PHENIX Highlights

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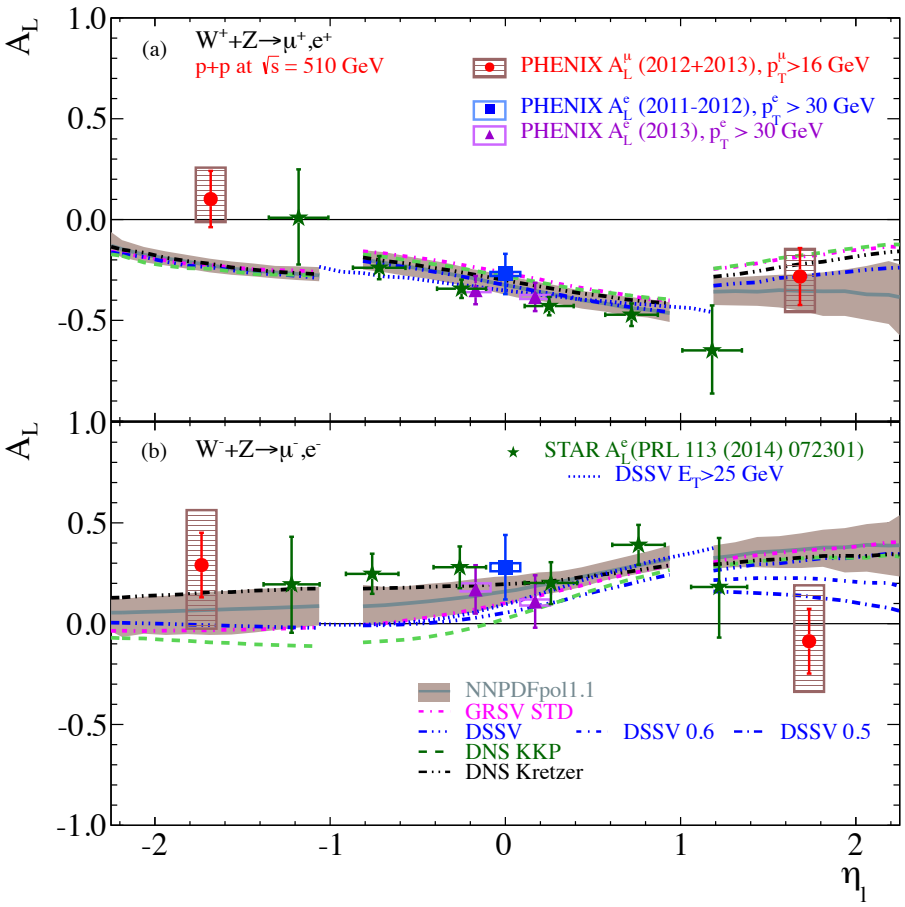
Overview

- PHENIX has been busy
  - Spin
  - High-p_T
  - Heavy Flavor
  - Collectivity in Small Systems
  - Direct Photons
- Since the last User's Meeting
  - 15 publications published or in referee review
  - 7 Theses have been defended.
  - 70 talks at 23 conferences have been given.

Spin

W A_L Finalized



p+p

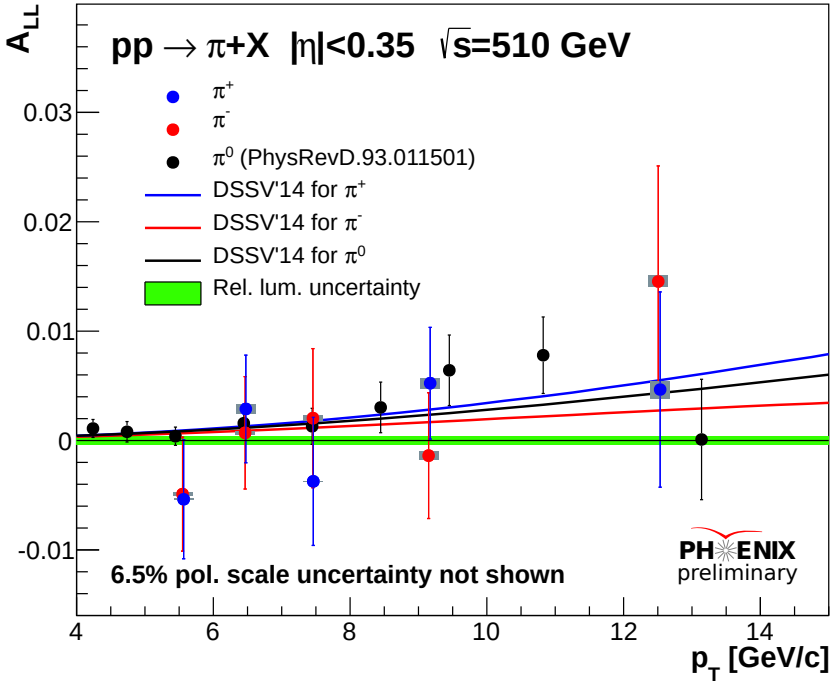
arXiv:1804.04181 submitted to PRD

- A_L sensitive to light sea quarks
- Asymmetries from global fits mostly consistent with our results

$\pi^{\pm}$ A_{LL}

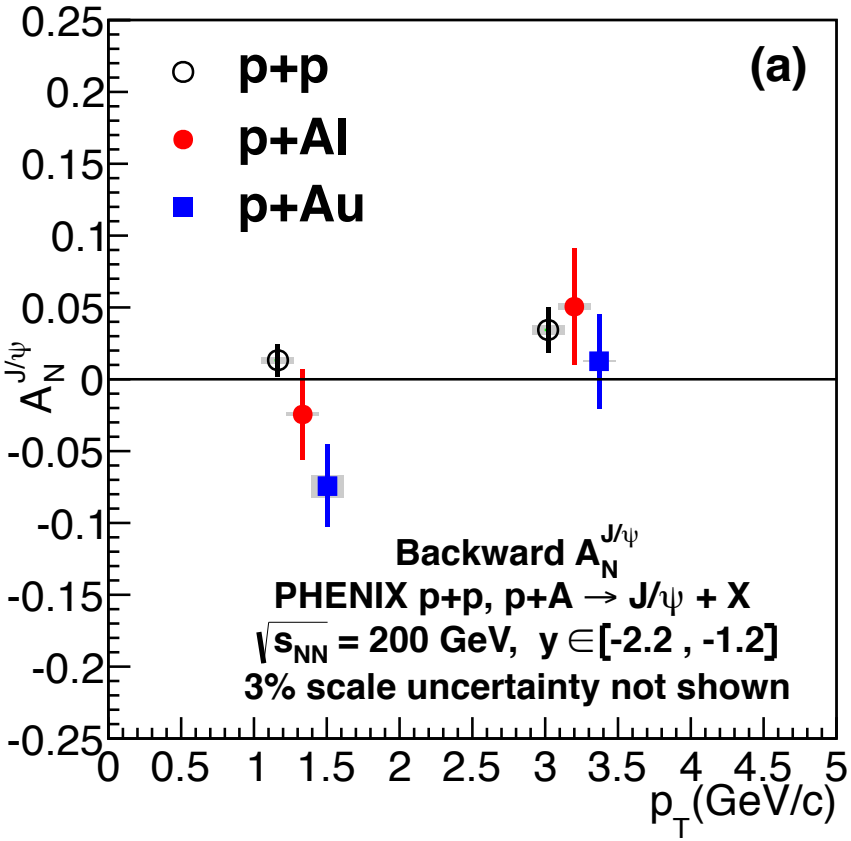
p+p

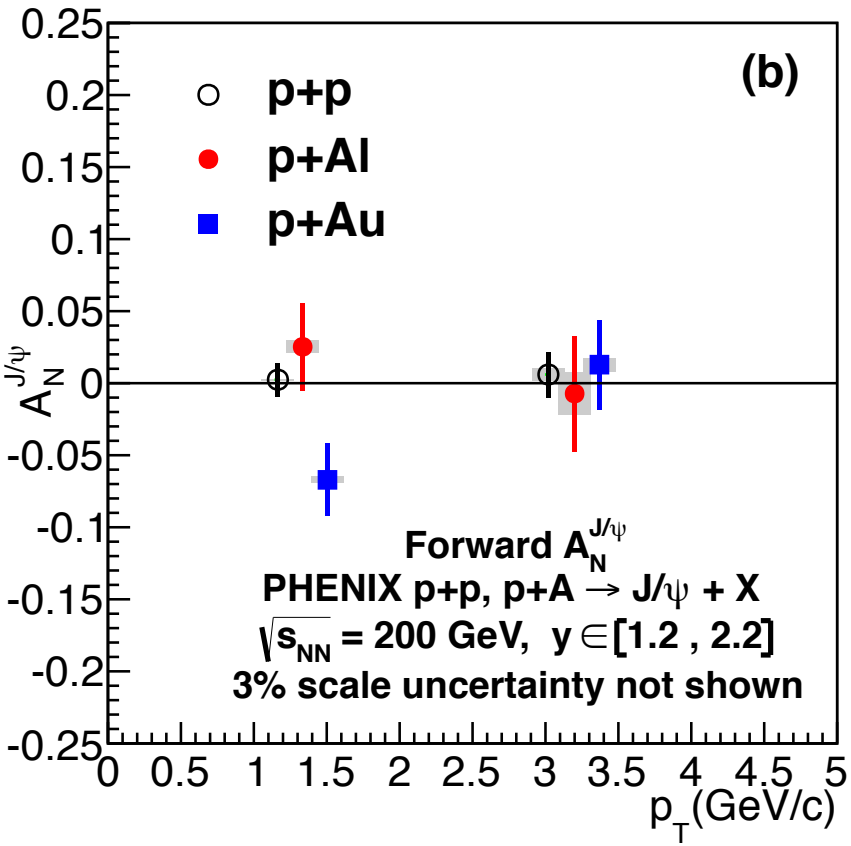
- First charged pion A_{LL} measured at 510 GeV
- Ordering of asymmetries sensitive to the sign of Δg



J/ψ A_N in polarized p+A

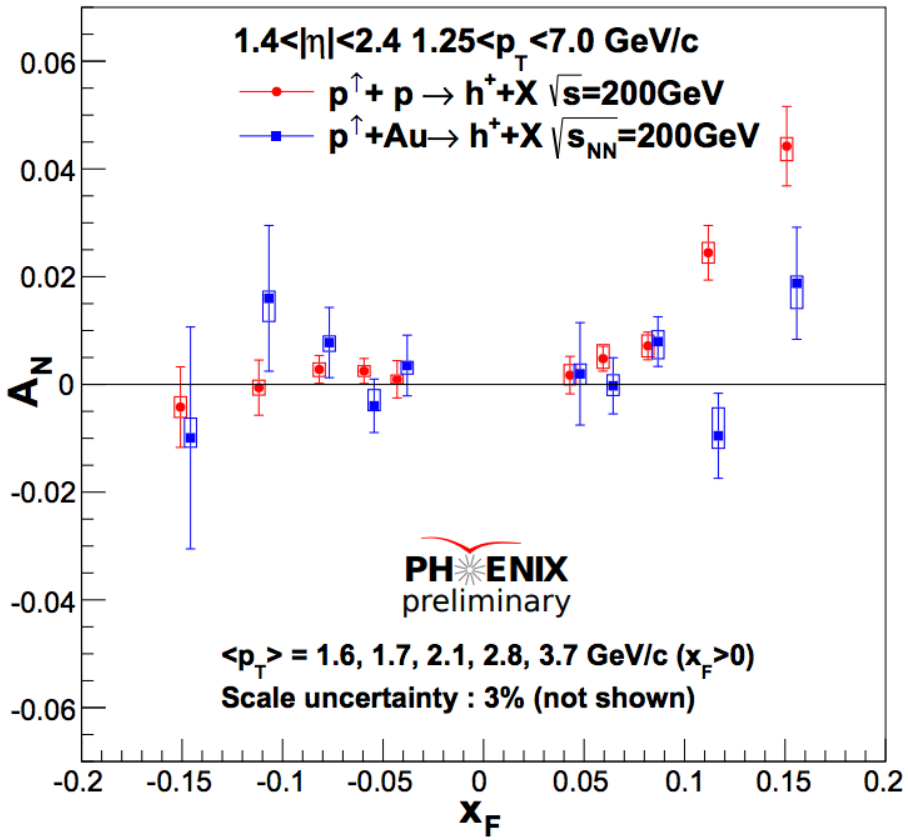
arXiv:1805.01491 submitted to PRD





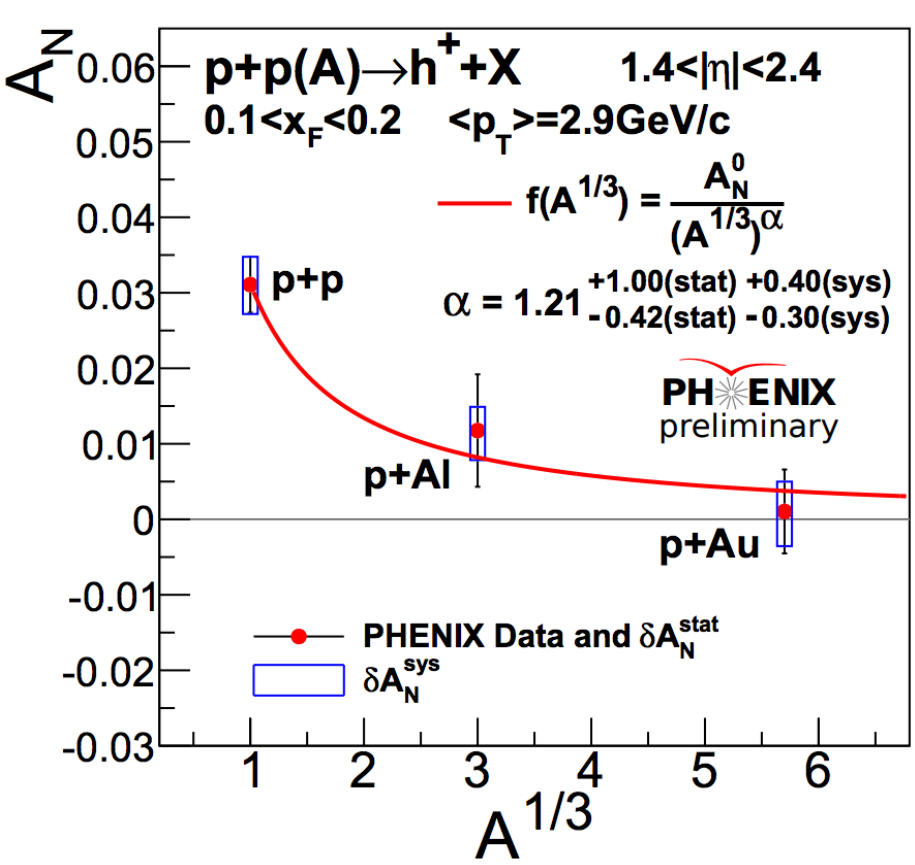
- J/ψ $A_N \neq 0$ for low p_T p+Au, some novel mechanism?

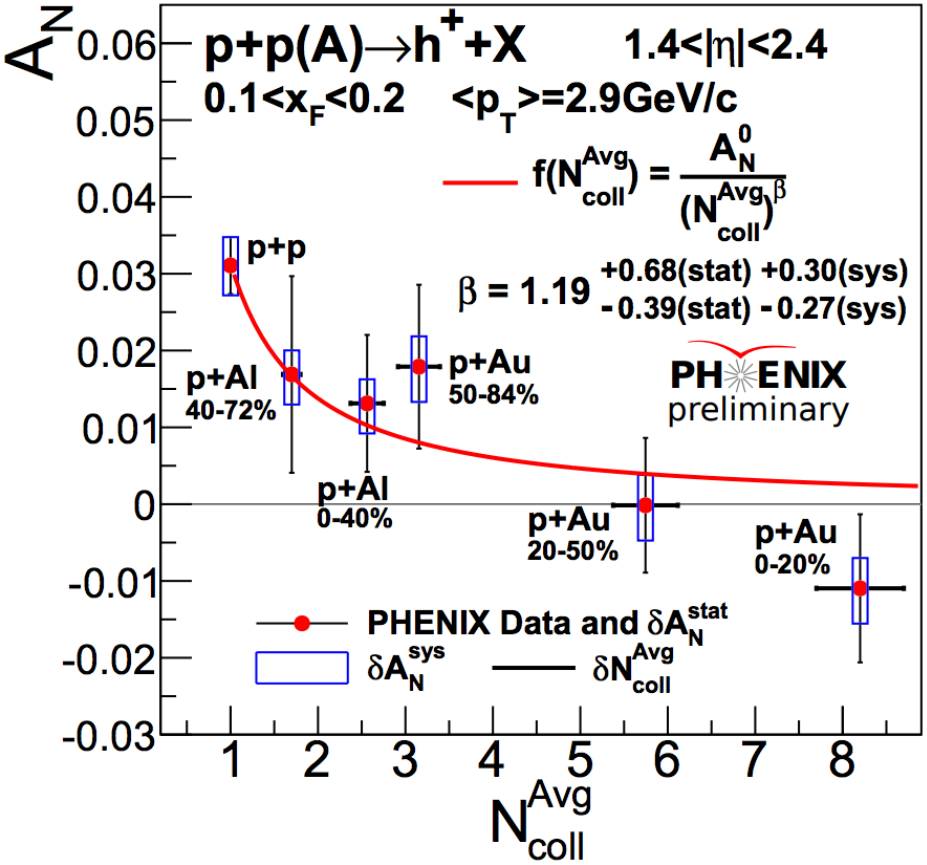
Charged Particle A_N in p+A



- Positive charged hadrons have non-zero asymmetry at forward (proton-going) rapidity.
- Smaller asymmetry in p+Au for $x_F > 0.1$.

