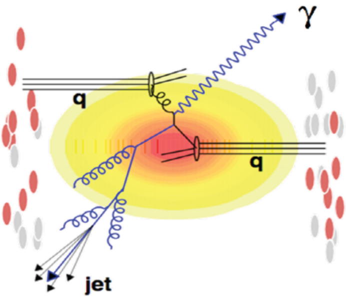
Study of Cold and Hot Nuclear Matter Effects on Jets with Direct Photon-Triggered Correlations from PHENIX

Joe Osborn for the PHENIX Collaboration

February 7, 2017

Direct Photons: The Golden Channel

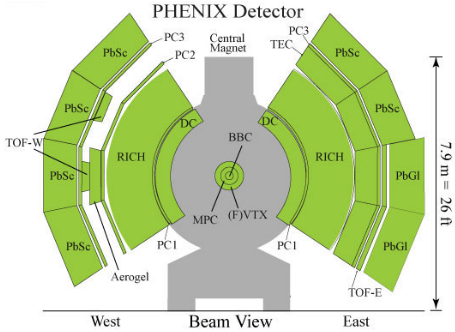
- Only interact electromagnetically!
- Direct photons are one of the most direct measure of the initial partonic hard scattering
- Allows probe of initial partonic dynamics before effects from gluon radiation, medium interaction with QGP, QCD effects from color flow, etc.



- NEW measurements of $\gamma - h^{\pm}$ in a suite of systems from PHENIX!
- $p + p$ at $\sqrt{s}$= 510 GeV
- p+A at $\sqrt{s_{NN}}$ =200 GeV
- d+Au at $\sqrt{s_{NN}}$ =200 GeV
- Au+Au at $\sqrt{s_{NN}}$ =200 GeV

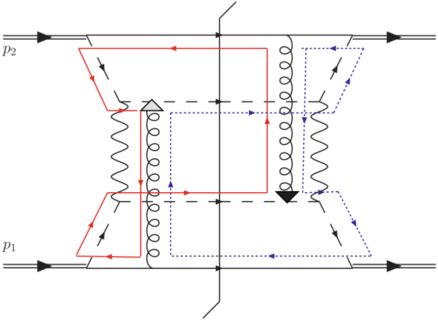
The PHENIX Detector

- Two central arms cover $\phi \sim \pi$ and $|\eta| < 0.35$
- EMCal measures γ and $\pi^0 \to \gamma\gamma$
- Drift Chamber (DC) and Pad Chamber (PC) tracking system measures charged hadrons
- Beam-Beam Counters (BBC) and Zero-Degree Calorimeters (ZDC) measure collision centralities in collision systems with a nucleus

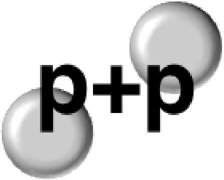


QCD as a Non-Abelian Gauge Theory

- Prediction of QCD factorization breaking in dihadron production from $p+p$ collisions in a transverse-momentum-dependent 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



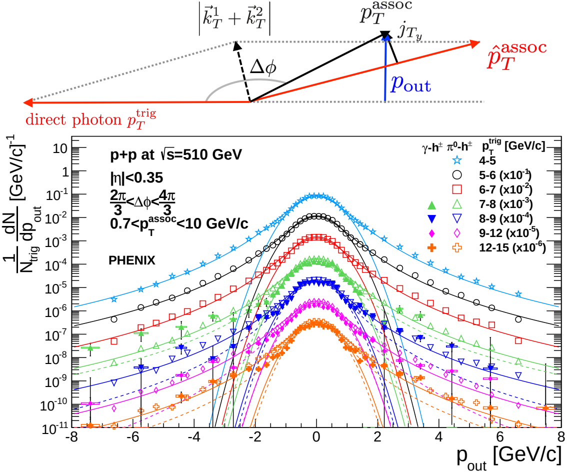
- $\geq$2 gluons exchanged with proton remnants leads to predicted breakdown due to non-Abelian nature of QCD



$$\sqrt{s} = 510 \text{ GeV}$$

Nonperturbative Momentum Widths and Factorization Breaking

- Measure p_{out} nonperturbative momentum widths as a function of p_T^{trig}
- Perturbative transverse-momentum-dependent (TMD) evolution, which comes directly from the generalized TMD QCD factorization theorem, predicts increasing momentum widths with hard scale of interaction



