Systematic study of high p_T hadron production in small collision systems by the PHENIX experiment at RHIC

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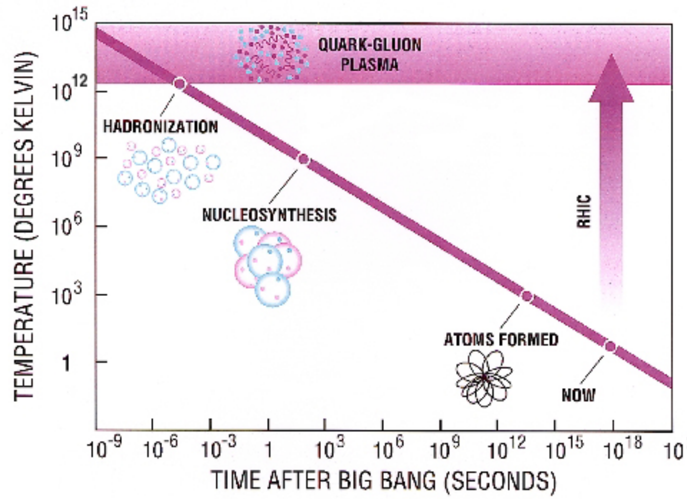
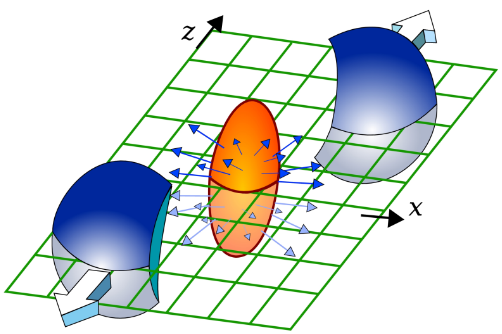
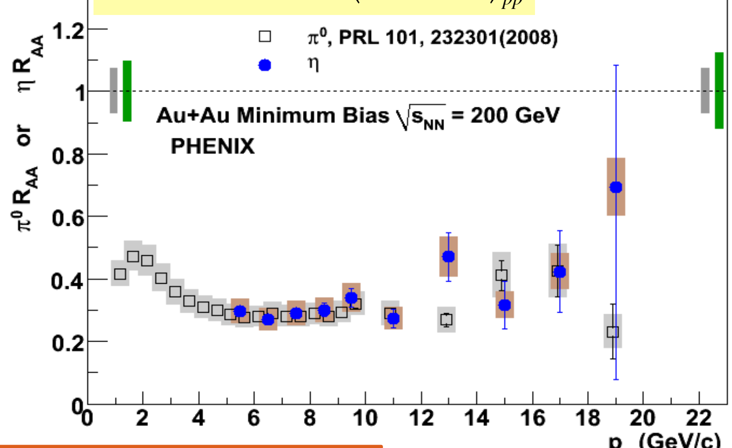
Quark Gluon Plasma (QGP)

- Partonic (quarks and gluons) matter believed to have existed in the early Universe.
- QGP formation by colliding heavy ions at high energies (RHIC, LHC, etc.)
- Confirmation of its formation by comparing with the system known **not to** form QGP
  - *p*+*p*, *p*+A collisions
  - Particle flow, high p_T hadron suppression, etc.



$$R_{AA} = \frac{\left(d^3N/dp^3\right)_{AA}}{(N_{coll}/\sigma_{inel})\left(d^3\sigma/dp^3\right)_{pp}}$$





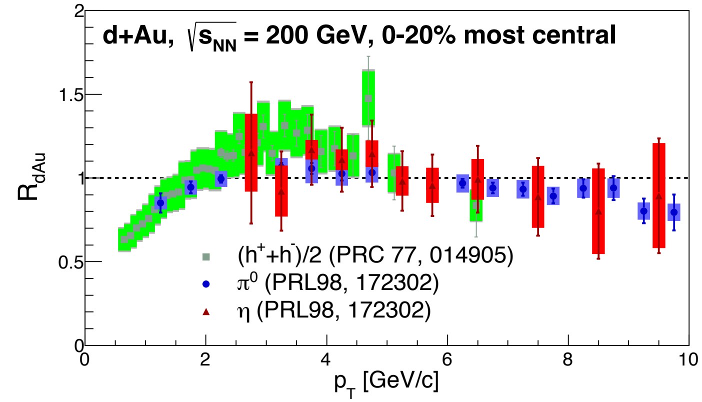
$$\frac{d^3N}{p_T dp_T dy d\varphi} \propto [1 + 2v_2(p_T)\cos 2(\varphi - \phi_{RP}) + \ldots]$$

PRC82, 011902(R) (2010)

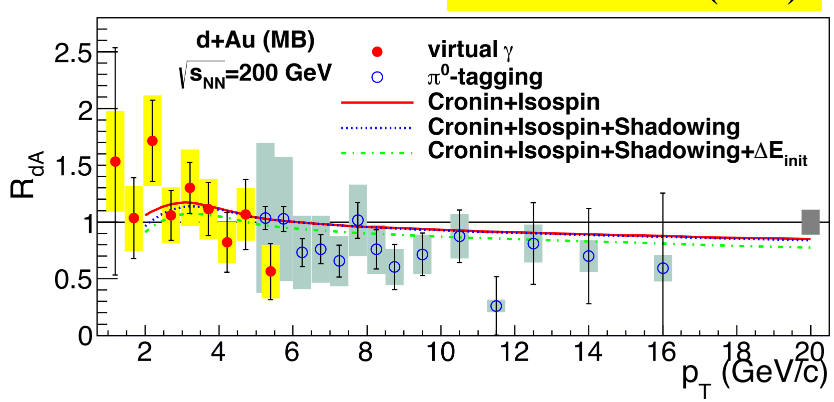
Small system *~was simple and a baseline~*

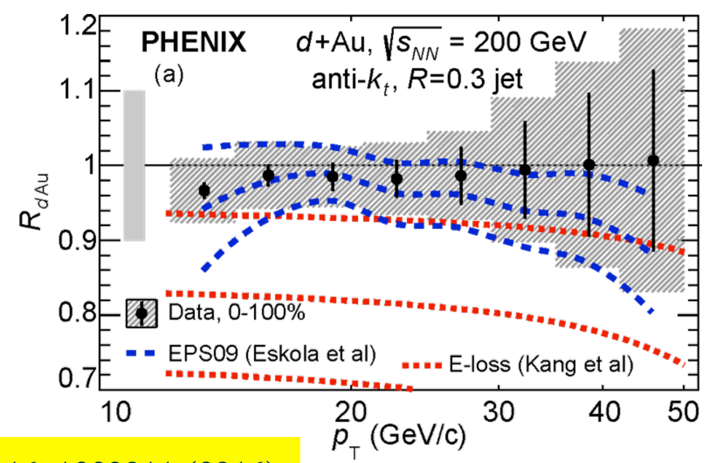
- Why were we interested in small system collisions (i.e., *p*/*d*/^{3}He+Au):
  - To confirm the high-p_T hadron suppression in Au+Au is due to final state effects (QGP), and not cold nuclear matter (CNM) effects.
  - CNM effects include: k_T broadening, shadowing, CNM energy loss, …

- Measured R_{dAu}:
  - Jets/hadrons and direct photons in minimum bias *d*+Au collisions are consistent with unity up to high-p_T
  - As expected from parton distribution function (EPS09).



PRC 87, 054907 (2013)



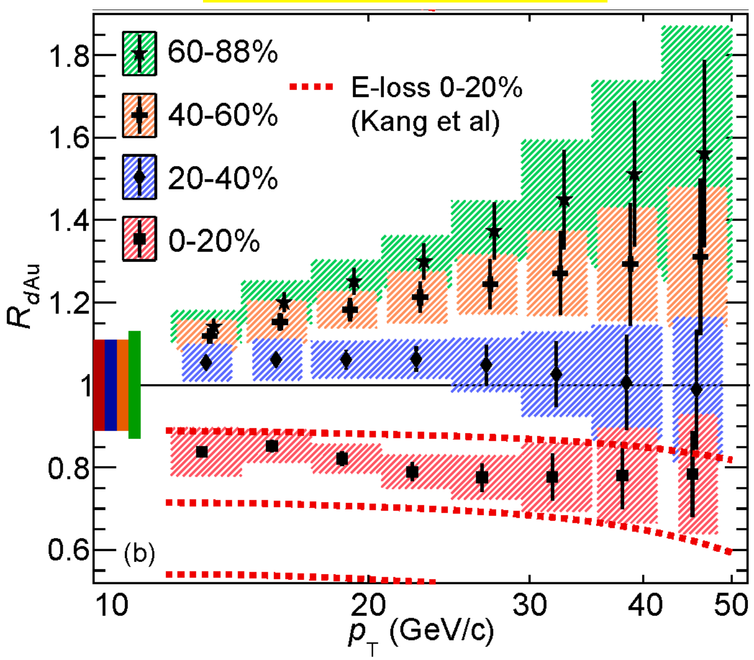


PRL 116, 1223011 (2016)

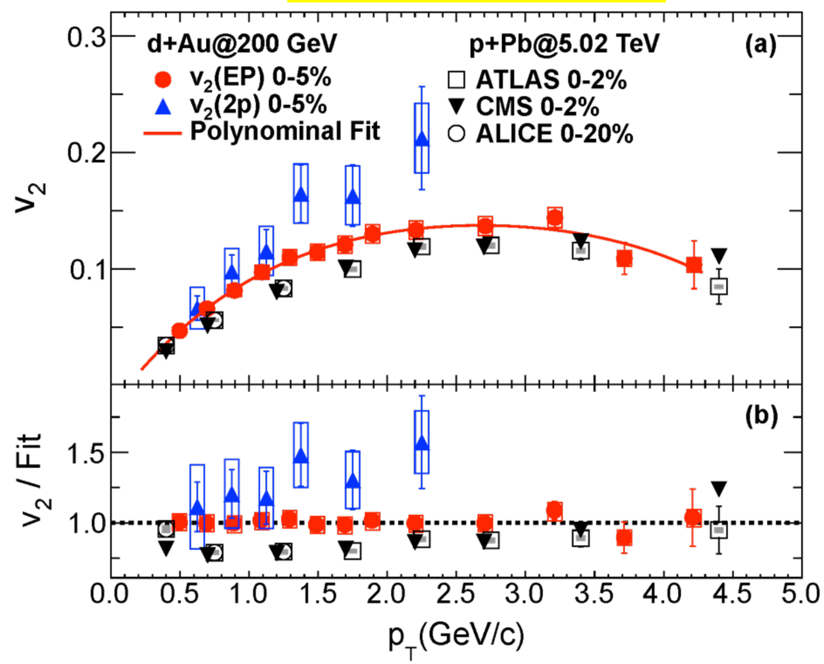
Small system is no longer simple

- Jets R_{dA} shows strong centrality dependence
  - Suppression in most central, enhancement in most peripheral
- Strong flow like A+A is seen in most central *d*+Au collisions
  - Similar observation by the LHC experiments
  - We didn't anticipate "flow" in a small system like *p*/*d*+A

PRL 116, 1223011 (2016)

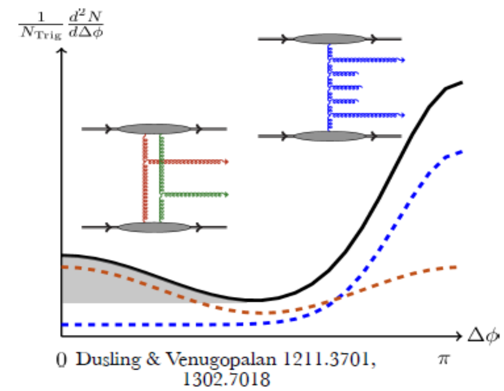


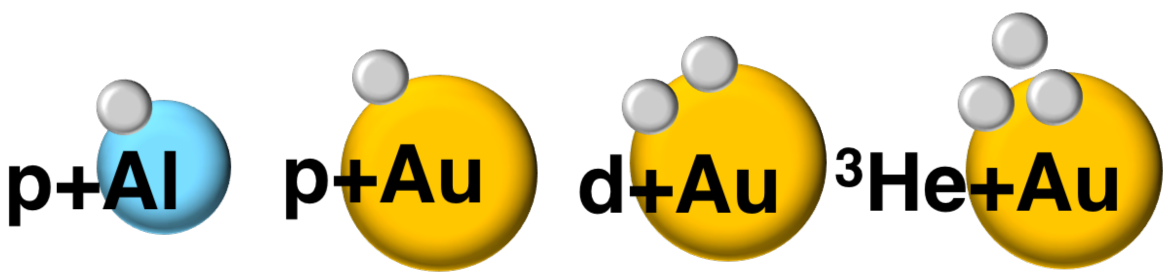
PRL114, 192301 (2015)

