Overview of heavy ion physics at PHENIX (recent results)

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8 January 2019

Key ingredient of **nuclear** physics:

Change the **nucleus**

$\sqrt{s}$ [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

Key ingredient of **nuclear** physics:

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39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

Outline

Large systems

—Single particle R_{AA} results, multiple species and collisions **New!**

—π^0-h correlations in Au+Au **New!**

—Spectra of charm and bottom in p+p **New!**

—v_2 of charm and bottom in Au+Au

Small systems

—π^0-h correlations in ^{3}He+Au **New!**

—Drell-Yan measurement in p+Au **New!**

—Longitudinal dynamics in small systems **Now published!**

—Small systems geometry scan **Now published!**

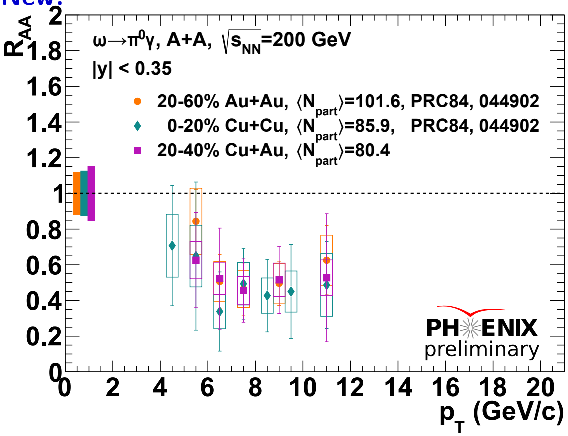
—Direct photon measurements in p+Au

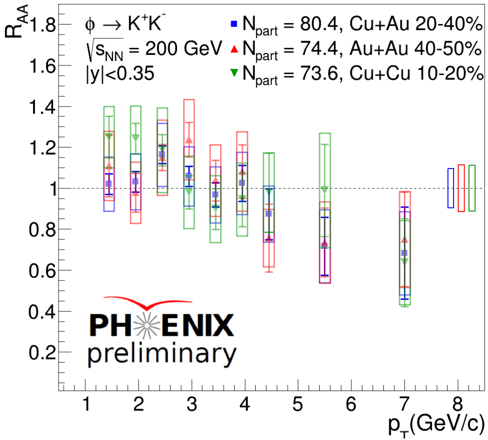
Intermission

Large Systems

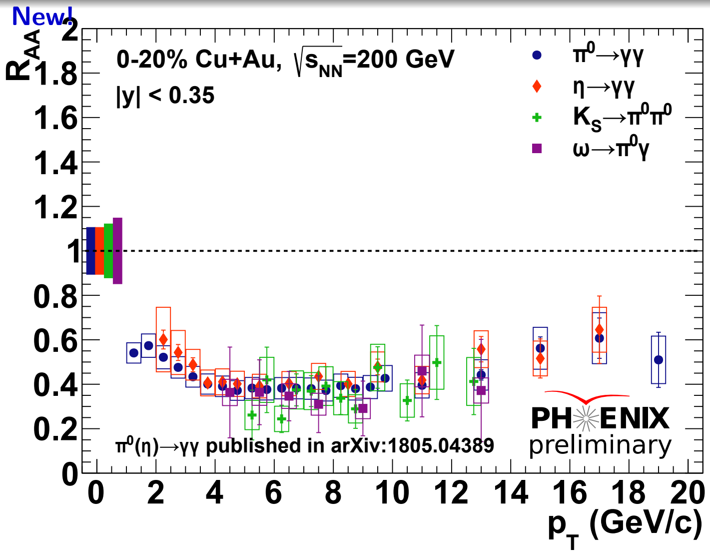
Identified particle R_{AA} in large systems

New!





ω and ϕ mesons behave similarly in Cu+Cu, Cu+Au, Au+Au



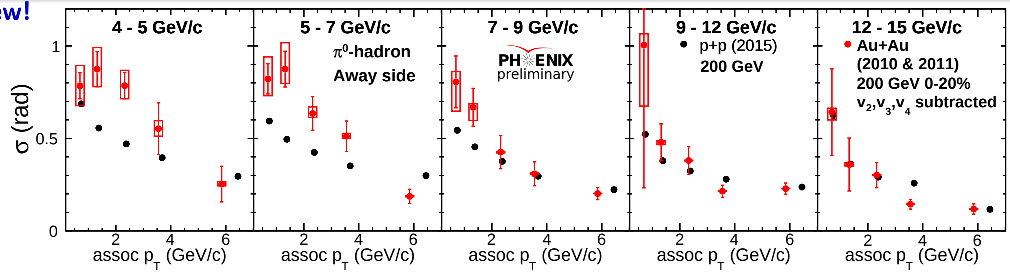
R_{AA} of identified neutral mesons

π^0, η, K_S^0, ω

Similar behavior for all species at high p_T

π^0-h in Au+Au

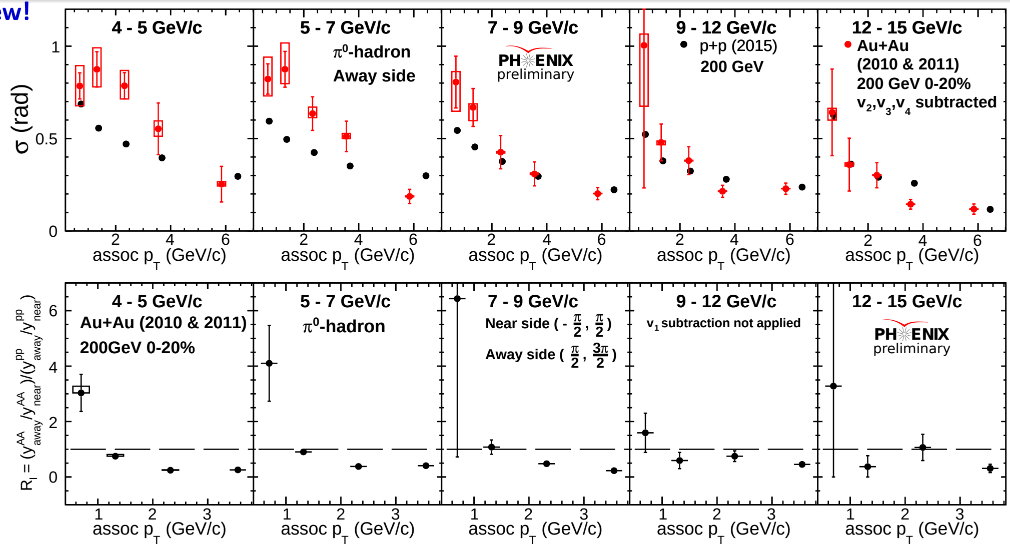
New!