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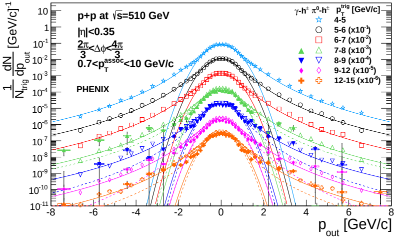
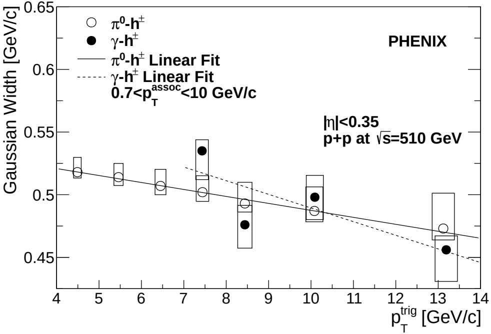
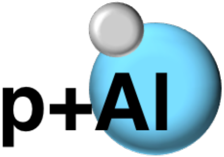
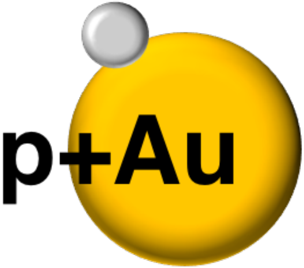
- Perturbative transverse-momentum-dependent (TMD) evolution, which comes directly from the generalized TMD QCD factorization theorem, predicts increasing nonperturbative momentum widths with hard scale of interaction
- PHENIX measures decreasing widths! Due to factorization breaking? Now on arXiv:1609.04769



p_{out} only in nearly back-to-back region



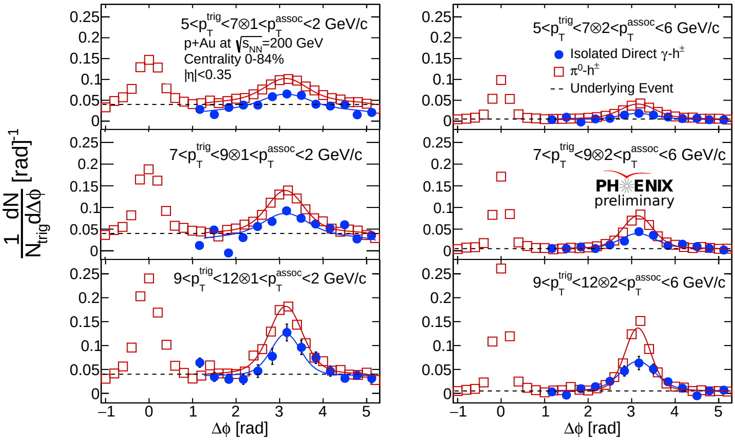




$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

Effects From Factorization Breaking in p+A?

π^0-h$^\pm$, Direct γ-h$^\pm$

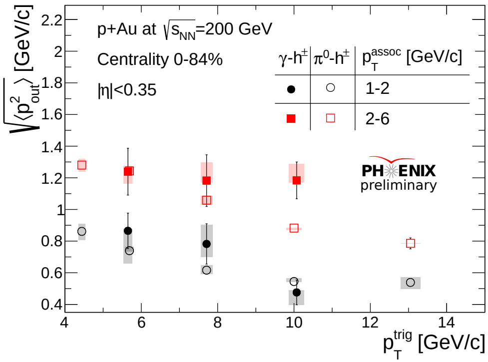


- New p+Au and p+Al $\gamma - h^\pm$ and $\pi^0 - h^\pm$ measurements
- Continue studying factorization breaking effects but in a nuclear environment

Effects From Factorization Breaking in p+A?