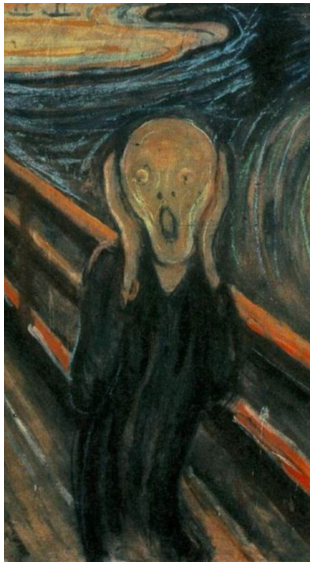


Journey to new worlds

- Initial state effects, e.g. CGC, will affect to production cross-section of particles and their orientation
- Mini-QGP production?
  - Final state effects, e.g. hydrodynamics will produce flow-like structure
- If there is QGP, detail investigation of the interaction of partons with the medium will give insight on its characteristics
- Systematic study of the leading hadron spectra in small systems will help

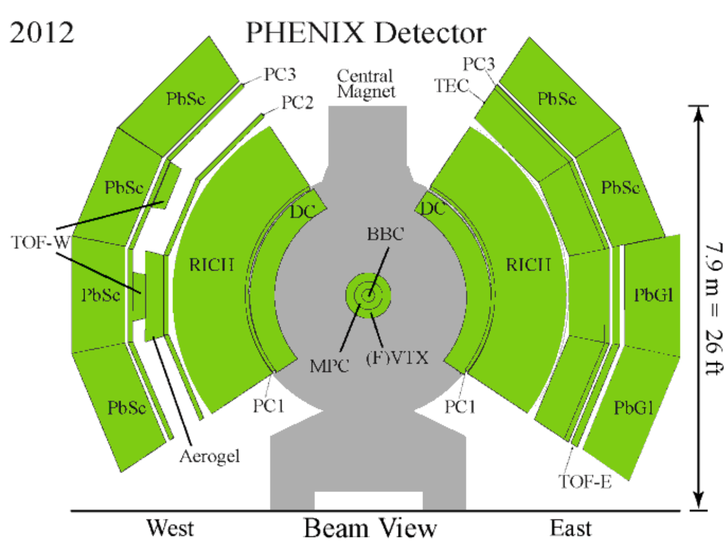


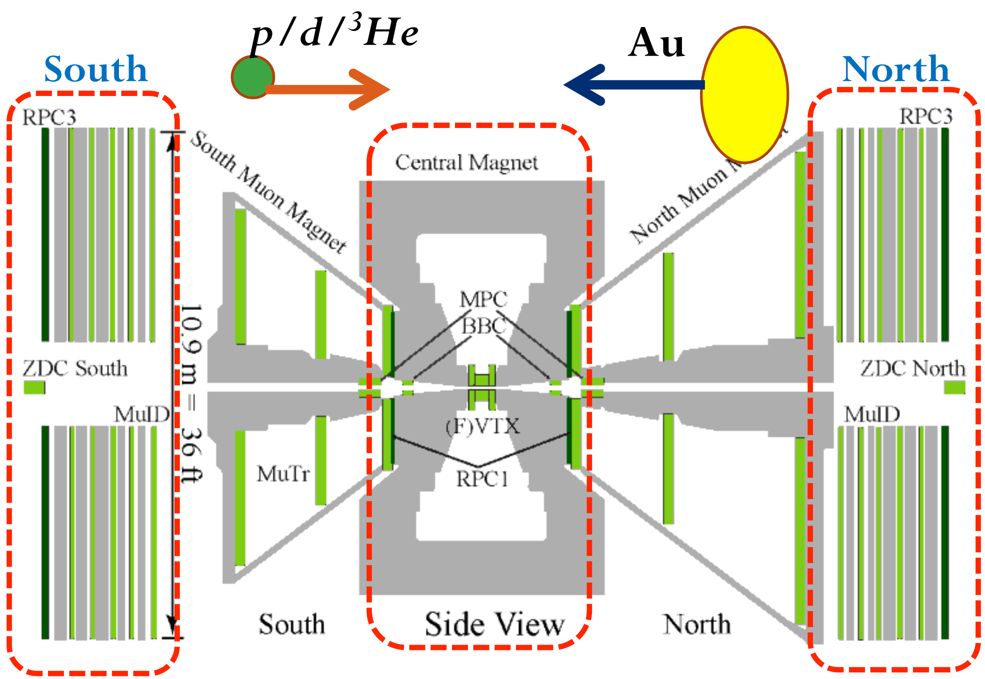




PHENIX detector and dataset

- Integrated luminosities, triggered by BBC:
  - Year-3 and -8 d+Au: 2.74 μb^{-1} (1.1 pb^{-1} pp-equiv), 80 μb^{-1} (32.1 pb^{-1} pp-equiv)
  - Year-14 ^{3}He+Au: 25 nb^{-1} (15 pb^{-1} pp-equiv)
  - Year-15 p+Au, p+Al: 80 nb^{-1} (16 pb^{-1} pp-equiv), 275 nb^{-1} (7.4 pb^{-1} pp-equiv.)
- Particle identification and tracking:
  - π^0 by Electromagnetic Calorimeter in central arm ($|\eta|<0.35$)
  - Hadrons by muon arms ($3.1<|\eta|<3.9$)



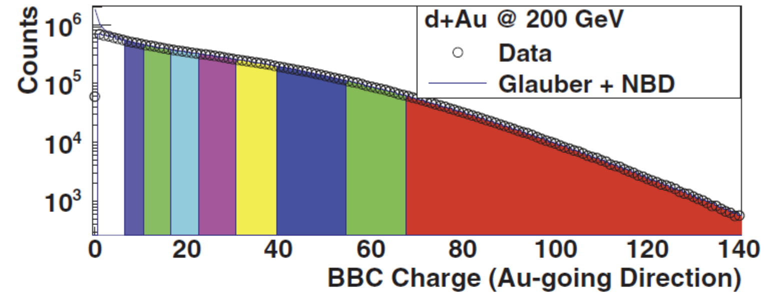


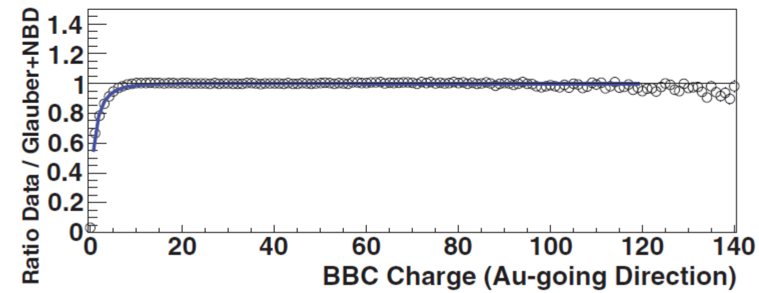
Event trigger and bias

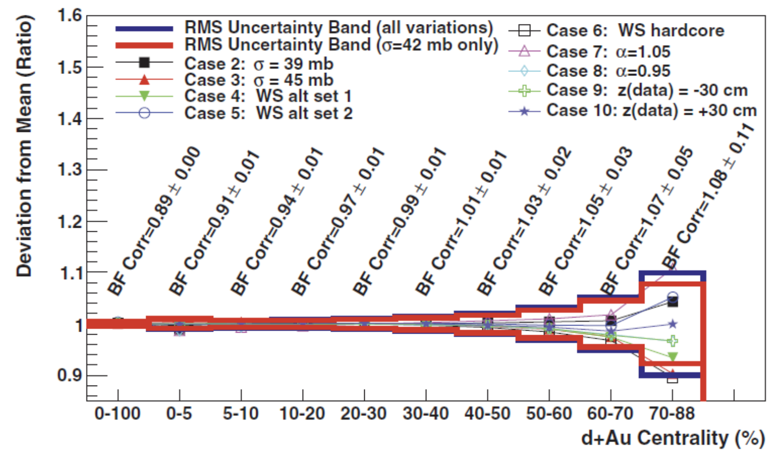
- Min. Bias trigger has inefficiency
  - Measured BBC charge distribution was compared with a Glauber Monte Carlo simulation folded with a negative binomial distribution (NBD)
- Trigger efficiency is determined as **88%**.
  - Same for $p/d/^{3}$He+Au
- Bias factors (BF) for centrality selection are calculated
  - Bias is coming from auto-correlation between high p_T particle in mid-rapidity and backward multiplicity (where centrality is determined)

Cent (%)	0-20	20-40	40-60	60-88	0-100
p+Au BF	0.90	0.98	1.02	1.00	0.86
d+Au BF	0.94	1.00	1.03	1.03	0.89
^{3}He+Au BF	0.95	1.02	1.02	1.03	0.89

PRC 90, 034902 (2014)

