PHENIX results on jet modification with π^0- and photon-triggered two particle correlations in p+p, $p(d)$+Au, and Au+Au collisions

Joe Osborn for the PHENIX Collaboration

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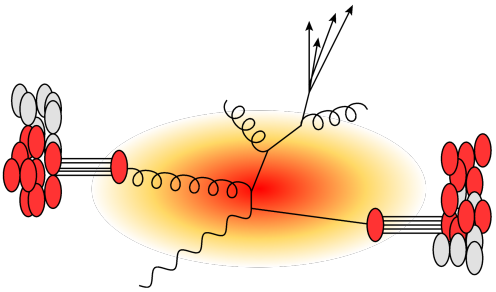
University of Michigan

Two-Particle Correlations

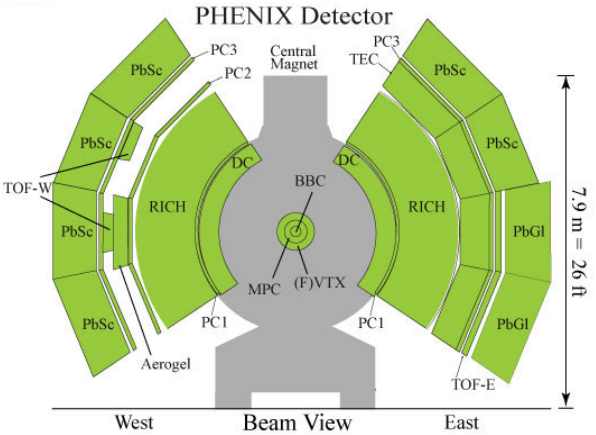
- Two-particle correlations provide the opportunity to study various QCD interactions
- π^0-h$^{\pm}$ correlations approximate dijet correlations and are sensitive to near- and away-side QCD interactions
- Direct photon-h$^{\pm}$ correlations provide additional benefits:
  - Photons are colorless
  - Sensitive to partonic interaction before effects from gluon radiation, QGP interactions, QCD effects from color take place

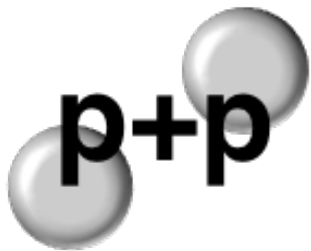


- New PHENIX results from $\sqrt{s_{NN}}$ = 200 GeV collisions:
  - p+p (π^0-h$^{\pm}$ and γ-h$^{\pm}$)
  - p+Al and p+Au (π^0-h$^{\pm}$)
  - d+Au (γ-h$^{\pm}$)
  - Au+Au (γ-h$^{\pm}$)

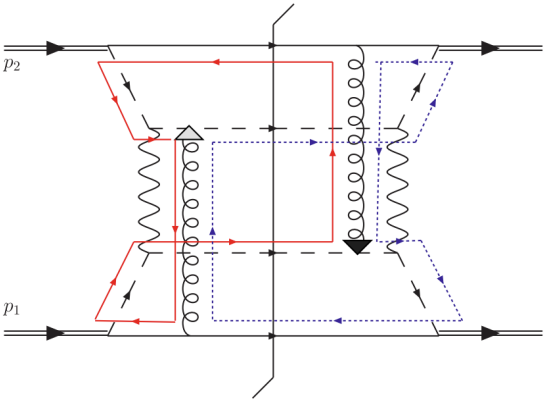
The PHENIX Detector

- 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
- Forward Beam-Beam-Counter (BBC) and Zero-Degree-Calorimeter (ZDC) measure centrality classes in p+A and A+A




p+p

QCD as a Non-Abelian Quantum Gauge Theory

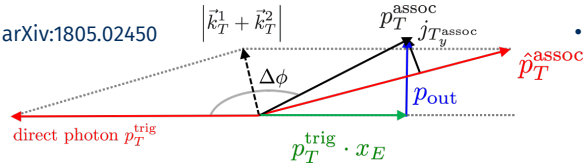


PRD 81, 094006 (2010)

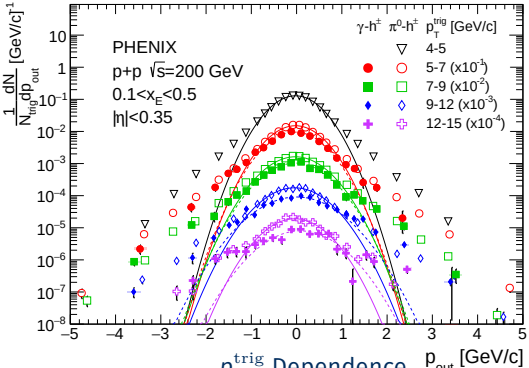
- Prediction of QCD factorization breaking in dihadron production from p+p collisions in a transverse-momentum-dependent framework
- Due to complex color flows through hard process and remnants
- Nearly back-to-back dihadron and direct photon-hadron correlations are sensitive to initial-state k_T and final-state j_T and may probe factorization breaking effects

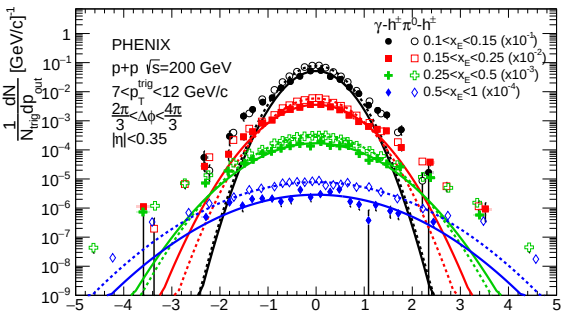
Multi-Differential Two-Particle Correlation Measurements

arXiv:1805.02450



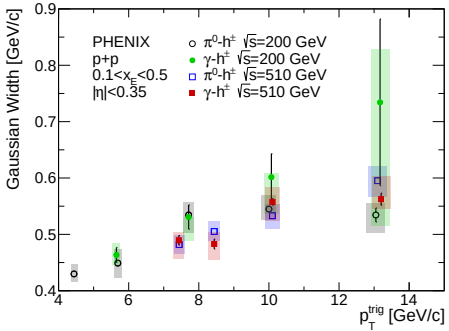
- Measure correlations as a function of p_T^{trig} with p_{out} and x_E, the transverse momentum component and longitudinal momentum fraction with respect to the trigger particle
- Fit small p_{out} region to Gaussian to measure nonperturbative away-side momentum widths