Charged Particle A_N in p+A

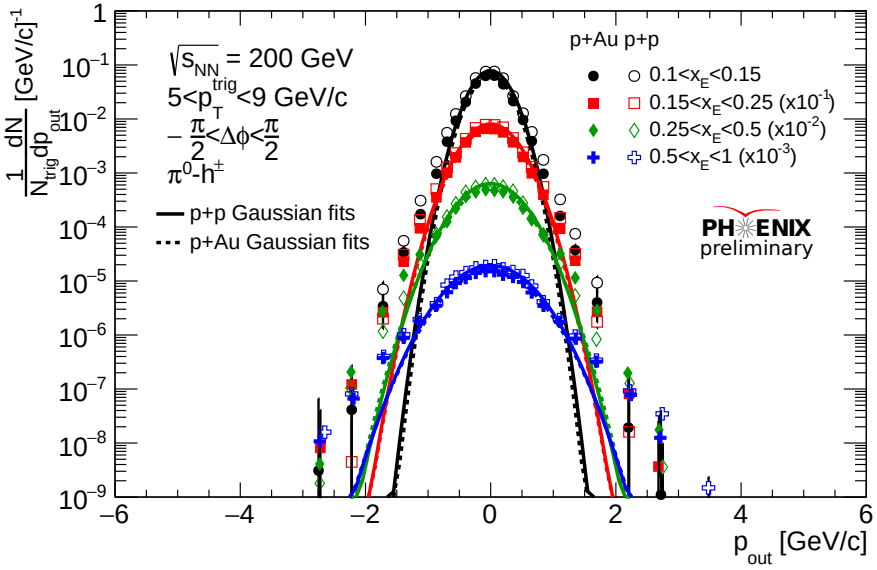


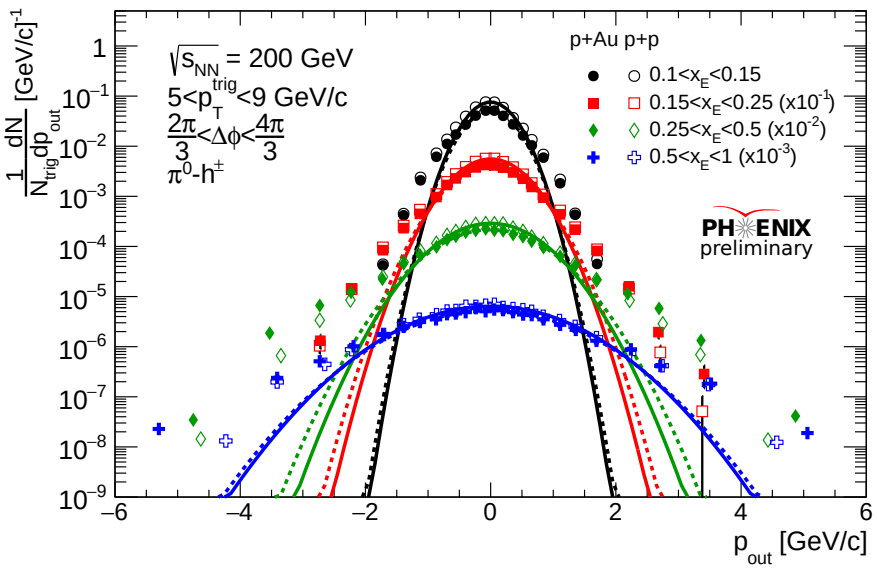


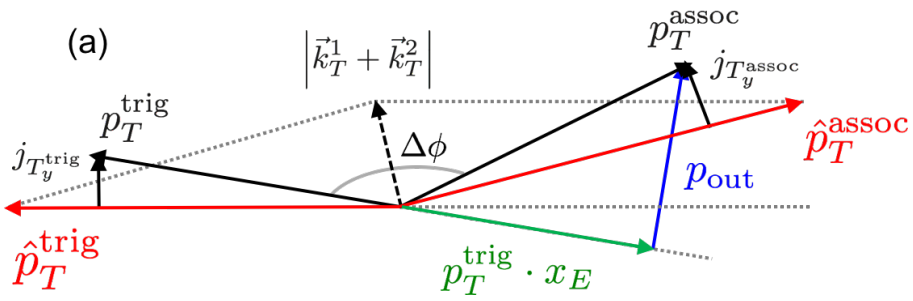
- A_N decreases with medium length and number of collisions.

High p_T.

$\pi^0 - h$ Correlations in p+A







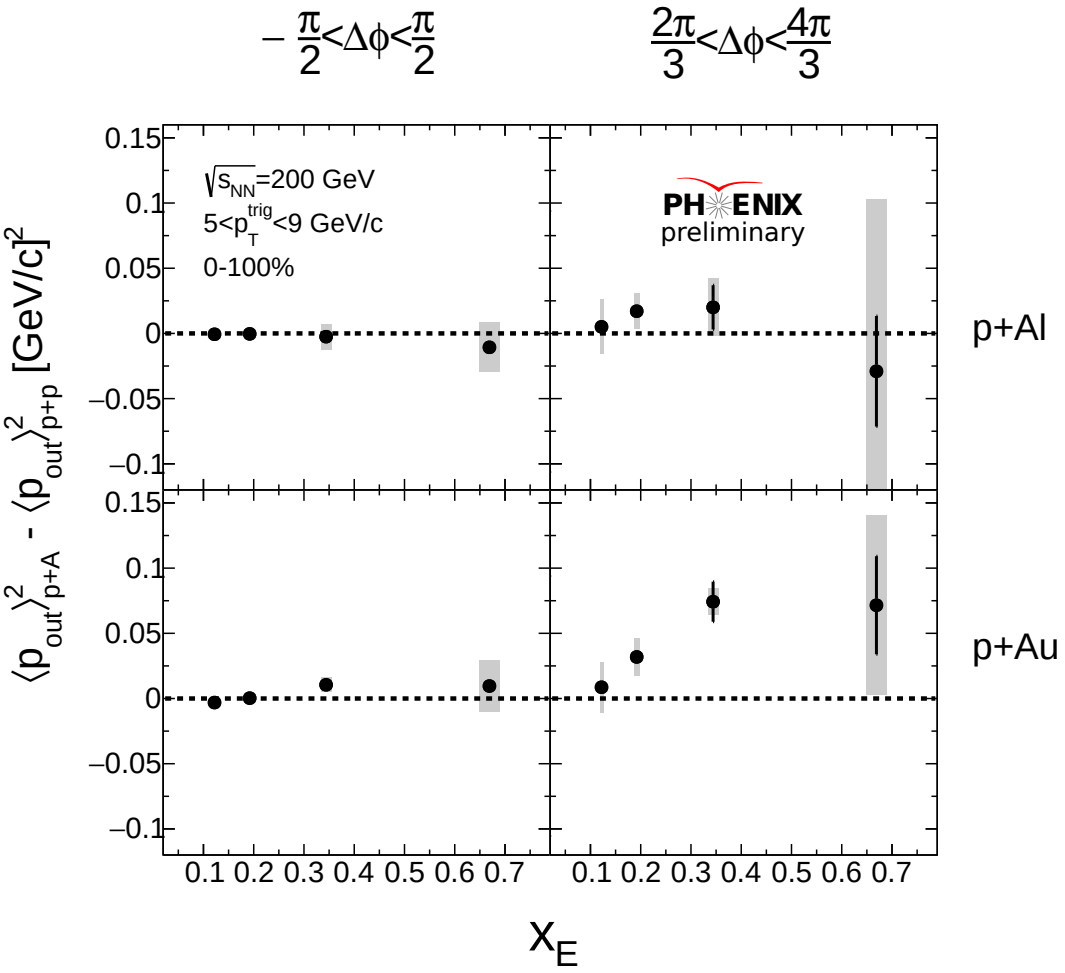
$$p_{out} = p_{T,assoc} \sin\Delta\phi$$

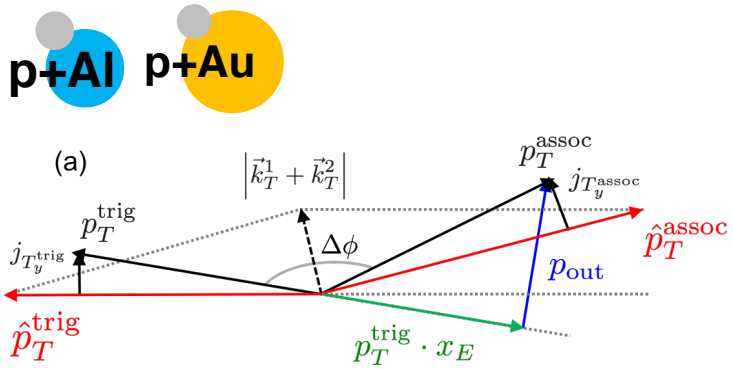
$$x_E = \left|\frac{p_{T,assoc}}{p_{T,trig}} \cos\Delta\phi\right|$$

- Near- and Away-sides have non-perturbative Gaussian core related to j_T and intrinsic k_T and power-law tails due to hard gluon radiation.

p+p data arxiv:1805.02450 (submitted to PRD)

Away-side Broadening in p+A

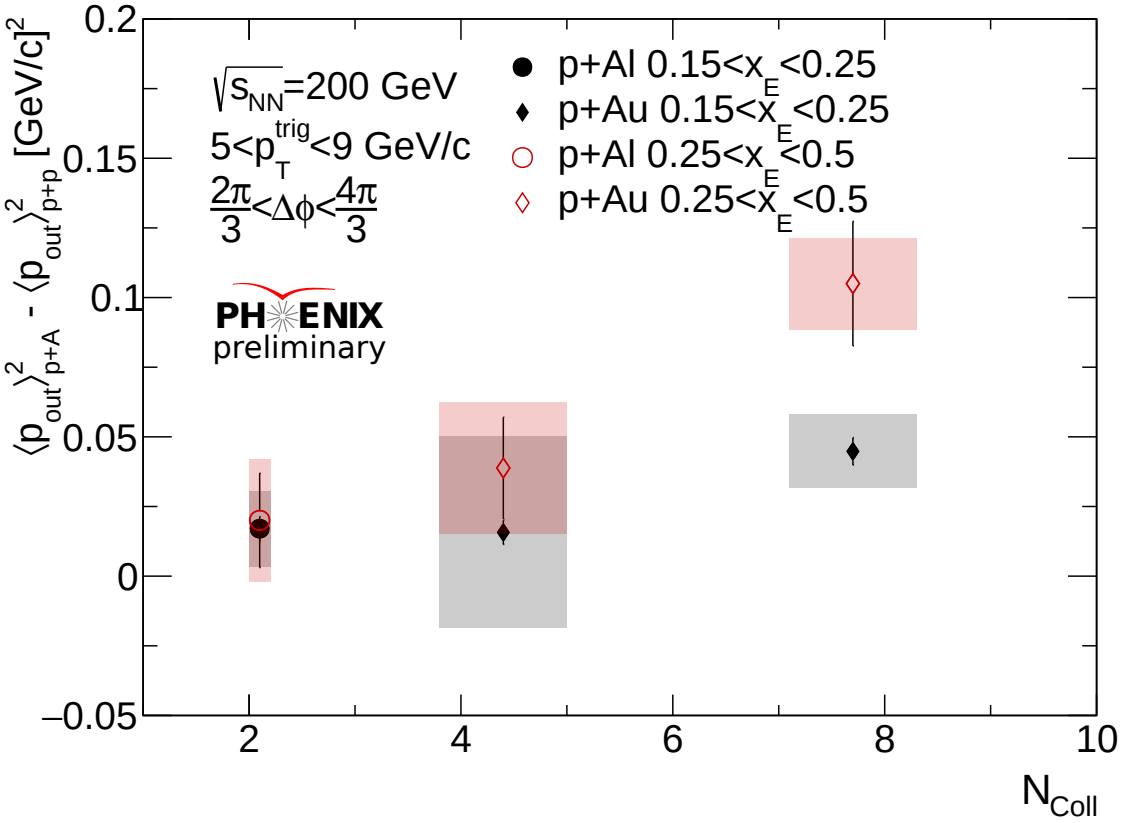


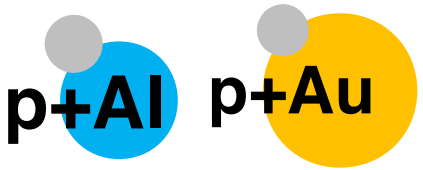


- Near side shows no change.
- Away side p_{out} increases for d+Au.

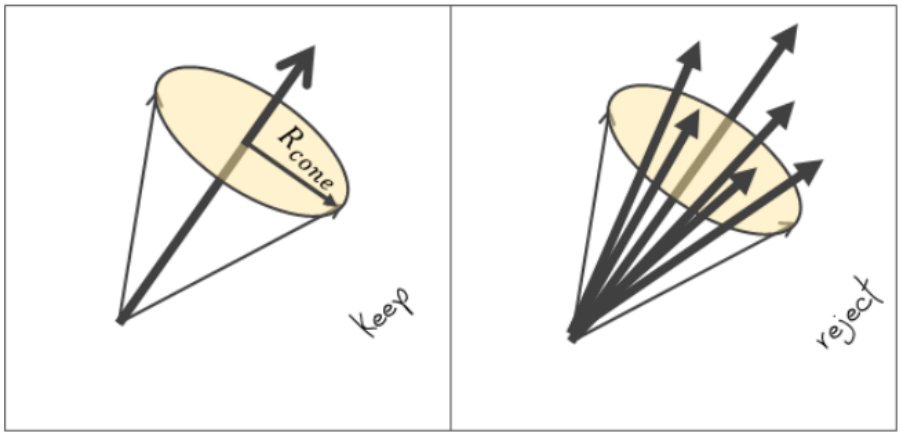
Away-side Broadening in p+A

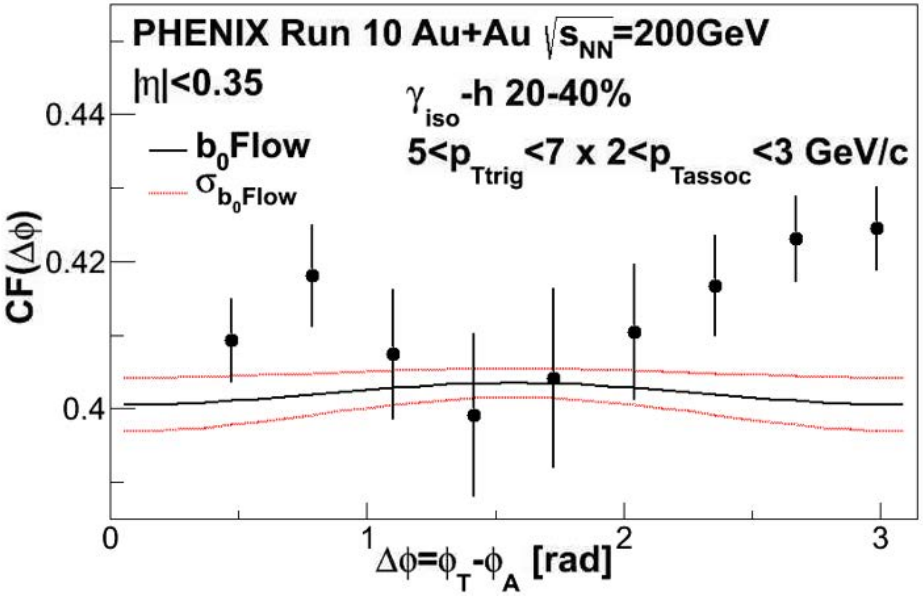
- Choose two x_E bins measure for 0-40% and 40-100% p+Au.
- Increase of non-perturbative widths with N_{coll}.
- The increase is on the order of 10's of MeV.
- Can we rule out $A^{1/3}$ multiple scattering picture?





Direct γ-h Correlations in Au+Au



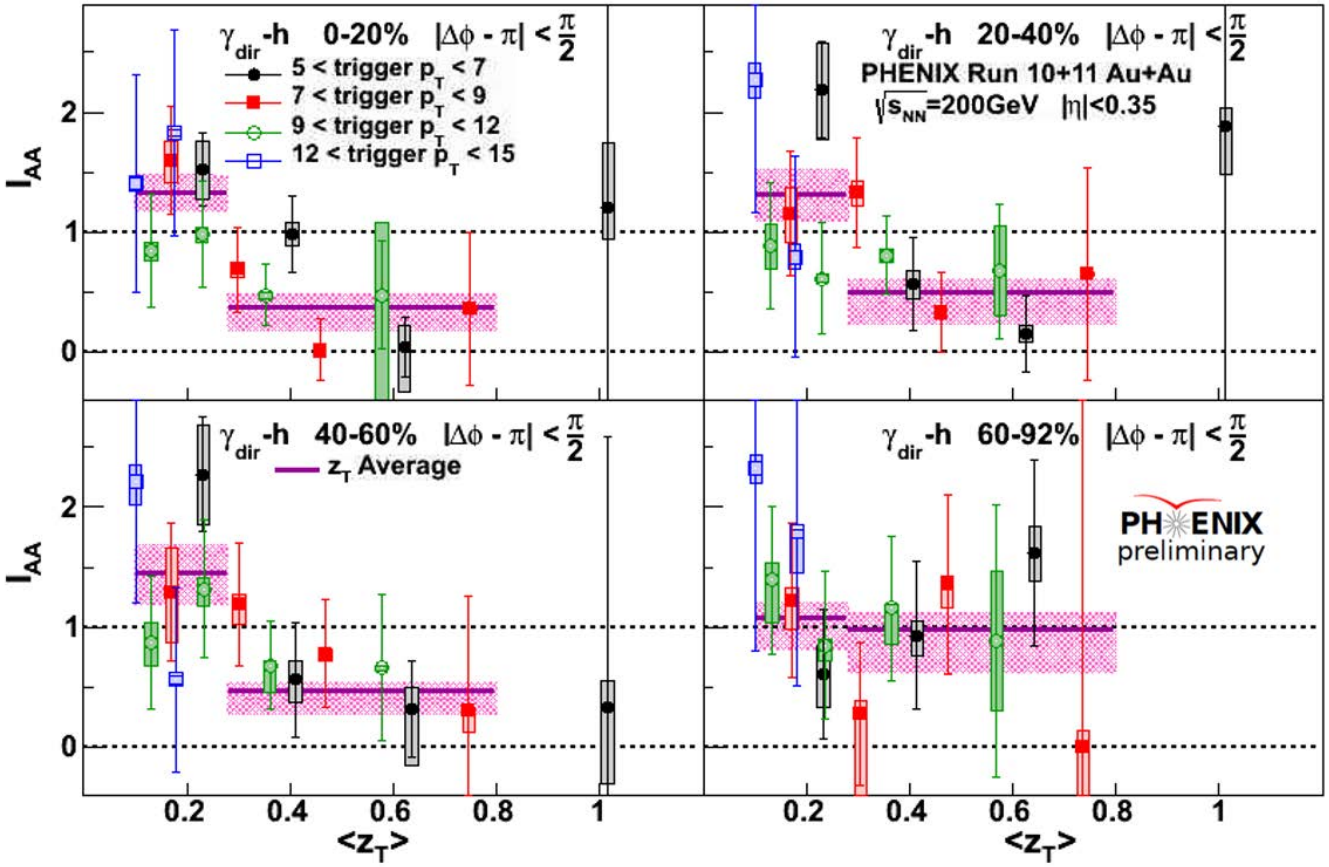


$$E_{TH} = 10\% E_\gamma + \text{Offset}$$

Cent	R_{cone}	Offset [GeV/c]
0-20%	0.1	2.0
20-40%	0.2	4.0
40-60%	0.2	2.0
60-92%	0.3	1.0

- Isolation cut in Au+Au preferentially selects photons out of the event plane – opposite sign on v_2 modulation in some p_T bins.