Broadening of the away side for low p_T,
similar width at high p_T

π^0-h in Au+Au

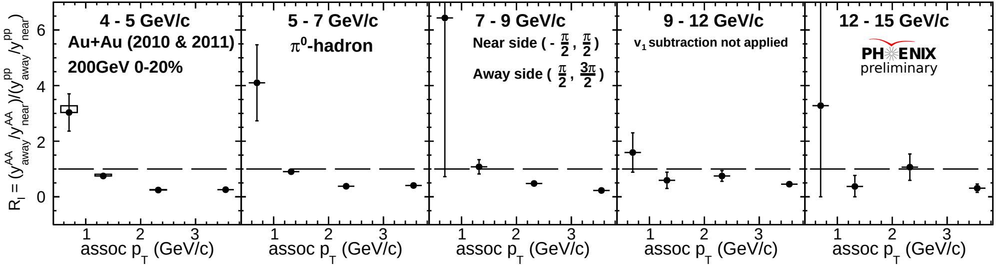
New!



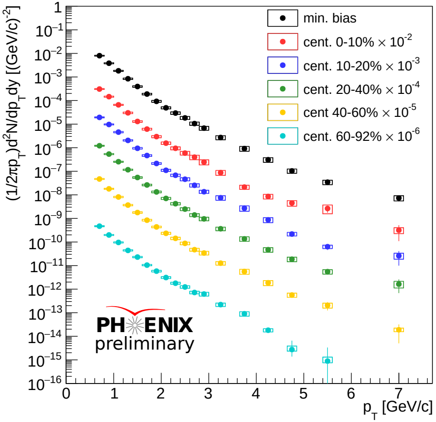
New!

Depletion at high p_T, enhancement at low p_T

$$R_I = \frac{Y^{AA}_{away} / Y^{AA}_{near}}{Y^{pp}_{away} / Y^{pp}_{near}}$$



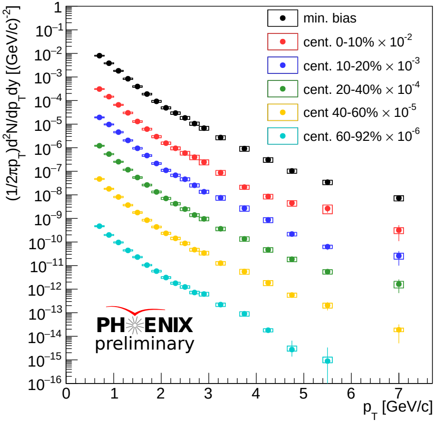
$c \to e$ and $b \to e$ in Au+Au and $p+p$

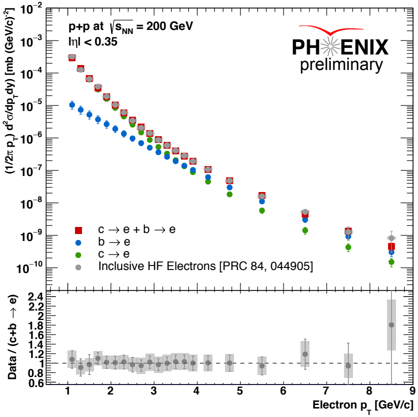


HF electron spectra, all centralities and using all available data

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

New!

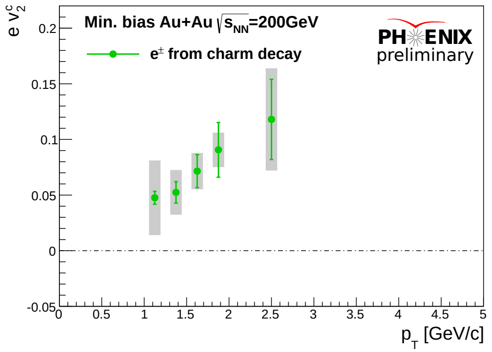


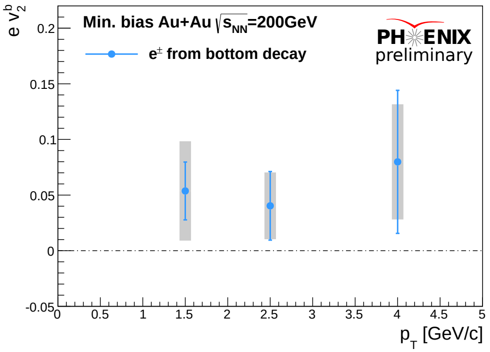


HF electron spectra, all centralities and using all available data

New $p+p$ reference data; new publication with R_{AA} on the way!

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

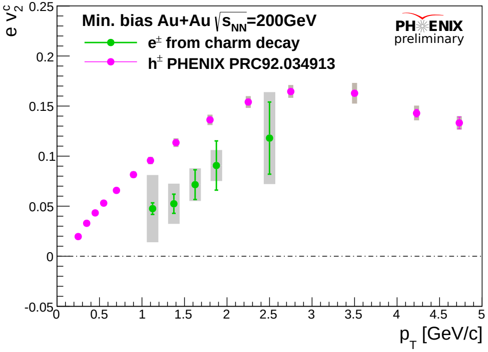


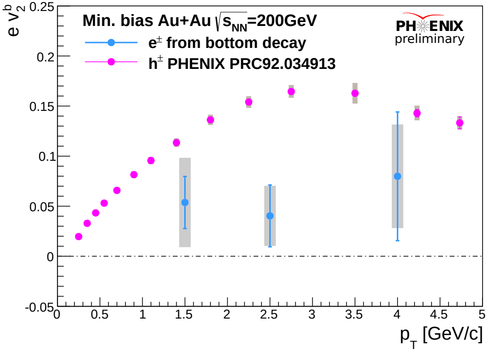


Charm $v_2 > 0$

Bottom $v_2 > 0$

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





Charm $v_2 > 0$

Bottom $v_2 > 0$

Both smaller than light flavor

Large Systems Summary

Single particle R_{AA} independent of collision species when selecting for similar N_{part}

Neutral mesons R_{AA} very similar in Au+Au despite different strangeness content
—Strangeness very important at low p_T but not at high p_T