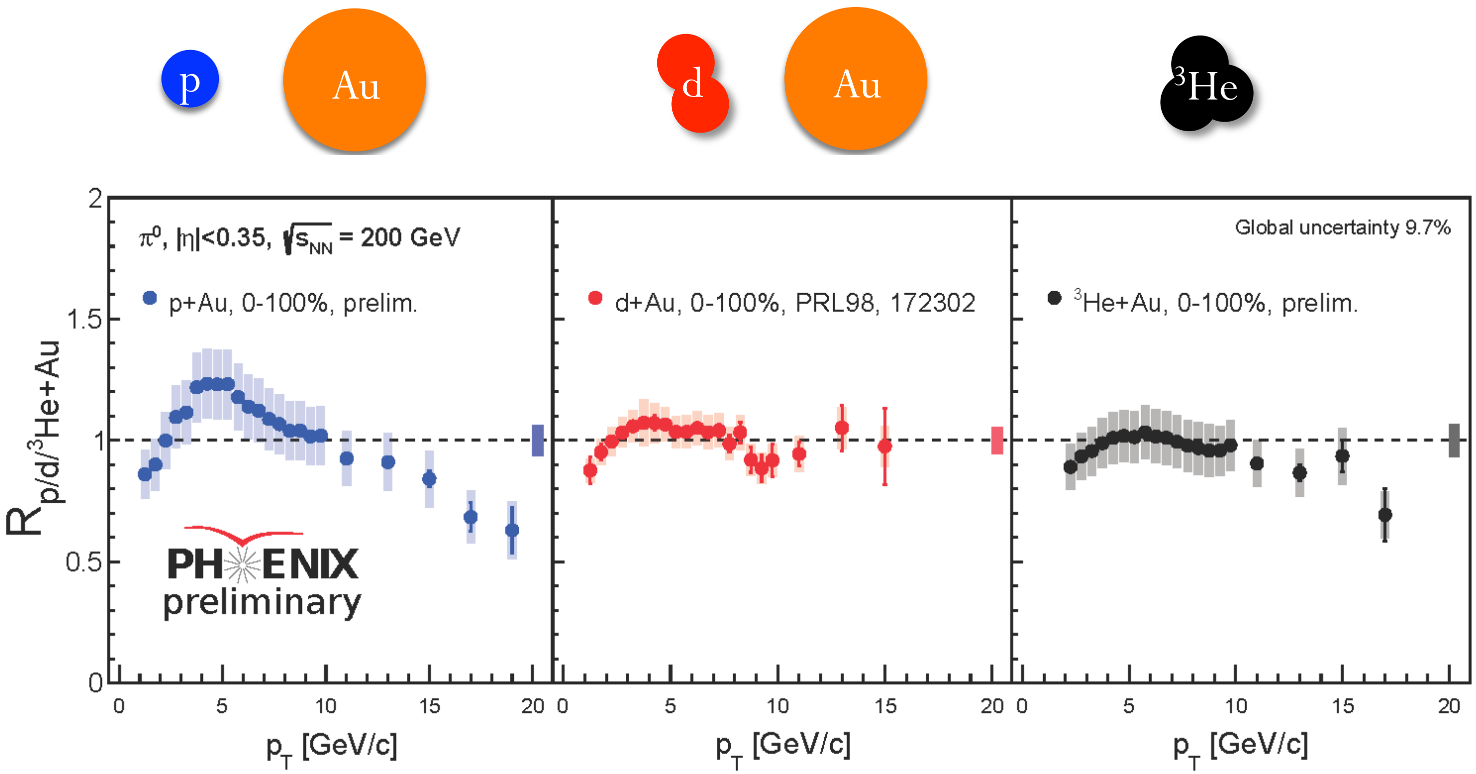




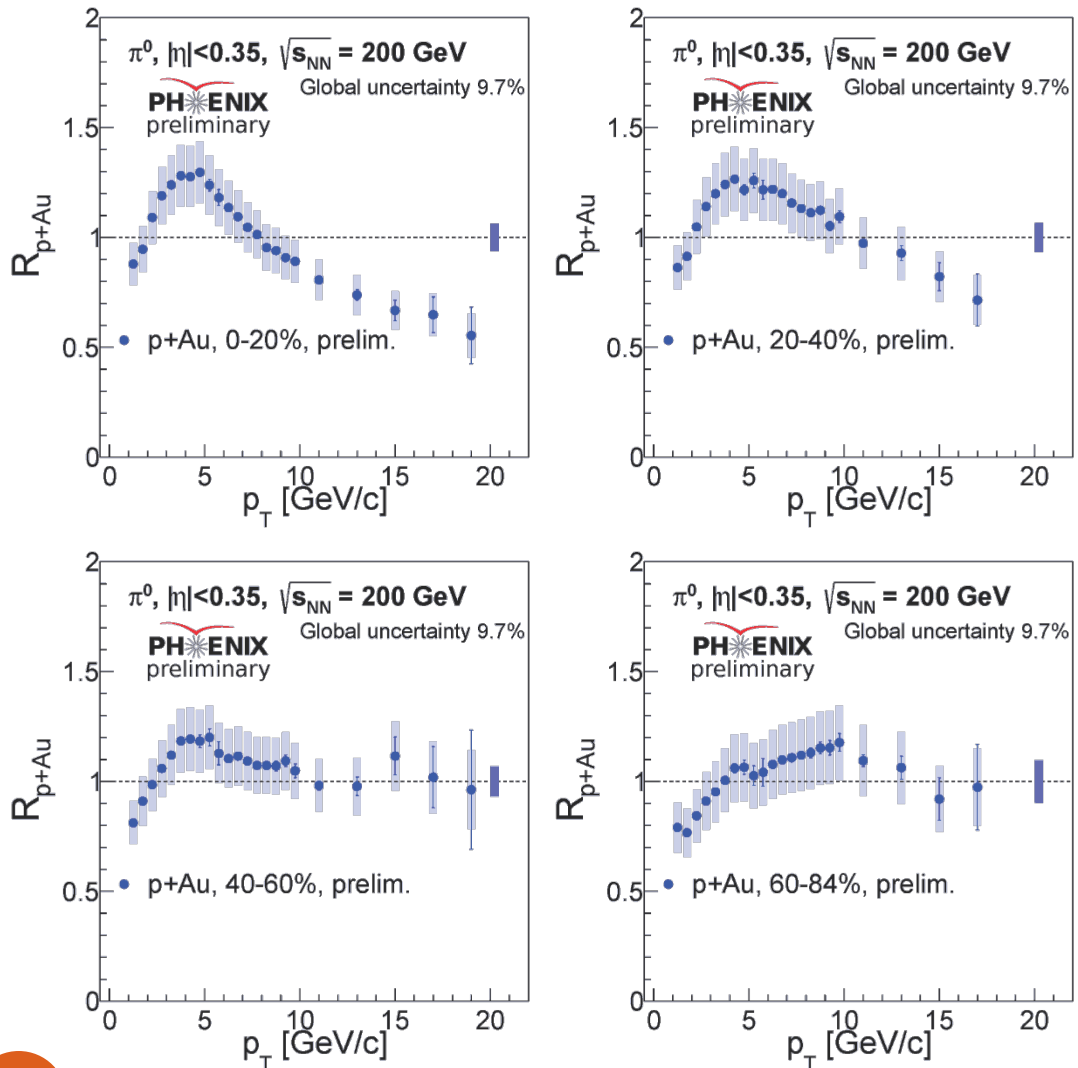


Nuclear modification factors for min. bias

- Comparison of the $R_{p/d/He+Au}$ for three collision systems
  - Enhancement at $p_T = 5$ GeV/c indicates a system size dependence
- Some hint of suppression at higher p_T (p_T>10GeV/c)?

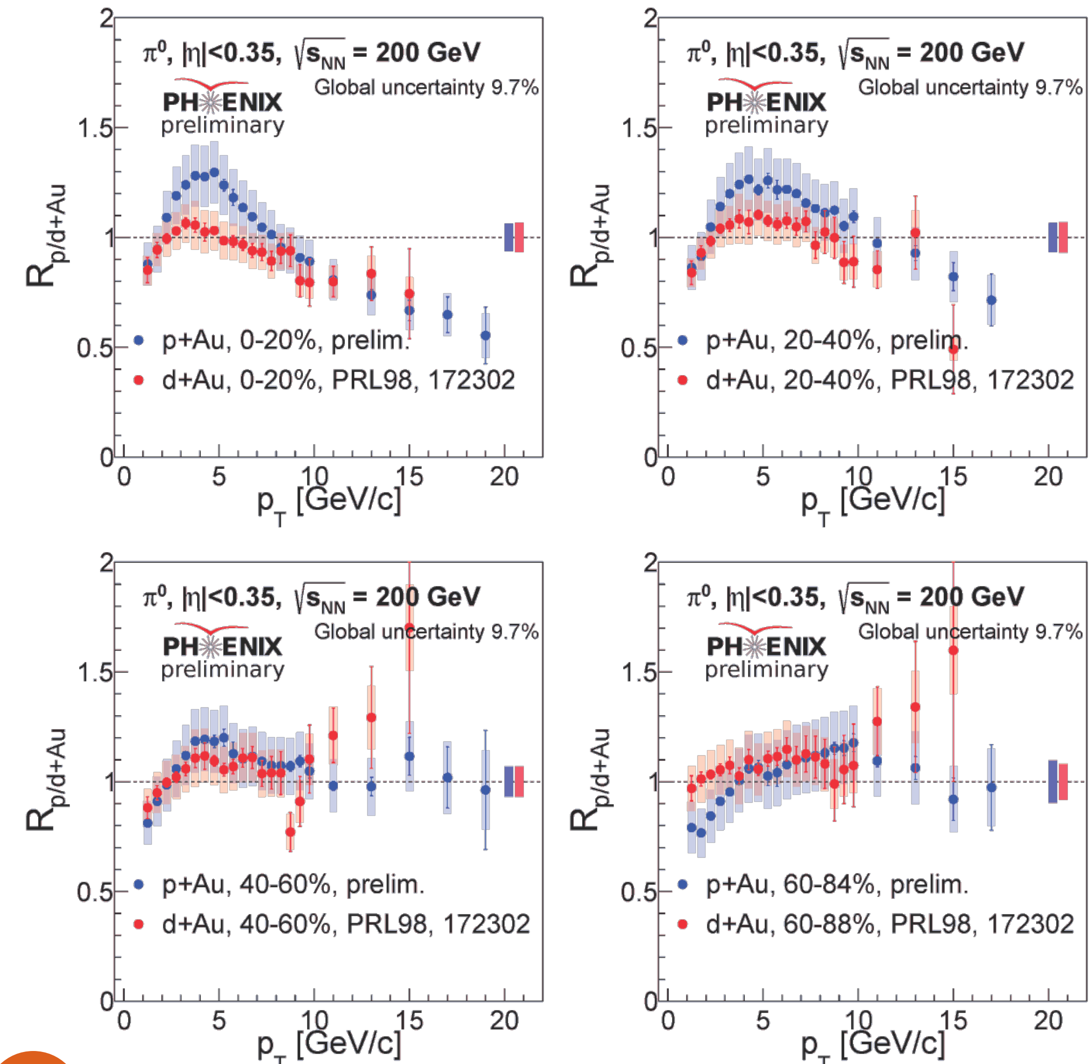


R_{p+Au} vs centralities



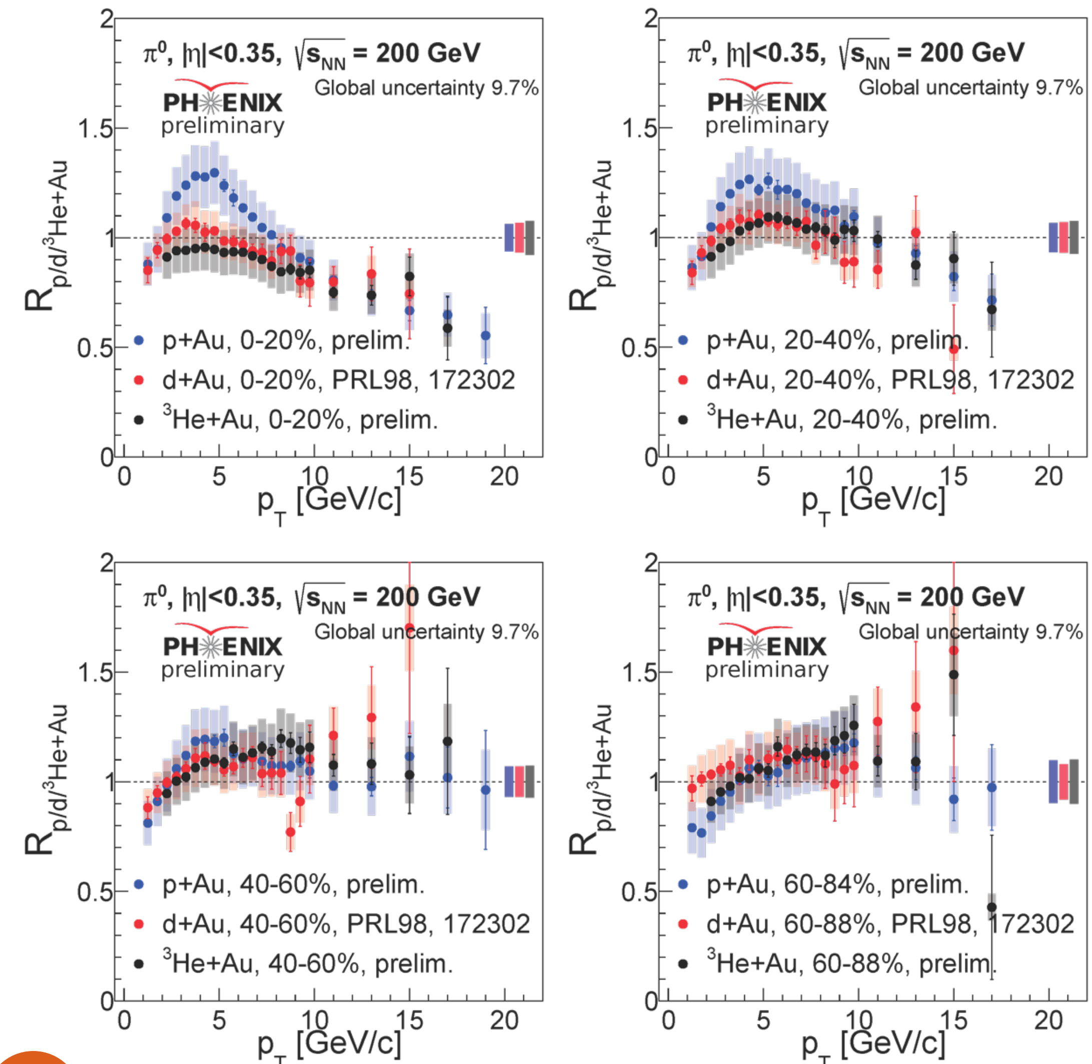
- Nuclear modification in centralities:
  - Centrality determined similarly as for large systems (PRC90,034902)
- ***p*+Au results show large centrality dependence**