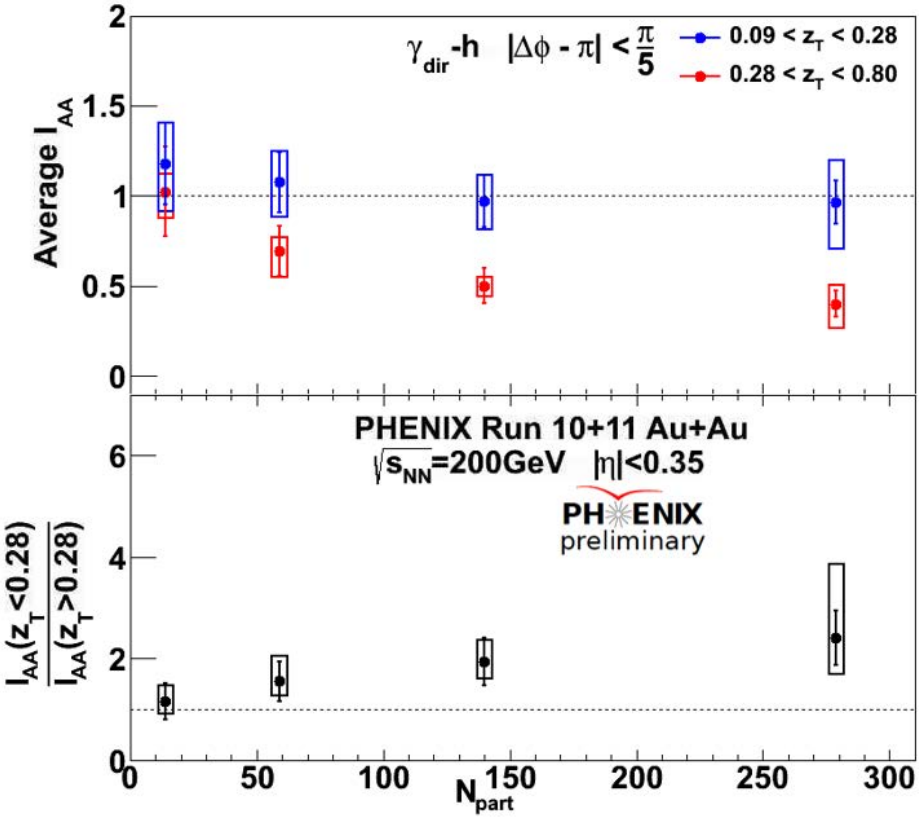
Direct γ-h I_{AA}



Au+Au

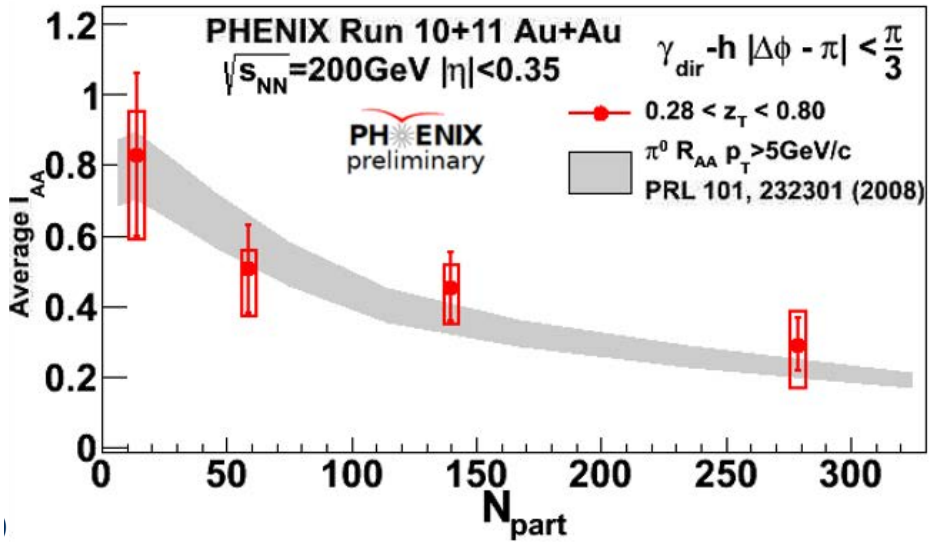
$$\langle z_T \rangle \equiv \langle p_{T,assoc}/p_{T,\gamma} \rangle \qquad I_{AA} = \frac{\text{Per} - \text{Trigger Yield}_{\text{Au+Au}}}{\text{Per} - \text{Trigger Yield}_{\text{p+p}}}$$

Direct γ-h I_{AA}



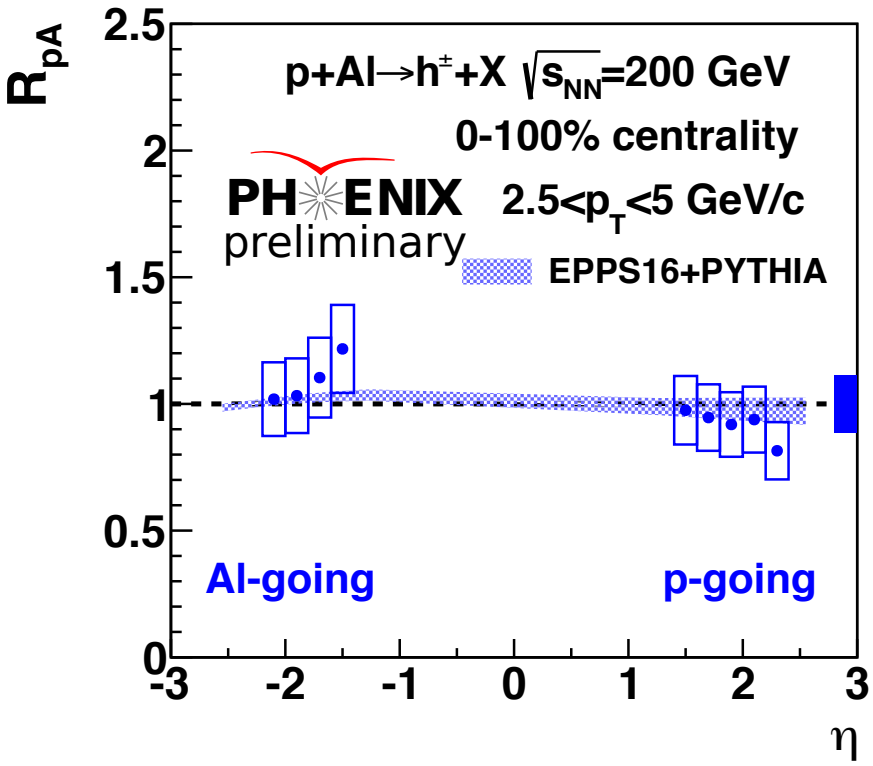
- "Head" region: low-z fragments become enhanced relative to the suppressed high-z fragments.

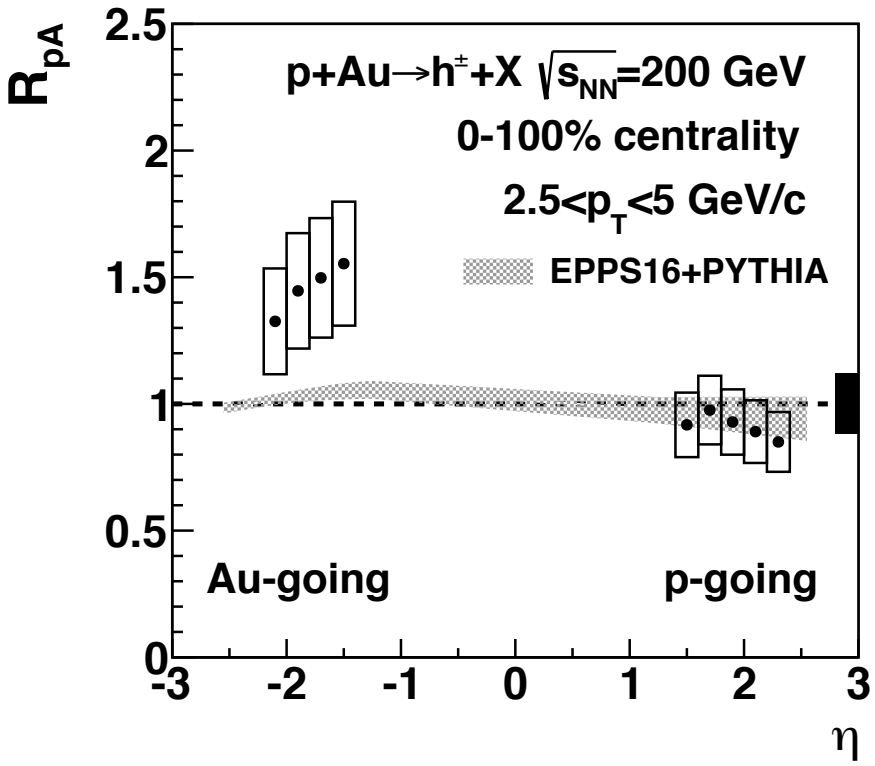
Au+Au

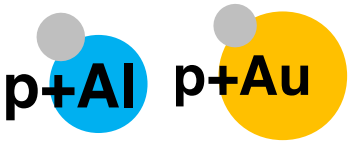


- Combing Run-10 and Run-11 + Isolation Cone increases S/B resulting in a more precise determination of I_{AA}.

Charged Hadrons in Muon Arms in p+Al and p+Au

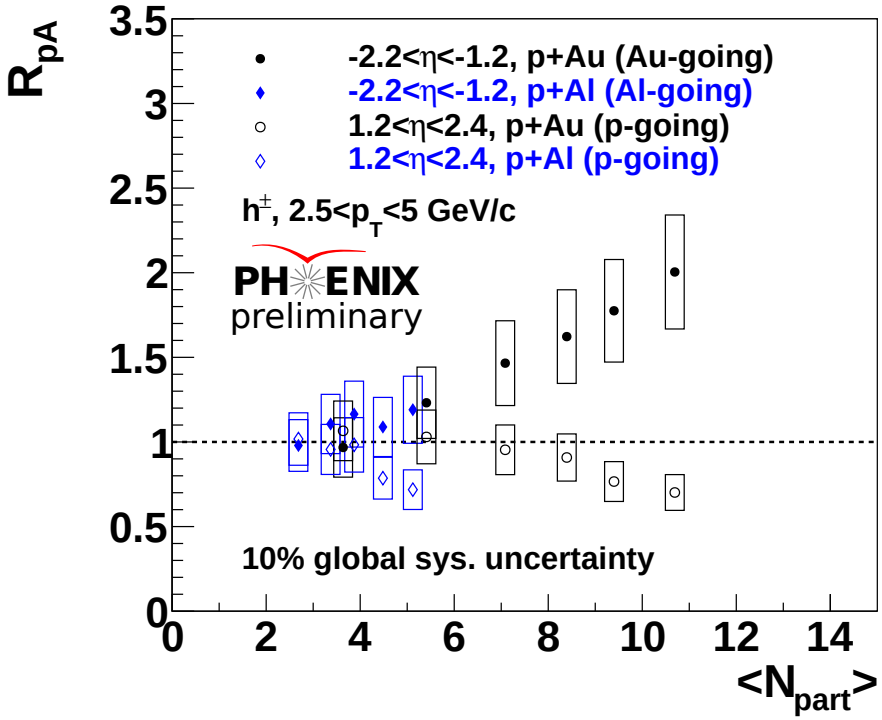


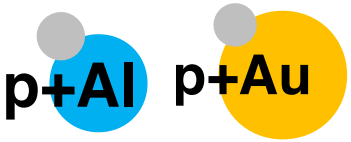




- EPPS16 describes p-going, not large enhancement in Au-going.

Hadron R_{pA} vs. N_{part}



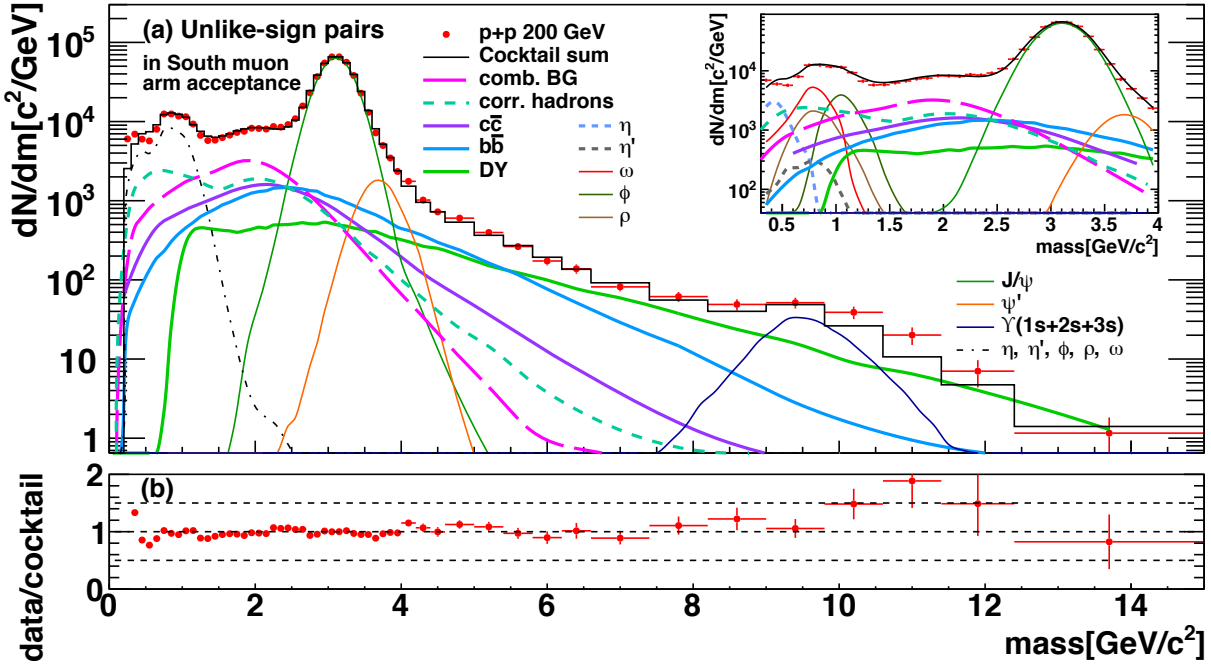


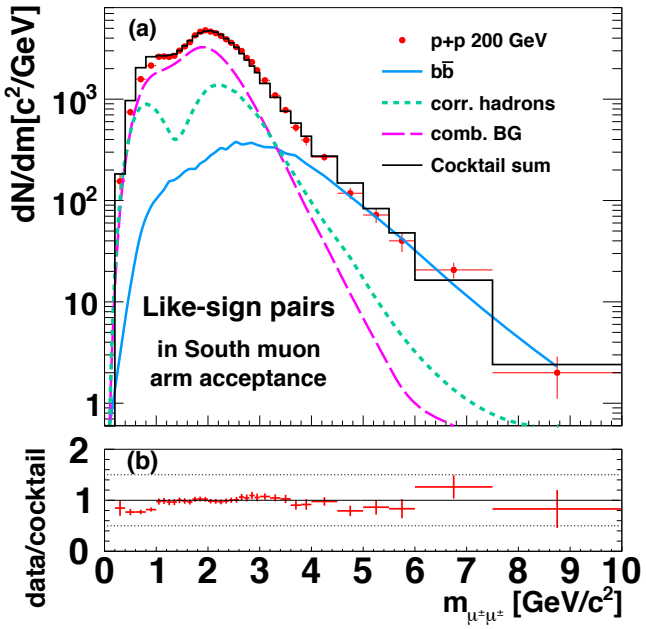
- Very large enhancement at intermediate p_T increases with centrality.
- Enhancement in ion direction larger than Cronin enhancement at midrapidity.

Heavy Flavor.