Correlation measurements show away-side broadening and low p_T enhancement
—Indicates momentum shift and large-angle radiation of high-p_T partons

Measurement of $c \rightarrow e$ and $b \rightarrow e$ spectra in p+p
—Publication with new R_{AA} coming soon

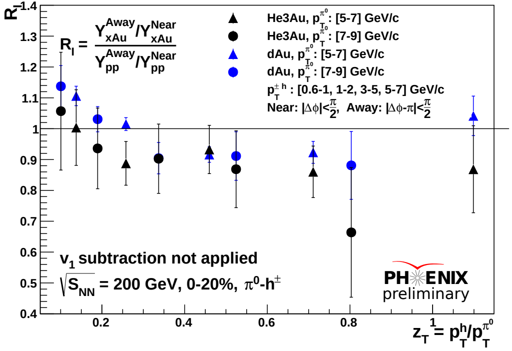
First measurement of bottom flow at RHIC
—May be consistent with zero, refinements and publication forthcoming

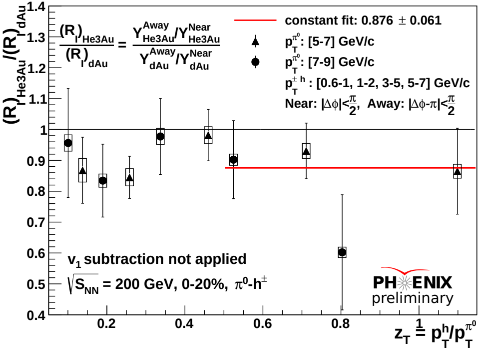
Intermission

Small Systems

π^0-h in small systems

New!

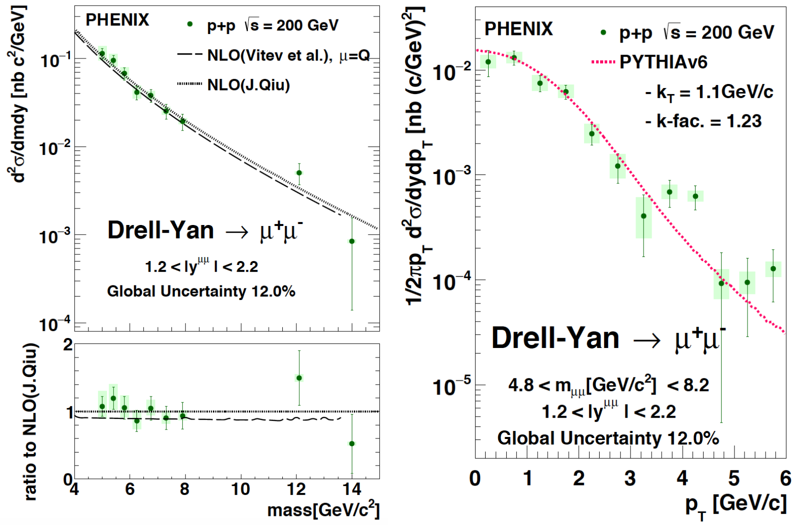




High-z_T depletion with low-z_T enhancement resembles large systems
How to understand? Need detailed theory calculations

Drell-Yan from angular correlations in $p+p$

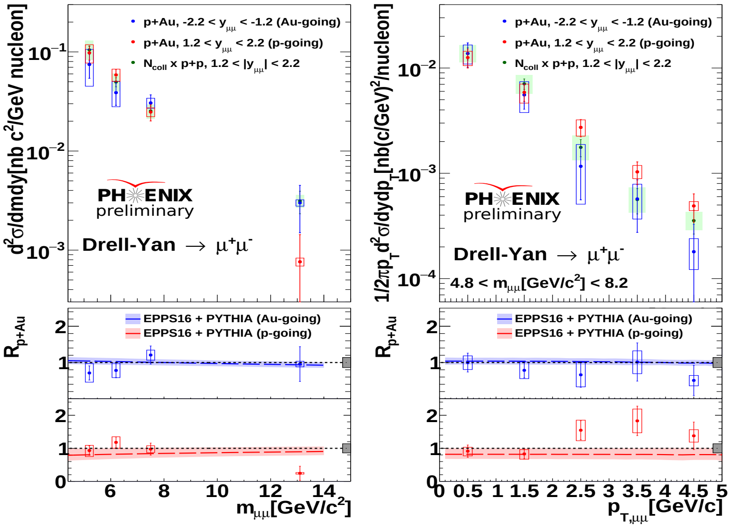
arXiv:1805.04075 (PRL)
arXiv:1805.02448 (PRD)



Drell-Yan well-described by NLO pQCD & PYTHIA

Drell-Yan from angular correlations in p+Au

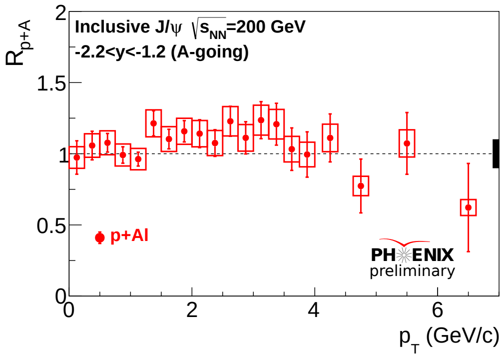
New!

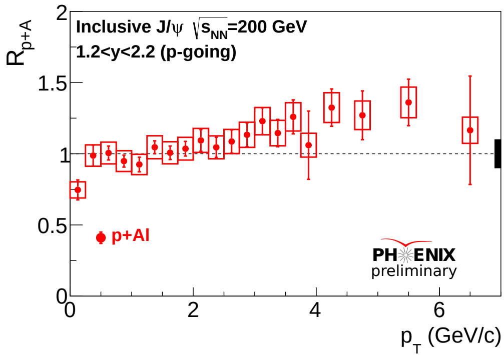


Hints of modification to Drell-Yan in p+Au, though large uncertainties prevent a firm conclusion

J/ψ nuclear modification in small systems

New!