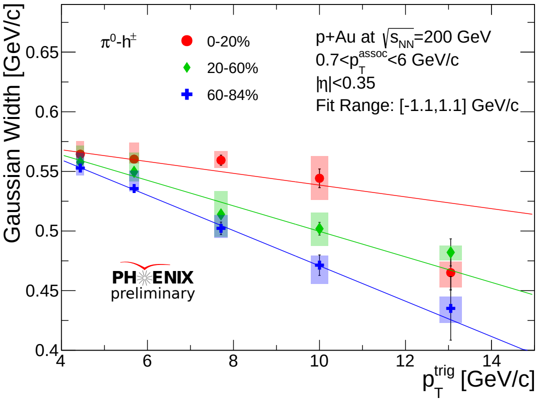
- New p+Au and p+Al $\gamma - h^{\pm}$ and $\pi^0 - h^{\pm}$ measurements
- Continue studying factorization breaking effects but in a nuclear environment
- Widths show stronger dependence on the hard scale p_T^{trig} than p+p at $\sqrt{s}$ =510 GeV
- Effects from nucleus: stronger gluon fields? Multiple scattering? Others??

Integrated RMS p_{out} across entire away-side jet



Centrality Dependence in $p+A$

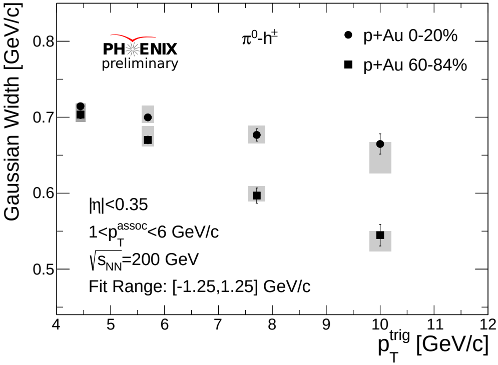
- Dihadron correlations in p+Au and p+Al show clear centrality dependence.
- Effects from k_T broadening? Multiple scattering? Flow? Others??
- Interpretations ongoing!



0-20% Centrality
20-60% Centrality
60-84% Centrality

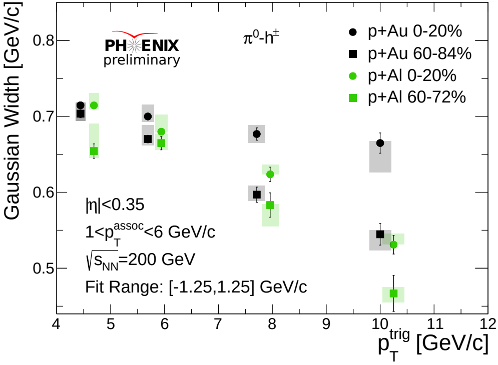
Cold Nuclear Matter Effects: Centrality Dependence on Nucleus Size

- Centrality dependence in p+Au clearly seen
- Is there a similar dependence in p+Al?



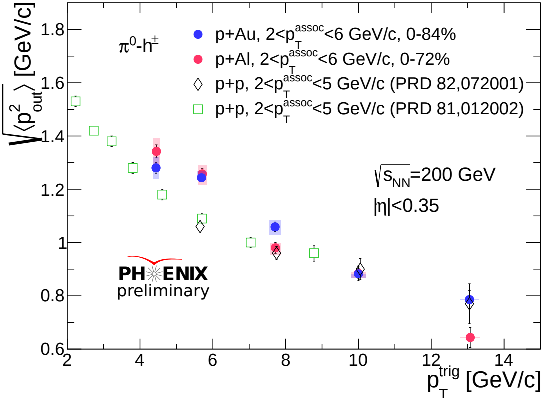
Cold Nuclear Matter Effects: Centrality Dependence on Nucleus Size

- Centrality dependence in p+Al as well, although not as strong as in p+Au
- Central and peripheral p+Al do not show as big a difference as central and peripheral in p+Au