Dimuon Continuum in $p+p$

1805.02448 submitted to PRD



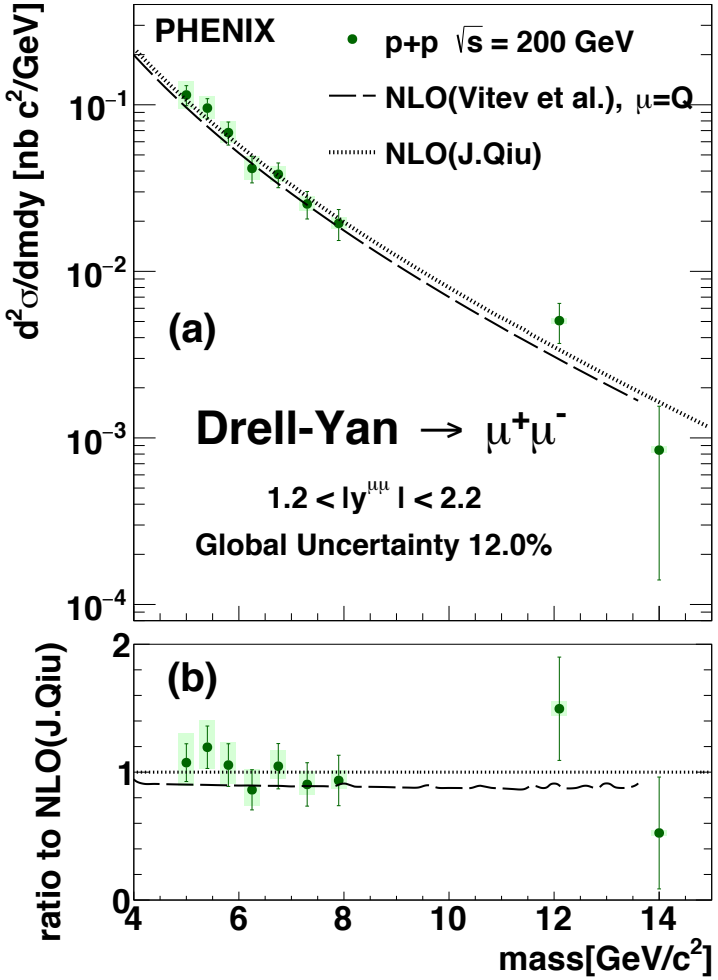


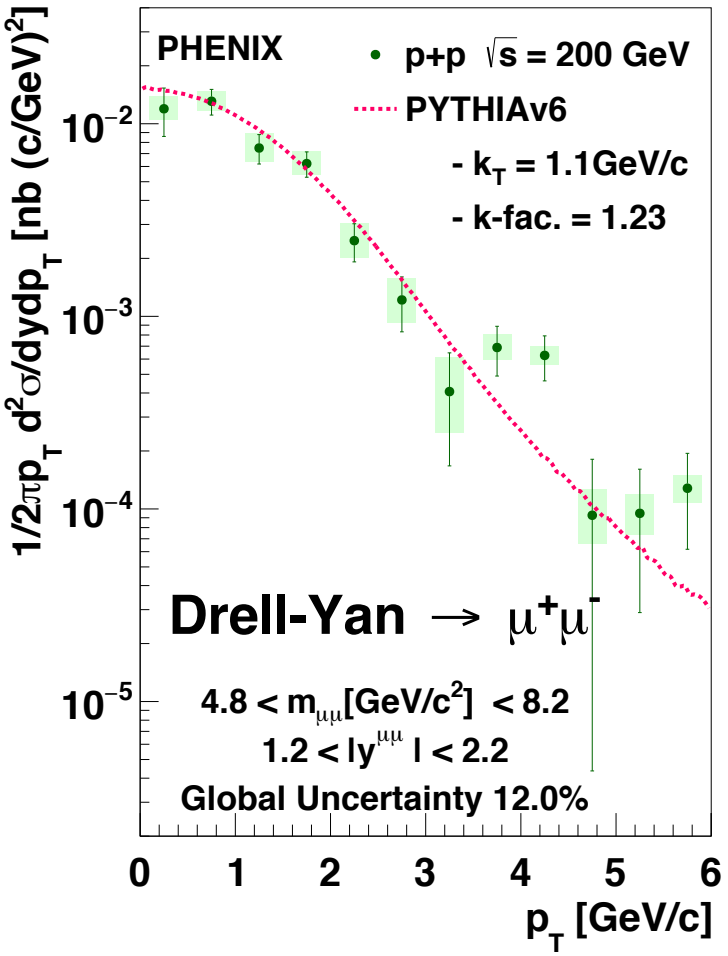
- Dimuon continuum well described by cocktail.
- Bottom dominates: high-mass, like sign.
- Drell-Yan dominates: high-mass, unlike sign
- Charm S/B largest: intermediate mass, unlike sign

p+p

DY$\rightarrow \mu^+\mu^-$

1805.02448 submitted to PRC



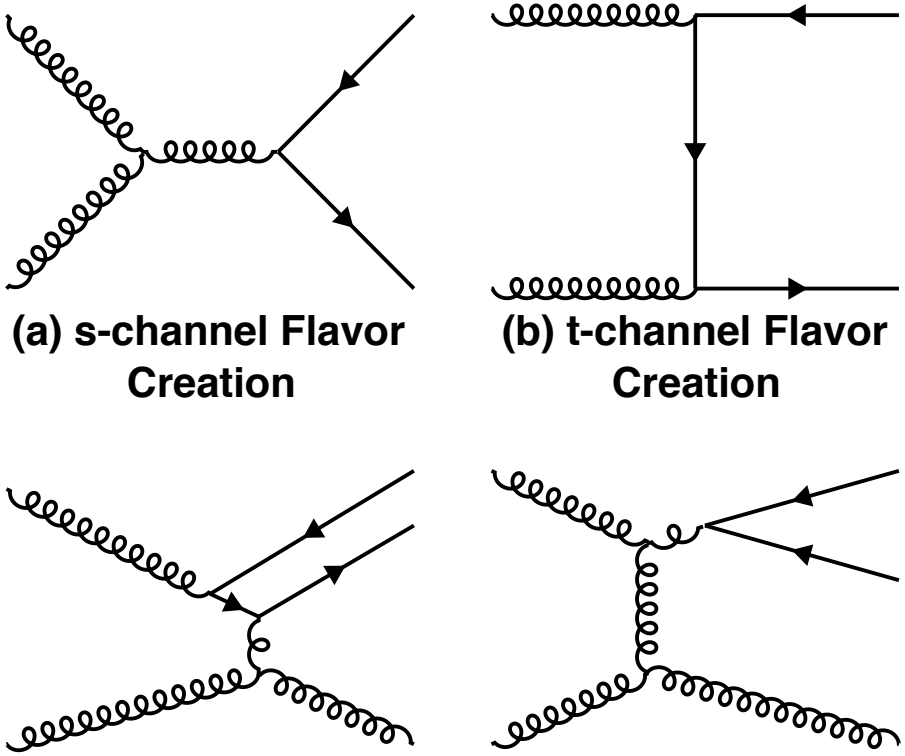


p+p

- Drell Yan mass and p_T spectrum well described by NLO and PYTHIA

$c\bar{c}$ and $b\bar{b}$ Production

- At leading order, $Q\bar{Q}$ produced back-to-back in azimuth.
- NLO diagrams can have very different azimuthal dependence
- PYTHIA event record contains information about NLO diagrams.



(a) s-channel Flavor Creation

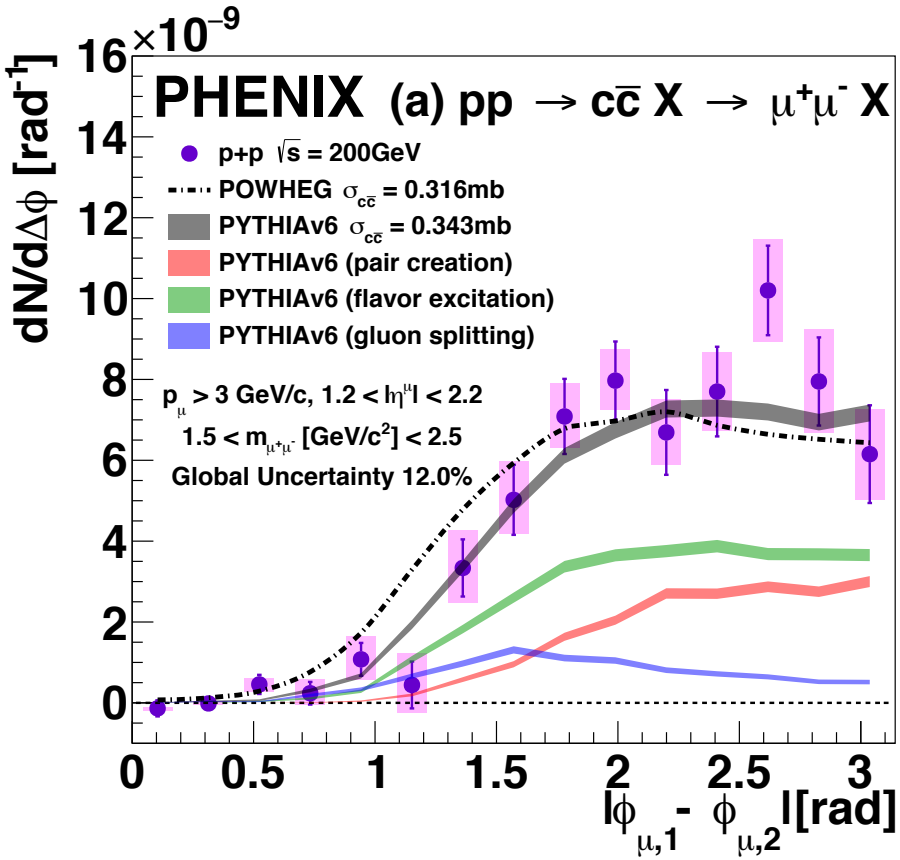
(b) t-channel Flavor Creation

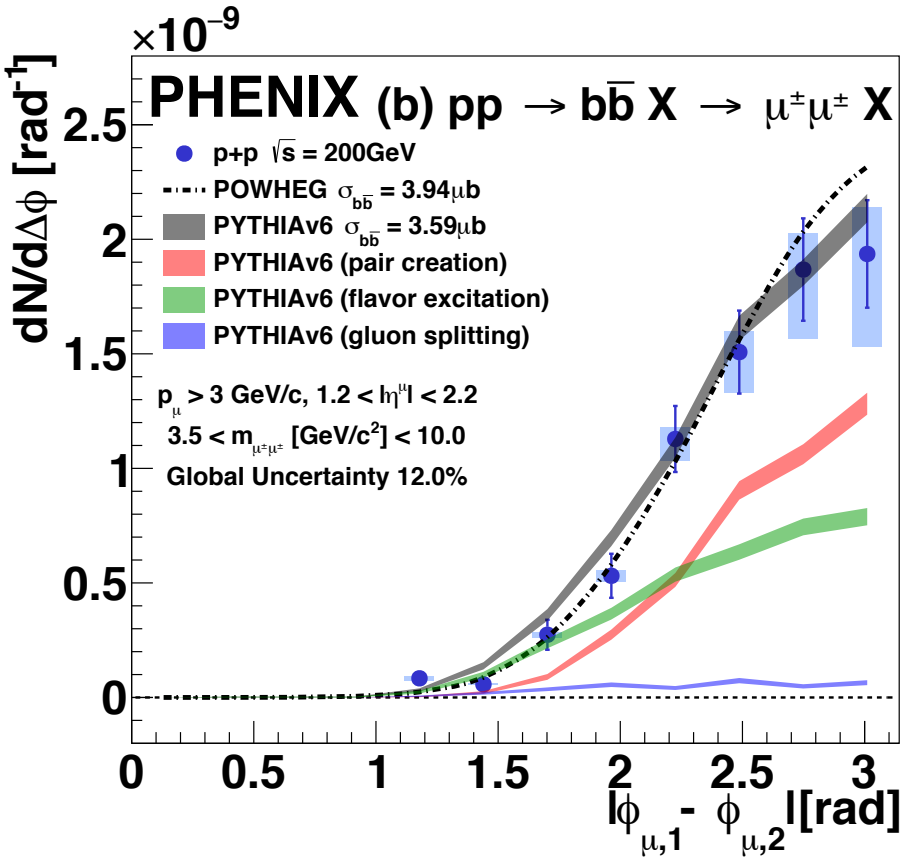
(c) Flavor Excitation

(d) Gluon Splitting

Dimuon Azimuthal Correlations

1805.02448 submitted to PRC



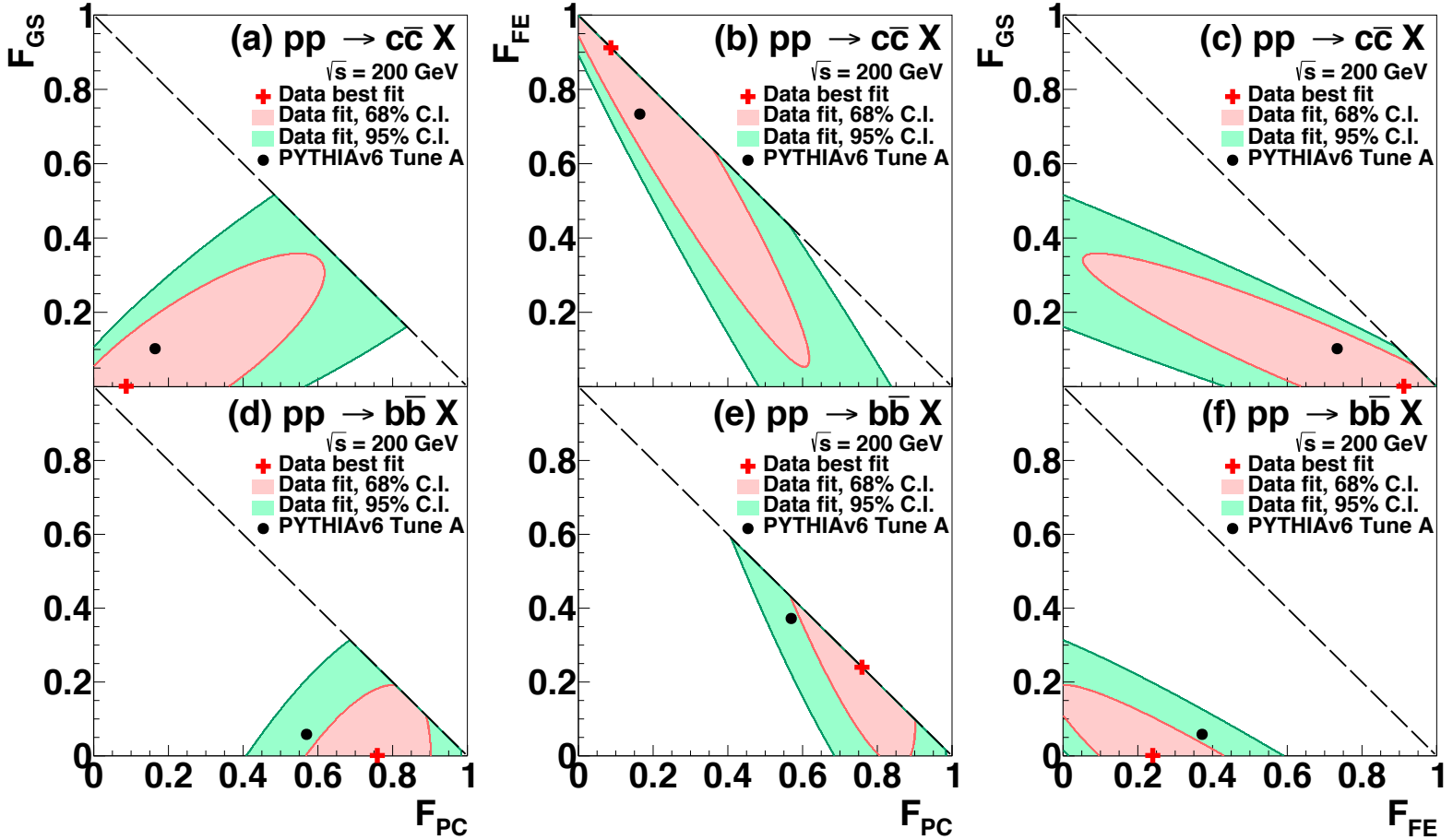


p+p

- At RHIC energies, gluon splitting a small component of charm and bottom production

Dimuon Azimuthal Correlations

1804.04075 submitted to PRL



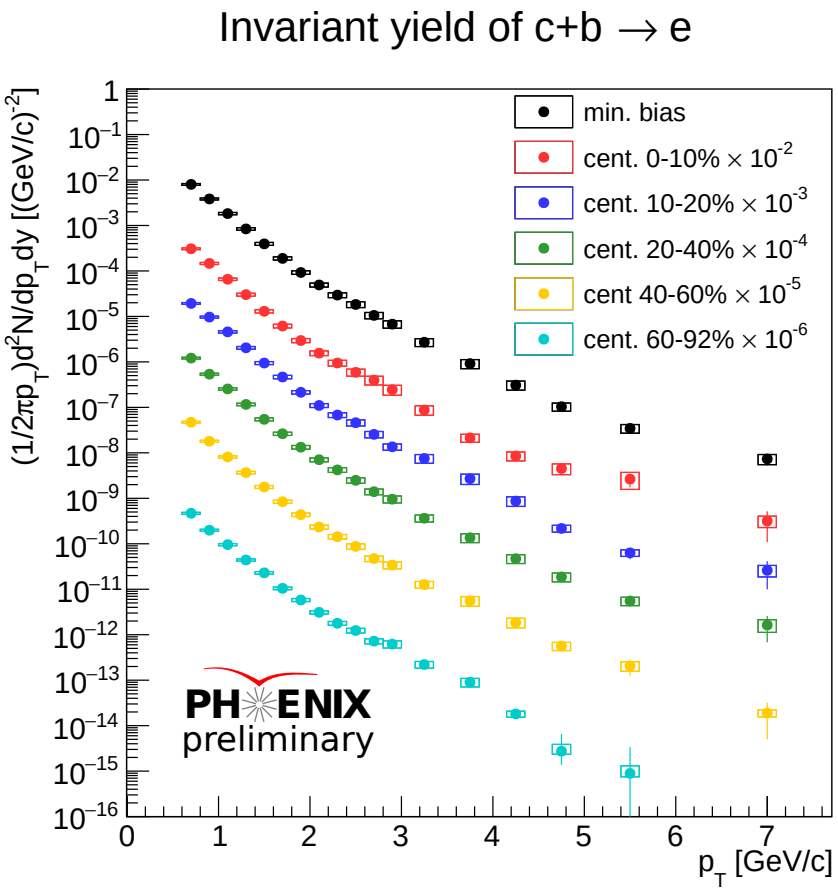
p+p

- Combine $\mu\mu$ with $e\mu$ (PRC **89** 034915) and ee (PRC **96** 024907) in a Bayesian statistical analysis.

