Photon can't exchange gluon with remnant—might expect weaker effects than dihadron case

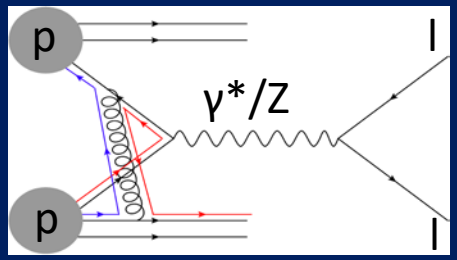
*Nonperturbative momentum widths observed to **decrease** in processes where factorization breaking predicted*



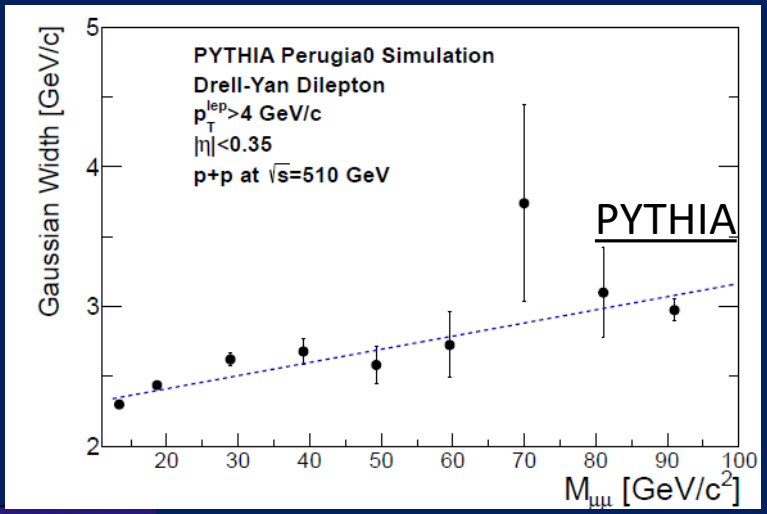
PHENIX Collab., arXiv:1609.04769

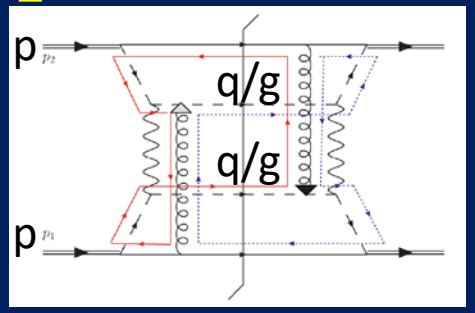
- Slope of decrease for both photon-hadron and dihadron correlations reproduced ~exactly in PYTHIA p+p event generator—could this effect be in PYTHIA??
  - Effectively yes! Unlike analytic pQCD calculations, PYTHIA forces *entire event including remnants* to color neutralize, implemented via something they call “color reconnection”

Comparing simulated Drell-Yan to simulated dihadron and photon-hadron

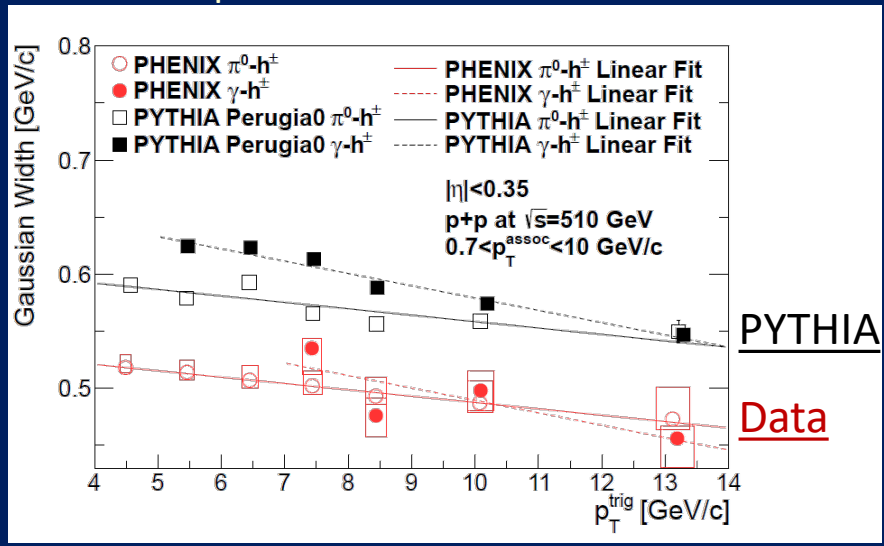


Example of TMD-factorized process:
Drell-Yan/Z production in PYTHIA simulation.
Momentum width increases with hard scale (M) as expected in CSS evolution