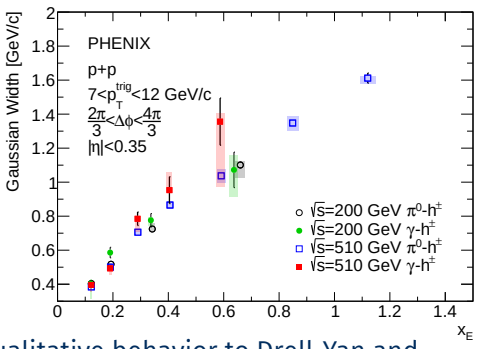




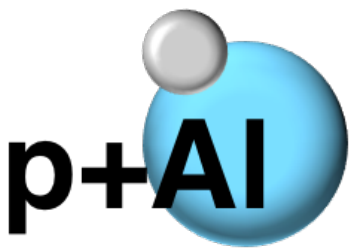
Nonperturbative Momentum Widths

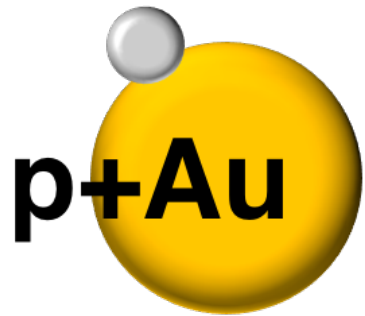
arXiv:1805.02450





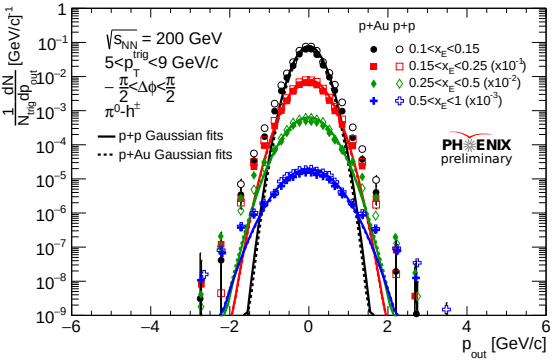
- Measured Gaussian widths display similar qualitative behavior to Drell-Yan and semi-inclusive DIS interactions, where factorization is predicted to hold
- Further phenomenological studies with all three processes will constrain magnitude of factorization breaking effects in hadronic collisions
- Comparison to previous $\sqrt{s}$ = 510 GeV measurements shows no $\sqrt{s}$ dependence


p+Al


p+Au

p+A Dihadron Correlations

- Dihadrons give additional nuclear surface bias in p+A collisions compared to direct photon-hadrons
- Measure the p_{out} distributions on both the near-side and away-side in p+p and p+A to compare the nonperturbative momentum widths



Near-side

p+A Dihadron Correlations

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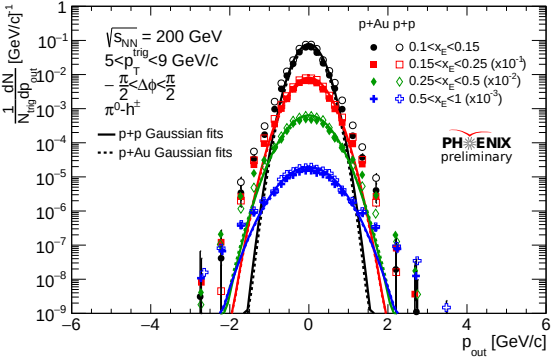
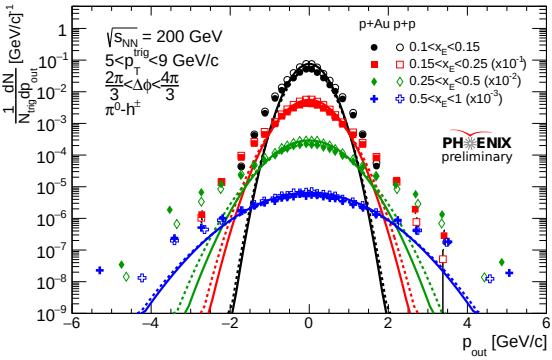
- Measure the p_{out} distributions on both the near-side and away-side in p+p and p+A to compare the nonperturbative momentum widths