J/ψ nuclear modification in small systems

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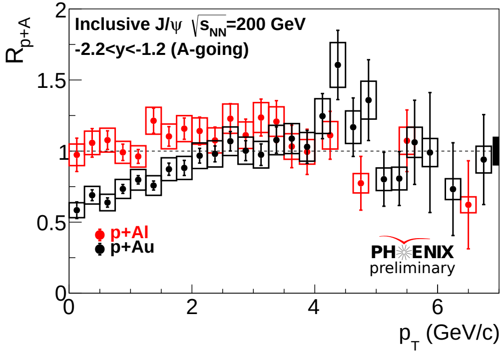

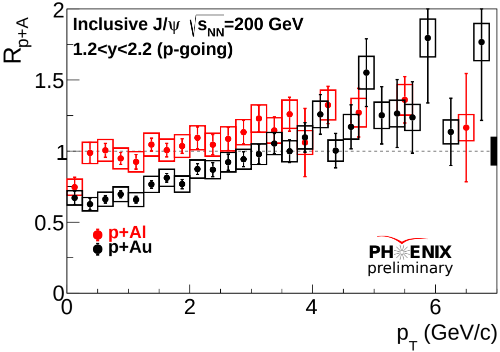

p+Al $\rightarrow$ p+Au—big change when increasing nuclear target size

J/ψ nuclear modification in small systems

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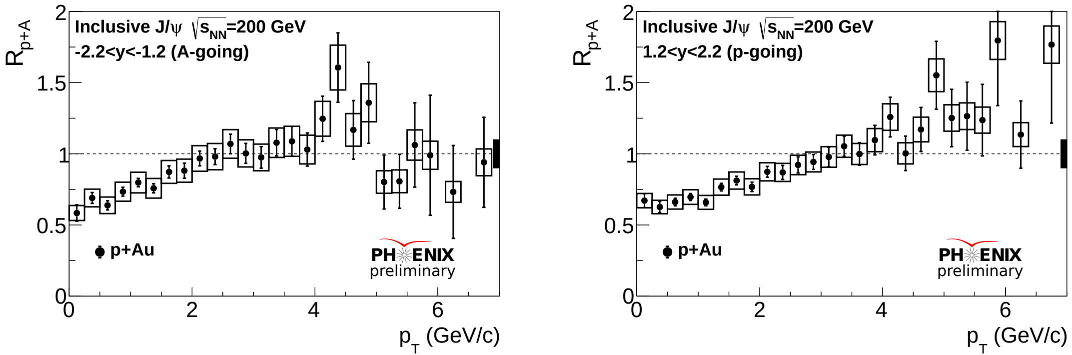

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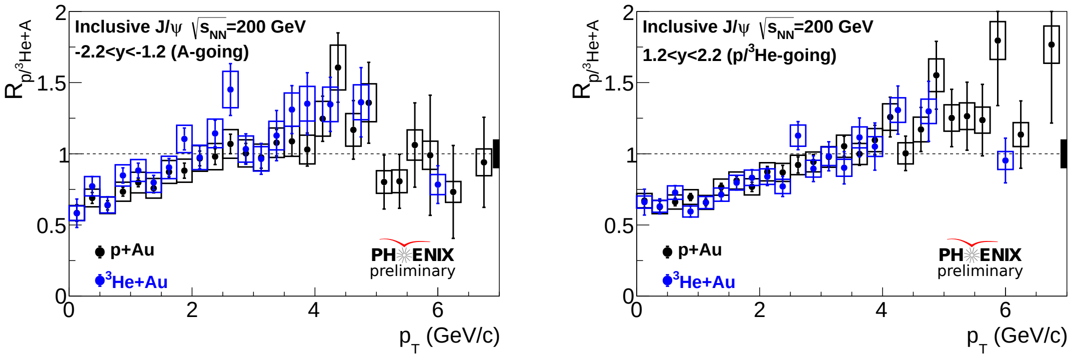


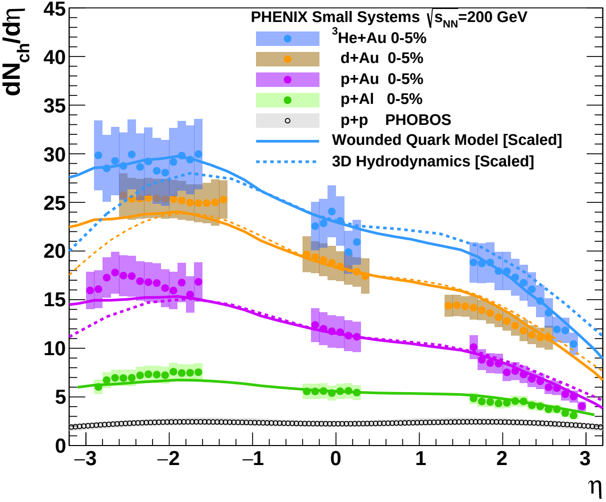
p+Al $\rightarrow$ p+Au—big change when increasing nuclear target size

p+Au $\rightarrow$ ^{3}He+Au—small change when increasing projectile size

Longitudinal dynamics in small systems

Now published!

Phys. Rev. Lett. 121, 222301 (2018)



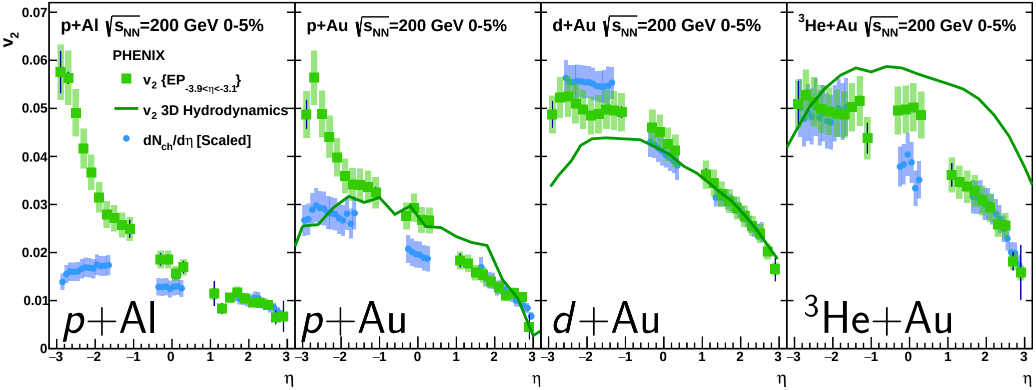
p+Al, *p*+Au, *d*+Au, ^{3}He+Au

Good agreement with wounded quark model

Good agreement with 3D hydro

Longitudinal dynamics in small systems

Now published! Phys. Rev. Lett. 121, 222301 (2018)