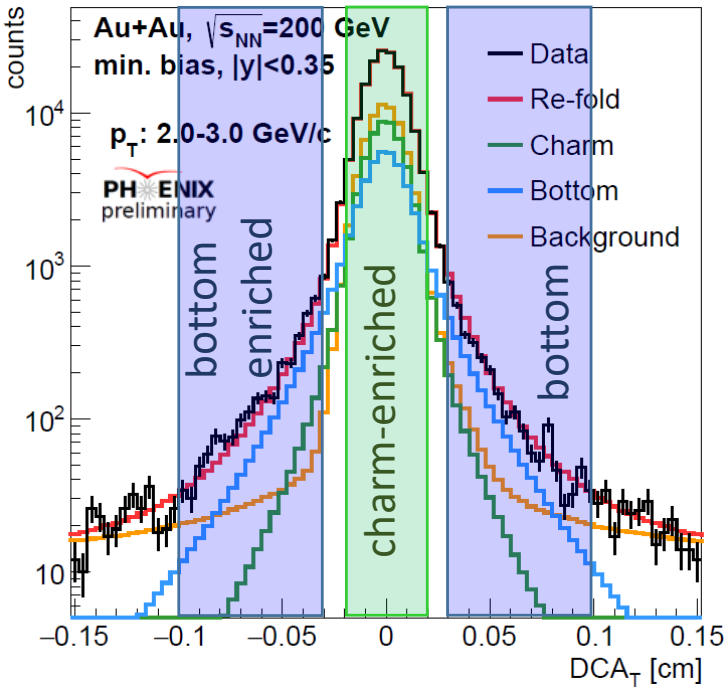
$c,b \rightarrow e$ in Au+Au

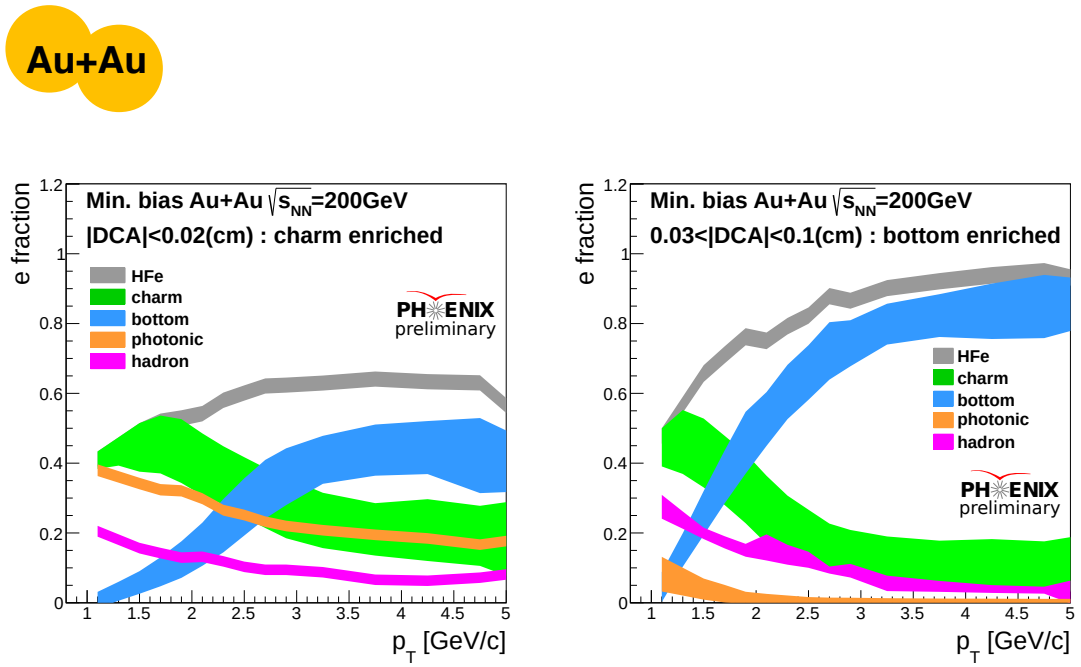
- Utilize the full statistics of the 2014 VTX data
- 4x statistics of 2010 dataset
- Decomposition into c and b separately using the DCA is ongoing.

Au+Au



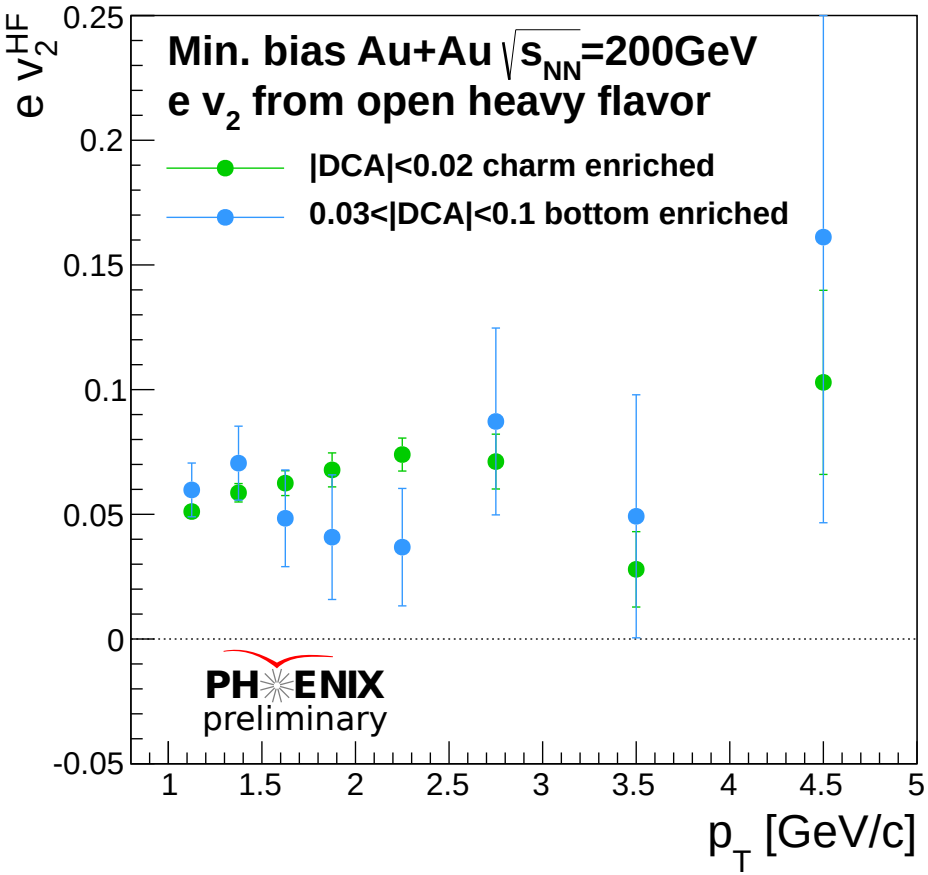
$c \rightarrow e$ and $b \rightarrow e$ v_2 in Au+Au

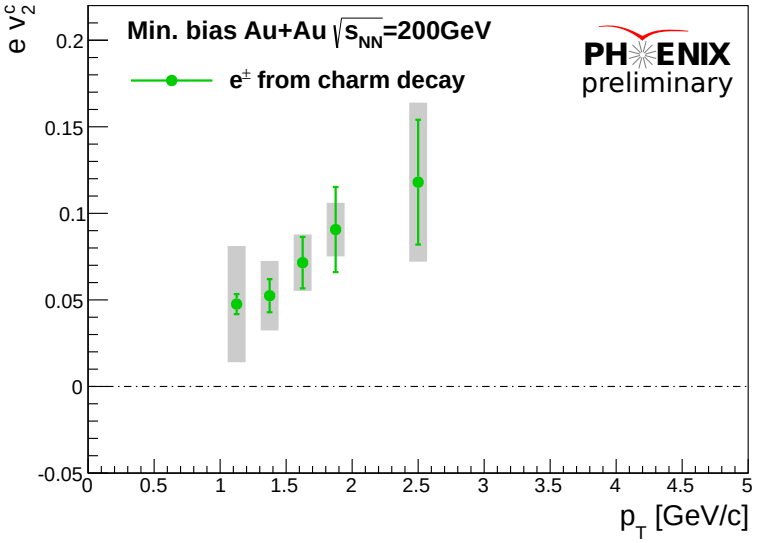


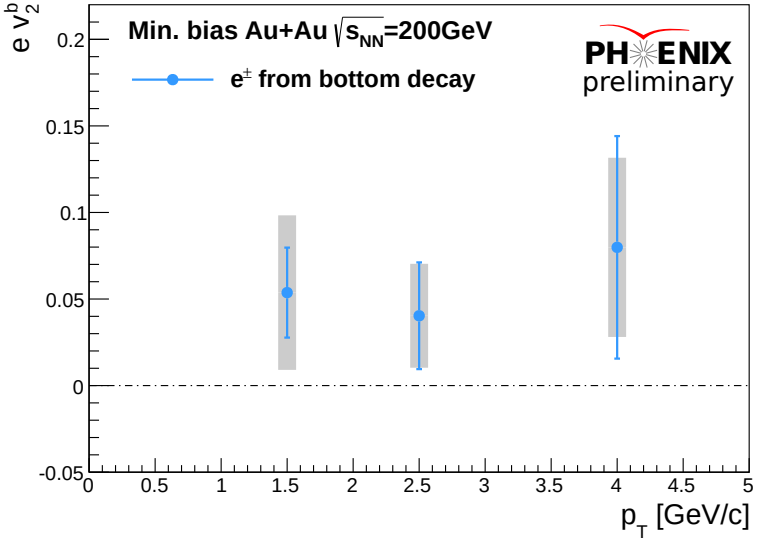


- Select regions of $\mathrm{DCA_T}$ enhance b and c.
- Subtract off other measured background v_2 i.e. from charged hadrons.

$c \to e$ and $b \to e$ v_2 in Au+Au







Au+Au

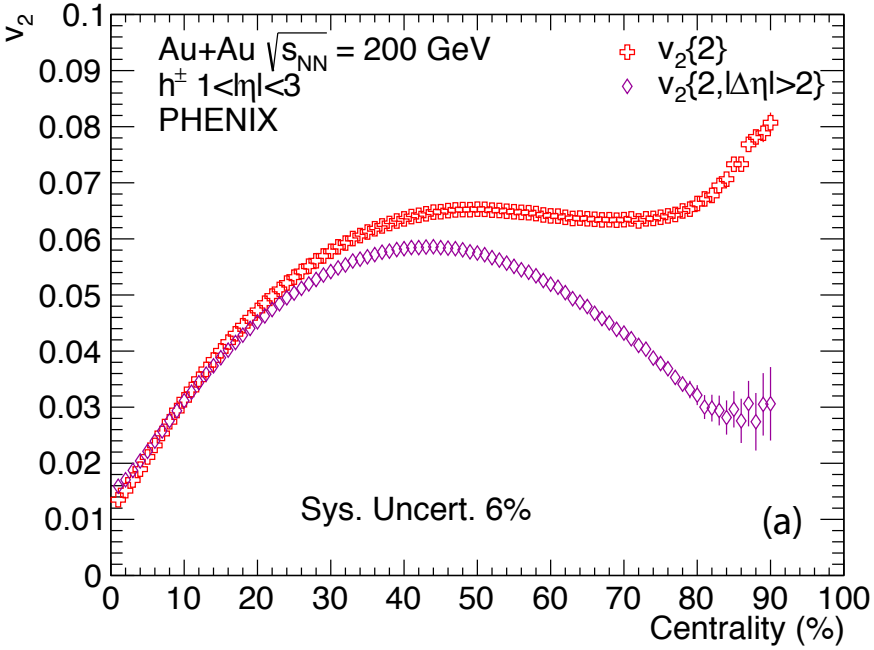
- Charm and Bottom $v_2 > 0$!

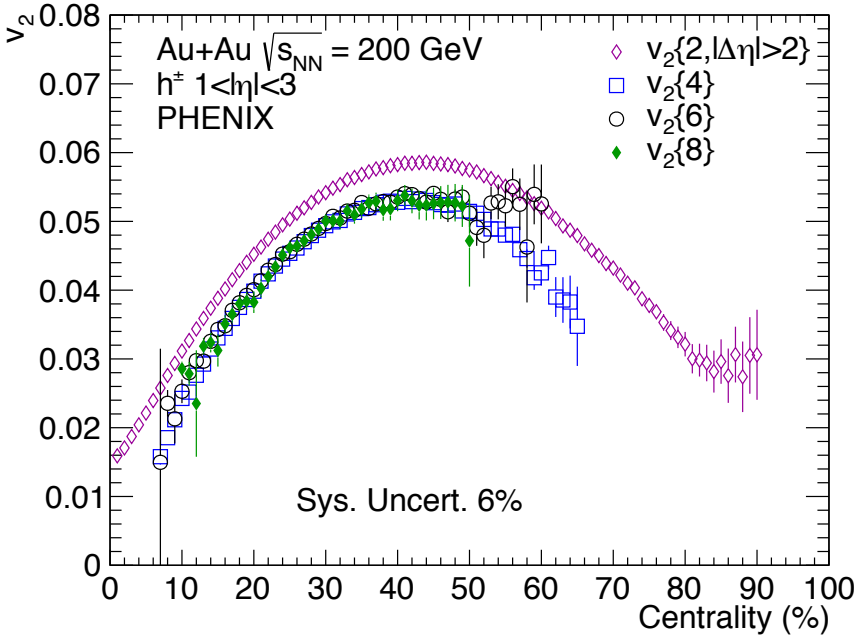
Collectivity.

Multiparticle Cumulant Analysis in Au+Au

Au+Au

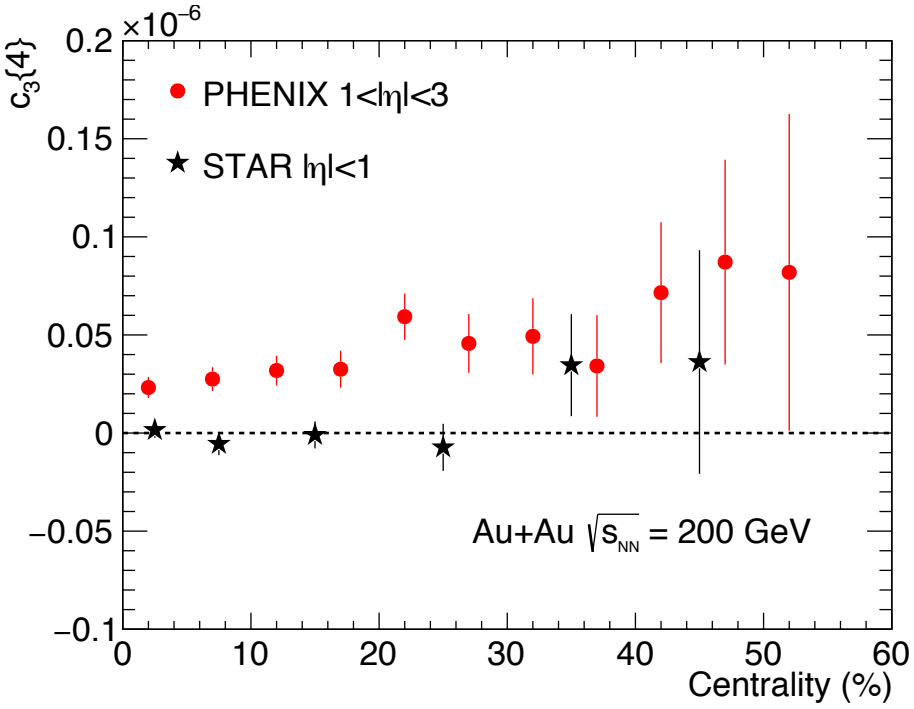
arXiv:1804.10024 Submitted to PRC





- Use FVTX (1< $|\eta|$ <3) tracks.
- Requiring $|\Delta\eta| > 2$ reduces non-flow contribution to v_2.
- $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$.