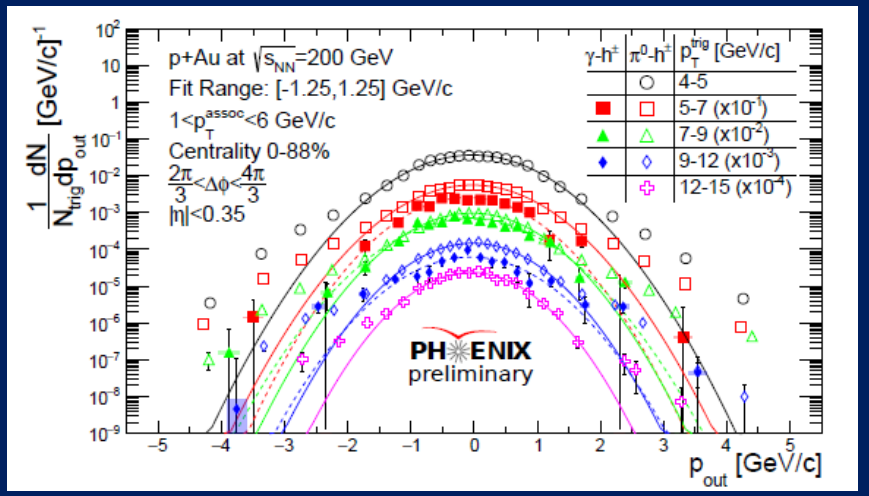
Non-TMD-factorized process: π^0+h, γ+h
Data and PYTHIA simulation:
Both show width decreases with scale (p_T^{trig}) in contrast to prediction from CSS evolution

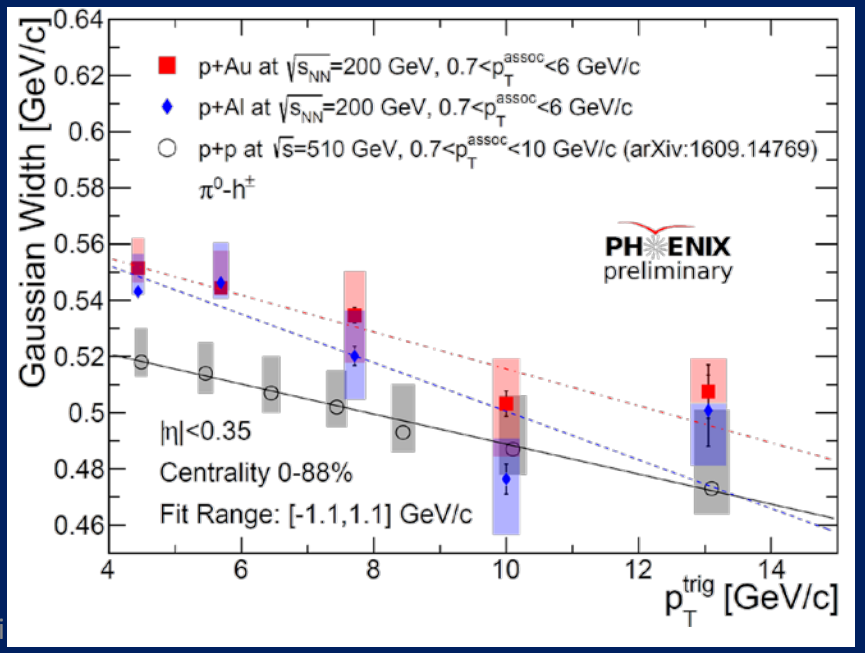


Dihadron correlations in p+A collisions

- Stronger gluon field from nuclear remnant than proton remnant → stronger potential effects due to factorization breaking?

- Gaussian transition to power law observed in p_{out} distribution as for p+p case
- Again decreasing widths with hard scale, for both p+Au and p+Al
  - Steeper than than (higher-energy) p+p?
  - 200 GeV p+p analysis underway
- Larger momentum widths than p+p
  - Larger initial-state k_T in nucleus?
  - Multiple scattering in nucleus?