$R_{p/d+Au}$ vs centralities



- Nuclear modification in centralities:
  - Centrality determined similarly as for large systems (PRC90,034902)
- ***p*+Au results show large centrality dependence**
- ***d*+Au results agree with *p*+Au at high-p_T**

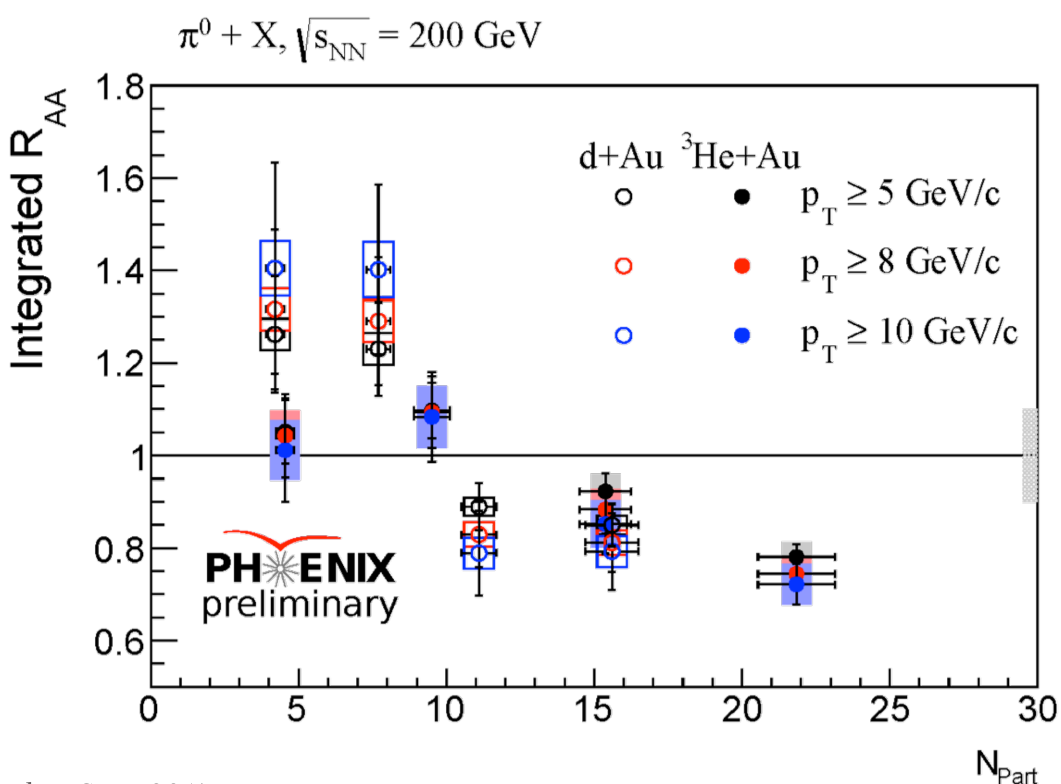
$R_{p/d/^3He+Au}$ vs centralities



- Nuclear modification in centralities:
  - Centrality determined similarly as for large systems (PRC90,034902)
- ***p*+Au results show large centrality dependence**
- ***d*+Au results agree with *p*+Au at high-p_T**
- **^{3}He+Au results agree with *p*+Au and *d*+Au at high-p_T**
- **At moderate p_T an ordering is seen as a function of systems**

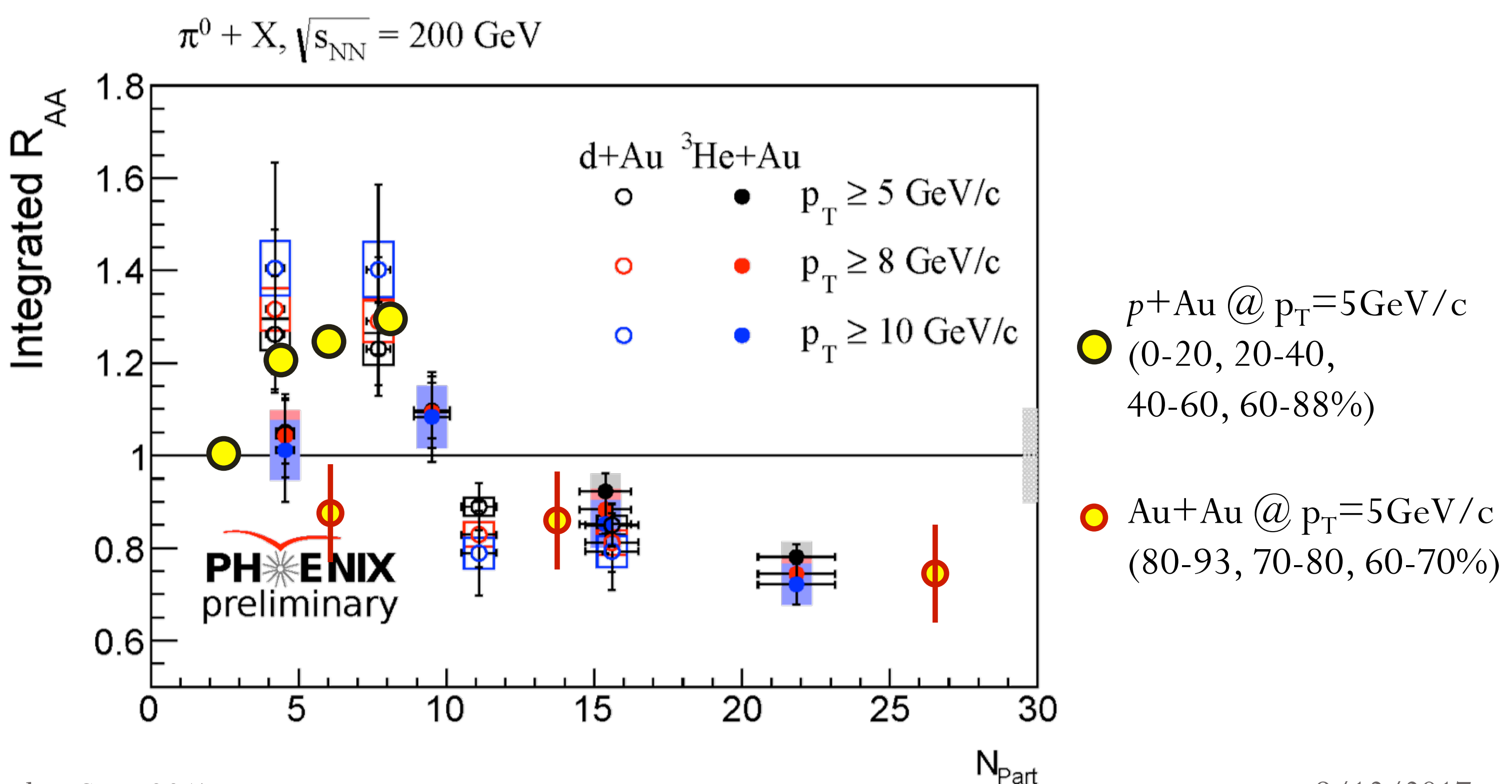
Integrated R_{AA} in *d*+Au and ^{3}He+Au

- At higher N_{part}, *d*+Au and ^{3}He+Au show very similar N_{part} dependence
- At lower N_{part}, *d*+Au collisions show more enhancement
  - More Cronin effect, or less suppression (energy loss)



Integrated R_{AA} in *p/d/*^{3}He/Au+Au

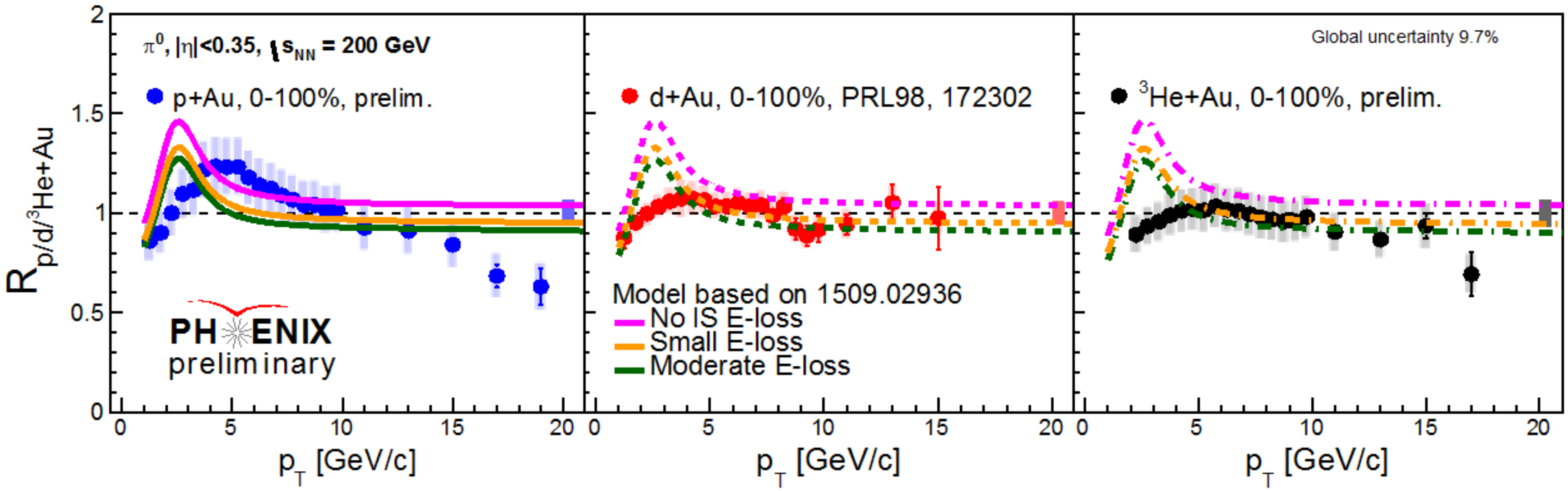
- Integrated R_{AA} for *p/d/*^{3}He/Au+Au
- R_{AA} from all three systems converge for N_{part}>~12
  - Similar ***hot*** matter is produced?
- System ordering of R_{AA} is seen for N_{part}<12 is seen; $R_{pAu} \sim R_{dAu} > R_{HeAu} > R_{AuAu}$



Cold nuclear energy loss?

- Different energy loss scenarios (no, small or moderate) are comparable to the data at high-p_T
- System dependent enhancement change at low-p_T is not reproduced
  - The peak positions are also different
  - Additional parameters to be tuned?

PRD 93, 074030, and priv. comm. with I.Vitev

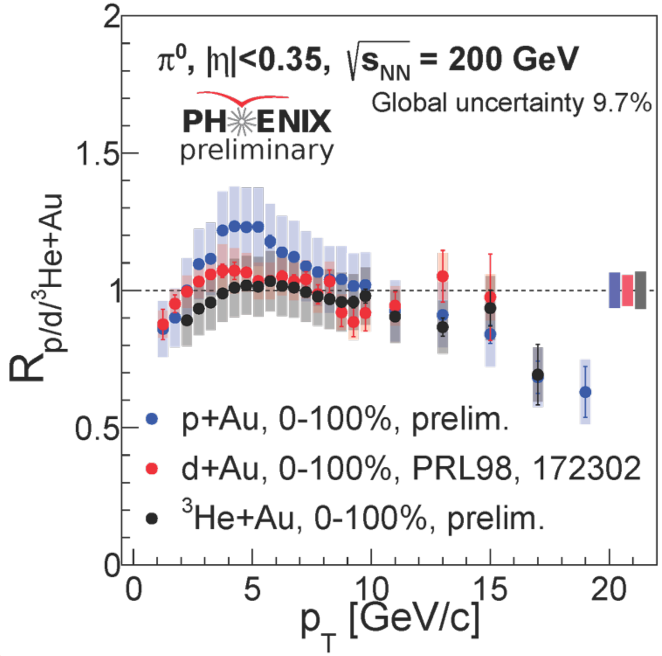


Multiple scattering ?