Multiparticle Cumulant Analysis in Au+Au

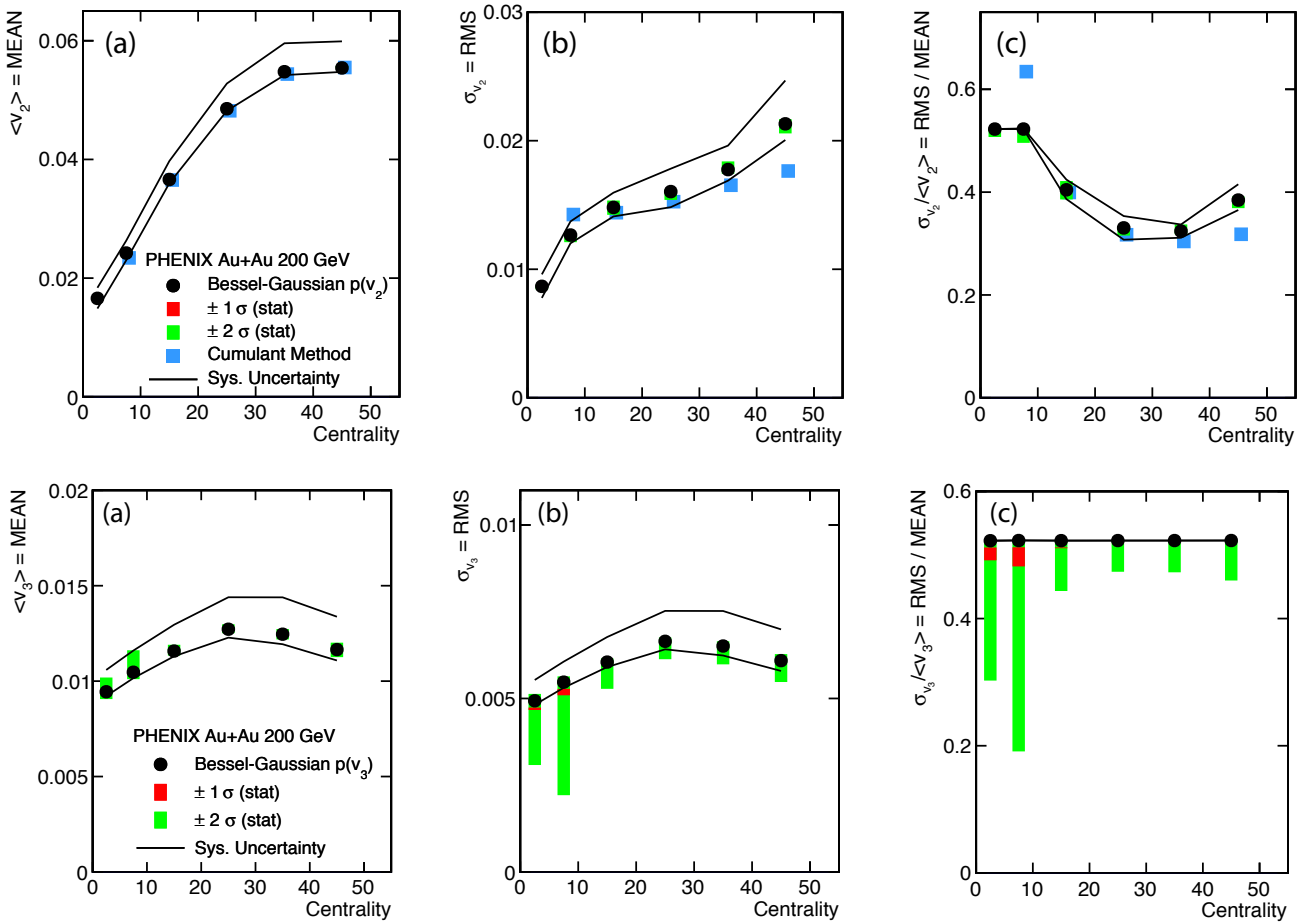


- $v_3\{4\} = (-c_3\{4\})^{1/4}$ so $v_3\{4\}$ is complex valued, likely dominated by fluctuations.
- Attempt to unfold event-by-event fluctuations assuming Bessel-Gaussian, does not work.
- Forward fold instead.

Au+Au

arXiv:1804.10024 Submitted to PRC

Multiparticle Cumulant Analysis in Au+Au



- v_2 results from folding consistent with cumulants.
- Can extract v_3 and fluctuations.
- $\sigma_{v_3}/v_3 = 0.52$, a limit of Bessel-Gaussian, indicated large variance.

Au+Au

arXiv:1804.10024 Submitted to PRC

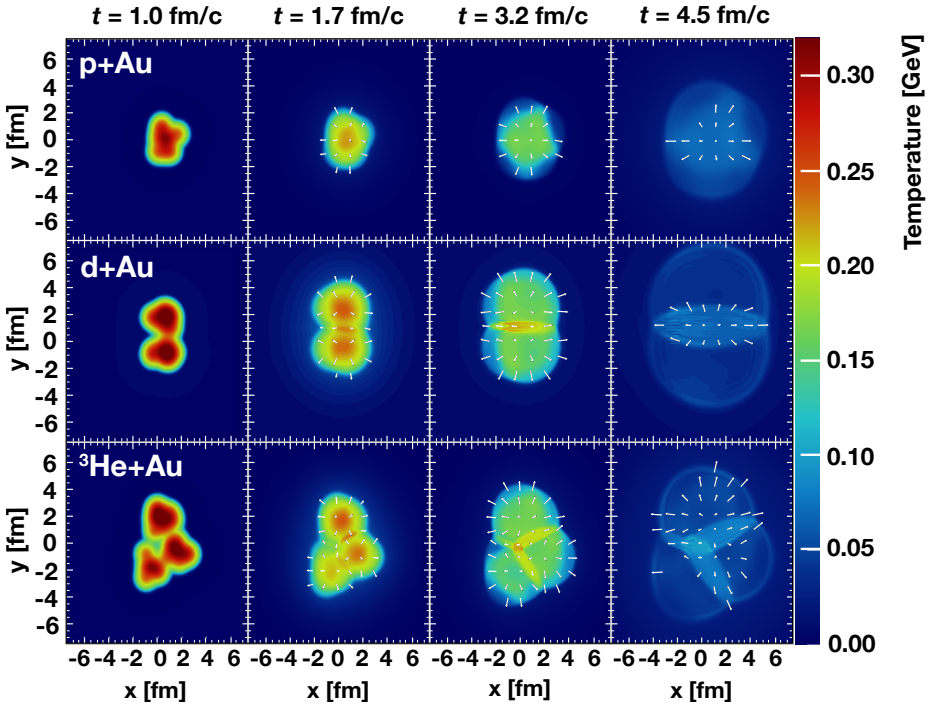
Geometry Scan Motivation

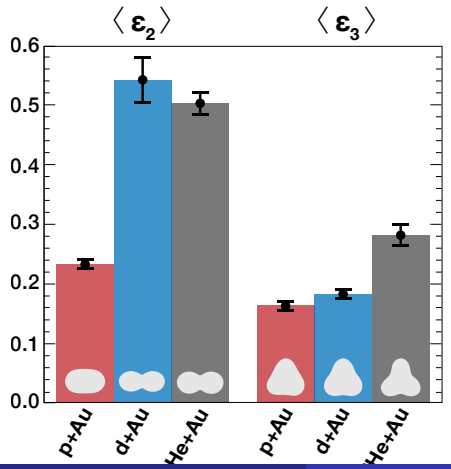
- Changing target varies initial geometry: circular → elliptical → triangular.
- If momentum anisotropy drives collectivity expect

$$v_2^{^3He+Au} > v_2^{d+Au} > v_2^{p+Au}$$
$$v_3^{^3He+Au} > v_3^{d+Au} > v_3^{p+Au}$$

- If geometry drives collectivity expect

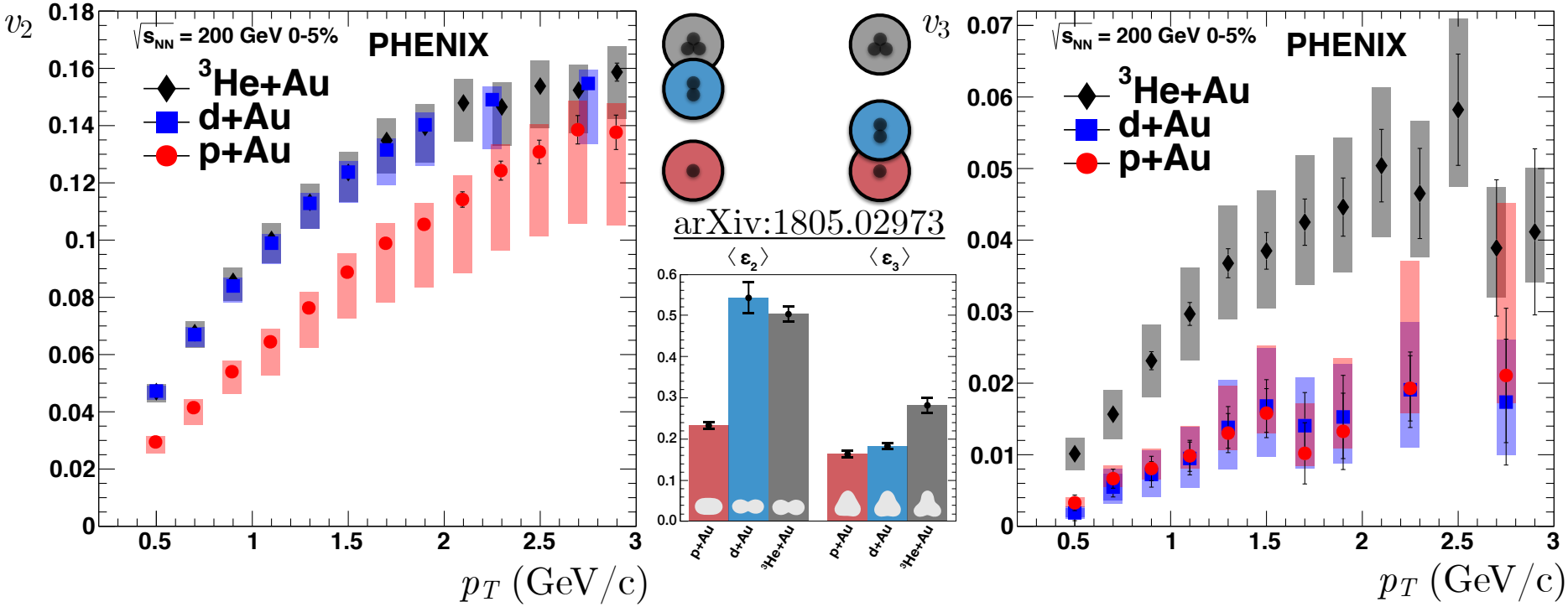
$$v_2^{^3He+Au} \approx v_2^{d+Au} > v_2^{p+Au}$$
$$v_3^{^3He+Au} > v_3^{d+Au} \approx v_3^{p+Au}$$





Asymmetric System Geometry Scan: Unidentified Hadrons

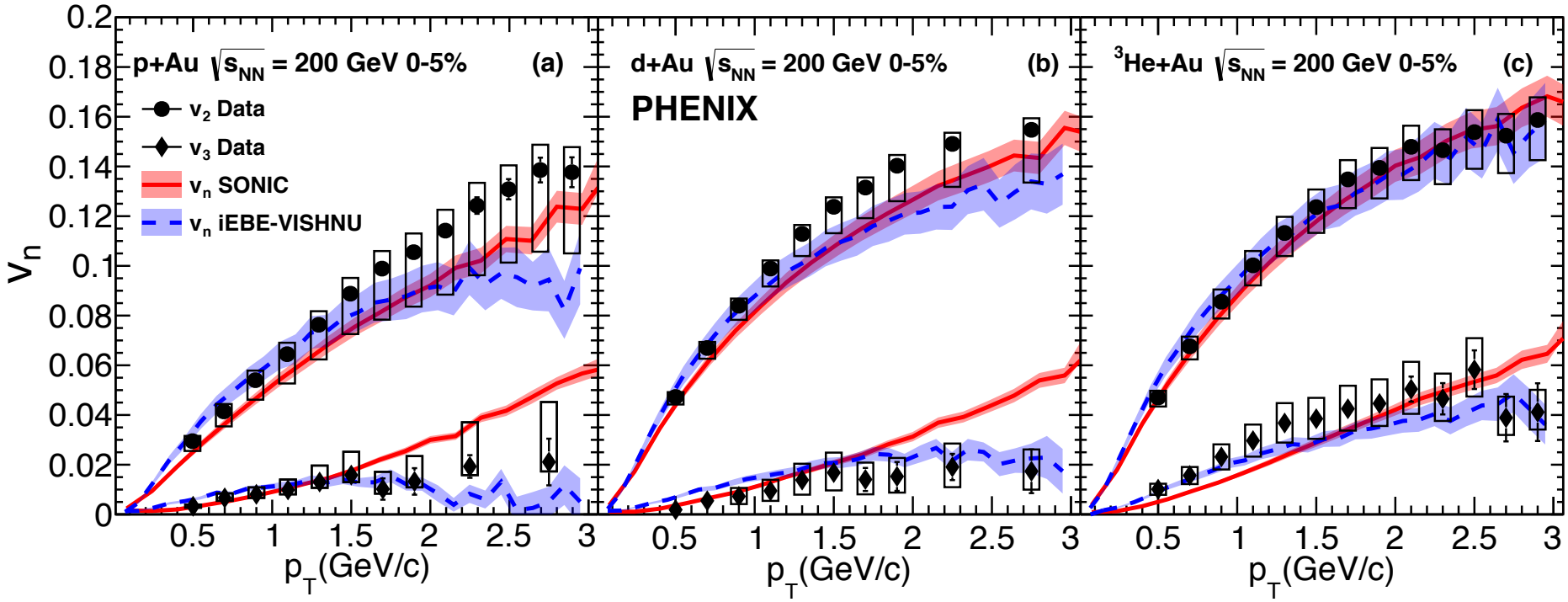
submitted to Nature Physics



- v_2 ordering follows eccentricity – origin is geometry not momentum anisotropy.

Asymmetric System Geometry Scan: Unidentified Hadrons

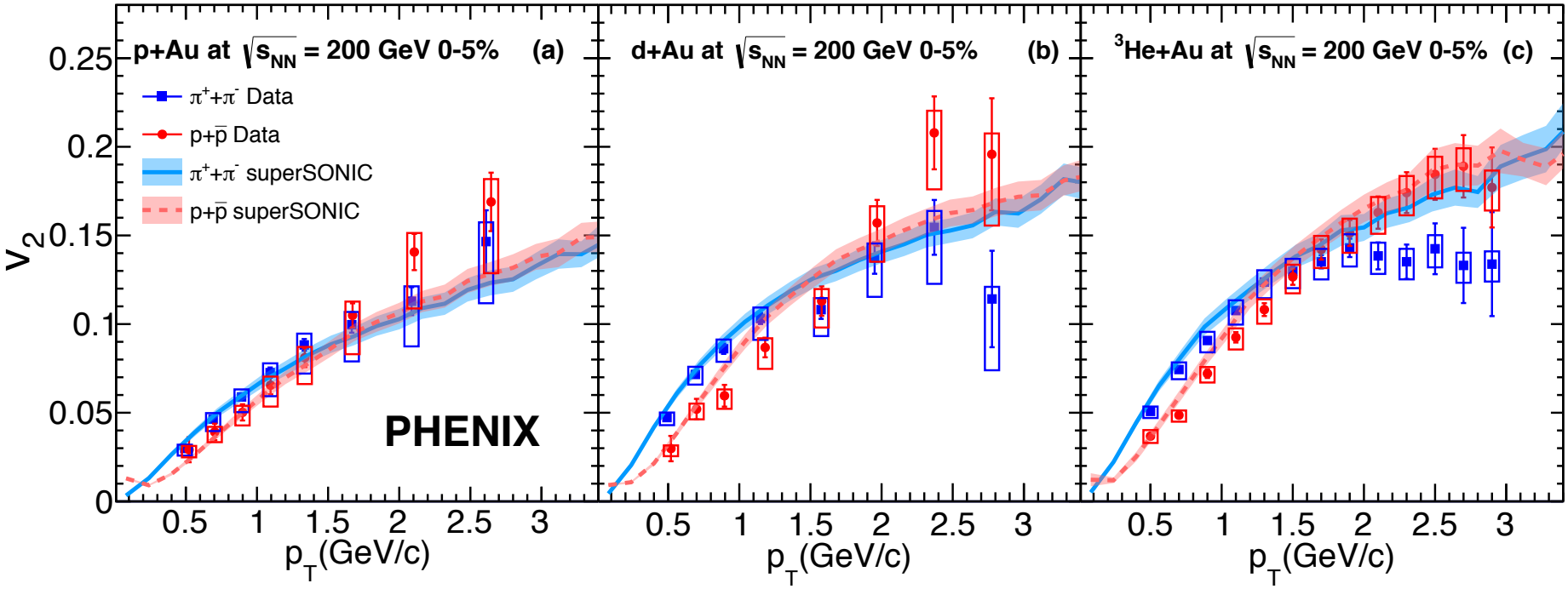
arXiv:1805.02973 submitted to Nature Physics



- Hydro does surprisingly well – small droplets of QGP formed even in p+Au.

Asymmetric System Geometry Scan: Identified Hadrons

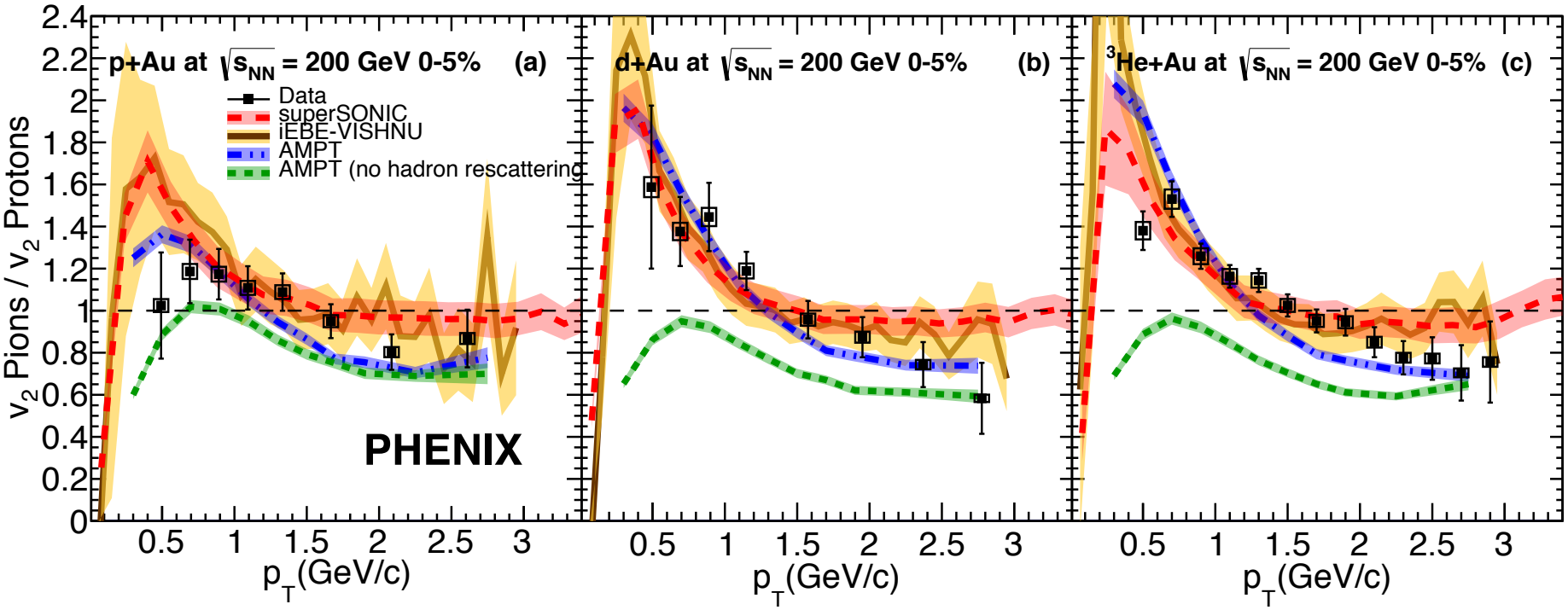
arXiv:1710.09736 accepted for PRC



- Hydro also compares well to identified particle v_2 measured at low p_T.
- Predicts $v_2^{\pi} \approx v_2^{p}$ at high p_T.