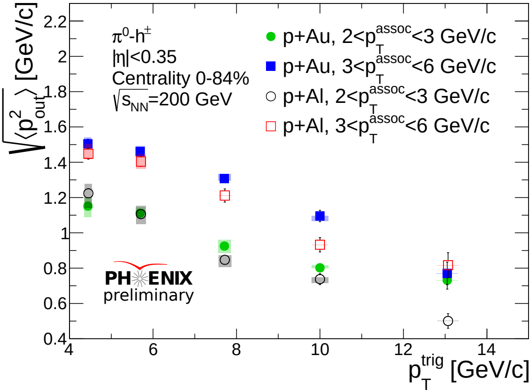
System Size Dependence in p+A and p+p

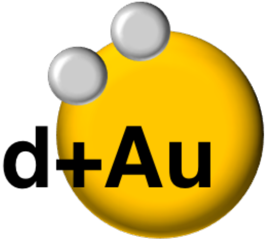
- Root mean square of p_{out} shows increase in acoplanarity around 4-8 GeV/c $p_T^{\pi^0}$ when compared to p+p
- Relationship to π^0 R_{AA} in p+A? See talk by N. Novitzky: Wednesday 11:00 AM

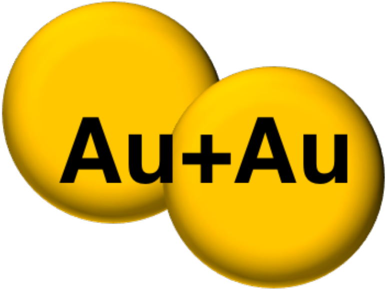


Cold Nuclear Matter Effects: Dependence on Nucleus Size

- Nuclear dependence on $\sqrt{\langle p_{out}^2 \rangle}$ and thus k_T and j_T
- Clear systematic decrease between dihadron nonperturbative widths in p+Al and p+Au



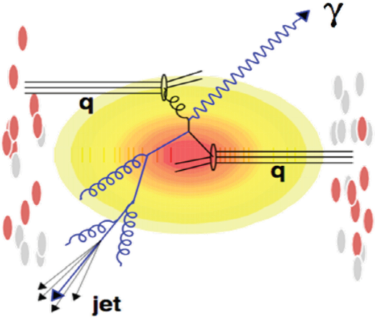




$$\sqrt{s_{NN}} = 200 \text{ GeV}$$

Fragmentation Function Modification in Small/Large Systems

- At leading order $p_T^\gamma \approx p_T^{\rm jet}$, thus $z_T = p_T^h/p_T^\gamma$
- Changing to $\xi = \ln(1/z_T) = \ln(p_T^\gamma/p_T^h)$, we can write the fragmentation function approximately as $D_q(\xi) = 1/N_{\rm evt} dN(\xi)/d\xi$
- Access jet fragmentation function with integrated away-side yield
- Modification of FF: $D_{AA}/D_{pp} \sim Y_{AA}/Y_{pp} = I_{AA}$



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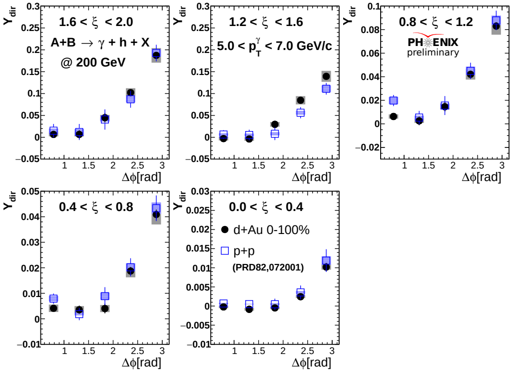
d+Au