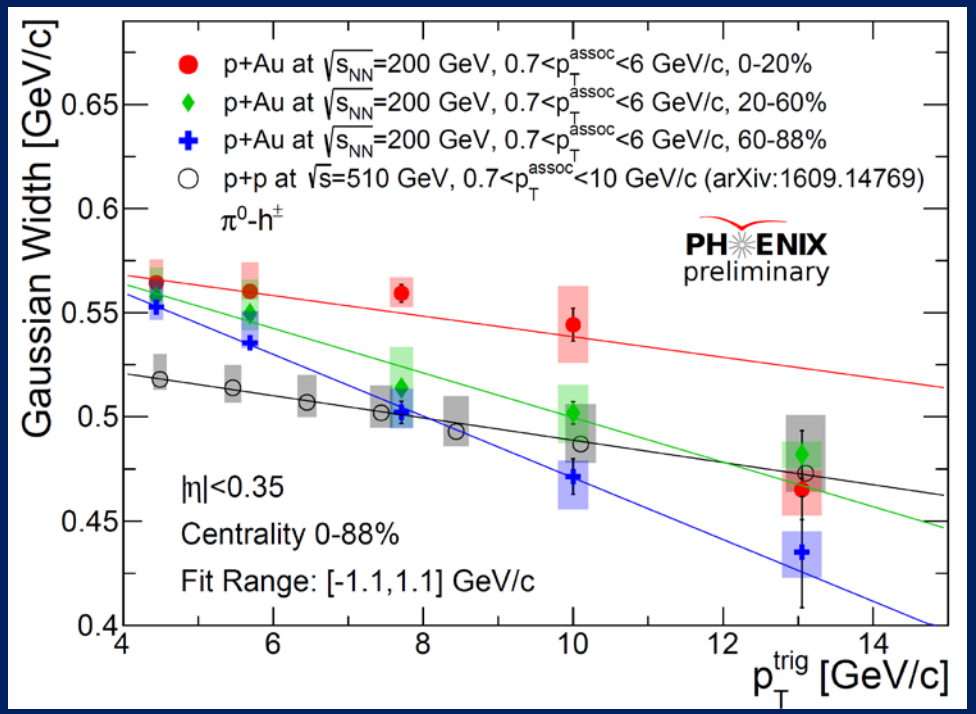




Dihadron correlations in p+A collisions: Centrality dependence

- Unexpected qualitative behavior—steeper negative slope of momentum width versus hard scale for more *peripheral* p+Au collisions

- Most *central* p+Au collisions show most similar slope to p+p



Summary

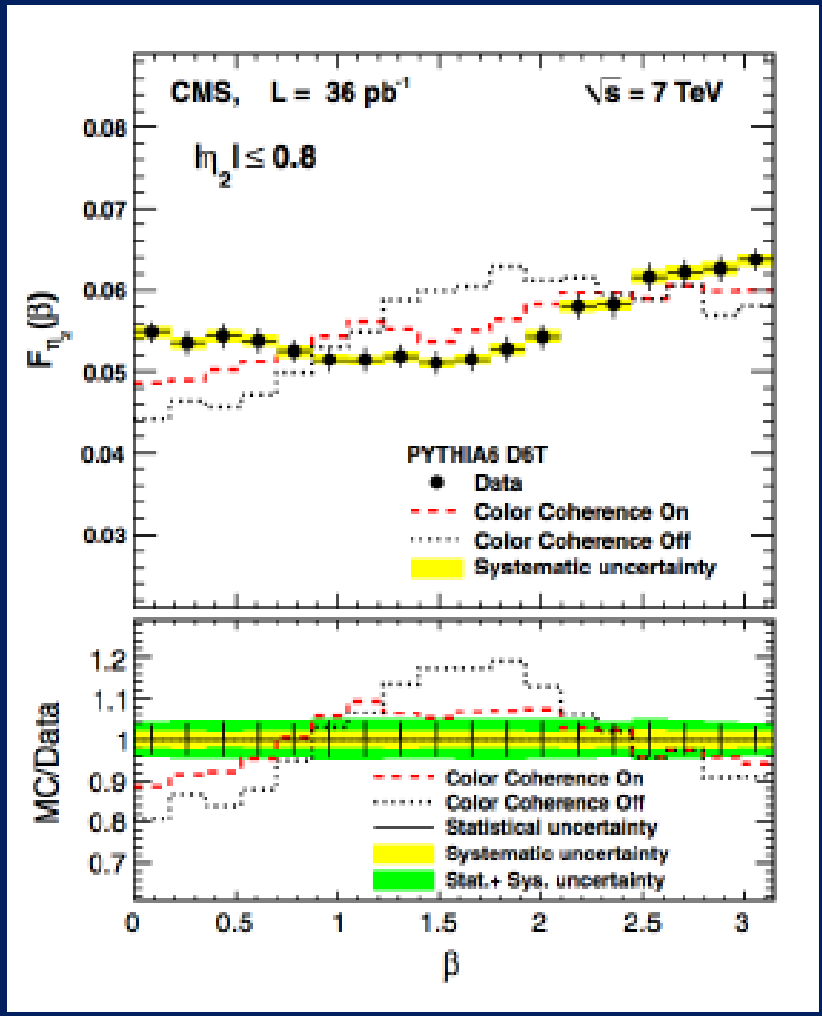
- We’re rolling up our sleeves and ready to start tackling QCD at new levels these years, explicitly digging into its non-Abelian nature
  - Hadronic collisions give access to QCD in its full glory!

