Possible Color Entanglement Effects in p+p and p+A Collisions

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Overview

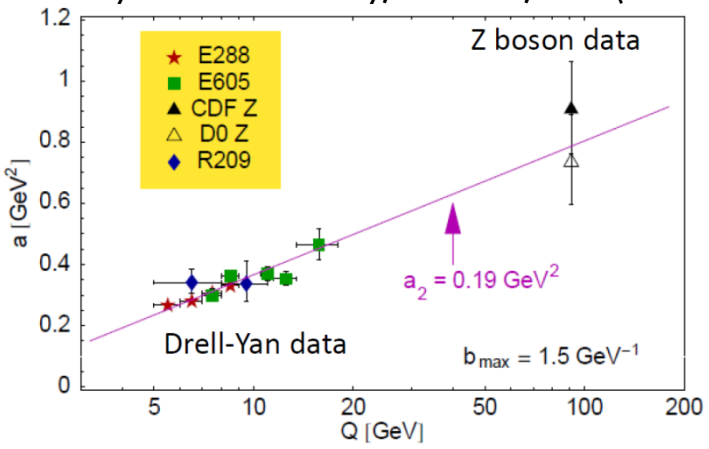
- Color entanglement and factorization breaking
- Observables at PHENIX
- Results
  - $\Delta\phi$ correlations
  - Transverse momentum dependent widths
  - Comparison to PYTHIA
- Conclusions

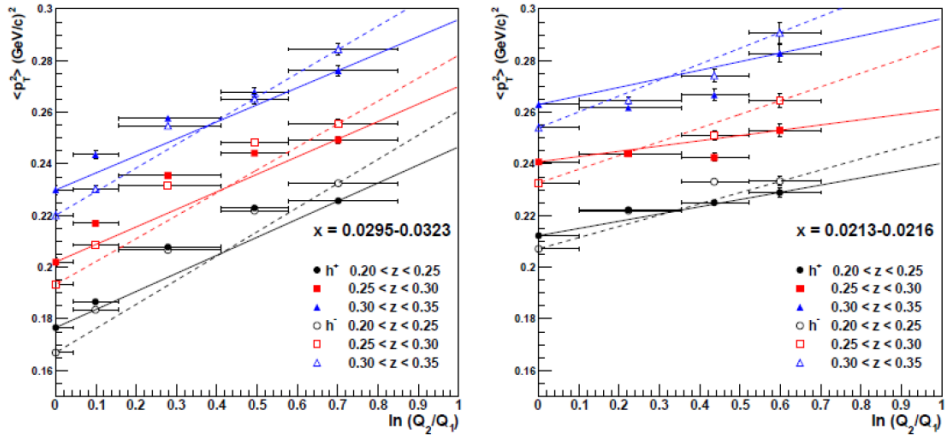
Color Entanglement and Factorization Breaking

- Due to the non-Abelian nature of QCD, Rogers and Mulders (2010) predicted that quarks can become correlated across colliding protons in hadron production processes sensitive to nonperturbative transverse momentum effects
- Rather than two factorized parton distribution functions, correlated partons across protons would be described by a single nonperturbative correlation function
- Measuring the evolution of nonperturbative transverse momentum widths as a function of the hard interaction scale can help distinguish these effects from other possibilities (Collins-Soper-Sterman predicts the widths to increase with hard scale)

Collins-Soper-Sterman Evolution

Konychev & Nadolsky, PLB 633, 710 (2006)



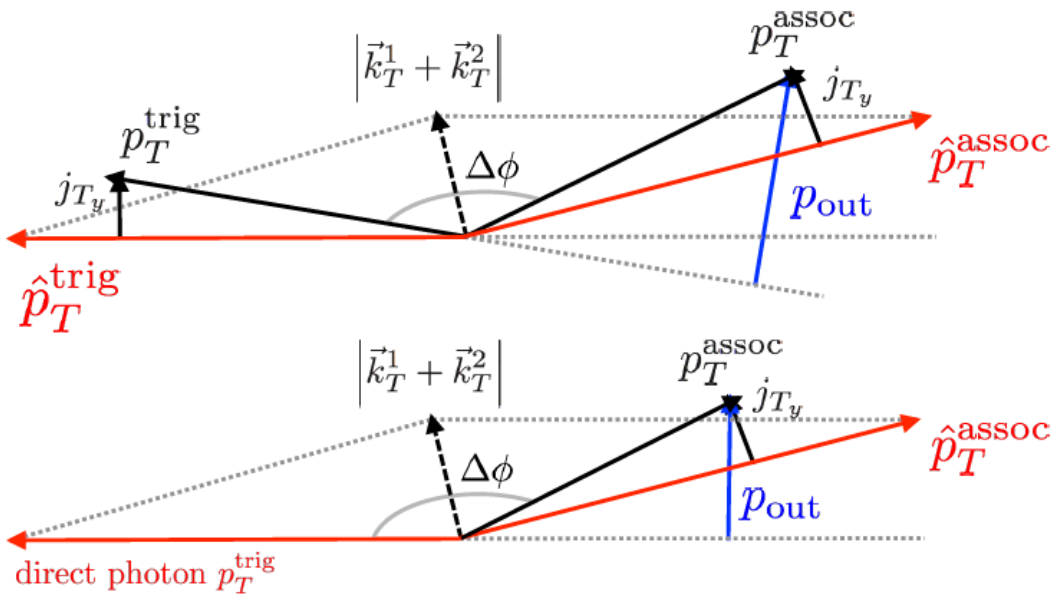


C. A. Aidala, B. Field, L. P. Gamberg, and T. C. Rogers
PRD 89, 094002 with COMPASS, EPJ C73, 2531 (2013)

- Comes directly from proof of TMD factorization
- Drell-Yan, SIDIS, e+e- annihilation
- Predicts nonperturbative momentum widths to increase with hard scale
- Experimental and phenomenological confirmation