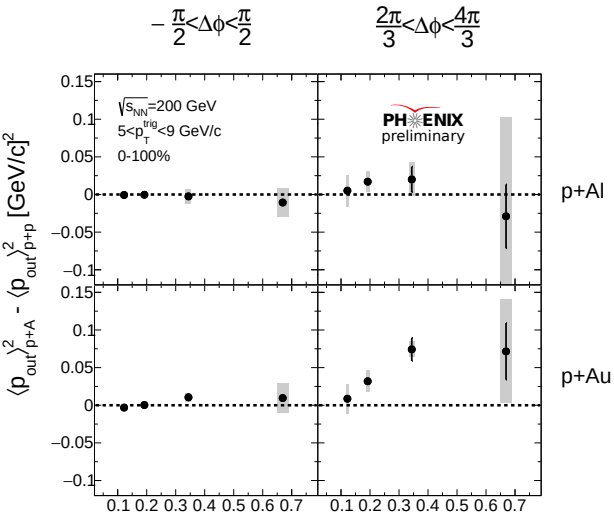


Near-side



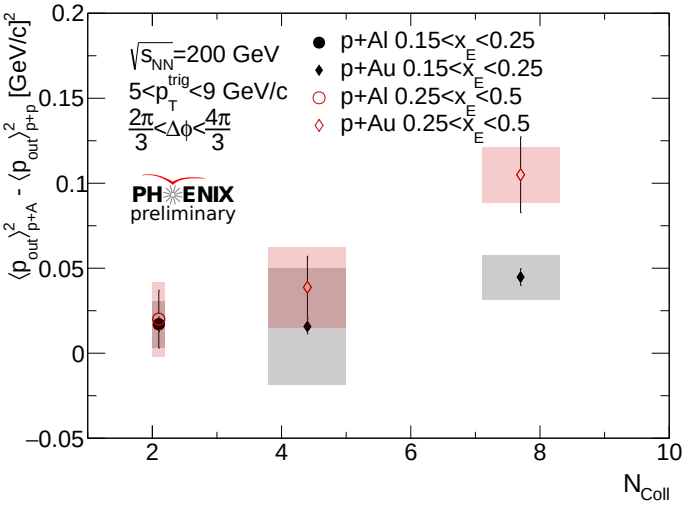
Far-side

p+A and p+p Transverse Momentum Width Differences



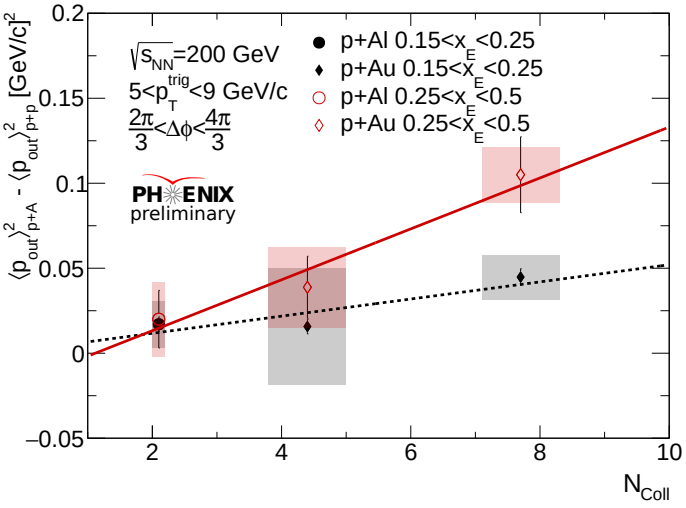
- Measure squared width differences between p+A and p+p
- No significant near-side width differences (left column)
- Nonzero away-side transverse momentum broadening in p+Au at certain $x_E = z_T \cos\Delta\phi$

Transverse Momentum Width Broadening with N_{coll}



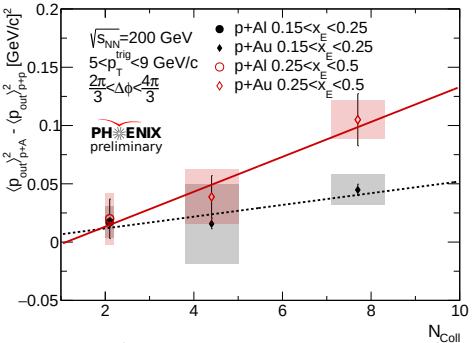
- p_{out} away-side width differences are shown as a function of N_{coll} for two longitudinal momentum fraction x_E bins

Transverse Momentum Width Broadening with N_{coll}



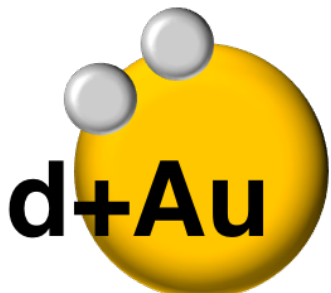
- p_{out} away-side width differences are shown as a function of N_{coll} for two longitudinal momentum fraction x_E bins
- Width differences display positive dependence with N_{coll} shown as linear fits

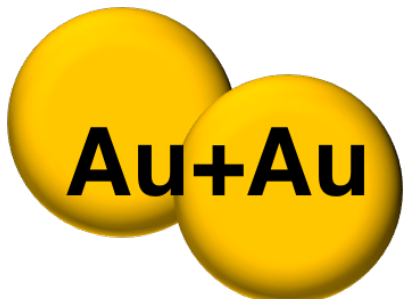
Transverse momentum Width Broadening and N_{coll}



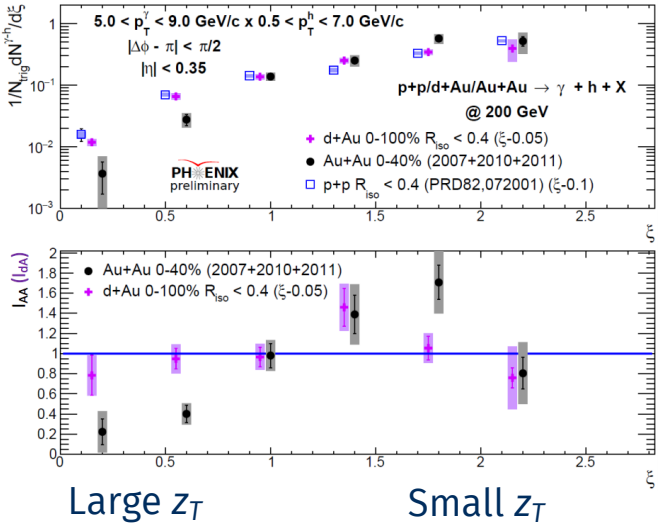
- p_{out} away-side width differences are shown as a function of N_{coll} for two longitudinal momentum fraction x_E bins
- Width differences display positive dependence with N_{coll} shown as linear fits

- Physical effects that may contribute?
  - v_2 and v_3 systematically ruled out as contributors
  - Near-side widths suggest no final-state fragmentation modification
  - π^0 and hadrons are within “Cronin” peak, “Cronin” mechanisms at play?
  - Transverse momentum broadening with N_{coll} suggests energy loss, similar to Drell-Yan (e.g. PRL 83, 2304 (1999))
  - Additional (small) initial-state k_T for partons in nucleus?