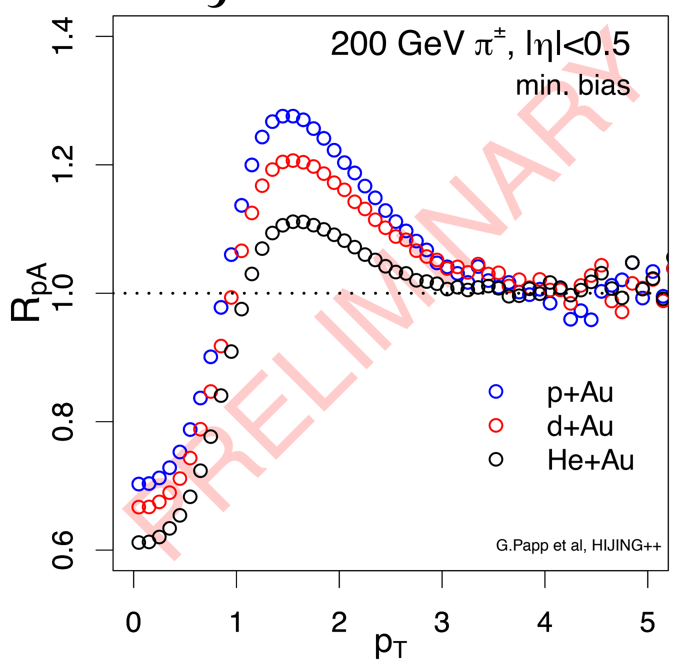
- HIJING++ simulation shows similar trend between collision systems
  - Ingredient: multiple scattering + shadowing effect
- HIJING++ predicts the Cronin peak around p_T = 1.5-2GeV/c
  - Much lower than in the data (p_T ~ 5 GeV/c)

based on 1701.08496
private comm. with G. Papp

PHENIX Data



HIJING++ simulation

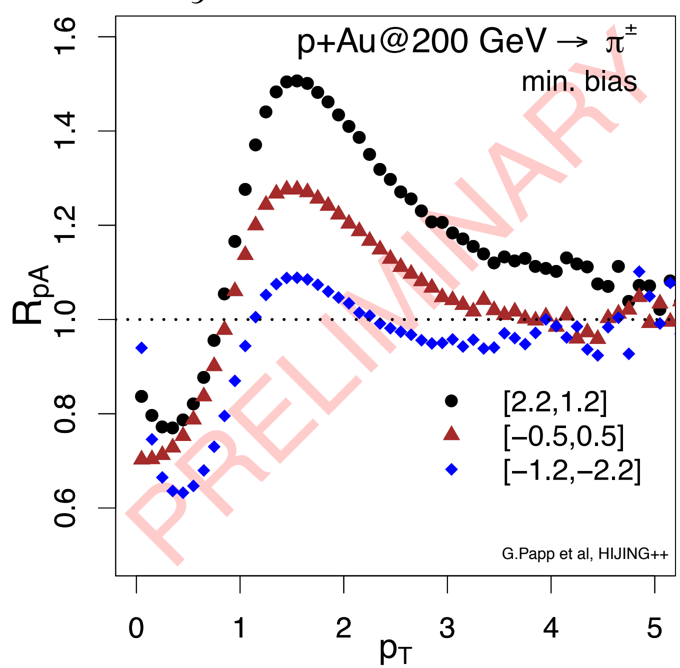


Lessons from model comparison

- Cold nuclear energy loss alone can't describe the trend of nuclear modification factors for $p/d/^{3}$He+Au collisions

- Multiple scattering + shadowing scenario seems to describe the spectra
  - This scenario predicts **larger** (**smaller**) enhancement in the **forward** (**backward**) in comparison to **mid-rapidity**

HIJING++ simulation



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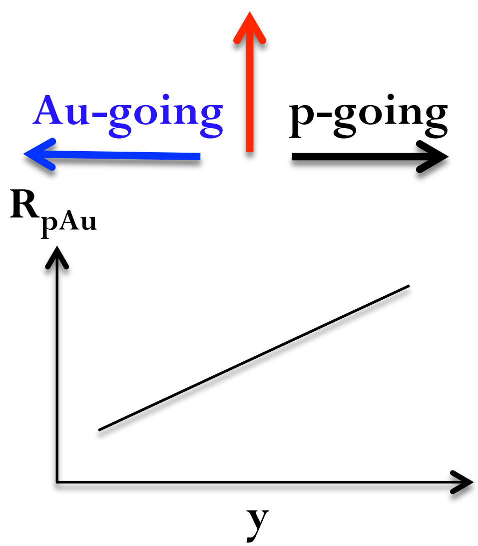

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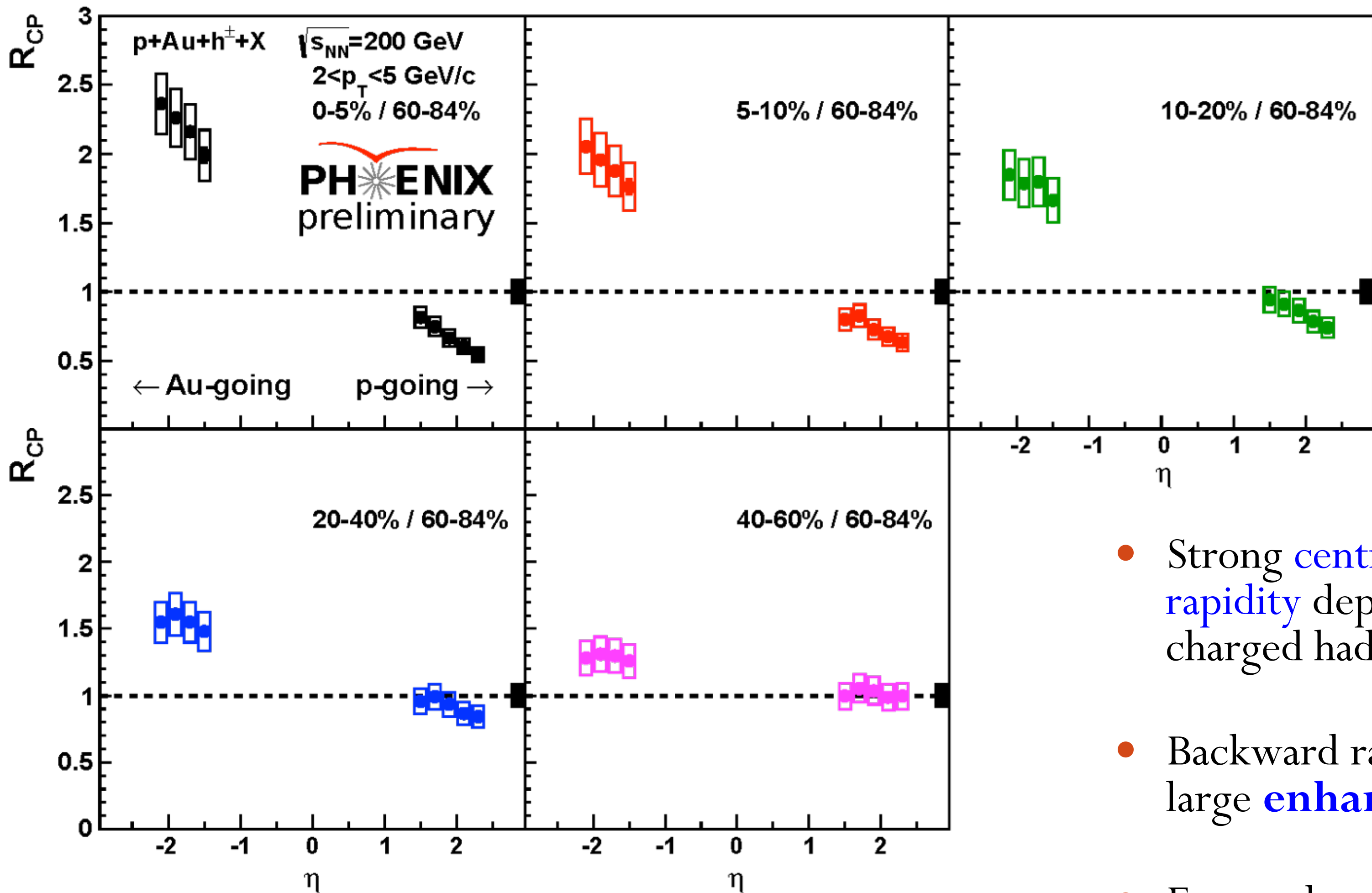
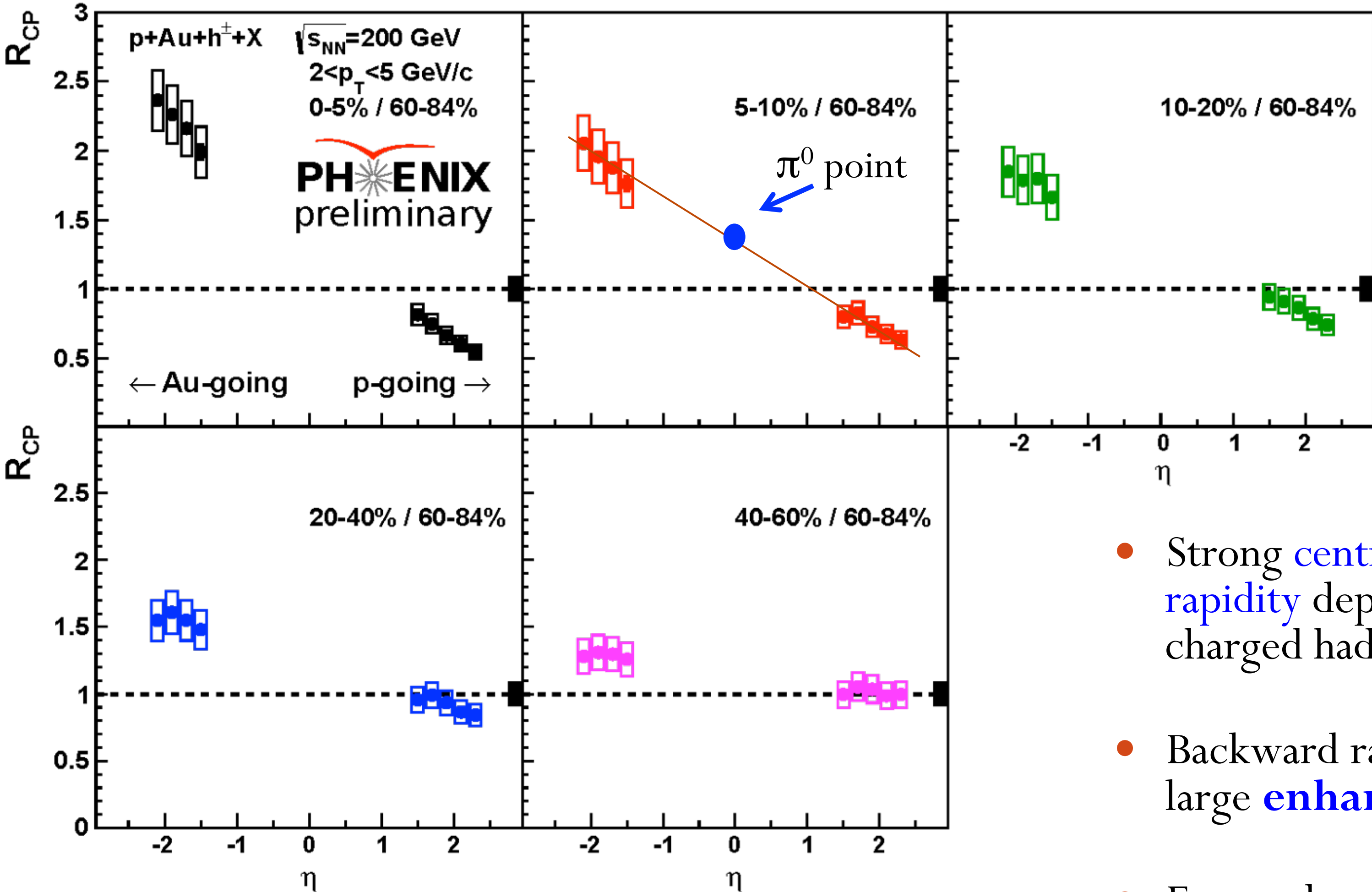
Looking forward and backward



- Strong centrality and rapidity dependence of charged hadrons
- Backward rapidity shows large **enhancement**
- Forward rapidity shows **suppression**