- Will be exciting to continue testing and exploring ideas and phenomena related to color flow and factorization breaking in upcoming years . . .

Extra

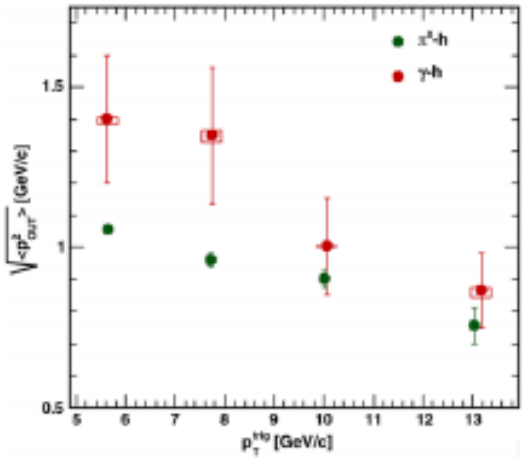
Possible links to "color coherence" at Tevatron and LHC?

- D0, CDF, CMS have all published evidence for "color coherence effects"
  - CMS: EPJ C74, 2901 (2014)
  - CDF: PRD50, 5562 (1994)
  - D0: PLB414, 419 (1997)
- Few citations—relatively little-known work thus far. Have initiated discussion with CMS to get different communities talking
  - Detailed color flow effects in QCD an emerging area!



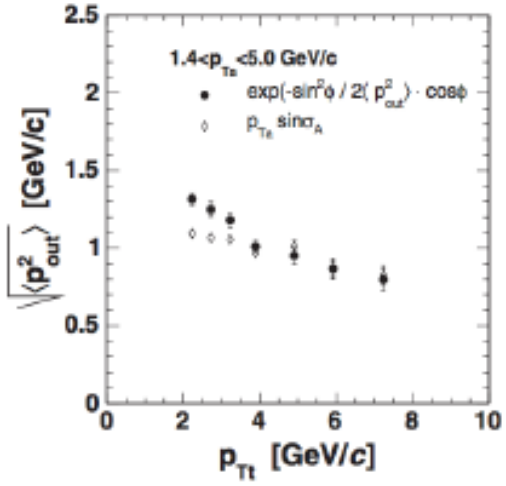
Other measurements showing decreasing nonperturbative momentum widths

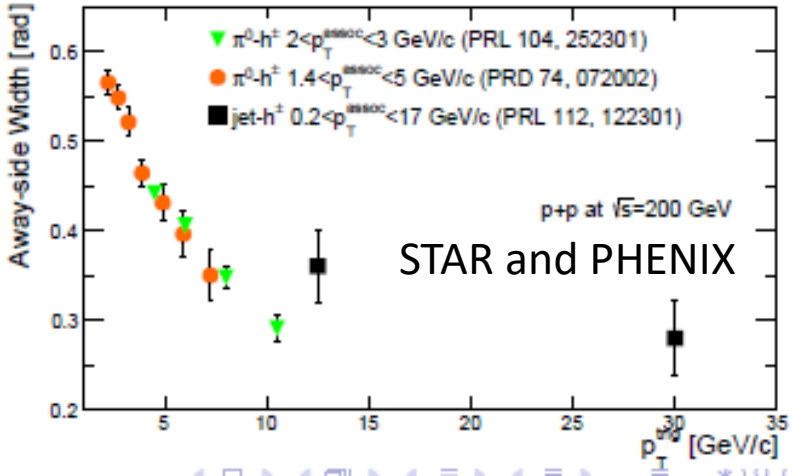
- Other RHIC publications show the same effect in $\sqrt{\langle p_{out}^2 \rangle}$ and away-side width
- All previous analyses motivated by different physics goals: fragmentation functions, partonic energy loss in QGP, etc.