$p+p$



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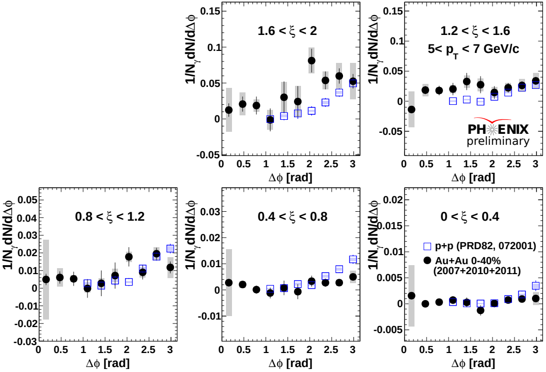
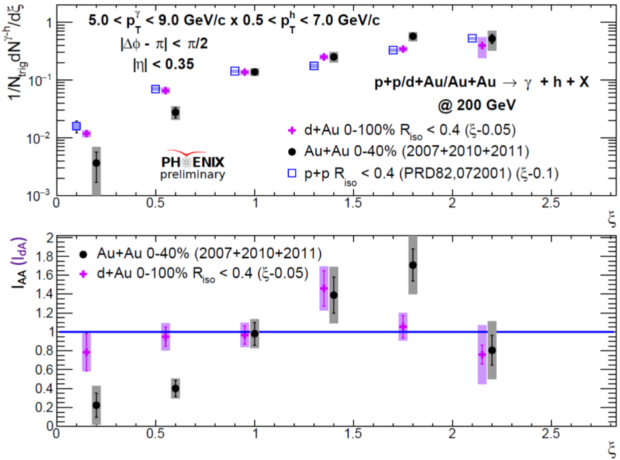


Au+Au

$p{+}p$

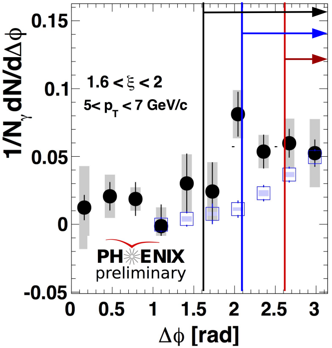
d+Au and Au+Au Fragmentation Modification

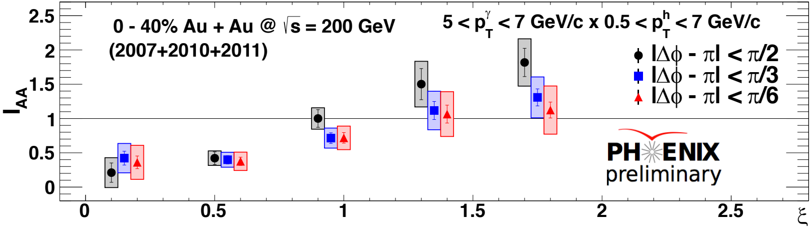


- Significant yield modification in Au+Au - Suppression at small ξ (large p_T^h) and enhancement at large ξ (small p_T^h)
- No significant modification within uncertainties in d+Au

Au+Au Suppression/Enhancement

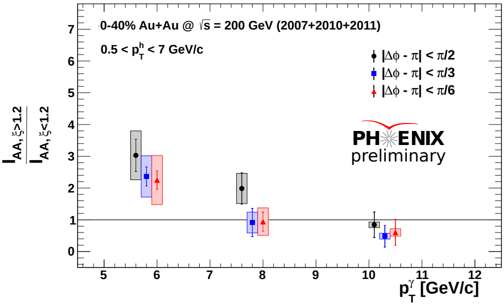
- Study enhancement and suppression as a function of integration range
- Lost energy goes into soft hadron production away from $\Delta\phi \sim \pi$
- Effect most pronounced for softest jets with full away-side integration