Opposite trend compared to HIJING++ prediction

Looking forward and backward



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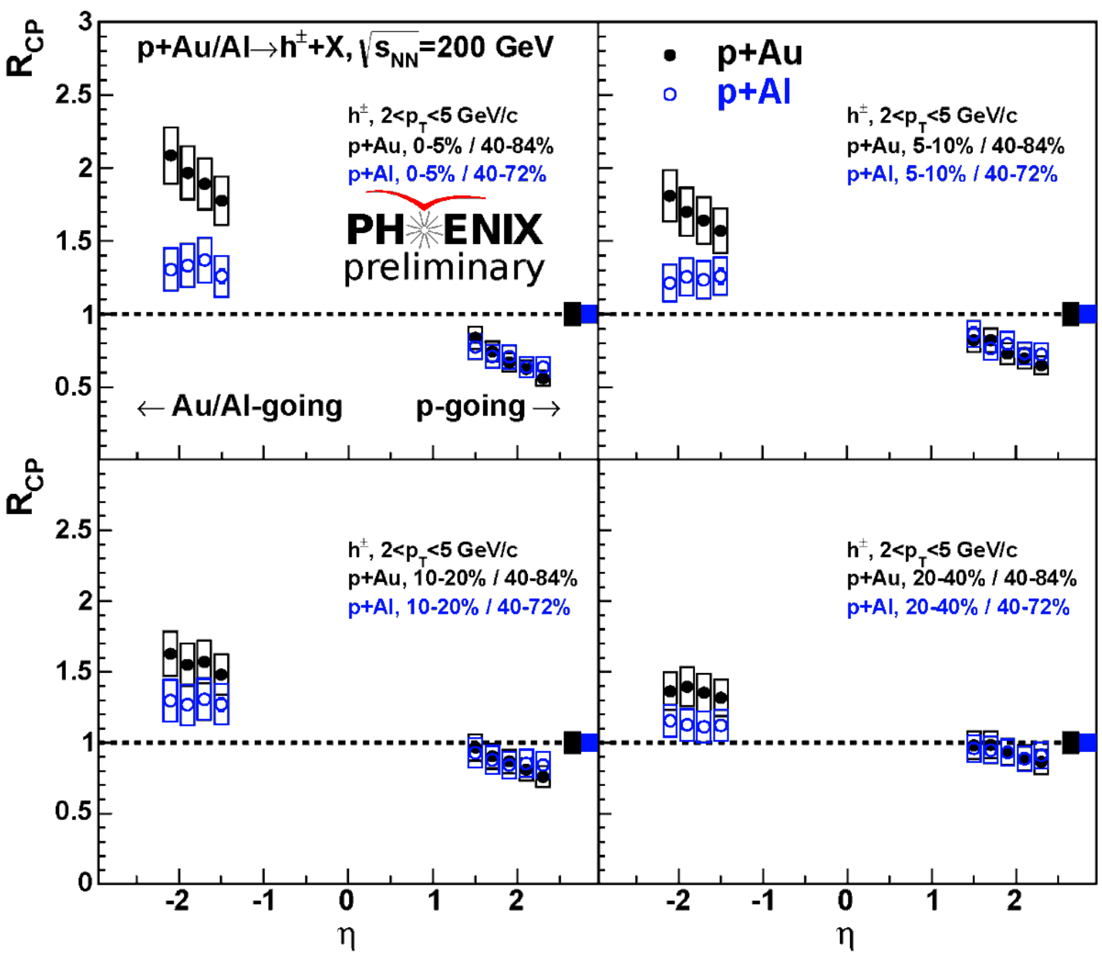
Opposite trend compared to HIJING++ prediction

p+Au and *p*+Al results

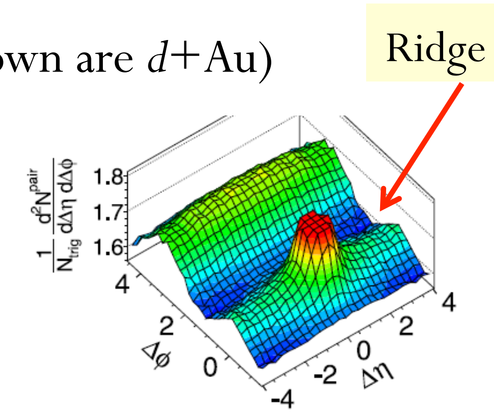


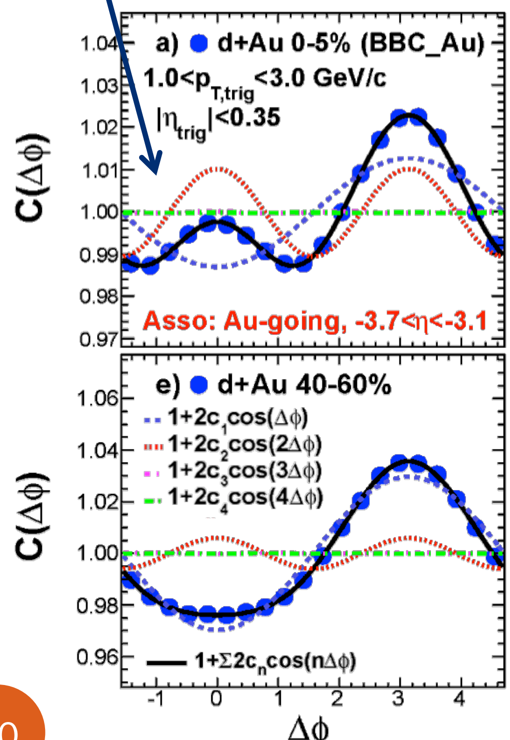
- Comparison of R_{CP} in same centralities in p+Au and *p*+Al collisions:
- **Forward** hadrons shows **same suppression**
- **Backward** hadron production show smaller **enhancement** in *p*+Al than in *p*+Au collisions
- EPS09 tells that the nuclear PDFs are not very different for Au and Al

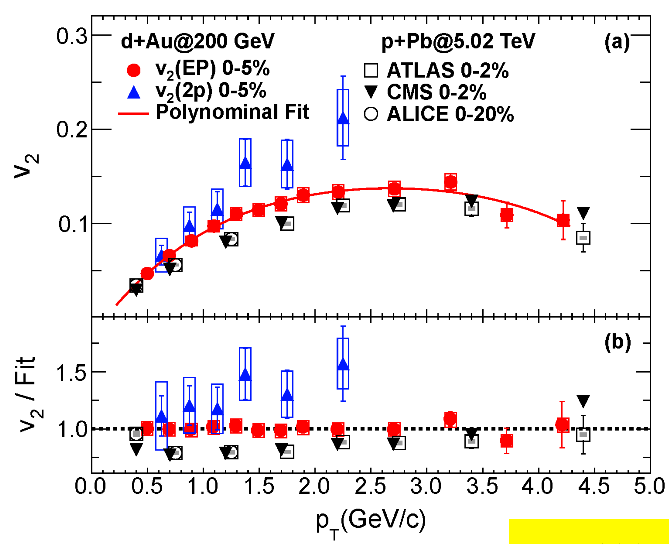
What makes this backward enhancement?

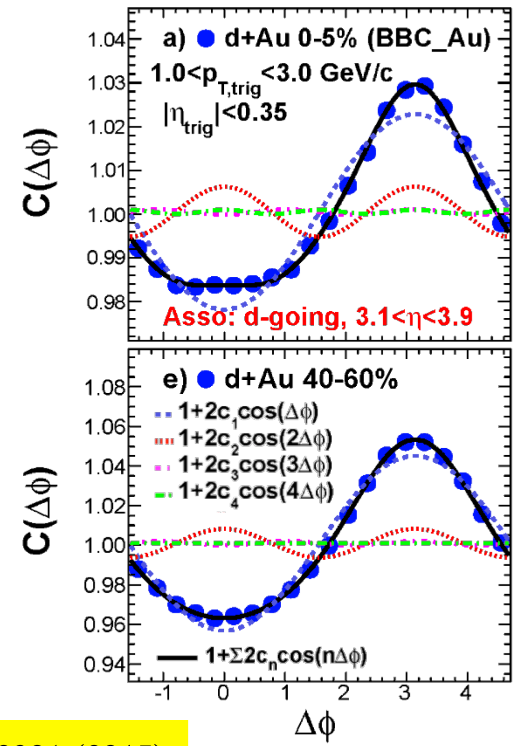
Remainder: possible flow in *p*/*d*/^{3}He+Au

- We observed flow and ridge-like structures over rapidities (shown are *d*+Au)
  - Similarly for *p*/^{3}He+Au (PRL 115, 142301, PRC95, 034910)
- Ridge is prominent when associating with Au-going particles
  - And most central, i.e. 0-5%







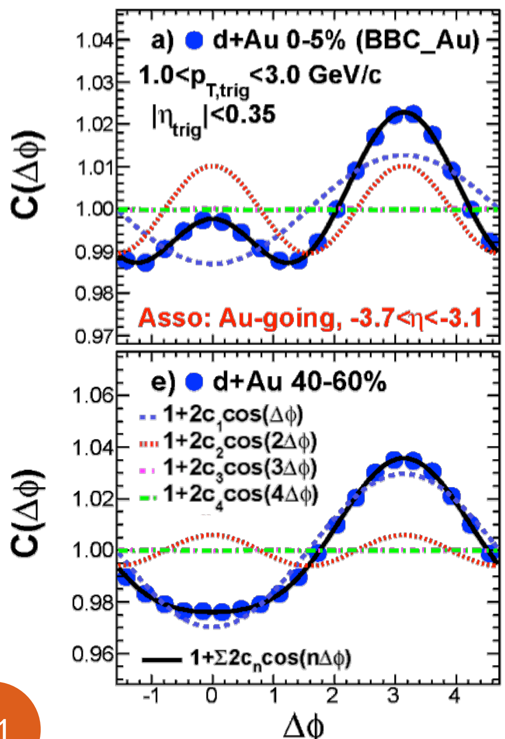


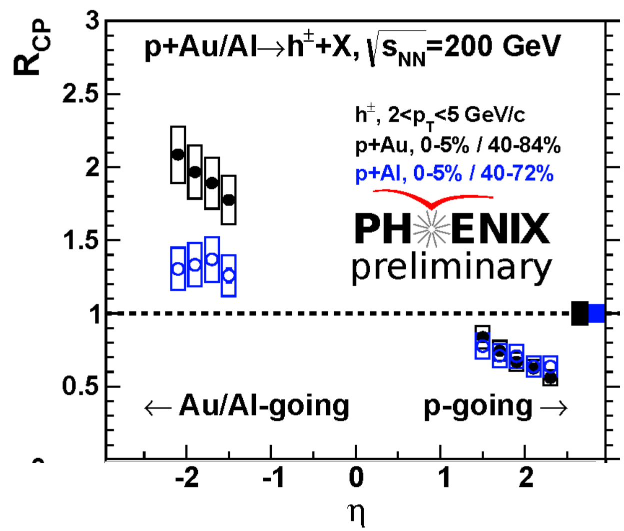
PRL114, 192301 (2015)

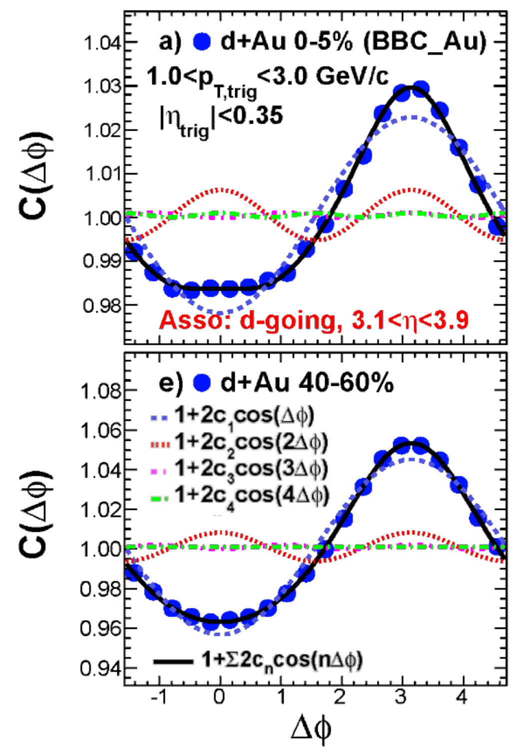
Possible explanation for *p*+Au>*p*+Al

- If it is from mini-QGP, the ridge yield will be higher for larger nucleus
  - i.e., $R_{cp}(p+Au)>R_{cp}(p+Al)$ for $\eta<-1$ (PHENIX case)
  - π^0-h correlations show larger $(<p^2_{out}>)^{1/2}$ in central p+Au compared to p+Al
    - see, J. Frantz talk

- Does it consistently explain the observed η-dependence of hadron R_{cp}?