PRD 82, 072001 (2010) (PHENIX)

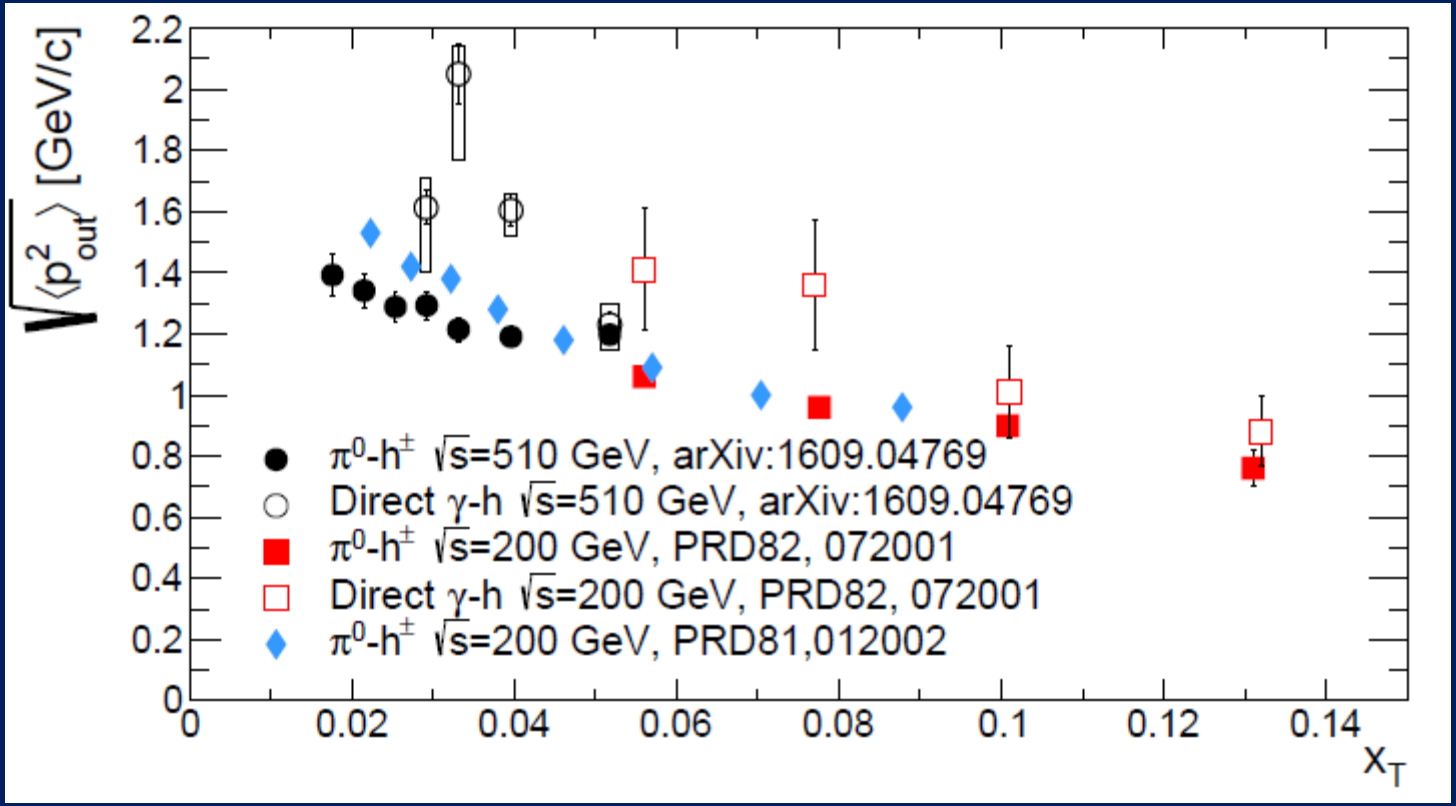
PRD 74, 072002 (2006) (PHENIX)