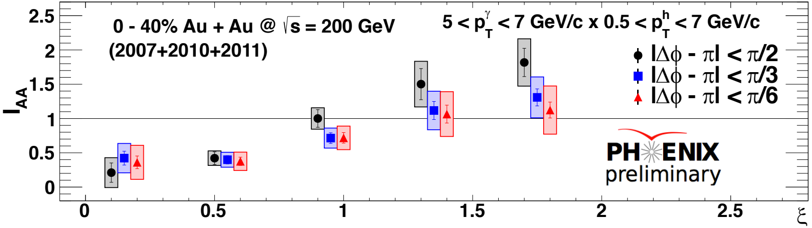




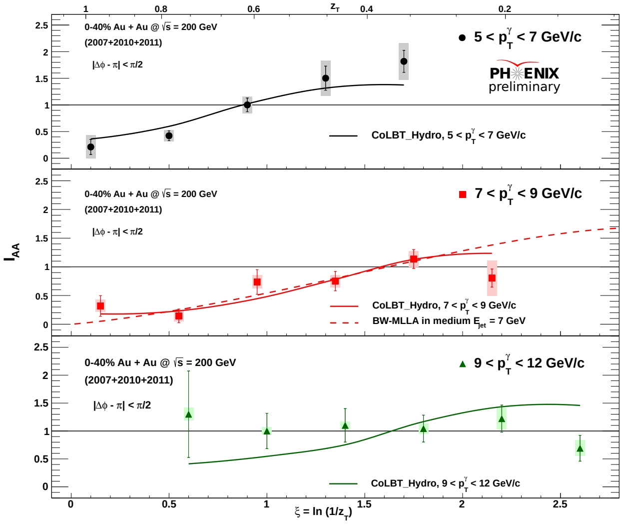
Au+Au Suppression/Enhancement

- Enhancement of soft particle production shows p_T dependence
- Harder jets are more p+p like in structure
- Lost energy from high p_T hadrons being redistributed to soft large angle particles





Comparison to Theory: Au+Au



Transition not at fixed ξ - medium response in addition to redistribution of lost energy?

- Reminder: $\xi = \ln(p_T^\gamma / p_T^h)$
- Linear Boltzmann Transport
  - He, Luo, Wang and Zhu, Phys. Rev. C 91, 054908 (2015)
- Modified Leading Log Approximation (MLLA)
  - Borghini and Wiedemann, arXiv:hep-ph/0506218 (2005)

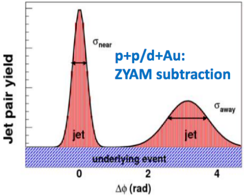
Conclusions

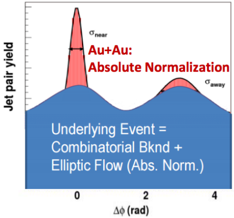
- New PHENIX measurements of $\gamma - h^{\pm}$ correlations in:
  - p+p at $\sqrt{s}$ =510 GeV (arXiv:1609.04769) - Effects due to factorization breaking of nonperturbative functions?
  - p+Au and p+Al ($\pi^0 - h^{\pm}$) at $\sqrt{s_{NN}}$ =200 GeV (preliminary) - Surprising centrality dependence to nonperturbative widths
  - d+Au at $\sqrt{s_{NN}}$ =200 GeV (preliminary) - No fragmentation function modification compared to p+p
  - Au+Au at $\sqrt{s_{NN}}$=200 GeV (preliminary) - Transition from enhancement to suppression of fragmentation function at different ξ with p_T^{γ}
- Other measurements in the works:
  - Poster by Tyler Danley: Cu+Au $\gamma - h^{\pm}$ at $\sqrt{s_{NN}}$=200 GeV
  - 2014+2016 Au+Au and 2015 p+p: RHIC "golden" data sets - significantly more data left to analyze!

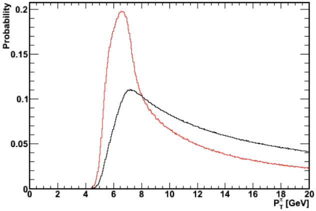
Back Up

Direct Photon Measurements in PHENIX

- Measure per-trigger yields
- Correct for acceptance with event mixing
- Statistically subtract remaining decay-photon background using equations 2 and 3







PRD 82, 072001 (2010)

$$Y(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN}{d\Delta\phi} \qquad (1)$$

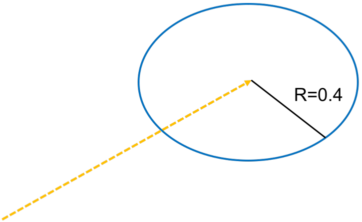
$$Y_{direct} = \frac{R_\gamma Y_{\mathrm{inclusive}} - Y_{\mathrm{decay}}}{R_\gamma - 1} \qquad (2)$$