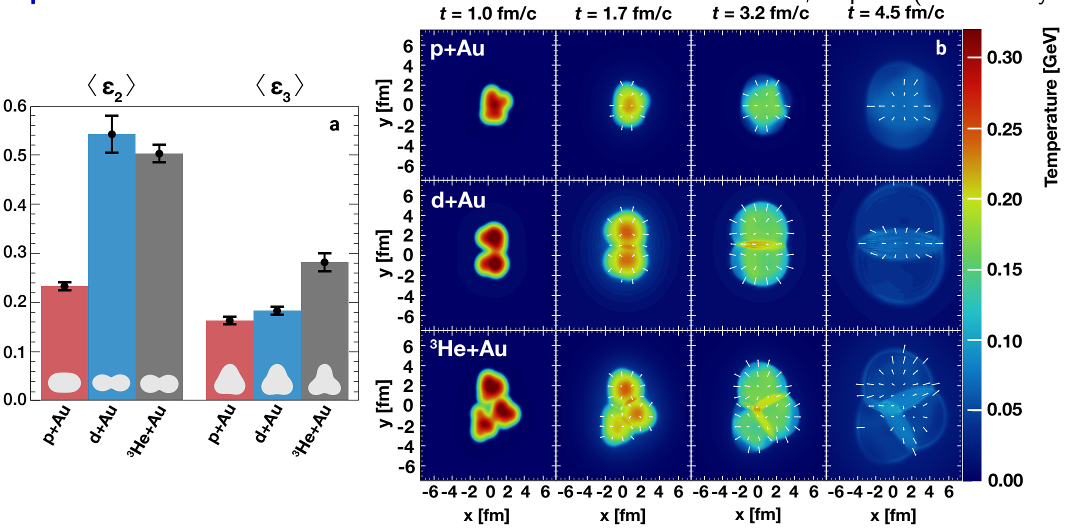


v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au

Good agreement with 3D hydro for p+Au and d+Au

Now published!

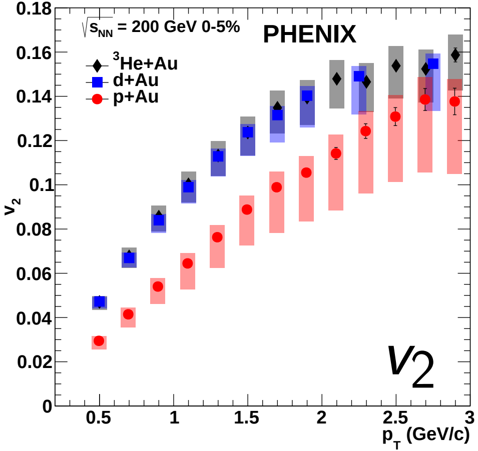
arXiv:1805.02973, in press (Nature Physics)

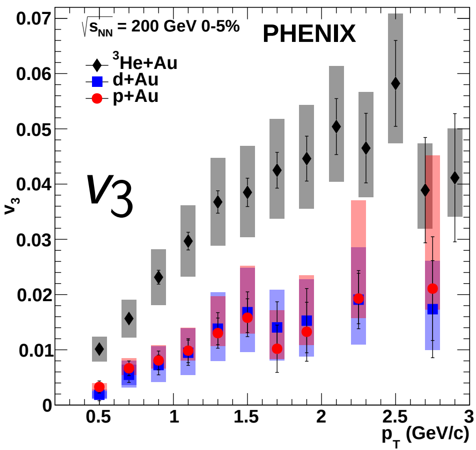


Testing hydro by controlling system geometry

Now published!

arXiv:1805.02973, in press (Nature Physics)





v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

—Regardless of mechanism, the correlation is geometrical

Testing hydro by controlling system geometry

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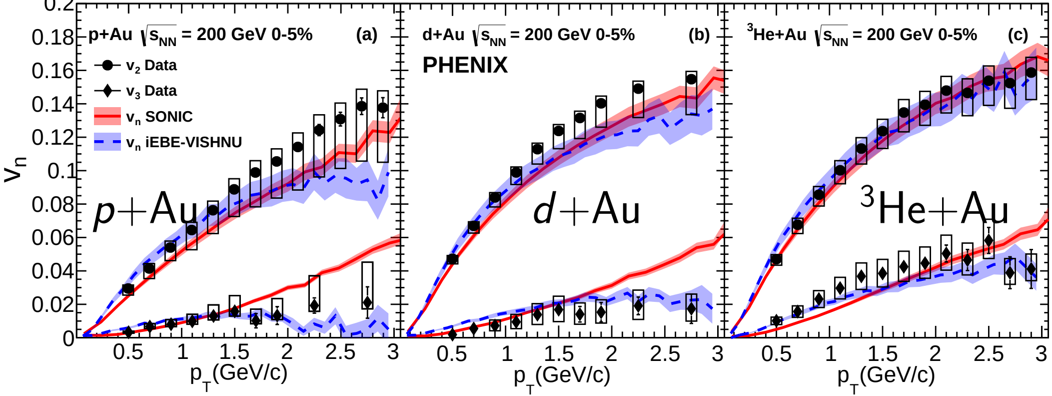