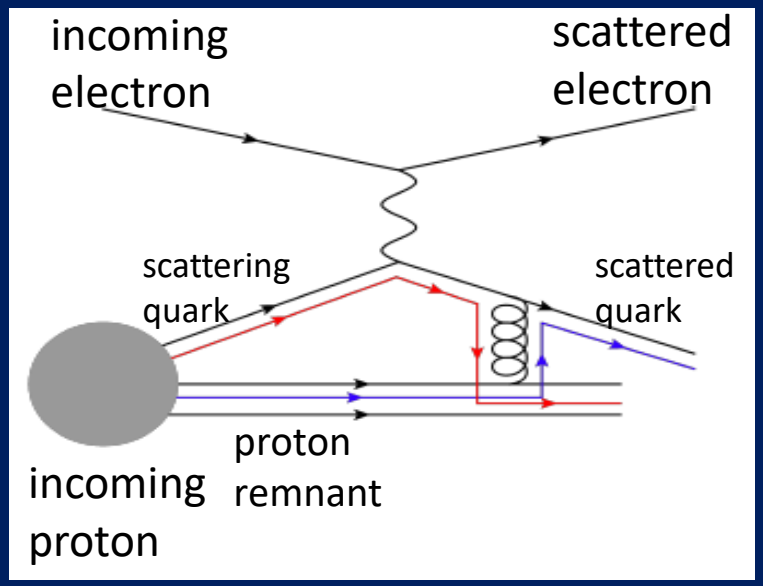
STAR and PHENIX

RMS p_{out} vs. x_T

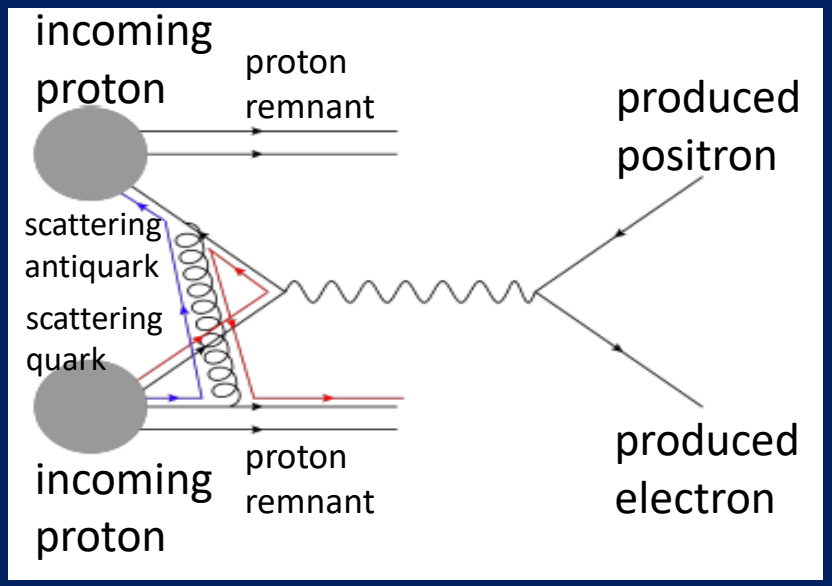


Modified universality of certain transverse-momentum-dependent distributions: Color in action!

Deep-inelastic lepton-nucleon scattering: Final-state color exchange



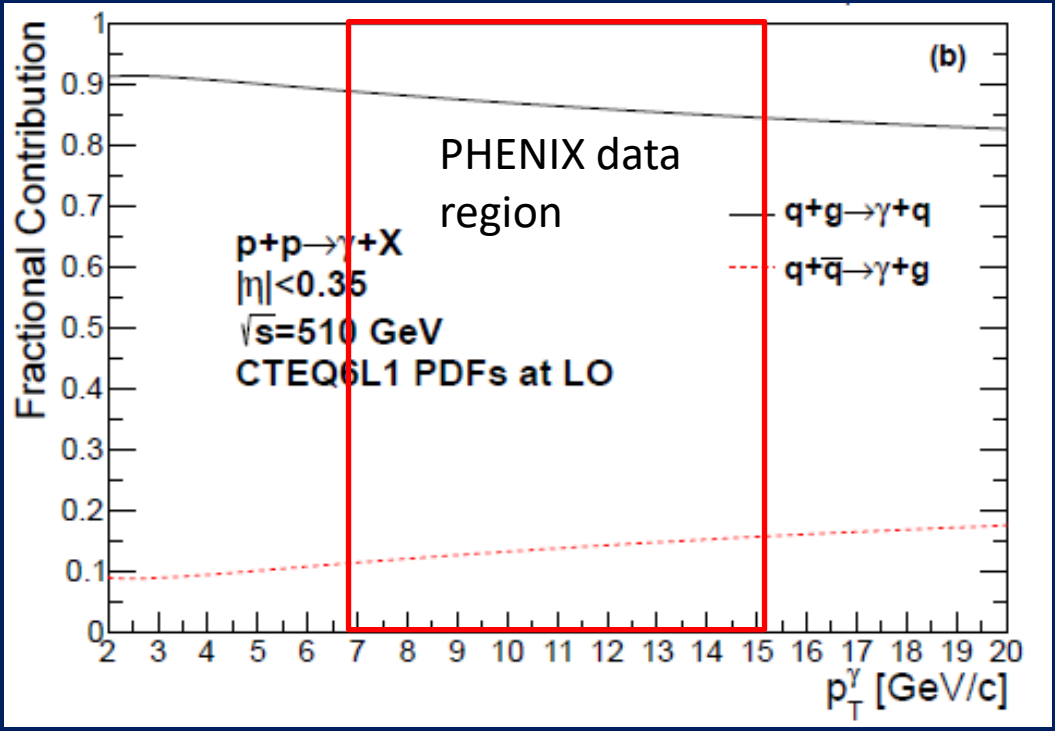
Quark-antiquark annihilation to leptons: Initial-state color exchange