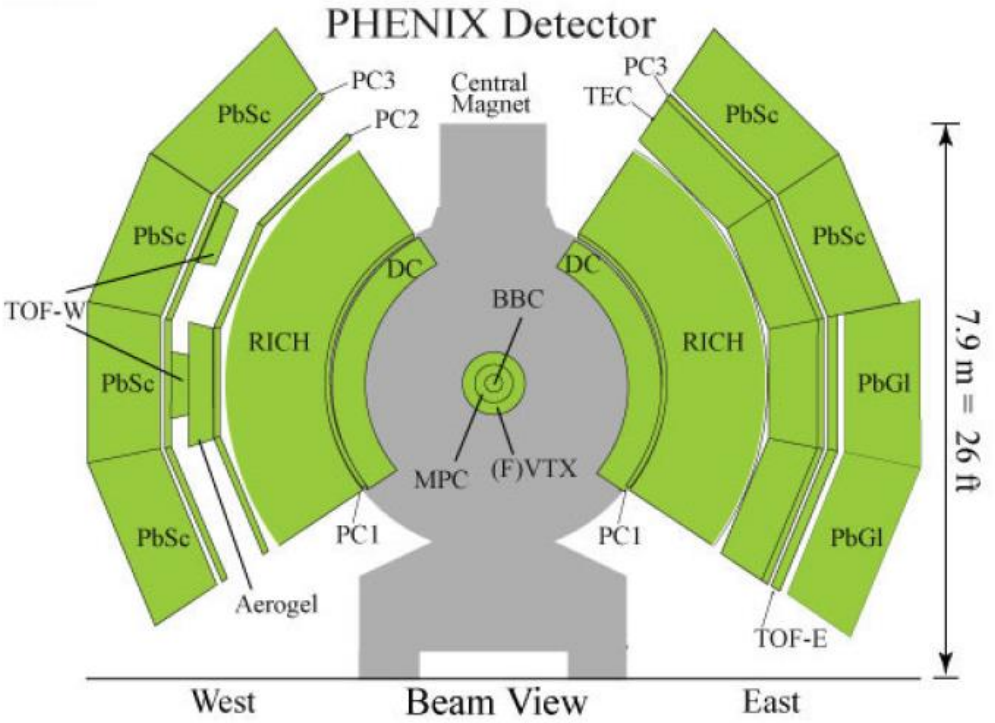
Observables

- Look at π^0-hadron and γ-hadron correlations, which are sensitive to nonperturbative transverse momentum in the initial state (in the proton) and final state (hadronization)