v_2 and v_3 vs p_T described very well by hydro in all three systems

—Strongly suggests QGP droplets in hydro evolution

Testing hydro by controlling system geometry

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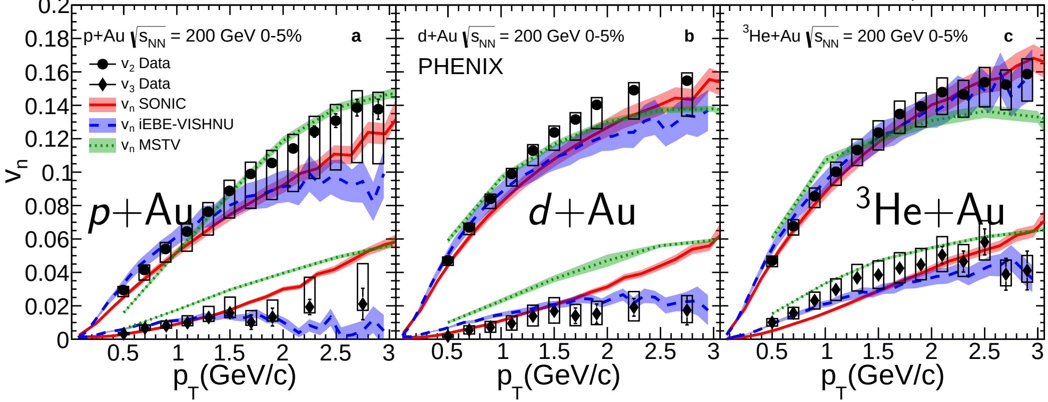
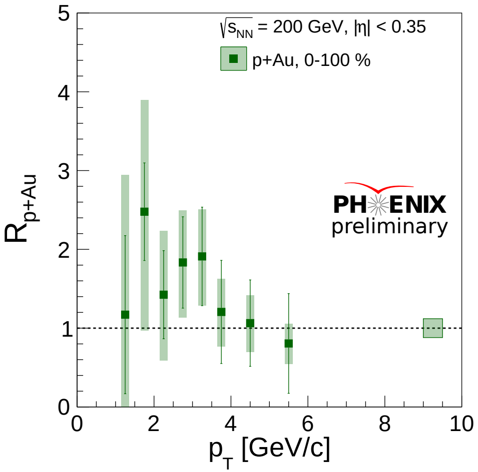


v_2 and v_3 vs p_T described very well by hydro in all three systems

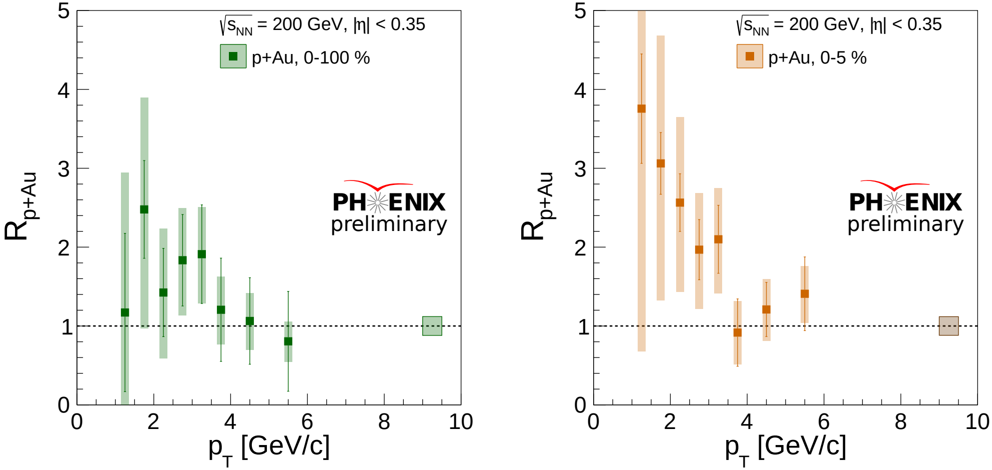
—Strongly suggests QGP droplets in hydro evolution

Initial state model does good job for v_2 but misses strong geometry dependence of v_3

Photons in small systems

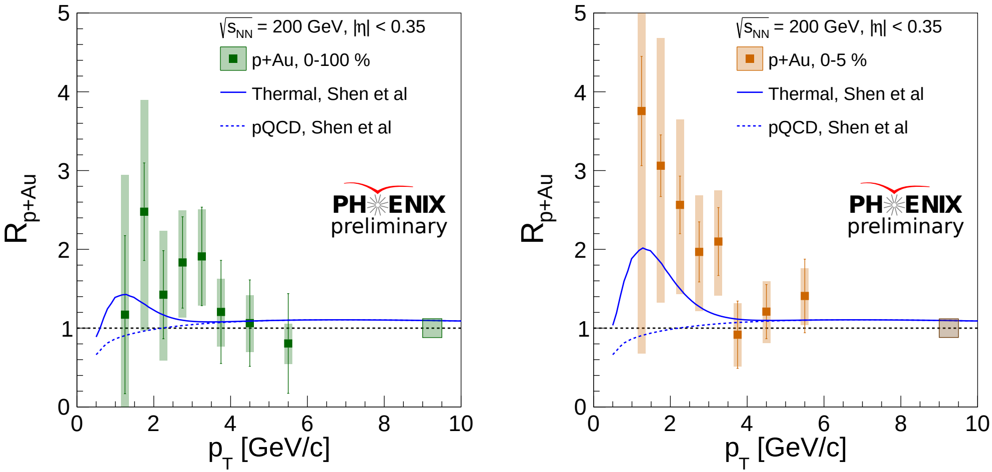


Photons in small systems



Thermal photons in p+Au?

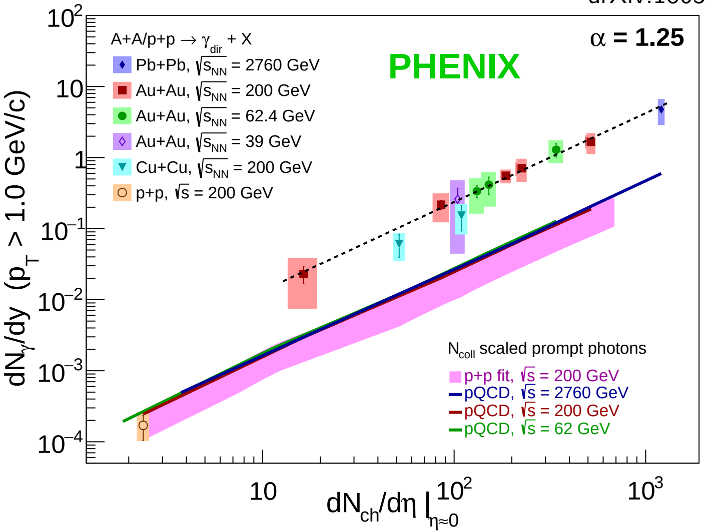
Photons in small systems



Thermal photons in p+Au? Theory from Phys. Rev. C 95, 014906 (2017)

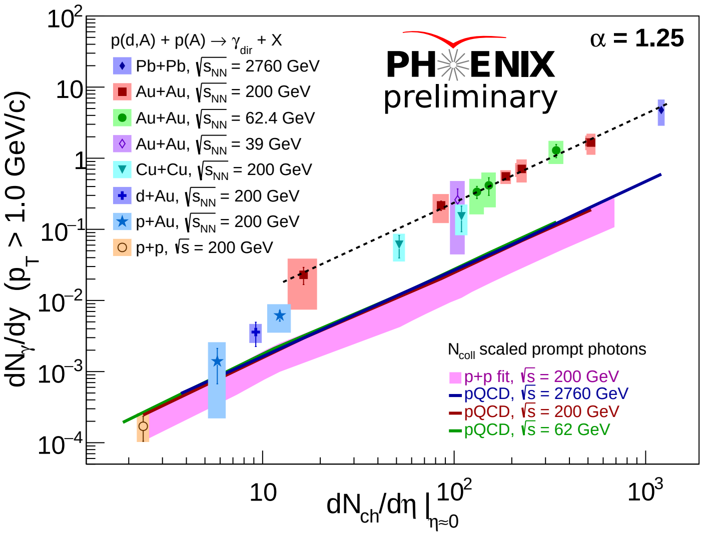
Photon yields

arXiv:1805.04084, submitted to Phys. Rev. Lett.