$$R_\gamma = \frac{N_{\mathrm{inclusive}}}{N_{\mathrm{decay}}} \qquad (3)$$

Isolation Cut in Small Systems

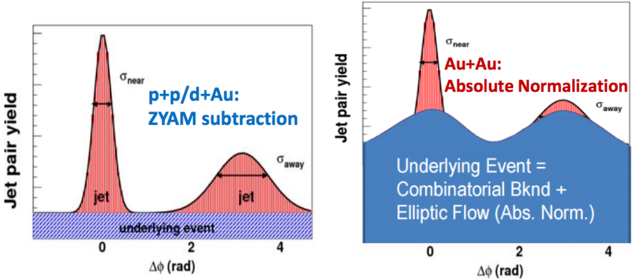
- Implement an isolation cone cut in small systems to reduce NLO fragmentation photon contribution
- Require sum of p_T of tracks and electromagnetic clusters in R=0.4 to be less than 10% of photon's energy

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Flow Subtraction in Large Systems

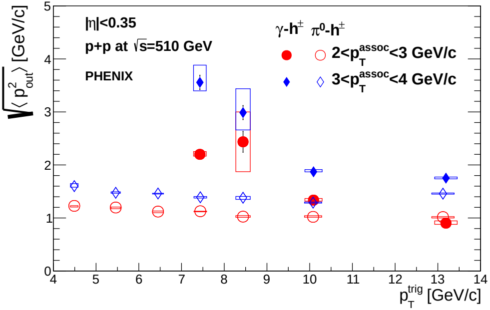
- Elliptic flow contribution subtracted in Au+Au (eq 4)
- Some flow underlying event left in the small system measurements (p+A and d+Au) that is not subtracted
- No underlying event subtraction in p+p



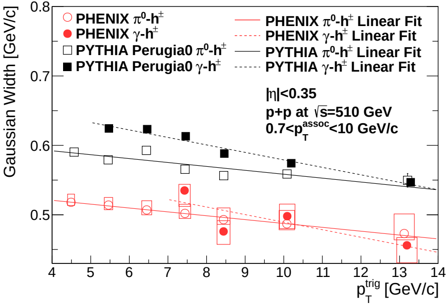
$$Y \propto Y(\Delta\phi) - b(1 + 2\langle v_2^{\gamma}\rangle\langle v_2^{h}\rangle \cos 2\Delta\phi) \quad (4)$$

Root Mean Square of p_{out} in p+p at $\sqrt{s}$ =510 GeV

- RMS of p_{out} gives away-side jet width in momentum space
- Includes perturbative and nonperturbative contributions (i.e. whole away-side jet)
- Shows stronger dependence on p_T^{trig} in $\gamma - h^{\pm}$ than in $\pi^0 - h^{\pm}$



Gaussian Widths with a PYTHIA Simulation

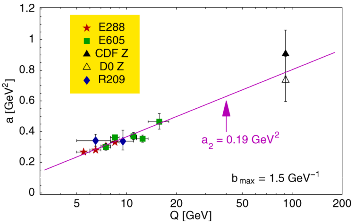


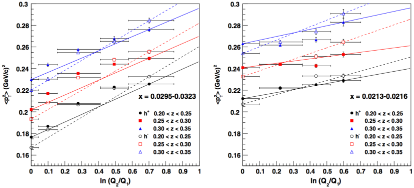
- Gaussian widths of p_{out} distributions also decrease with hard scale p_T^{trig}
- Sensitive to *only* nonperturbative k_T and j_T in the nearly back-to-back region $\Delta\phi \sim \pi$
- PYTHIA replicates slope almost exactly, but shows 15% difference in magnitude of widths

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

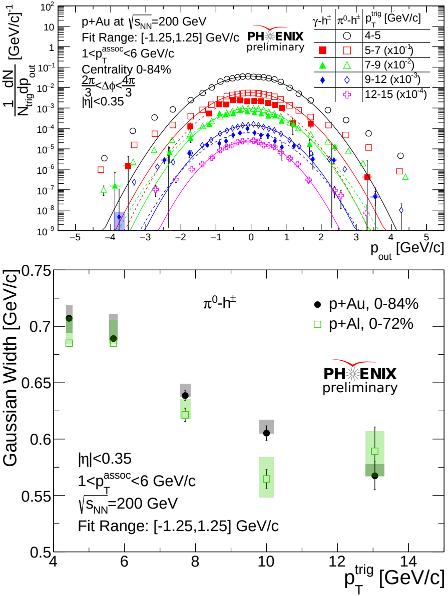
Phys. Lett. B 633, 710 (2006) (DY/Z)