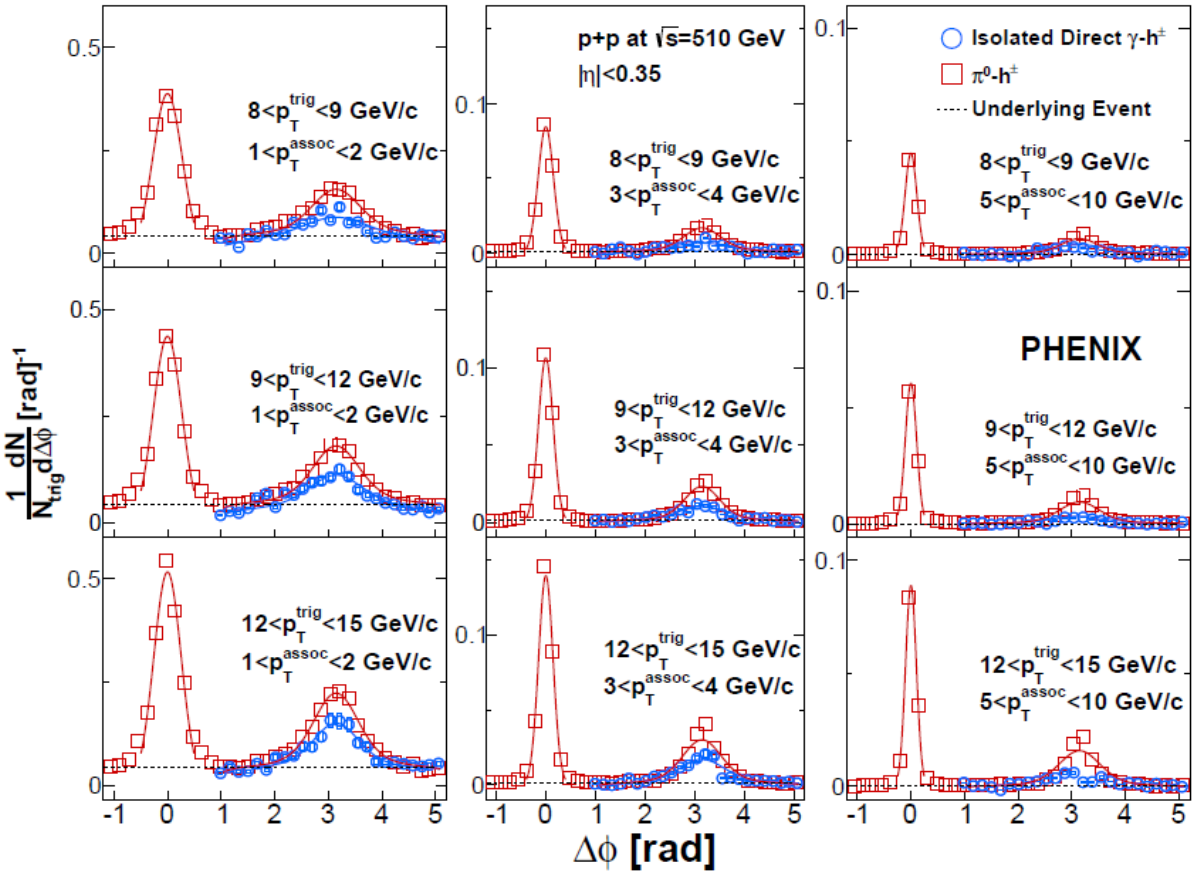
PHENIX

- Azimuthal coverage: 2 x $\pi/2$
- Psuedo-rapidity coverage: +/- .35
- Isolated direct photons and $\pi^0 \rightarrow \gamma\gamma$ detected by electromagnetic calorimeter
- Charged hadrons detected by Drift and Pad Chambers
- Centrality in p+A:
  - Integrated charge in beam-beam counters
  - Proxy for impact parameter



Δϕ Correlations

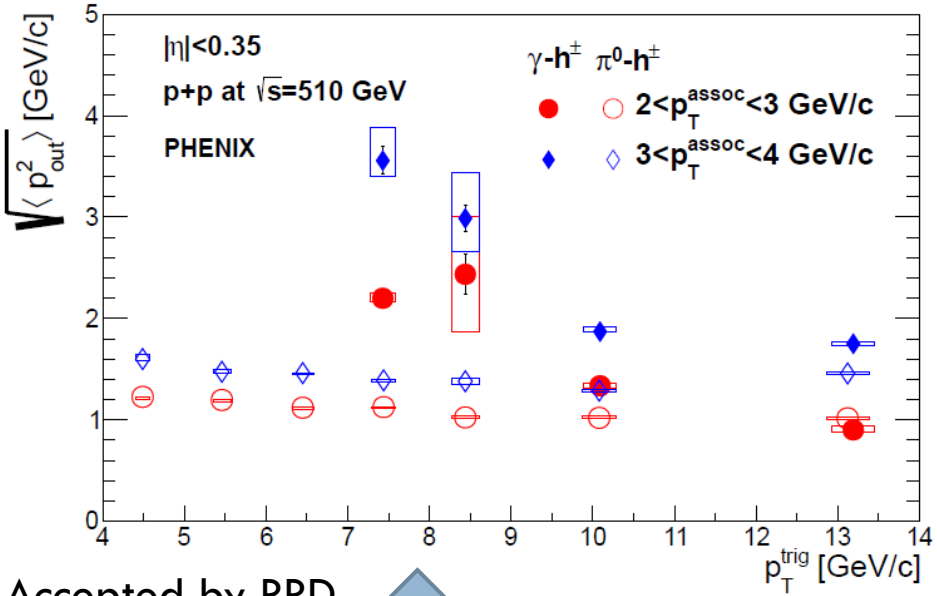
- Near-side peak Δϕ=0
- Isolation cut for γ-h → no near-side peak
- Away-side charged hadrons Δϕ=π
- Per trigger yield:



$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\varphi} = \frac{1}{N_{trig}}\frac{dN/d\Delta\varphi_{raw}}{dN/d\Delta\varphi_{mixed}\epsilon(p_T)}$$