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

Photon yields



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled p+p

p+Au and d+Au in between

Small Systems Summary

First measurement of Drell-Yan in small systems at RHIC
—Hint of enhancement but no firm conclusions

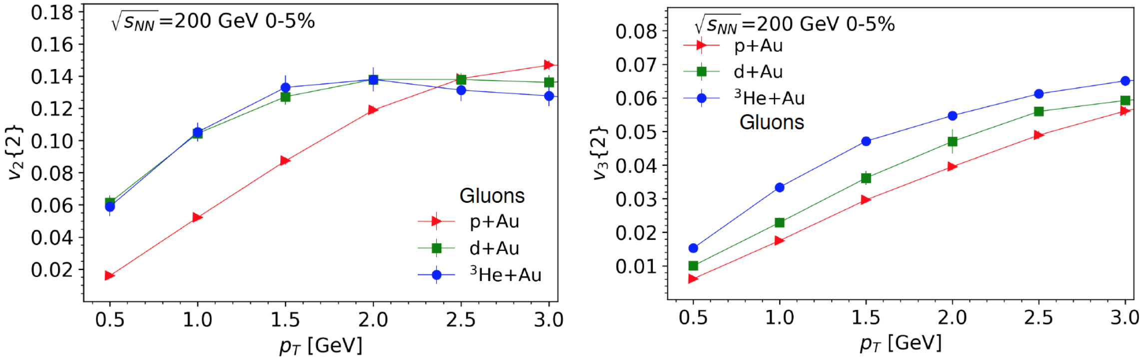
Comprehensive set of measurements of longitudinal dynamics
—Good support for wounded quark model and 3D hydro

Geometry scan results published in Nature Physics
—Hydro does better than initial state

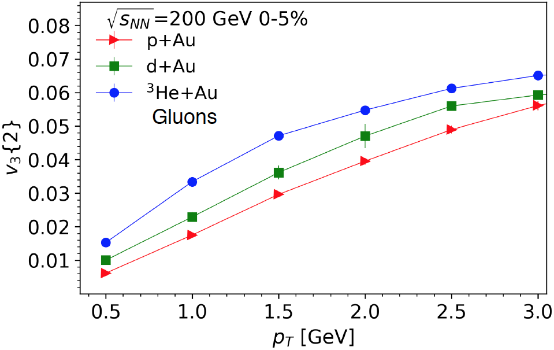
Photon enhancement in small systems
—Important additional evidence in support of QGP droplet formation in small systems

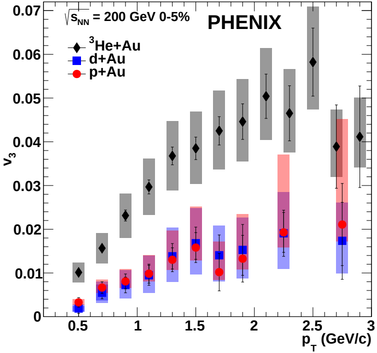
Additional Material

Testing hydro by controlling system geometry



Testing hydro by controlling system geometry



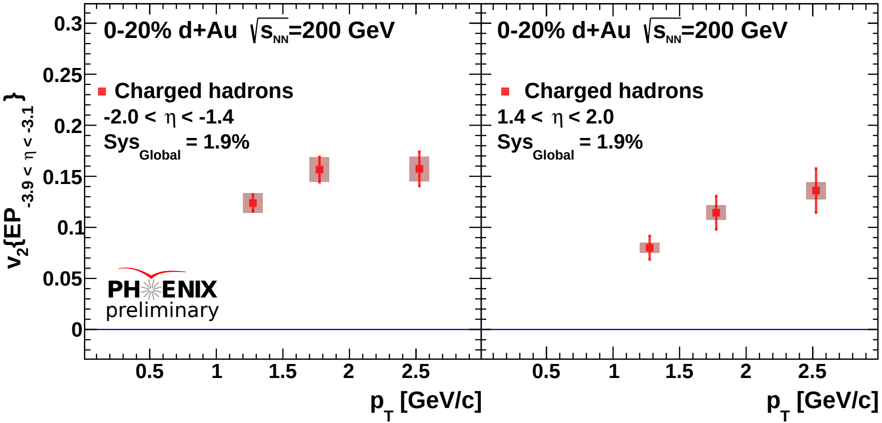


v_3 ordering is not quite right

—CGC: p+Au $<$ d+Au $<$ ^{3}He+Au

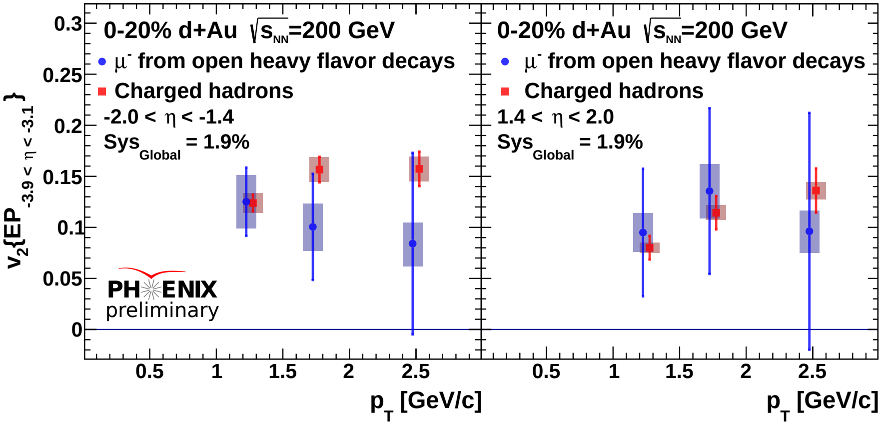
—Data: p+Au $\approx$ d+Au $<$ ^{3}He+Au