As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

Figures by J.D. Osborn

Partonic process contributions for direct photon production

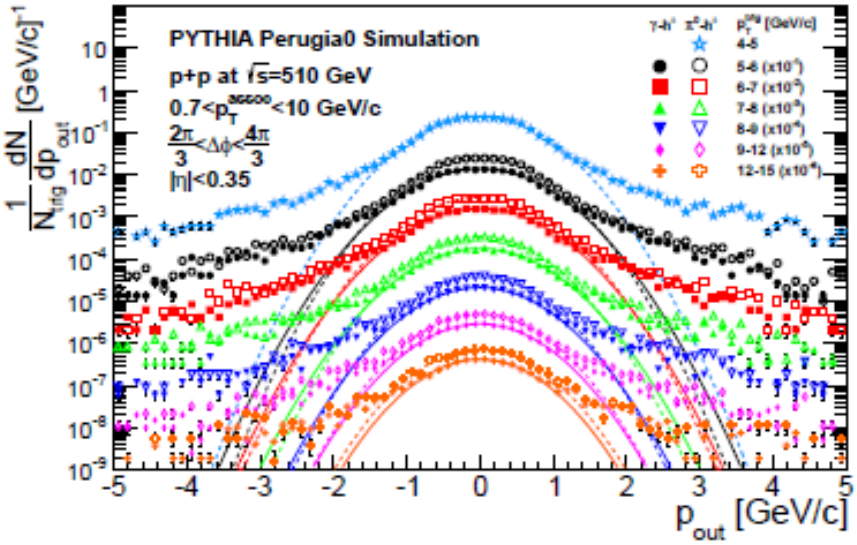


Quark-gluon Compton scattering still dominates at NLO - PLB140, 87 (1984)

PHENIX Collab., arXiv:1609.04769,
Submitted to PRD.
Calculation by T. Kaufmann

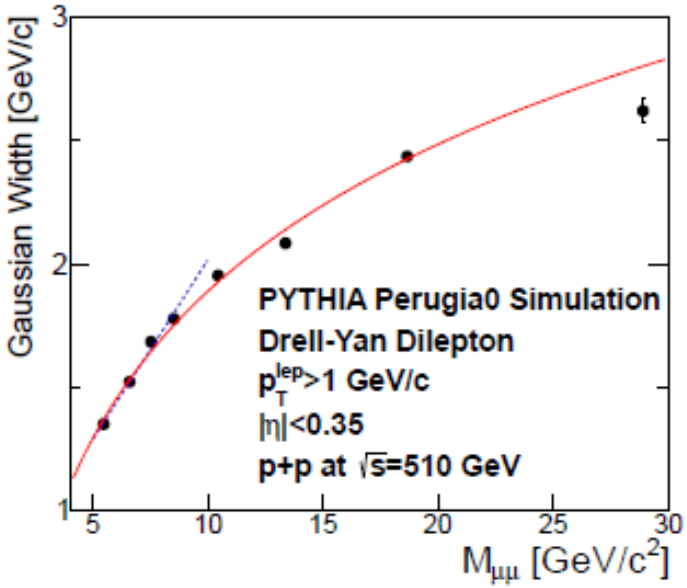
PYTHIA p_{out} distributions

- 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 Drell-Yan

- 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

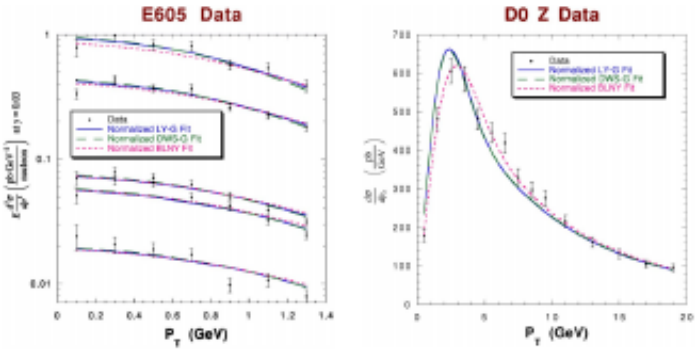


- Note rate of increase is significantly larger in magnitude also
- Red solid line shows log fit, blue dotted line shows linear fit

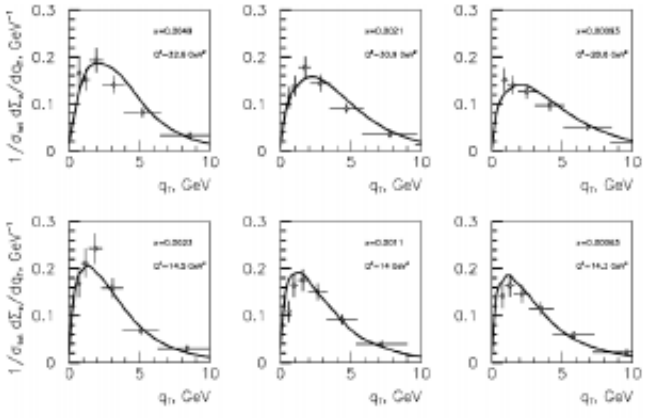
Nonperturbative momentum measurements in Drell-Yan and Z production

Other DY/Z and SIDIS Refs.