Accepted by PRD

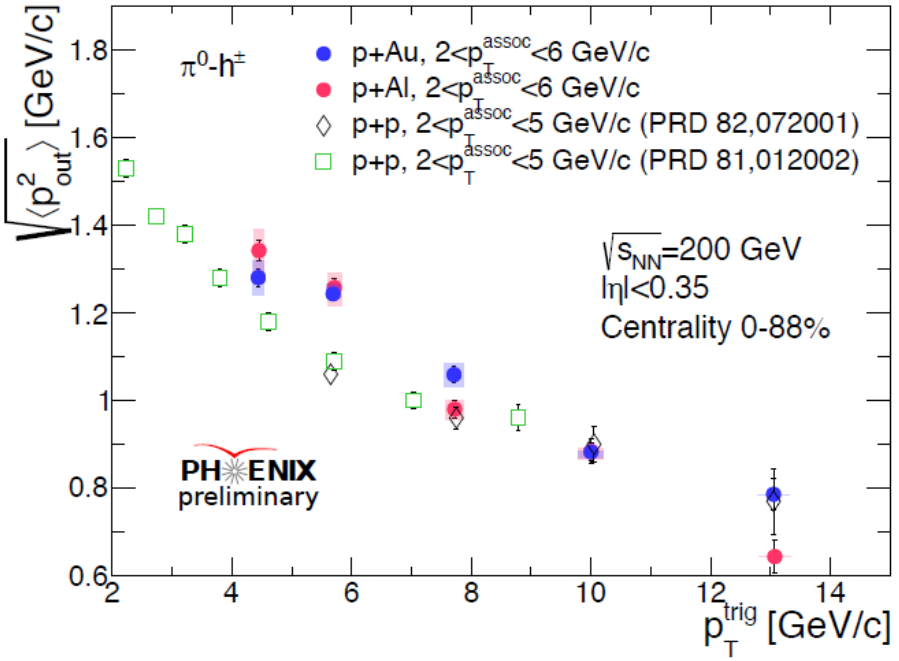
RMS of p_{out}



Accepted by PRD

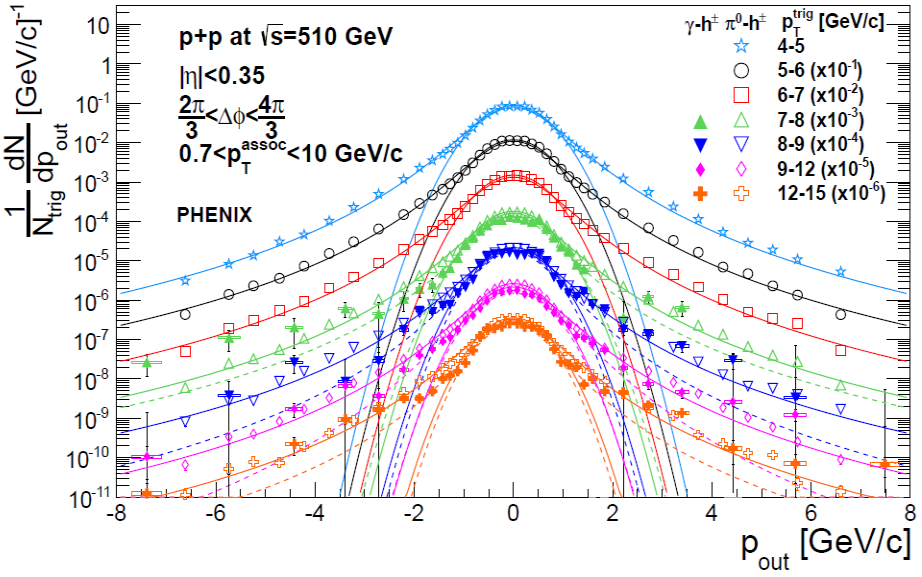
- Decrease for γ-hadron is large compared to π^0-hadron
- π^0-hadron has fragmentation function dependence

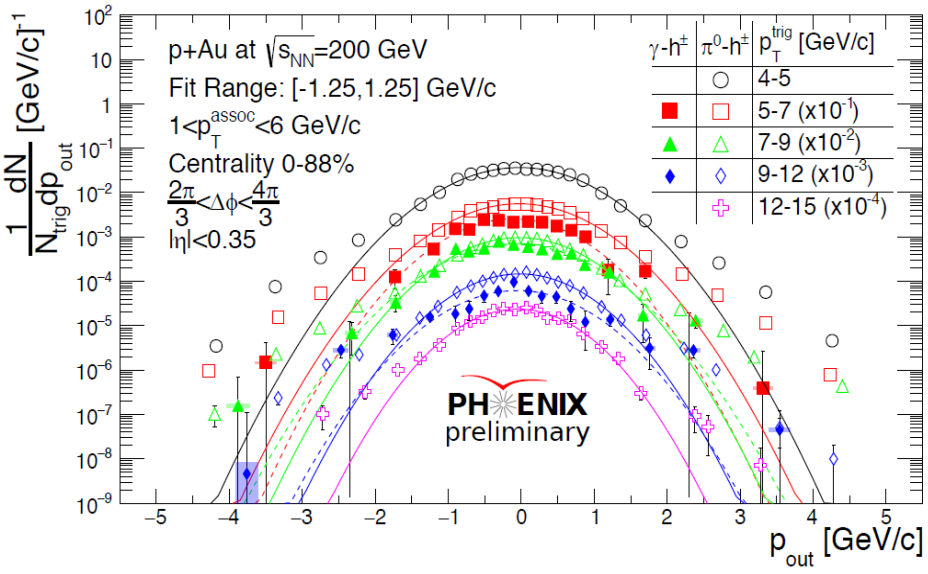
- Extracted from fit to away-side $\Delta\phi$ correlations
- Width of away-side jet decreases with hard scale