d+Au

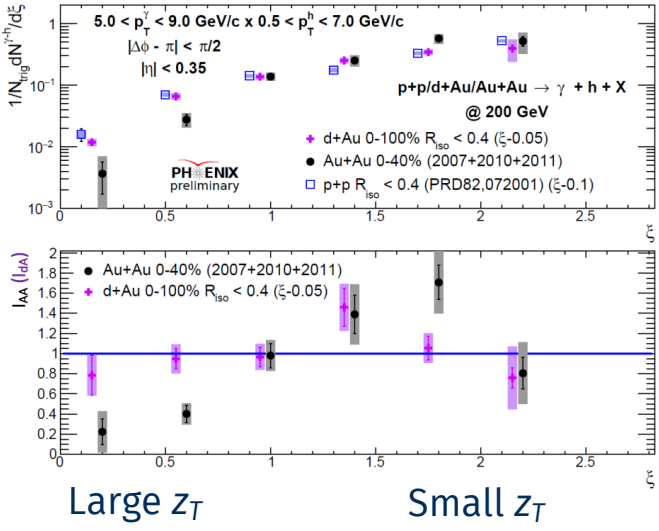

Au+Au

Fragmentation Function Modification with $\gamma - h^{\pm}$ in d+Au and Au+Au



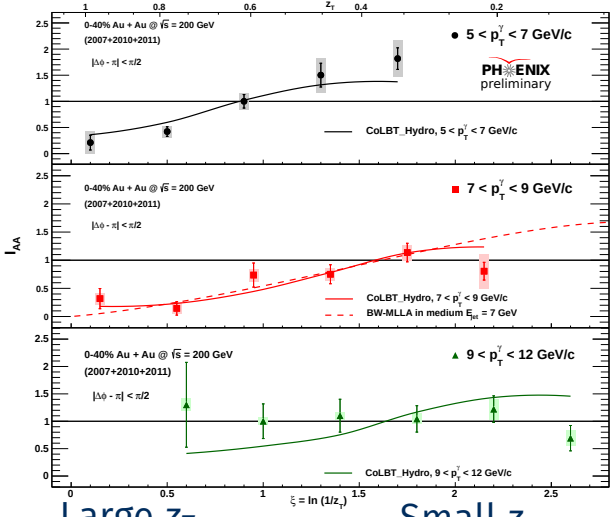
- Fragmentation function can be measured with away-side yields as a function of $\xi = \ln(1/z_T) = \ln(p_T^{\gamma}/p_T^{h})$ and $I_{AA} = Y_{AA}/Y_{pp}$

Fragmentation Function Modification with $\gamma - h^{\pm}$ in d+Au and Au+Au



- Fragmentation function can be measured with away-side yields as a function of $\xi = \ln(1/z_T) = \ln(p_T^{\gamma}/p_T^{h})$ and $I_{AA} = Y_{AA}/Y_{pp}$
- d+Au shows no significant modification from p+p
- Suppression of yield at small ξ, enhancement of yield at large ξ in Au+Au

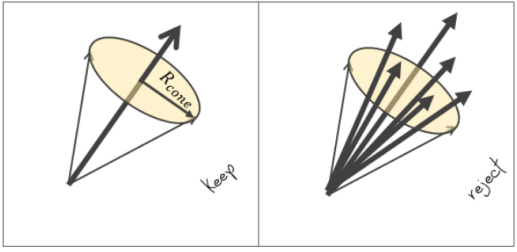
Yield Modification in Au+Au as a Function of p_T^γ



- Transition from suppression to enhancement not at a fixed $\xi = \ln(1/z_T) = \ln(p_T^\gamma/p_T^h)$
- Suggests transition is at an approximately fixed p_T^h
- Medium response in addition to redistribution of lost energy from high p_T hadrons?

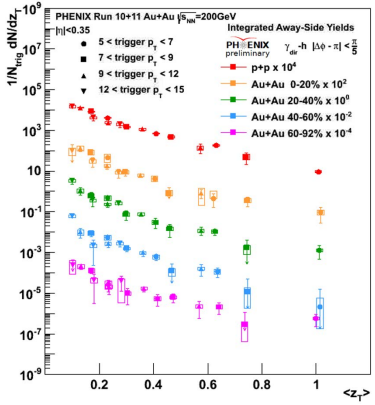
Isolation Cone Method in Au+Au

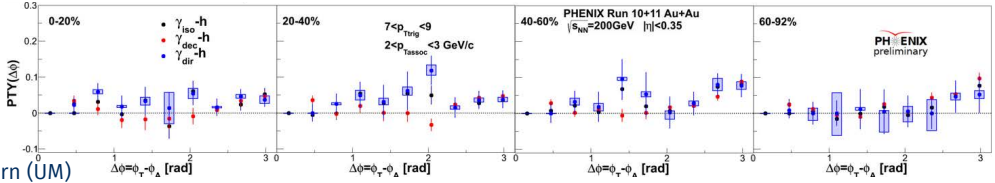
- Typical to use isolation cone in p+p and small systems
- First measurement utilizing isolation cone in Au+Au collisions from PHENIX



Isolation Cone Method in Au+Au

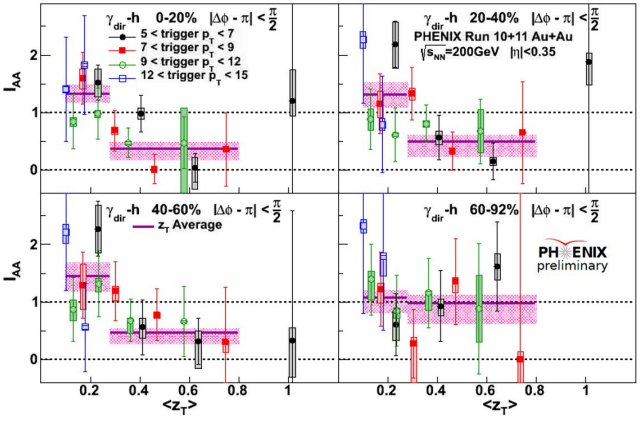
- Typical to use isolation cone in $p+p$ and small systems
- First measurement utilizing isolation cone in Au+Au collisions from PHENIX
- Example correlation functions as a function of $\Delta\phi$ (below) and integrated yields as a function of $\langle z_T \rangle = \langle p_T^h / p_T^\gamma \rangle$ (right)