Summary

- *p/d*+Au system is no longer a baseline or a simple system.

- PHENIX measured high p_T π^0 at mid-rapidity and hadrons at forward and backward rapidities in *p*+Au, *d*+Au and ^{3}He+Au at $\sqrt{s_{NN}}$=200 GeV.
  - $R_{p/d/He+Au} < 1$ at high-p_T, and moderate-p_T indicates ordering of $R_{pAu}>R_{dAu}>R_{HeAu}$

- Integrated R_{AA} from *p*+Au, *d*+Au, ^{3}He+Au and Au+Au converge for $N_{part}>\sim 12$.
  - System ordering of R_{AA} is seen for $N_{part}<12$, i.e., $R_{pAu}>R_{dAu}>R_{HeAu}>R_{AuAu}$.

- Cold energy loss alone can't explain the results
  - Multiple scattering scenario explains it, but is killed by η-dependent result

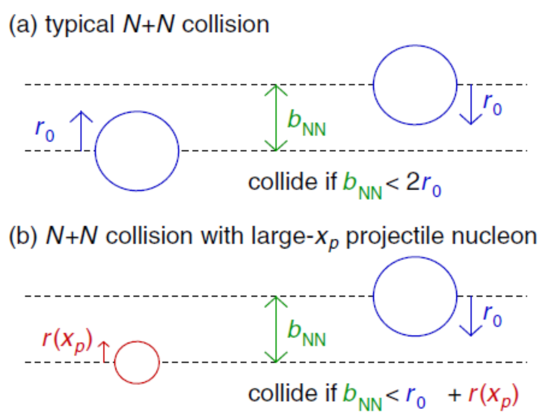
- Charged hadron R_{CP} in p+Au and p+Al showed that:
  - Backward rapidity is enhanced in both p+Au and p+Al; $R_{pAu} > R_{pAl}$
  - Forward rapidity is suppressed in both p+Au and p+Al; $R_{pAu} = R_{pAl}$

- **Both flow and R_{AA} are consistently explained by mini-QGP scenario?**

Backup

Shrinking nucleon?

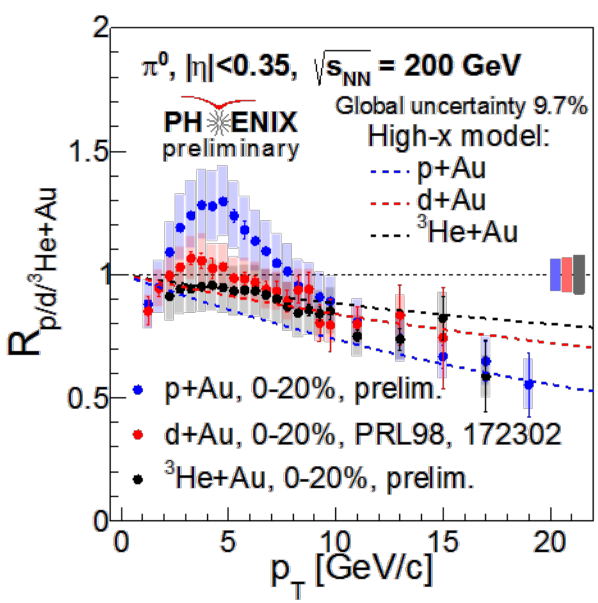
- A model including *x*-dependent parton-parton interaction cross-section
  - Effectively shrinking the size of nucleon (PRC 94, 024915 (2016), and priv. comm.)
- The model predicts clear ordering in most central and peripheral collisions
- The predicted trend is not well seen in data



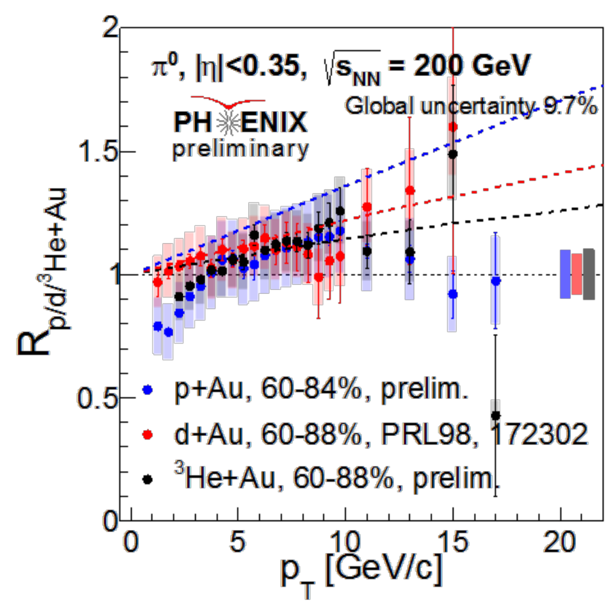
$$r(x_p) \equiv \exp(-\beta x_p) r_0. \quad \beta = 1.38$$

$$\sigma(x_p) \equiv \pi[r_0 + r(x_p)]^2 = \tfrac{1}{4}[1 + \exp(-\beta x_p)]^2 \sigma_{NN}.$$

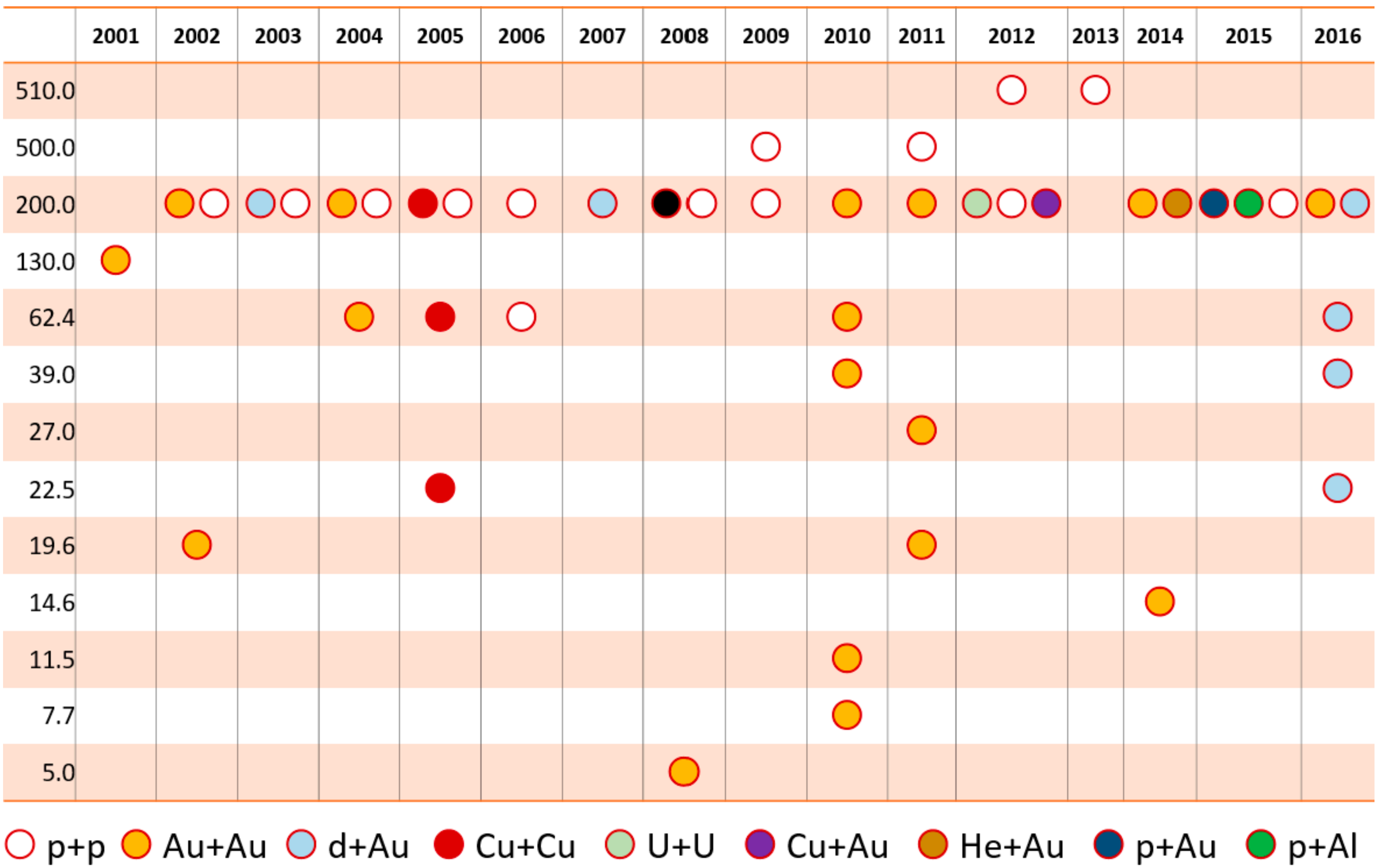
Most Central



Most Peripheral



Dataset collected by PHENIX

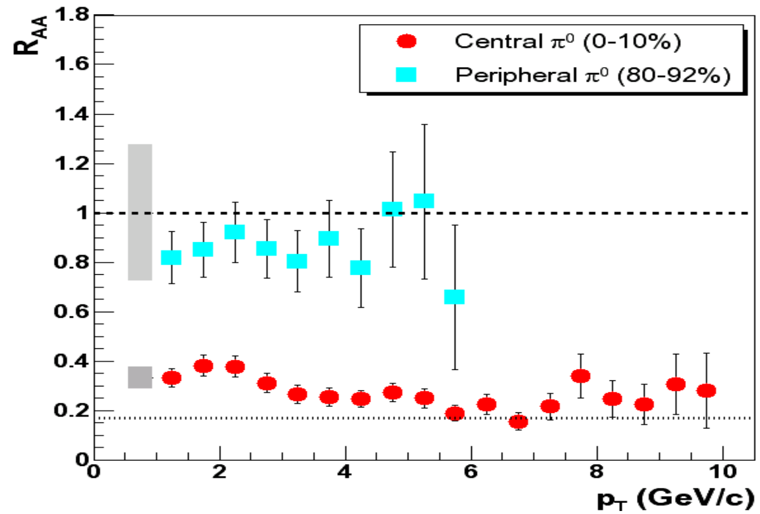


See details at http://www.rhichome.bnl.gov/RHIC/Runs/

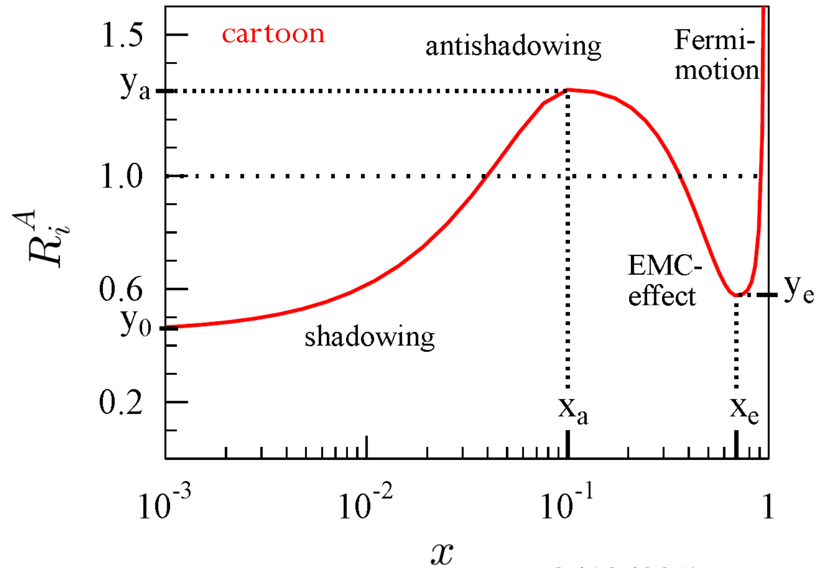
Why *were* we interested in *d*+Au collisions?