Asymmetric System Geometry Scan: Identified Hadrons

arXiv:1710.09736 accepted for PRC



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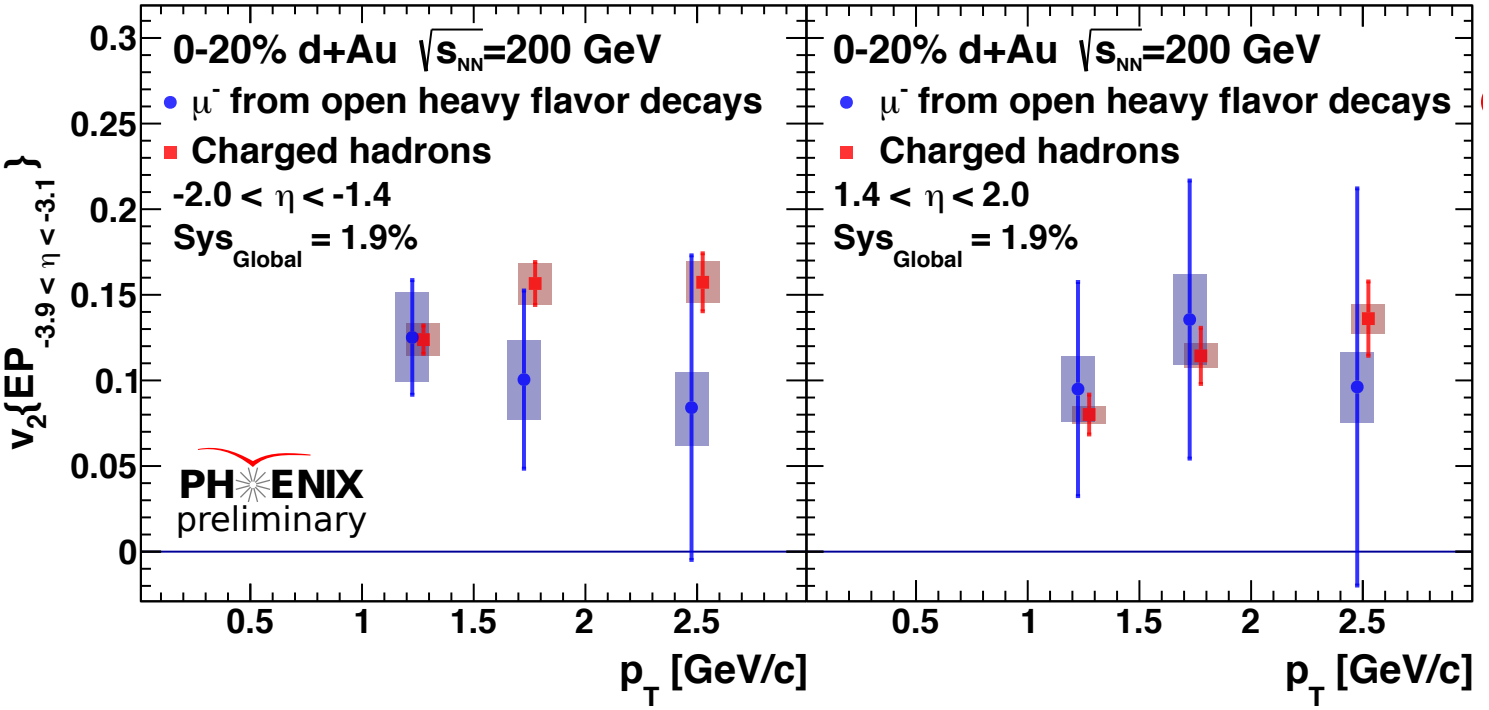
Heavy Flavor v_2 in d+Au



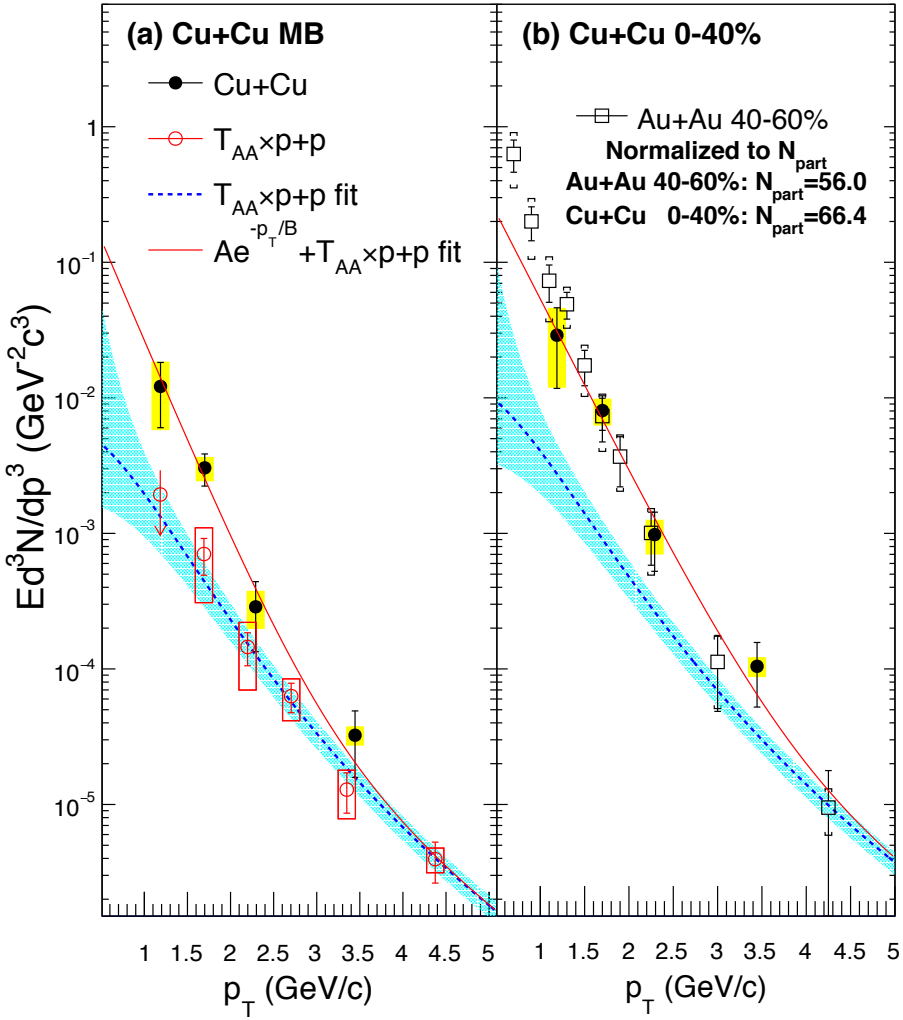
- Charged hadrons in muon arm acceptance flows.
- $v_2 > 0$ for heavy flavor muons 3.22σ (backward) and 2.16σ (forward)

Direct Photons

Direct Photons in Cu+Cu

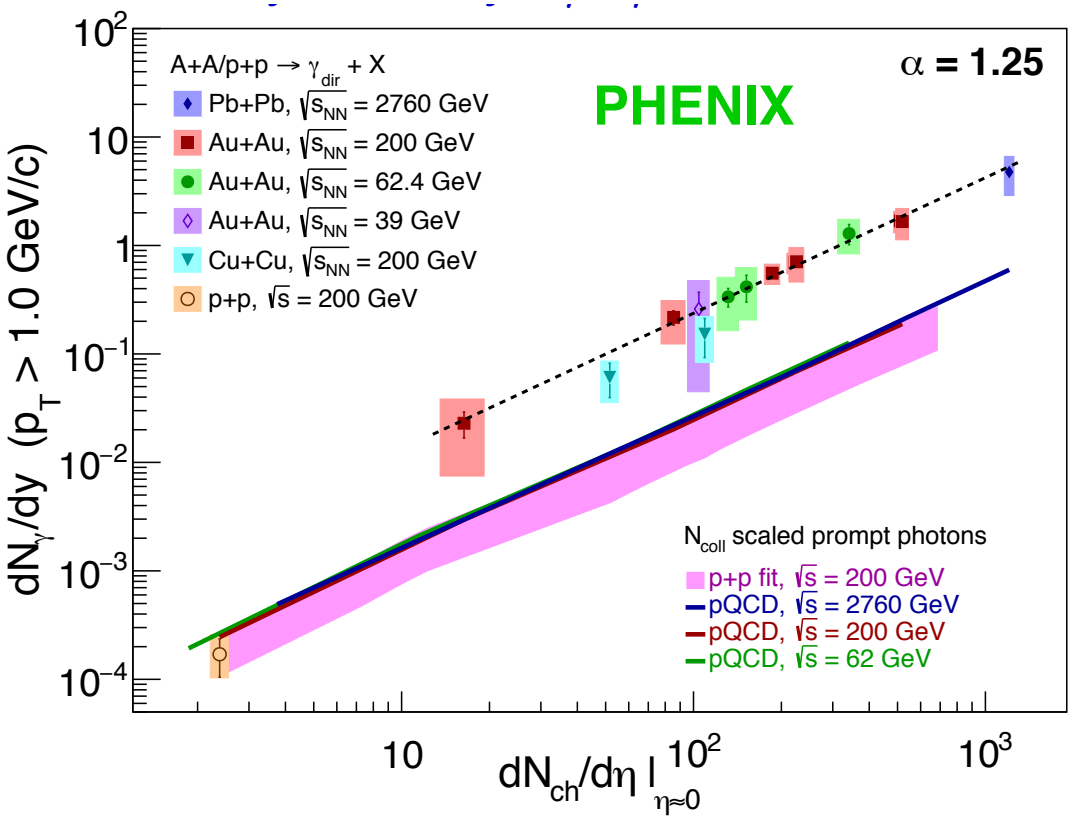
Cu+Cu

- Excess of virtual direct photons compared to N_{coll}-scaled $p+p$.
- Excess spectra similar between 0-40% Cu+Cu and 40-60% Au+Au with similar geometry.
- Inverse exponential slopes of excess: 285±53(stat)±57(sys).