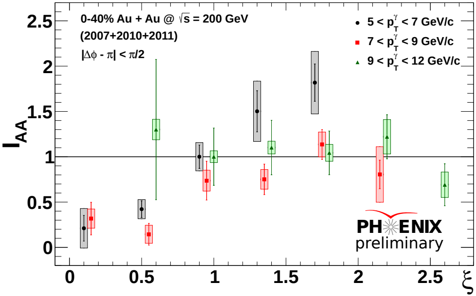


Phys. Rev. D 89, 094002 (2014) (SIDIS)

- p+Au p_{out} distributions exhibit transition from Gaussian to Power law
- Centrality integrated Gaussian widths of p_{out} for p+Au and p+Al
- Exhibit nuclear dependence of k_T and j_T as well
- p+Au systematically larger widths than p+Al

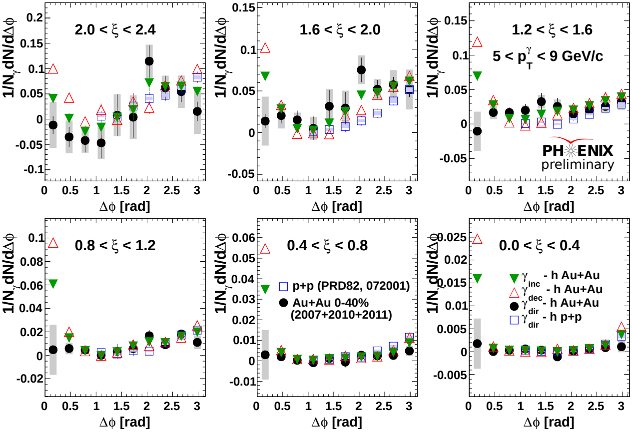


I_{AA} for Different p_T Ranges



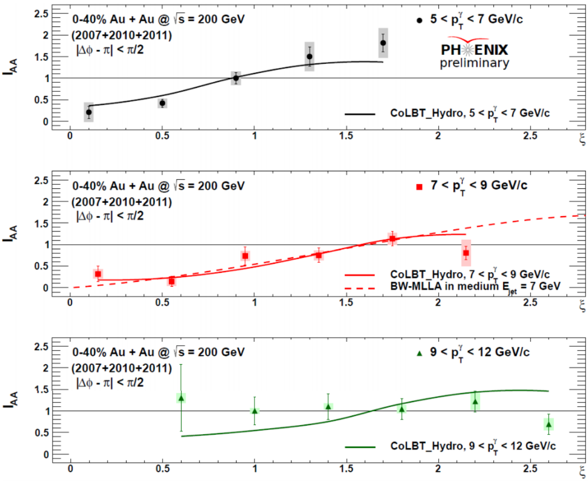
- I_{AA} shows dependence with p_T^γ
- Suppression and enhancement tends to disappear with increasing p_T^γ
- Transition from suppression to enhancement at different ξ for different p_T^{trig}

Au+Au $\Delta\phi$ Statistical Subtraction



- Au+Au per-trigger yield inputs for statistical subtraction
- Subtracting off background decay yield leaves ∼0 yield on near-side $\Delta\phi \sim 0$
- p+p near-side removed due to implementation of isolation cut

Comparison to Theory: Au+Au



Transition not at fixed ξ - medium response in addition to redistribution of lost energy?

- Linear Boltzmann Transport
  - Kinetic description of parton propagation
  - Hydrodynamic description of medium evolution
  - Track thermal recoil partons and their further interactions in the medium
  - He, Luo, Wang and Zhu, Phys. Rev. C 91, 054908 (2015)
- Modified Leading Log Approximation (MLLA)
  - Modeling the energy loss in the medium as an increased parton splitting probability
  - Borghini and Wiedemann, arXiv:hep-ph/0506218 (2005)