- In order to confirm the high p_T hadron suppression is due to final state effects, and not cold nuclear matter (CNM) effects
  - Need system without additional effects from a hot medium.

PHENIX, Phys. Rev. Lett. 91, 072301 (2003)

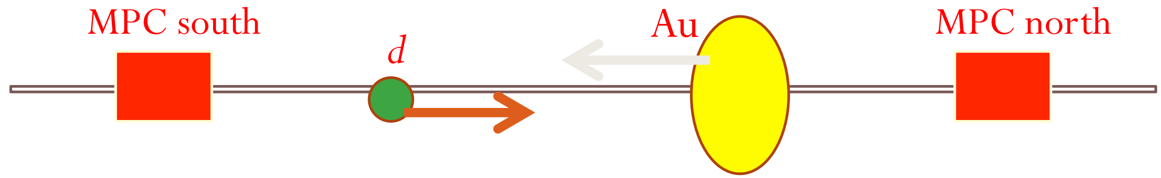


- CNM effects include:
  - k_T-broadening (Cronin enhancement at moderate p_T)
  - Shadowing of parton distributions
  - Cold nuclear matter energy loss
  - And possibly more…

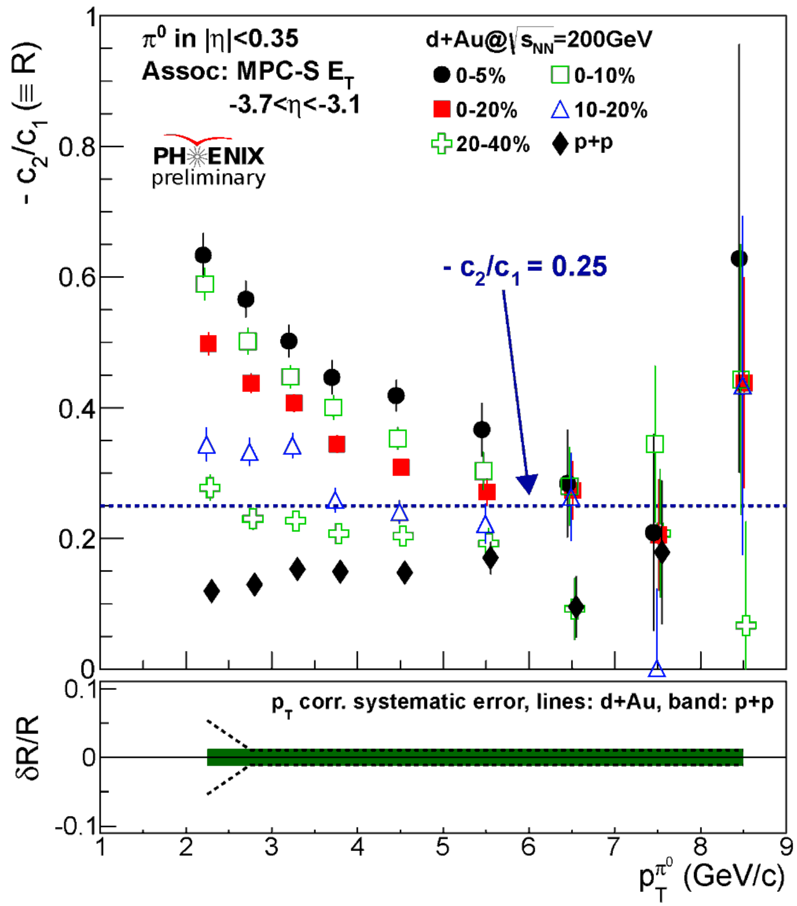


- *d*+Au was more favorable for RHIC operation because of better rigidity match
  - *p*+Au became feasible later

Ridge evolution in π^0-MPC south / Au-going...



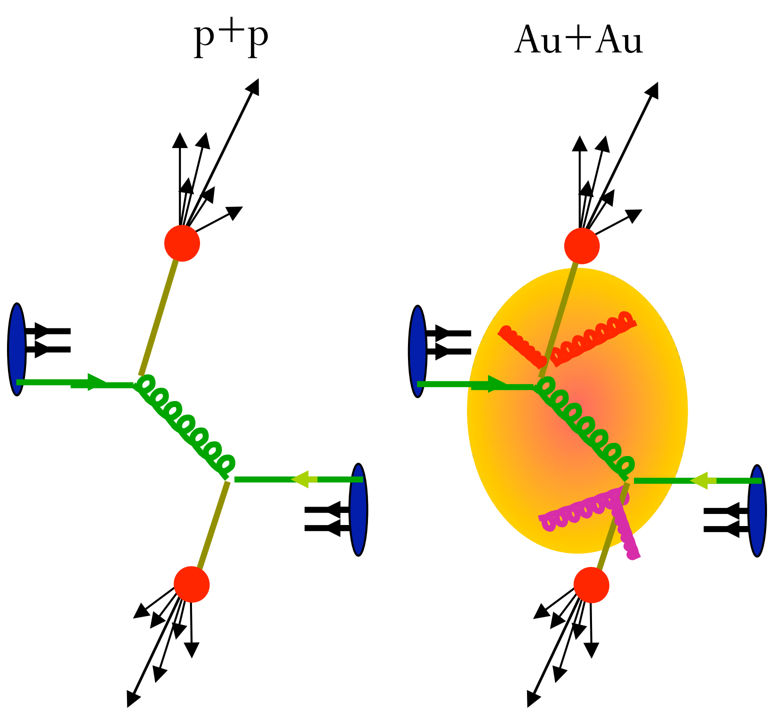
- $-c_2/c_1$ from π^0 - MPC south correlations
  - Au-going direction
  - Assuming c_1 is a proxy of jets or global momentum conservation
- Measure shape evolution by relative magnitude of 2nd order component
- $-c_2/c_1 > 0.25$ corresponds to near-side local maximum (if $c_3 = c_4 = 0$)



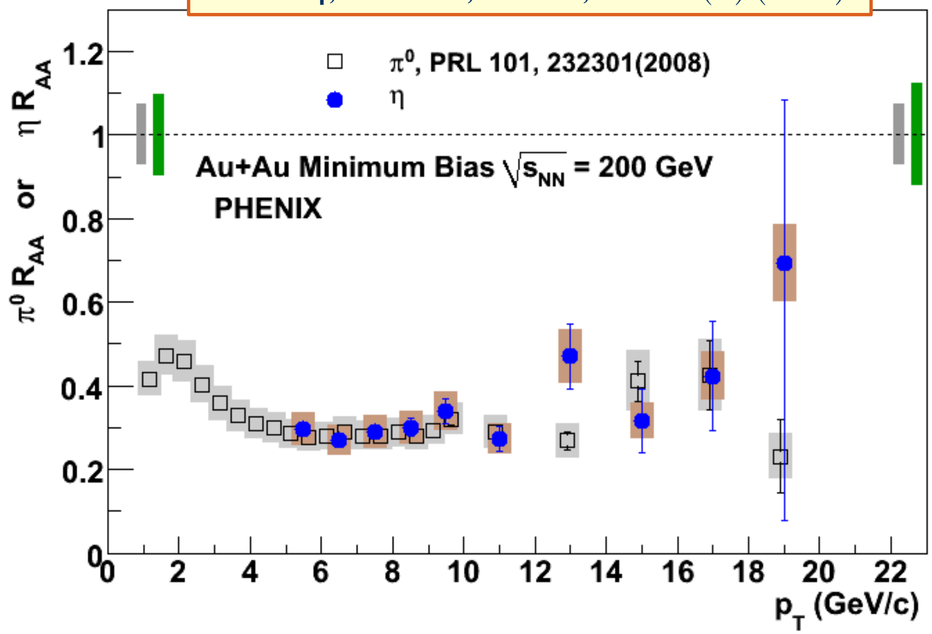
Yield suppression of leading particles

- Nuclear Modification Factor (R_{AA})
  - (Yield in A+A collision)/(Yield in p+p collision × N_{coll})
  - R_{AA} =1: No nuclear effect
  - R_{AA} <1: Suppression due to energy loss, etc.

$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{\frac{Ncoll}{\sigma_{inel}} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$



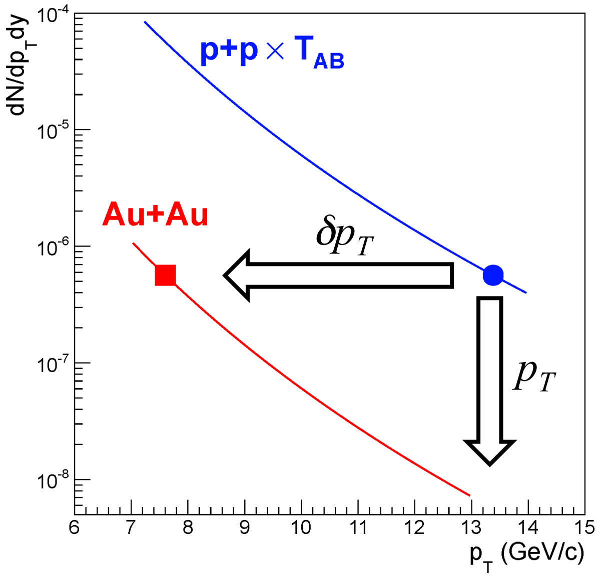
π^0 and η, PHENIX, PRC82, 011902(R) (2010)



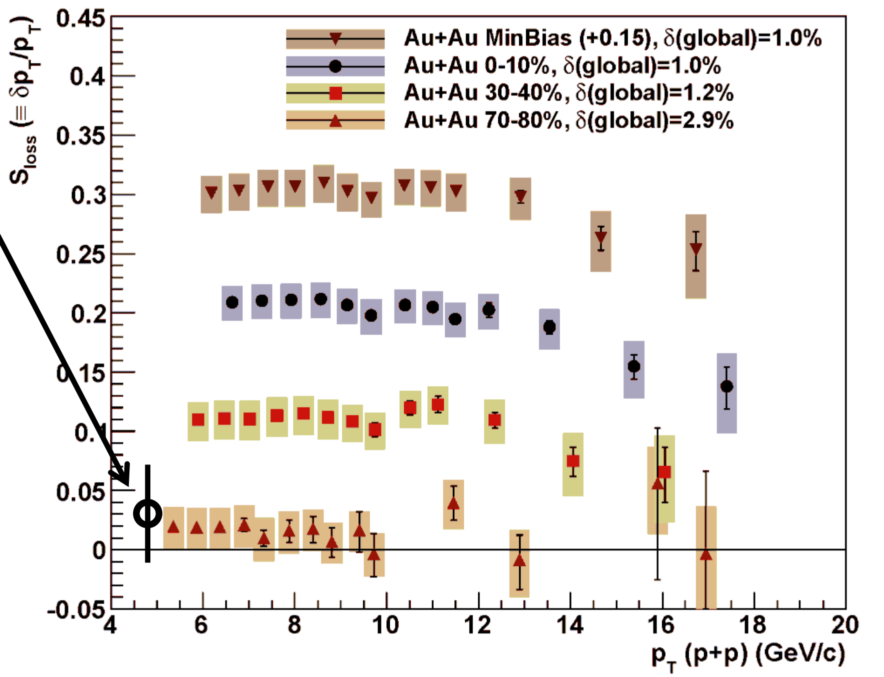
Fractional momentum loss in ^{3}He+Au

- R_{AA} can be rewritten in the form of fractional momentum loss ($\delta p_T/p_T$).
  - Instead of taking ratio of spectra, one can directly measure the spectra shift (δp_T)
- Most central (0-10%) ^{3}He+Au collisions shows similar R_{AA} as 60-70% Au+Au
  - At same cms energy, same R_{AA} implies same $\delta p_T/p_T$
- $\delta p_T/p_T = \sim 0.03$ in most central ^{3}He+Au collisions

$$p_T : p_T(p+p)$$
$$\delta p_T = p_T(p+p) - p_T(A+A)$$



PHENIX, PRC87, 034911(2013), PRC93, 024911 (2016)



Looking forward and backward