p_{out} Distributions

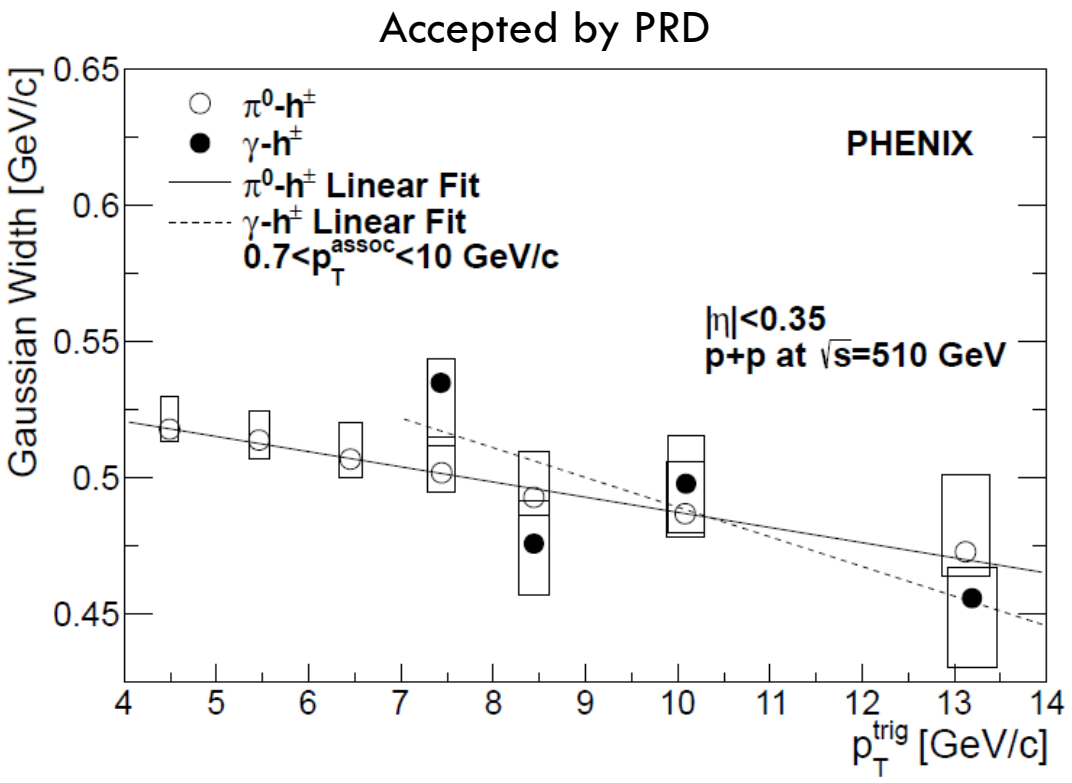
Accepted by PRD





- Gaussian fit region [-1.1,1.1] → nonperturbative (soft gluon radiation)
- Power law behavior → perturbative (hard gluon radiation)
- Kaplan function fits entire range for p+p data

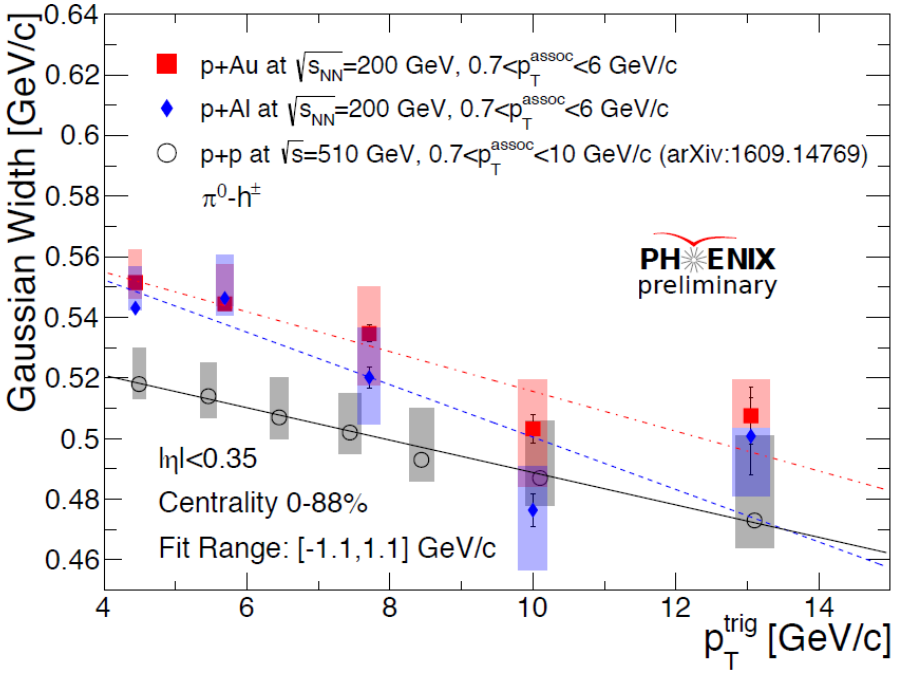
Evolution with Hard Scale

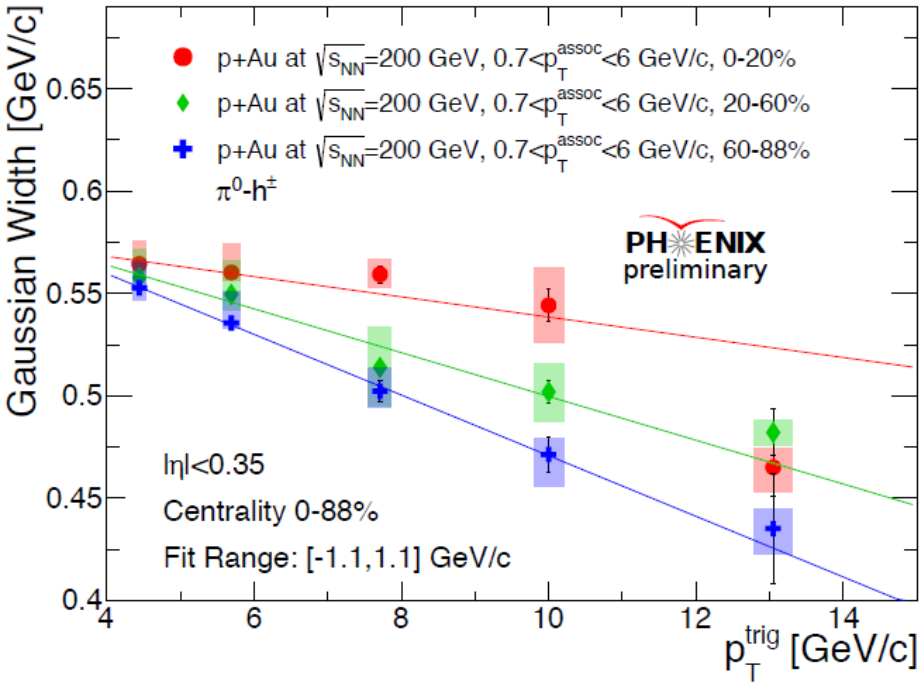


- Extracted from Gaussian fits to p_{out} distributions
- Gaussian widths sensitive only to nonperturbative contributions
- **Decrease with p_T^{trig} → Qualitatively opposite of SIDIS, DY**