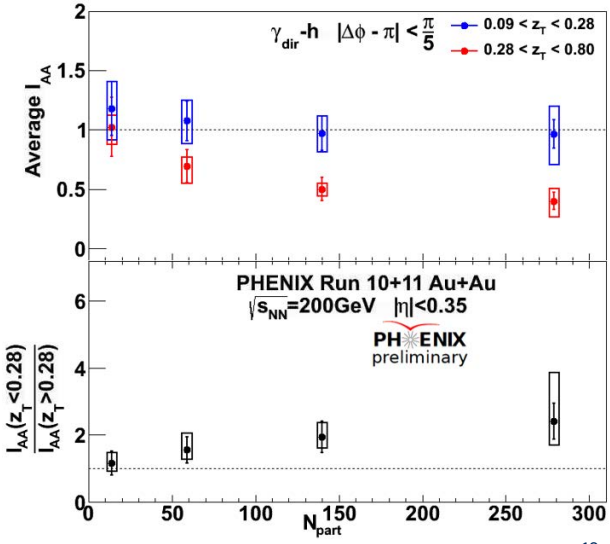
Away-Side Yield Suppression and Enhancement

- Measure $I_{AA} = Y_{AA}/Y_{pp}$ as a function of p_T^γ, $\langle z_T \rangle$, and centrality
- Purple lines show average across p_T^γ in two $\langle z_T \rangle$ regions in each centrality bin
- Can study the measured enhancement/suppression as a function of centrality with these averages

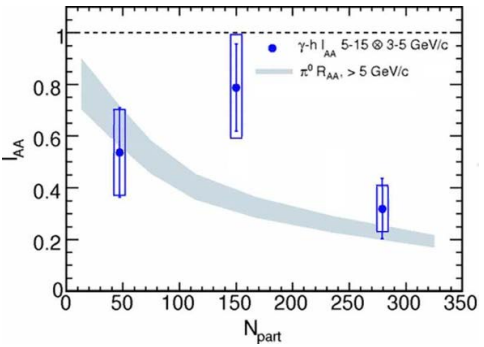


Away-side Yield Suppression and Enhancement

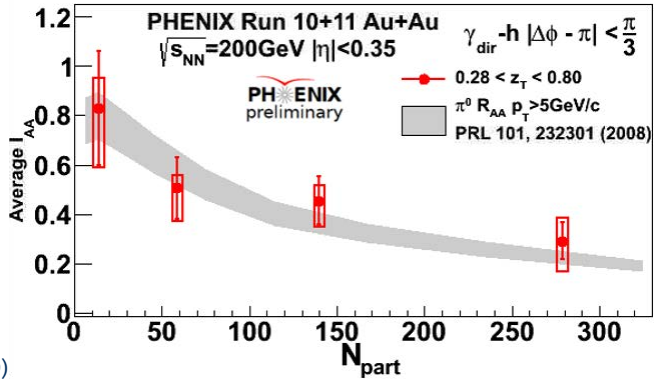
- Yield modification $I_{AA} = Y_{AA}/Y_{pp}$ determined in two $\langle z_T \rangle$ bins as a function of centrality for $|\Delta\phi - \pi| < \pi/5$
- Statistically significant monotonic increase of enhancement to suppression
- Provides information on redistribution of energy loss over a wide range of centrality



Large $\langle z_T \rangle$ Centrality Dependence



Previous PHENIX result, Phys. Rev. C 80, 024908 (2009)



- Isolation cut and larger statistical data greatly improves precision compared to previous PHENIX result
- Results give much better constraints on suppression of high p_T hadrons as a function of centrality in Au+Au direct photon-hadron correlations

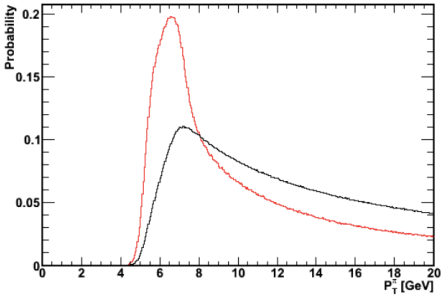
Conclusions

- In p+p collisions, new multi-differential results probe potential QCD factorization breaking effects due to QCD's non-Abelian nature
- Small transverse-momentum broadening has been observed in p+A dihadron correlations, potentially providing information on various cold nuclear matter effects
- Isolated direct photon-hadron correlations in d+Au collisions show no significant fragmentation function modification compared to p+p collisions
- New measurements of isolated direct photon-hadron correlations in Au+Au collisions provide better constraints on energy loss over a wide range of p_T^γ and centrality
- More measurements to come from PHENIX - Large Au+Au data sets in 2014 and 2016 are currently being analyzed!

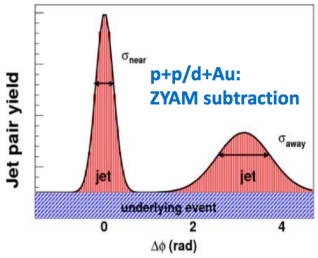
Back Up

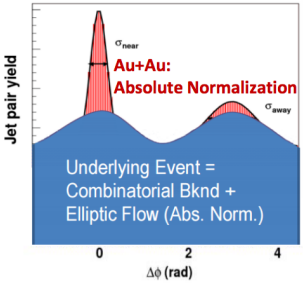
Direct Photon Measurements in PHENIX

- 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)





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

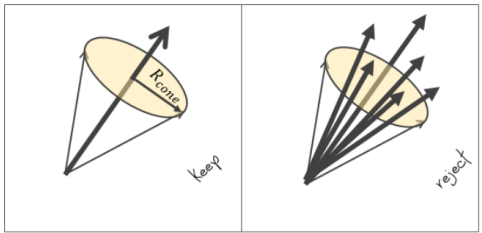
$$Y_{direct} = \frac{R_\gamma Y_{\text{inclusive}} - Y_{\text{decay}}}{R_\gamma - 1} \qquad (2)$$

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

Isolation Cut in Small Systems

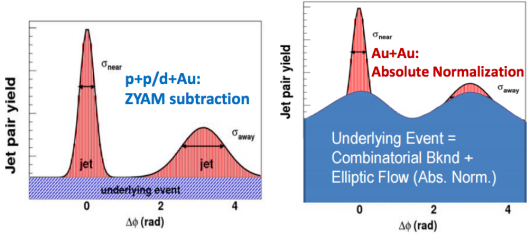
- Implement an isolation cone cut to boost signal-to-background ratio and reduce NLO fragmentation photon contribution
- Require sum of p_T of tracks and electromagnetic clusters in R=0.4 to be less than 10% of photon's energy