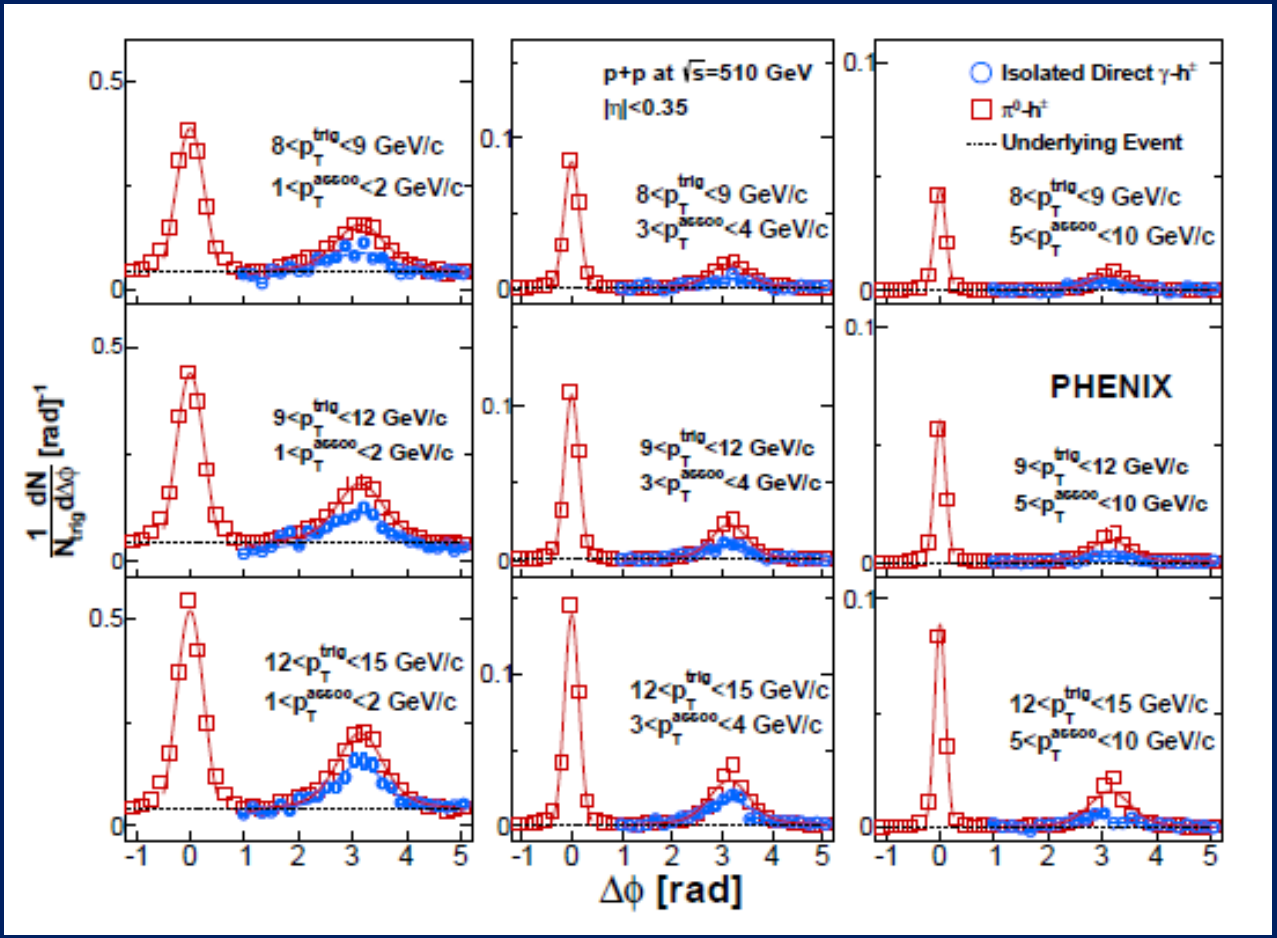
Phys. Rev. D 67, 073016 (2003)
(DY/Z)



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



Two-particle correlation distributions show expected jet-like structure



PHENIX Collab., arXiv:1609.04769

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 $p_T^{jet} = p_T^{trig,\pi^0} / \langle z_T \rangle$