System Size and Centrality Dependence

Hint that possible factorization-breaking effects stronger in p+A than p+p

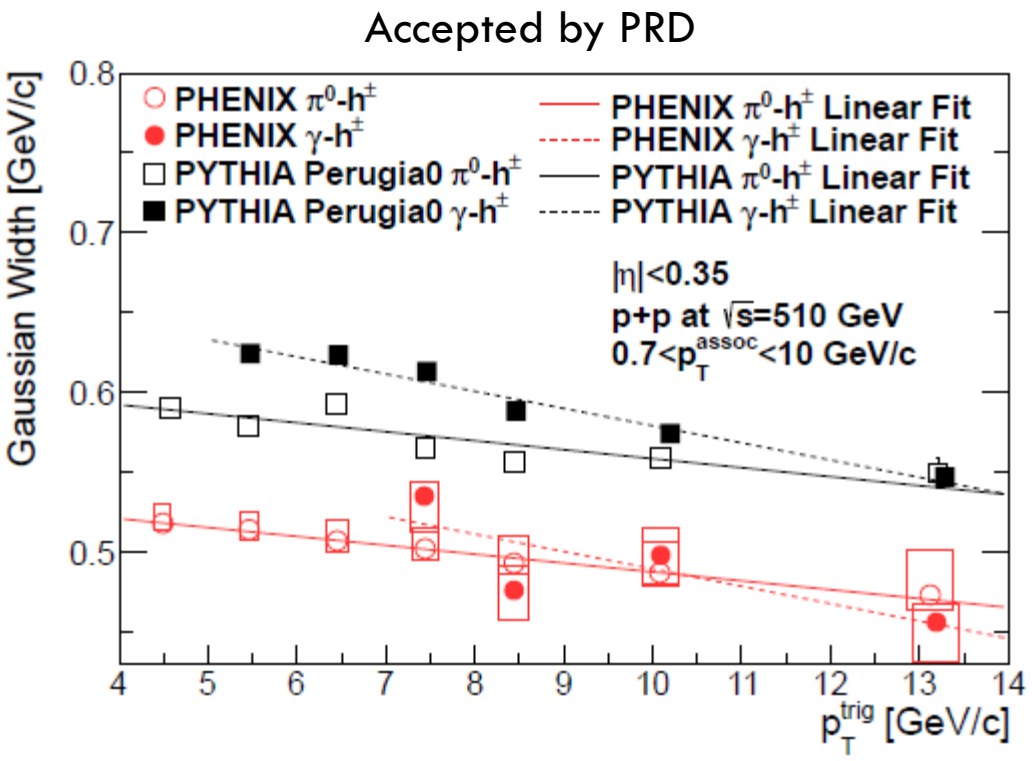




Centrality dependence could be due to multiple scattering interactions

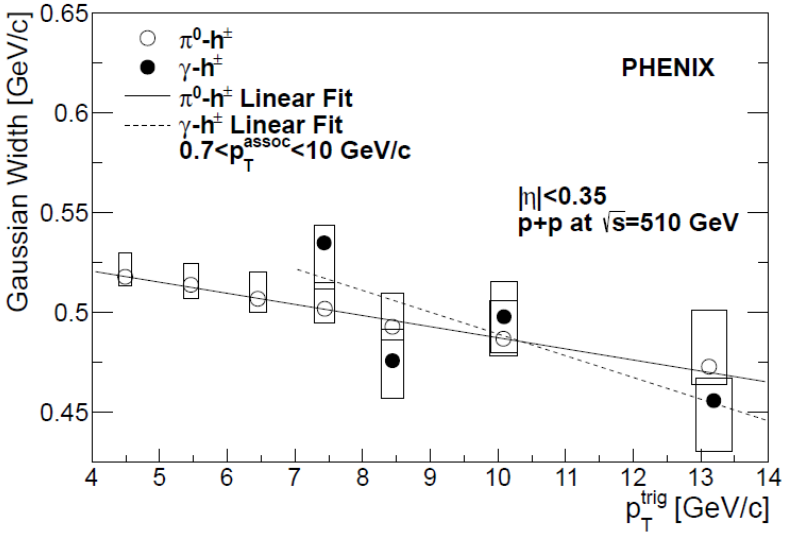
PYTHIA Simulations

- PYTHIA-generated slopes show almost perfect agreement with data
- Widths differ by about 15%
- PYTHIA possibly sensitive to factorization breaking effects? (gluon exchange between partons in hard scatter and remnants)