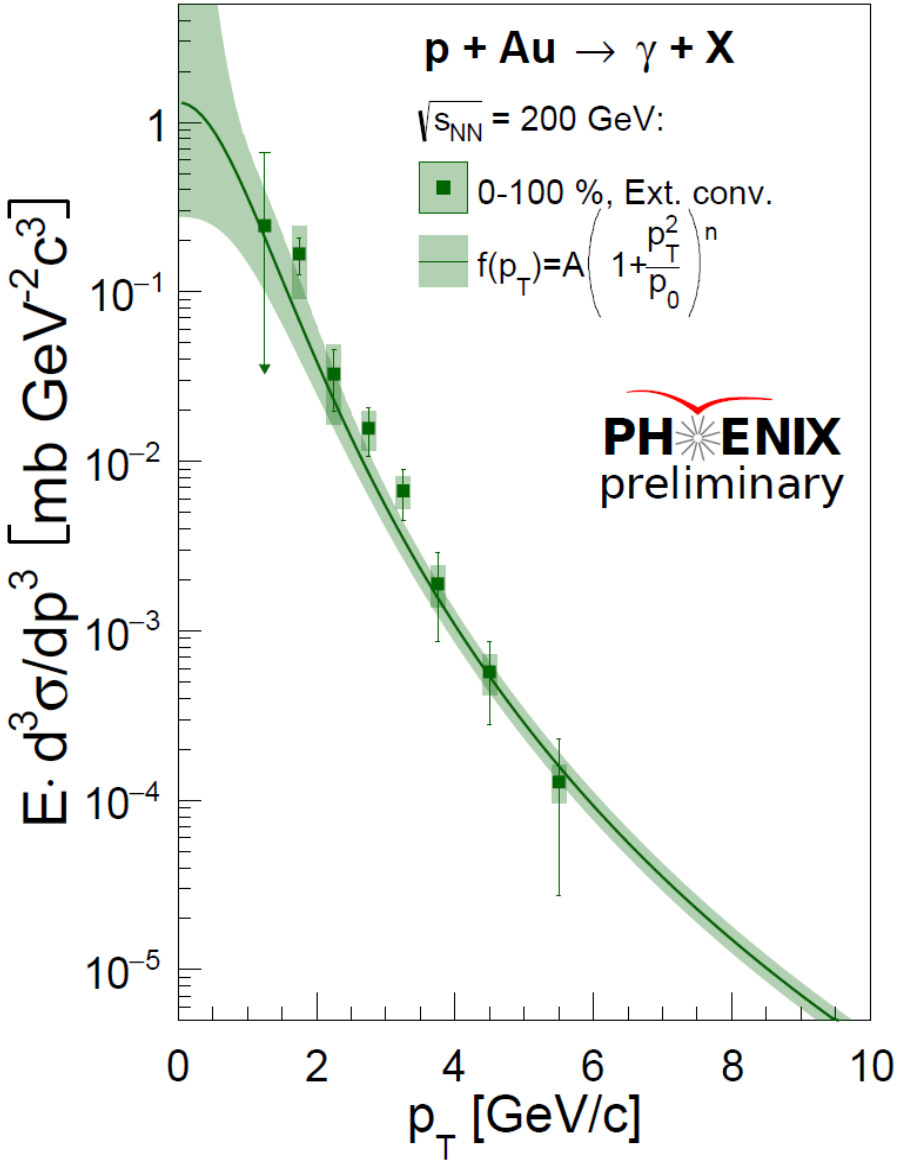
arXiv:1805.04066 Submitted to PRC

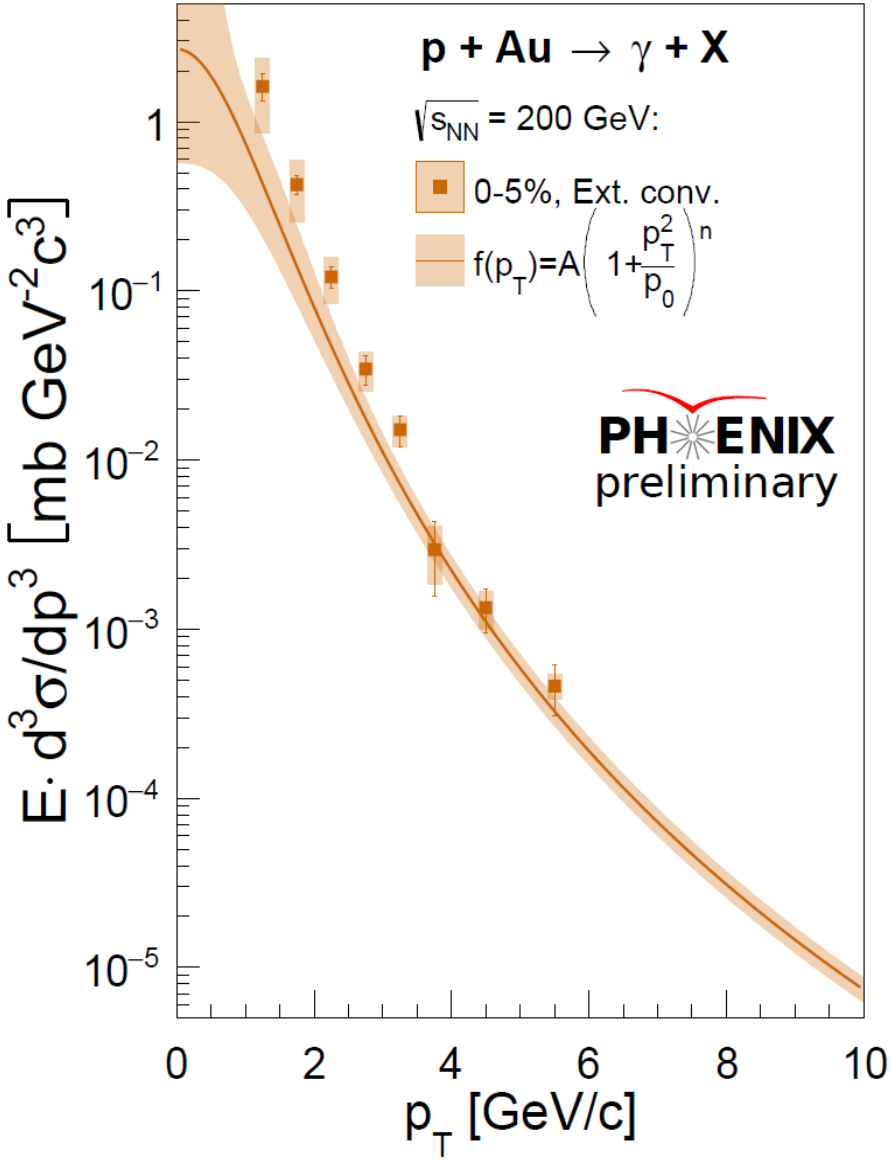
Direct Photons in A+A



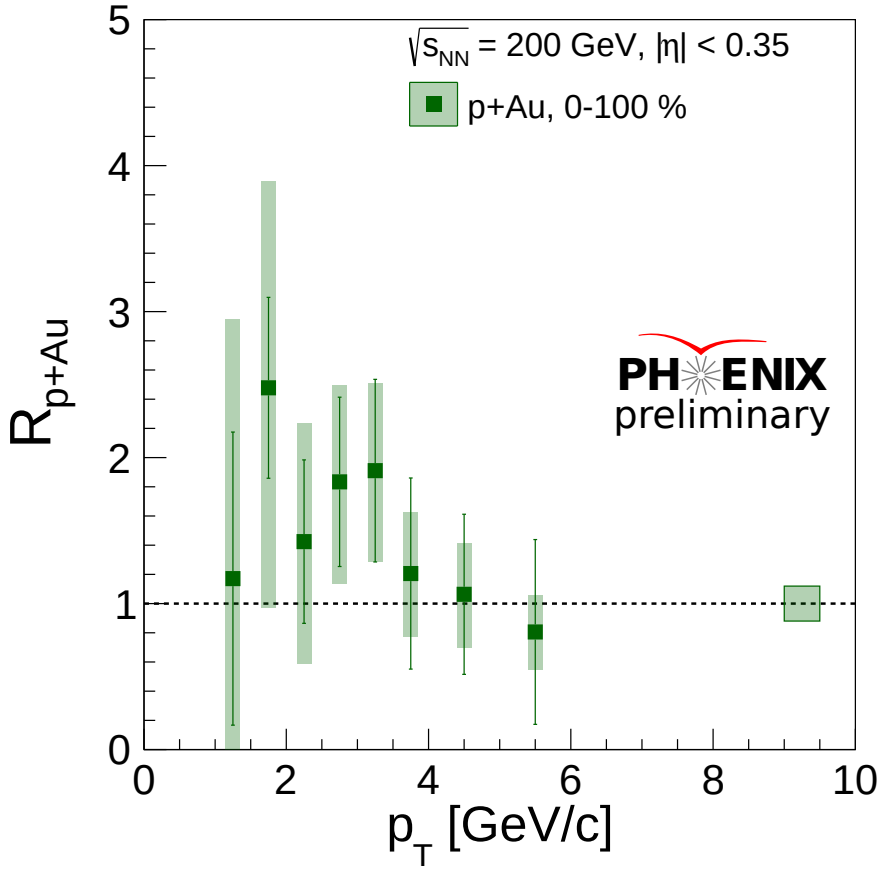
- Comparison of direct photons over many collision centralities, energies and species scales with $(dN/d\eta)^{1.25}$.
- Implies a common origin to the source of excess photons?

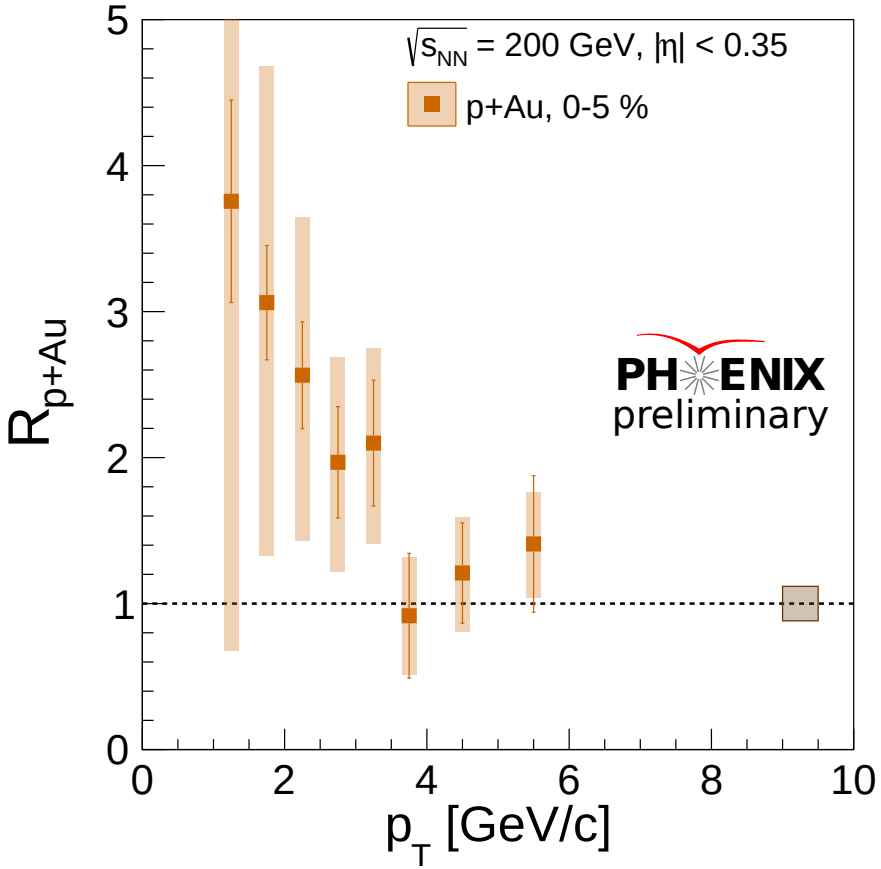
Direct photons in p+Au

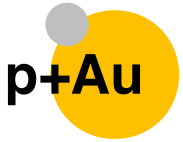




Direct photons in p+Au

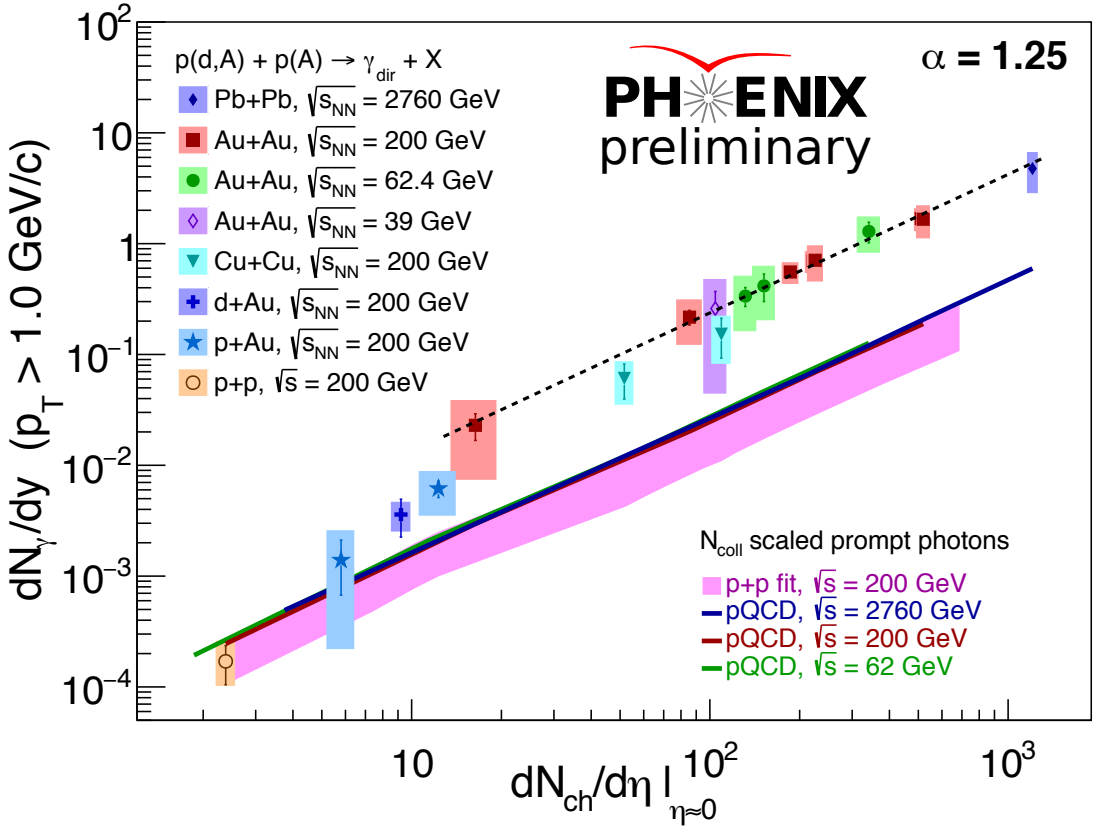






- $R_{AA} > 1$ systematically for most central p+Au. Origin?
- More evidence of thermalized QGP in p+Au?

Direct Photons in A+B



- p+Au and d+Au points between $p+p$ and A+A.
- Different origin for p(d)+Au excess compared to A+A?

Summary

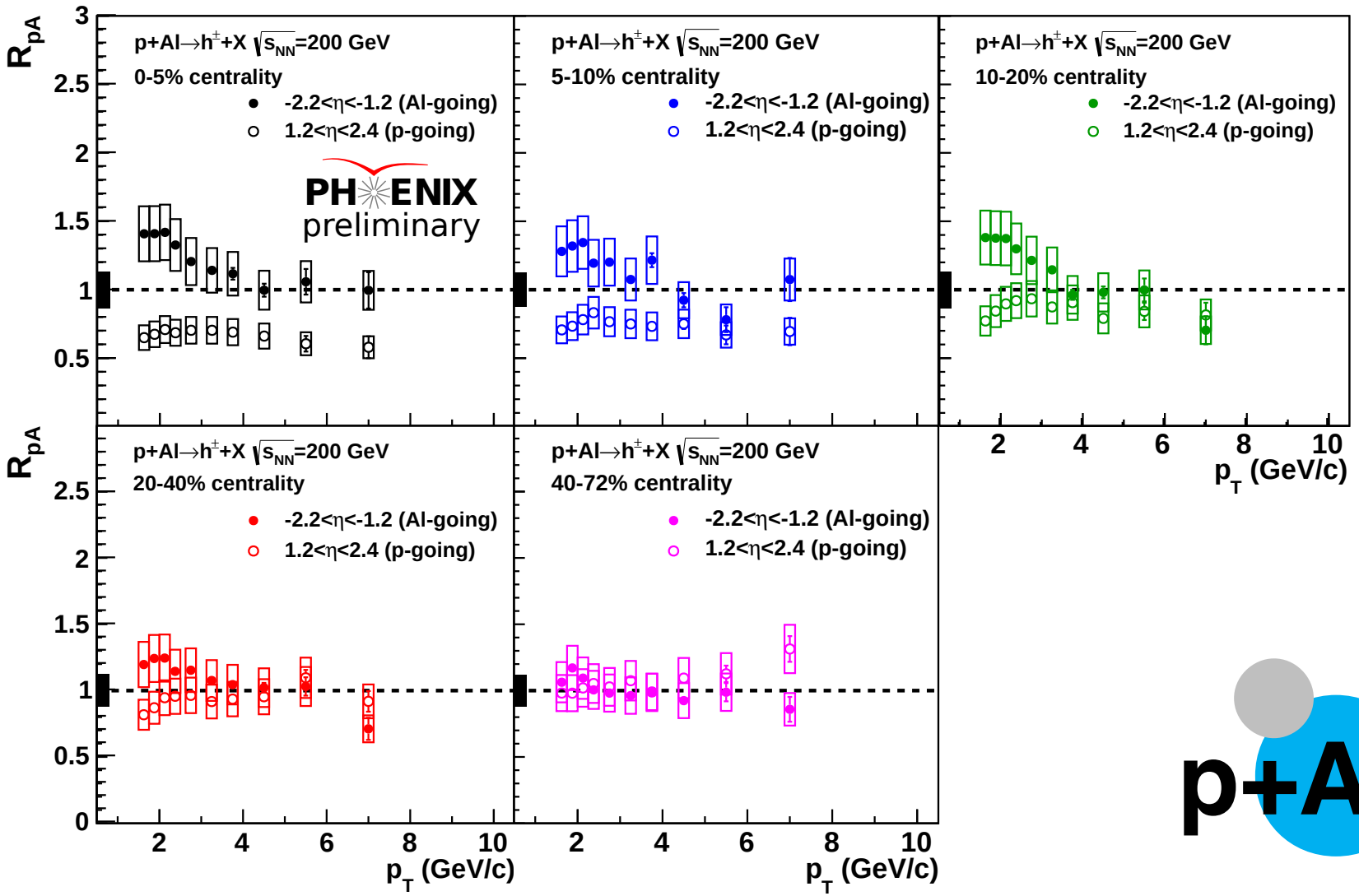
- PHENIX continuing to analyze high quality data making important contributions in
- Spin
  - Increasing the W measurement to higher η.
  - Finding novel asymmetries in p+A collisions.
- High-p_T
  - Two-particle away-side broadening in p+Au compared to p+p
  - Narrowing in on energy redistribution from modified isolated direct γ-hadron correlations in Au+Au
  - Large enhancement of Au-going hadrons from 2.5-5 GeV in the muon arms in p+Au compared to p+p.

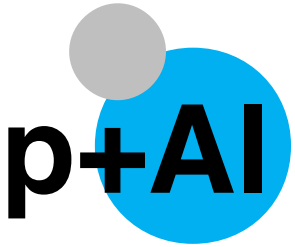
Summary

- Heavy Flavors
  - Dimuon (and $e\mu$ and ee) azimuthal correlation identify dominant production mechanism of heavy flavor in p+p
  - Full statistics of 2014 Au+Au data allow first measurement of $c \rightarrow e$ and $b \rightarrow e$ $v_2 > 0$.
- Collectivity
  - Geometry scan (p+Au, d+Au, ^{3}He +Au) indicates geometry the source of collectivity
  - Heavy quarks flow, too!
- Direct Photons
  - Excess of direct photons near 1 GeV in 0-5% p+Au collision.
  - Scaling of A+A direct photons yields "turns on" at small collision systems.

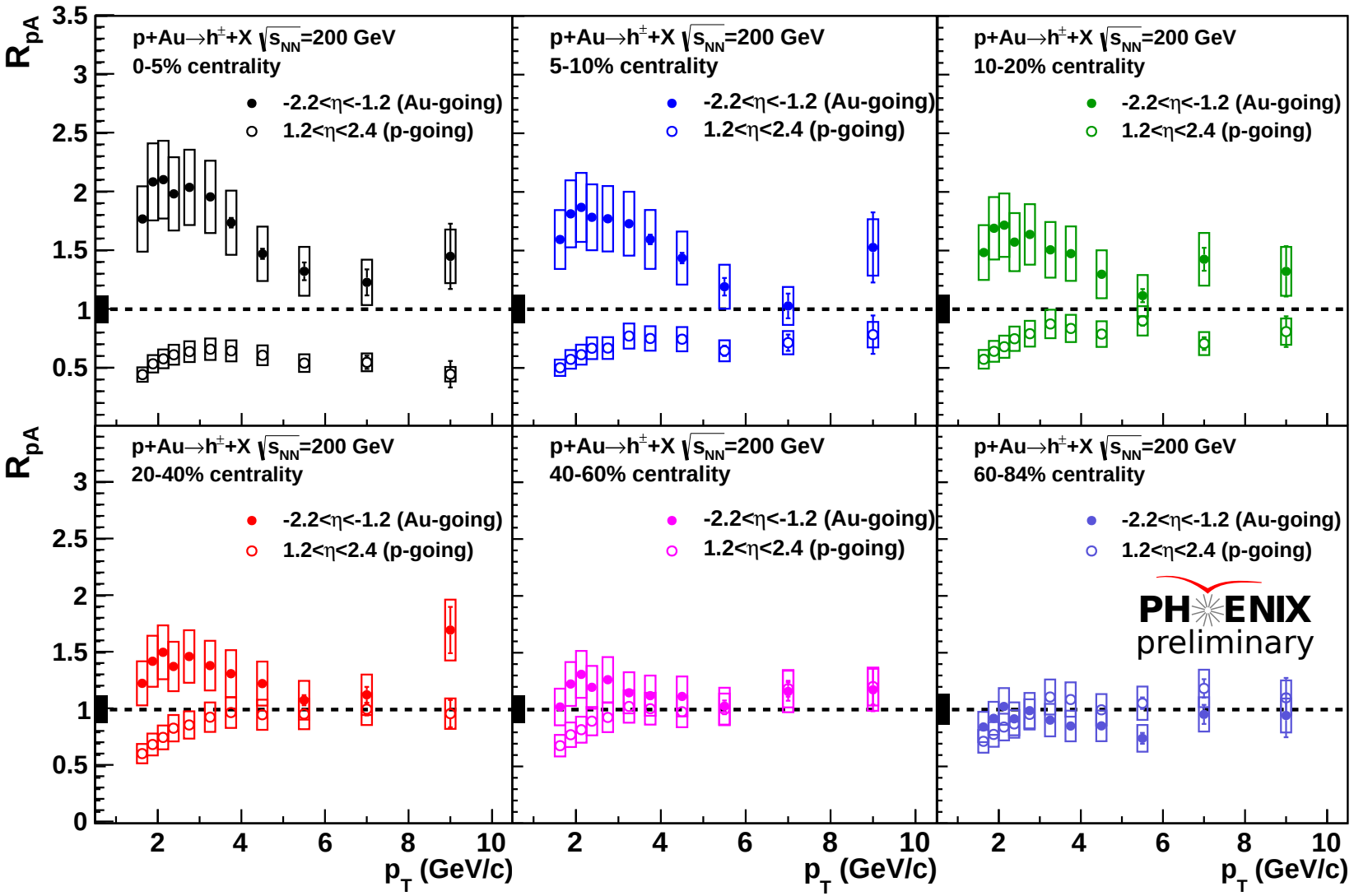
Backup

Hadron R_{pA} in p+Al





Hadron R_{pA} in p+Au



p+Au