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



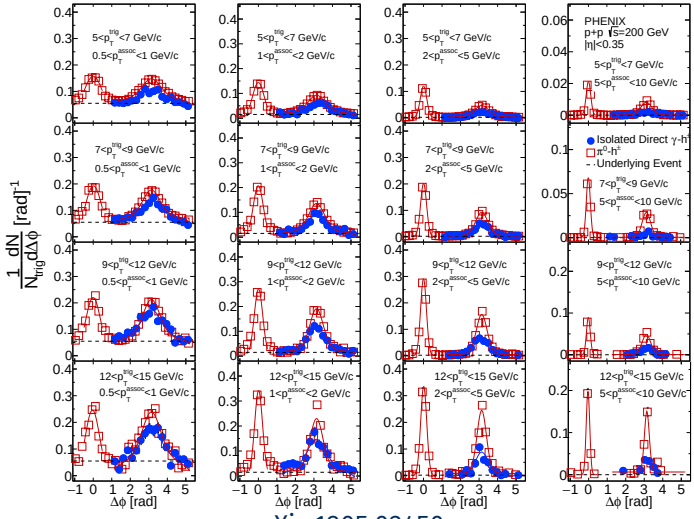
Flow Subtraction in Large Systems

- 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
- ZYAM underlying event subtraction in p+p/p+A/d+Au



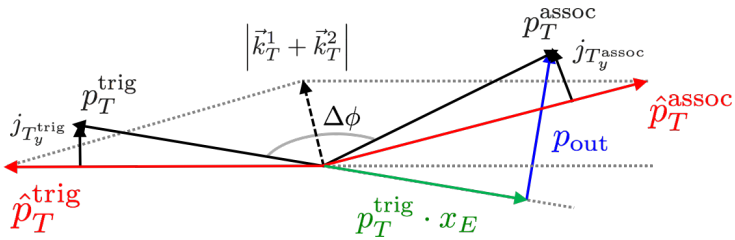
$$Y \propto Y(\Delta\phi) - b(1 + 2\langle v_2^{\gamma}\rangle\langle v_2^{h}\rangle \cos 2\Delta\phi) \tag{4}$$

$\Delta\phi$ Correlations in p+p $\sqrt{s}$ = 200 GeV



arXiv:1805.02450

π^0 Two-Particle Kinematics



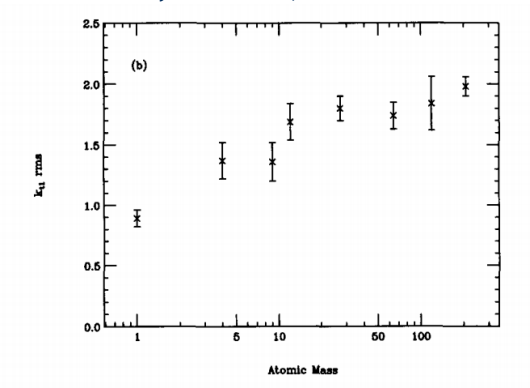
- In transverse plane of the correlation, i.e. beam pipe goes in and out of the page, these vectors can be defined in a dijet/dihadron correlation
- p_{out} and x_E are defined similarly in π^0-h$^{\pm}$ correlations
- The values are transverse and anti-parallel, respectively, to the leading trigger π^0

$$p_{out} = p_T^{\text{assoc}} \sin \Delta\phi \tag{5}$$

$$x_E = -\frac{p_T^{\text{assoc}} \cdot p_T^{\text{trig}}}{|p_T^{\text{trig}}|^2} = -\frac{|p_T^{\text{assoc}}|}{|p_T^{\text{trig}}|} \cos \Delta\phi \tag{6}$$

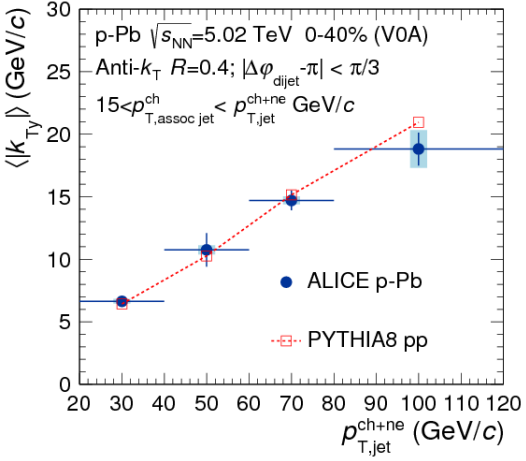
p+A k_T Broadening

Phys. Lett. B 259, 209 (1991)



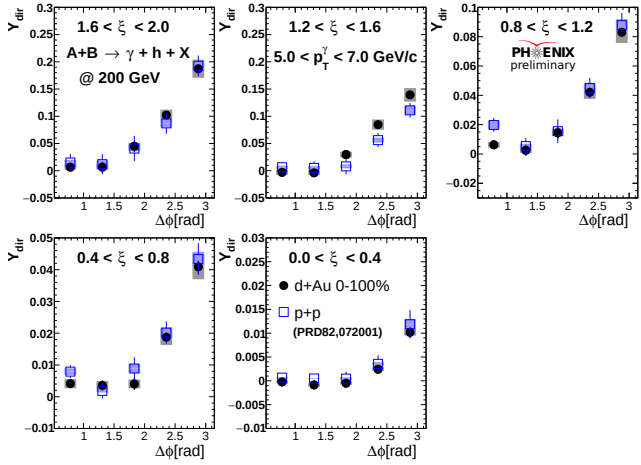
- Nuclear dependence of initial-state k_T in nuclei has been measured with jets at moderate $p_T > 4$ GeV/c
- Clear increase in dijet acoplanarity due to initial-state k_T with atomic mass

Phys. Lett. B 746, 385 (2015)



- Jets at larger p_T, outside "Cronin" peak, show no k_T difference between p+Pb and p+p