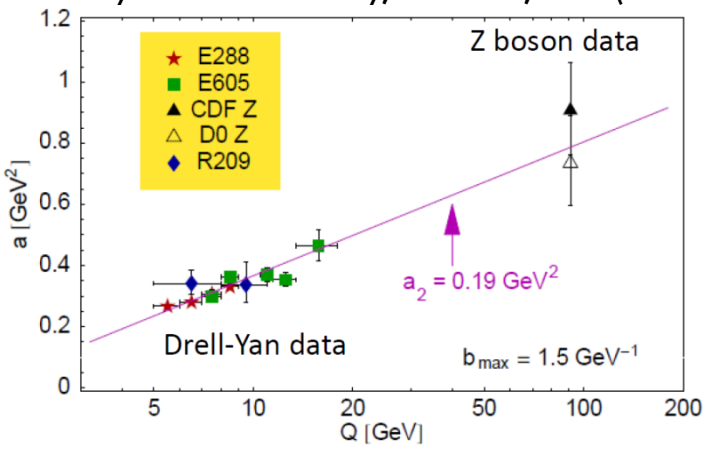


Conclusions

- Factorization breaking is predicted in processes sensitive to nonperturbative transverse momentum effects such as π^0-hadron and γ-hadron correlations in hadronic collisions
- These results show widths decrease with hard scale, suggesting **possible** TMD factorization breaking and color entanglement of partons across colliding protons

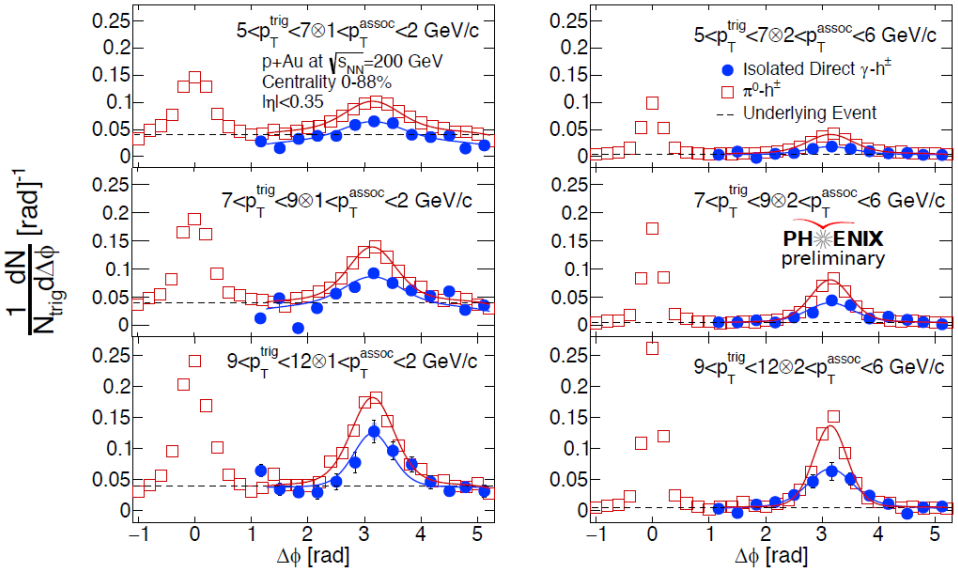


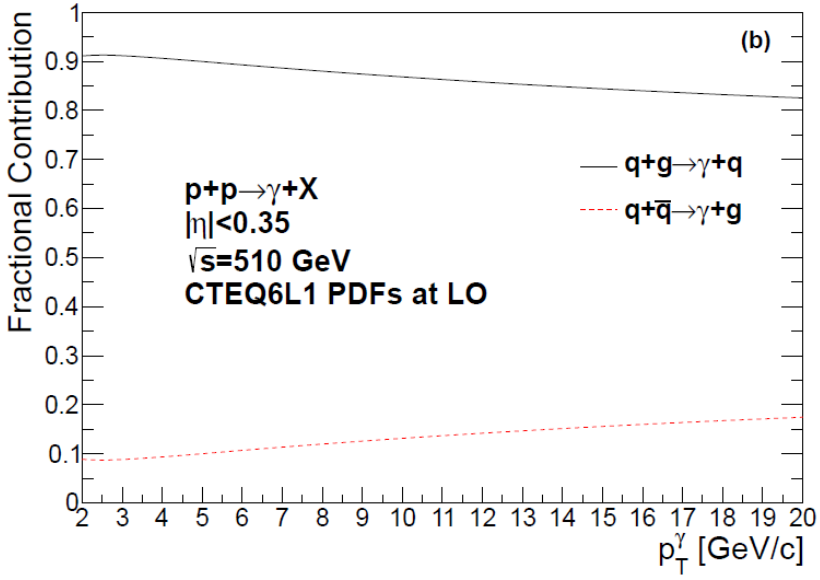
Konychev & Nadolsky, PLB 633, 710 (2006)