Example d+Au $\Delta\phi$ Correlations



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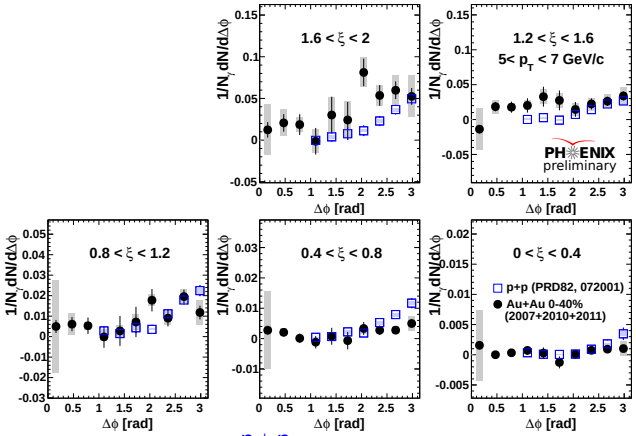


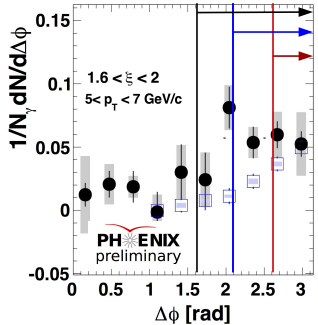
$p+p$

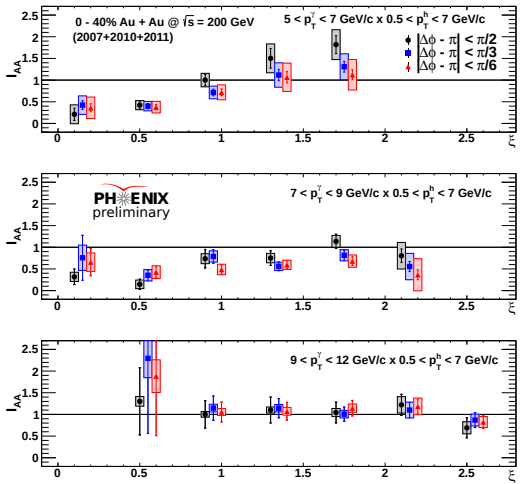
Au+Au

- Small ξ (large p_T^h) away-side suppression
- Large ξ (small p_T^h) large $\Delta\phi$ away-side enhancement
- Redistribution of energy due to interactions with medium

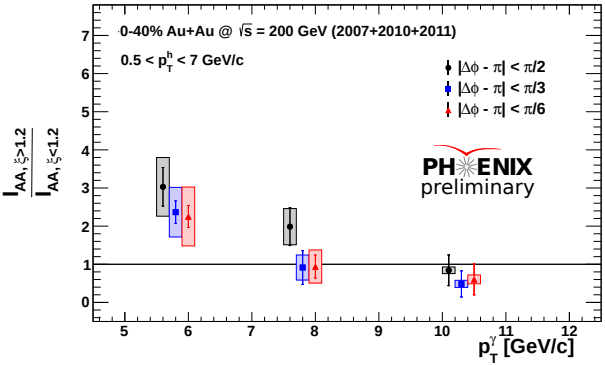
Au+Au Suppression/Enhancement with $\Delta\phi$

- 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





p_T^{γ} Dependence of Suppression and 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

Au+Au Isolation Cut Method

- Isolation cone criterion similar to small systems - sum energy in a cone around the candidate photon, and if it is less than a threshold the particle is considered isolated
- Thresholds depend on centrality, background event energy, and candidate photon energy

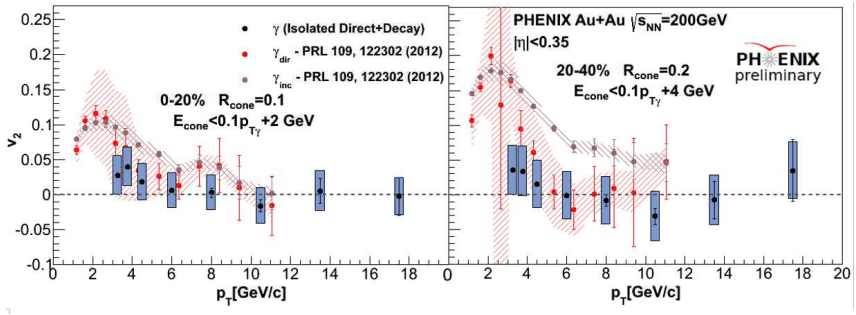
$E_{threshold}^{cone} = aE_{\gamma} + b$

Centrality	R_{cone}	a [GeV/c]	b [GeV/c]
0-20	0.1	0.1	2.0
20-40	0.2	0.1	4.0
40-60	0.2	0.1	2.0
60-92	0.3	0.1	1.0

Taken from N. Riveli, Ph.D. thesis, Ohio University (2014)

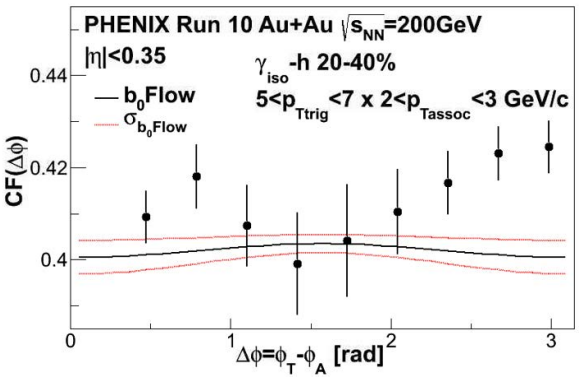
- Additional considerations due to isolation cut in Au+Au:
  - Measuring isolated particle v_2 for background subtraction
  - Potentially alters background level
  - Implementing into decay photon statistical subtraction

Illustration of v_2 Measurement with Isolation Cone



- Inclusive photon v_2 is large and not consistent with 0
- Isolation cut reduces direct photon v_2 at high p_T to be consistent to 0
- This is an example which shows the direct photon signal-to-background is boosted with the isolation cut
- Further decay photon statistical subtraction removes remaining decay background

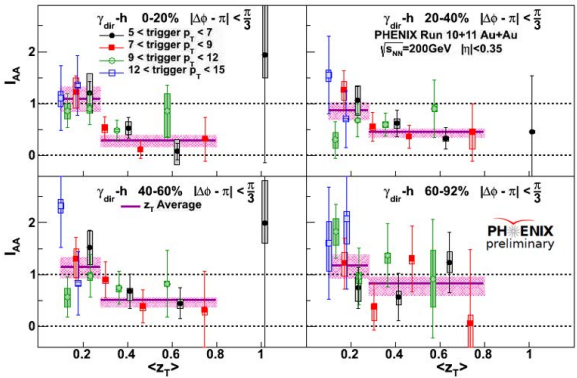
Example Isolated Au+Au Background Contribution



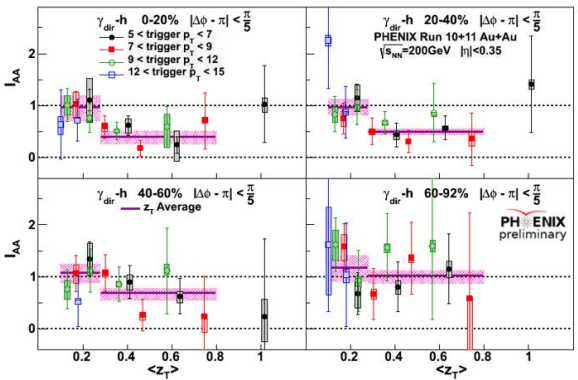
- Example correlation function shown with the modulated background contribution
- Modulated background consistent with underlying event region, indicating that background from isolated photons is properly accounted for
- The modulated background is negative due to the implementation of the isolation cut, which preferentially selects photons out of the event-plane

I_{AA} vs. $\langle z_T \rangle$ for Various $\Delta\phi$ Integration Ranges

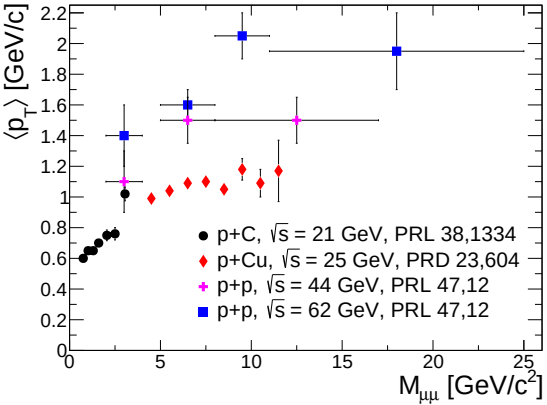
$|\Delta\phi - \pi| < \frac{\pi}{3}$

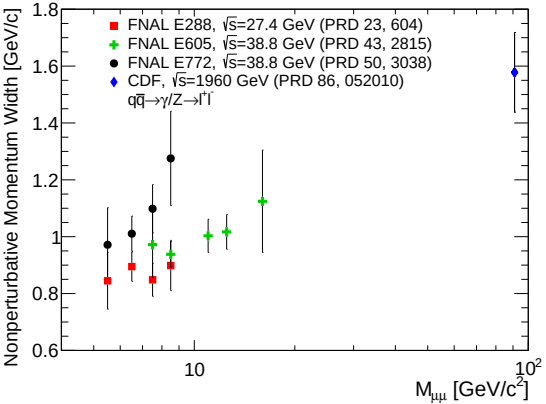


$|\Delta\phi - \pi| < \frac{\pi}{5}$



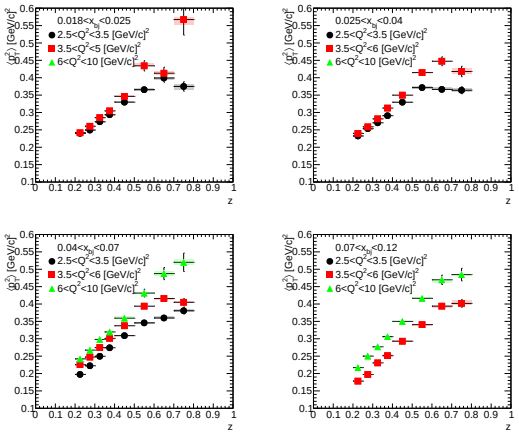
Drell-Yan Nonperturbative Momentum Widths

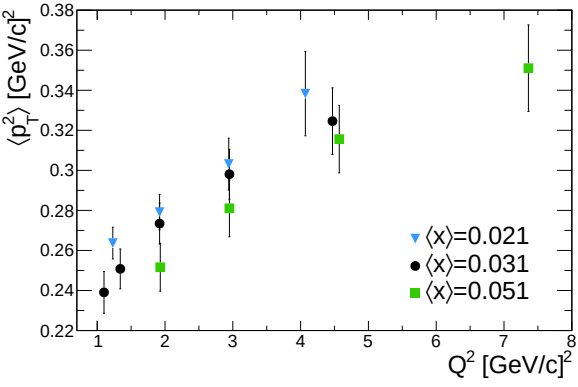




- $\langle p_T \rangle$ taken from publications as noted - include perturbative contributions
- Nonperturbative momentum widths taken from Gaussian fits to published cross sections

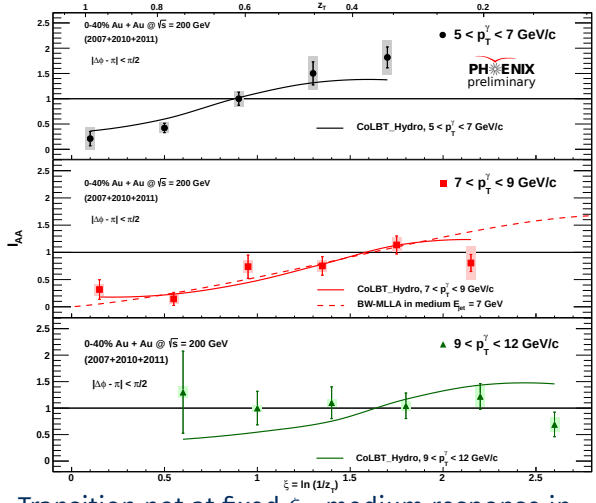
Semi-Inclusive DIS Nonperturbative Momentum Widths





- Hadron multiplicity data taken from COMPASS collaboration publication Eur. Phys. J. C 73, 2531(2013)
- Only include nonperturbative contributions at small p_T^2

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)