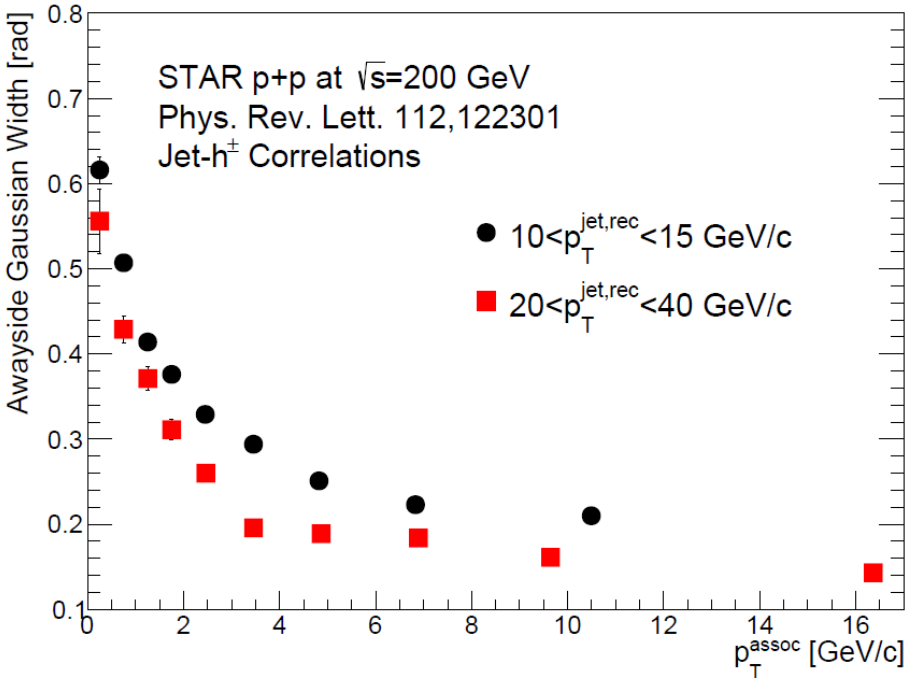


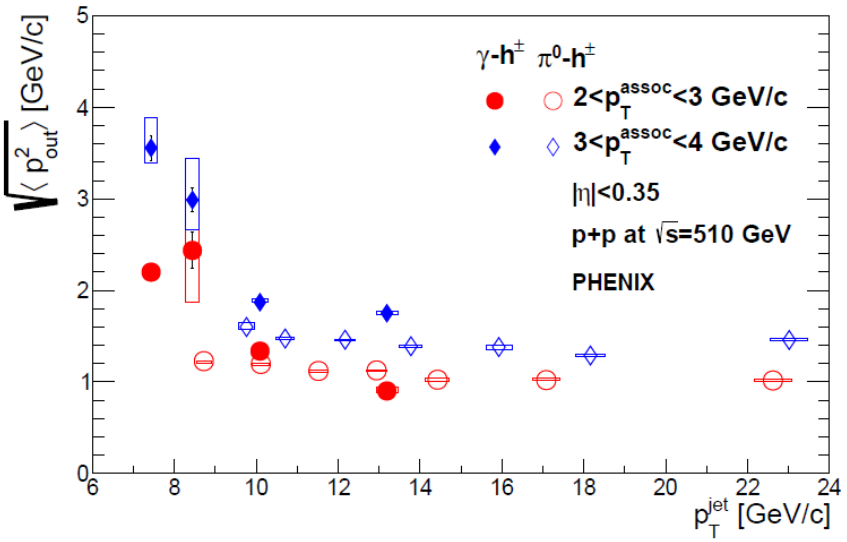
- Examining color interactions in PYTHIA could potentially further our understanding of these results
- Results from p+p collisions at $\sqrt{s}$ = 200 GeV coming soon! → Look at x_T scaling

Backup


$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}$ [rad]$^{-1}$
5<p_T^{trig}<7⊗1<p_T^{assoc}<2 GeV/c
p+Au at $\sqrt{s_{NN}}$=200 GeV
Centrality 0-88%
|η|<0.35
7<p_T^{trig}<9⊗1<p_T^{assoc}<2 GeV/c
9<p_T^{trig}<12⊗1<p_T^{assoc}<2 GeV/c
5<p_T^{trig}<7⊗2<p_T^{assoc}<6 GeV/c
Isolated Direct γ-h$^{\pm}$
π^0-h$^{\pm}$
Underlying Event
7<p_T^{trig}<9⊗2<p_T^{assoc}<6 GeV/c
PHENIX
preliminary
9<p_T^{trig}<12⊗2<p_T^{assoc}<6 GeV/c
Δφ [rad]
Δφ [rad]


Fractional Contribution
(b)
p+p→γ+X
|η|<0.35
√s=510 GeV
CTEQ6L1 PDFs at LO
q+g→γ+q
q+q̄→γ+g
p_T^{γ} [GeV/c]


STAR p+p at √s=200 GeV
Phys. Rev. Lett. 112,122301
Jet-h± Correlations
10<p_T^jet,rec<15 GeV/c
20<p_T^jet,rec<40 GeV/c
Awayside Gaussian Width [rad]
p_T^assoc [GeV/c]


γ-h± π0-h±
2<p_T^assoc<3 GeV/c
3<p_T^assoc<4 GeV/c
|η|<0.35
p+p at √s=510 GeV
PHENIX
√⟨p_out^2⟩ [GeV/c]
p_T^jet [GeV/c]

- Extract RMS of p_{out} from away-side charged hadrons

$$\frac{dN}{d\Delta\phi} = C_0 + C_1 \cdot \frac{dN_{\text{far}}}{d\Delta\phi}$$

$$\frac{dN_{\text{far}}}{d\Delta\phi} = \begin{cases} 0 & |\Delta\phi - \pi| > \frac{\pi}{2} \\ \dfrac{-p_T^{\text{assoc}} \cos\Delta\phi}{\sqrt{2\pi\langle p_{\text{out}}^2\rangle}\,\text{Erf}(p_T^{\text{assoc}}/\sqrt{2\langle p_{\text{out}}^2\rangle})} \times \exp\left(-\dfrac{|p_T^{\text{assoc}}|^2 \sin^2\Delta\phi}{2\langle p_{\text{out}}^2\rangle}\right) & |\Delta\phi - \pi| \leq \frac{\pi}{2} \end{cases}$$

- p_{out} yields
  - Hadrons: $2\pi/3 < \Delta\phi < 4\pi/3$