Small systems flow



charged hadrons

Small systems flow—heavy flavor

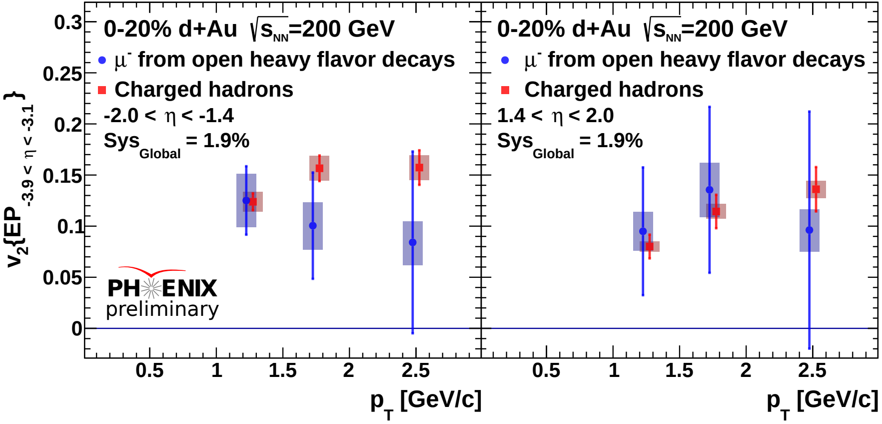


charged hadrons

heavy flavor muons

Nonzero v_2 for heavy flavor in d+Au

Small systems flow—heavy flavor



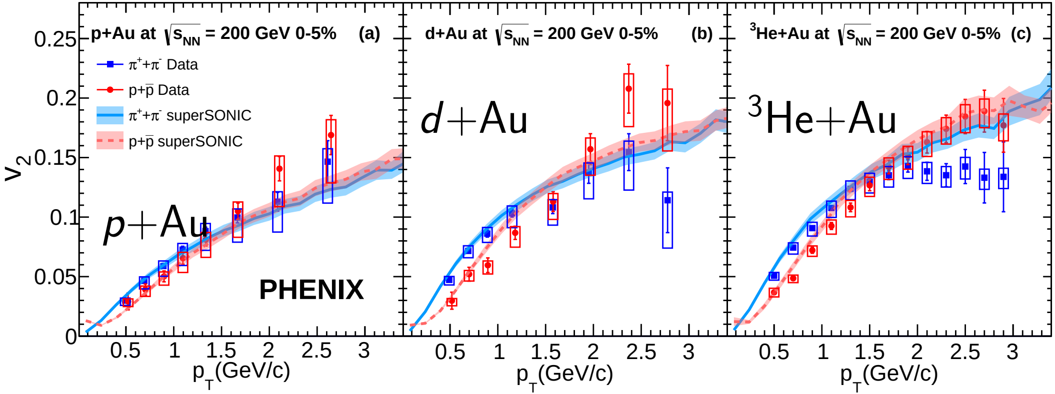
charged hadrons

heavy flavor muons

Nonzero v_2 for heavy flavor in d+Au

3.22σ, 2.16σ for $v_2 > 0$ at backward, forward (99.9%, 98.5% one-sided)

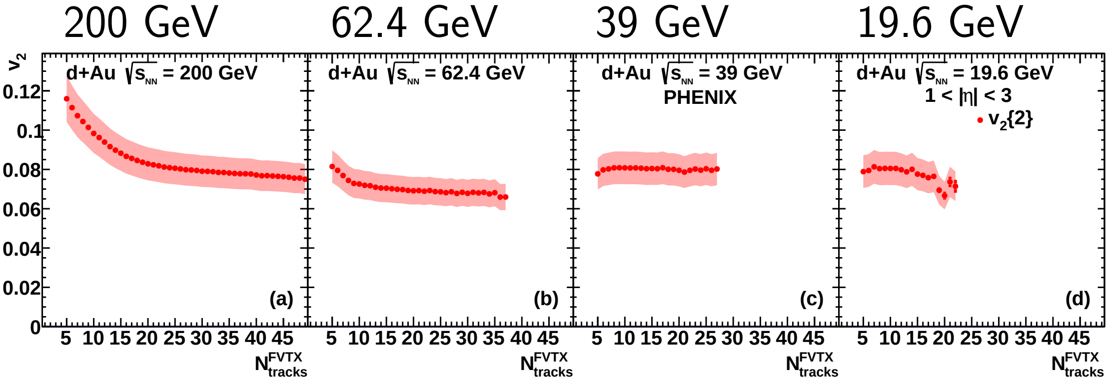
Phys. Rev. C 97, 064904 (2018)



Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au
—Mass ordering well-described by hydro

d+Au beam energy scan

Phys. Rev. Lett. 120, 062302 (2018)



d+Au beam energy scan

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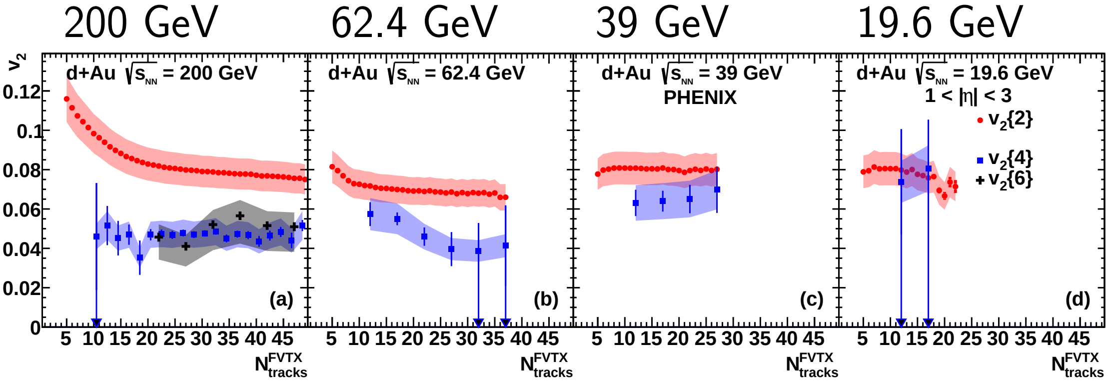
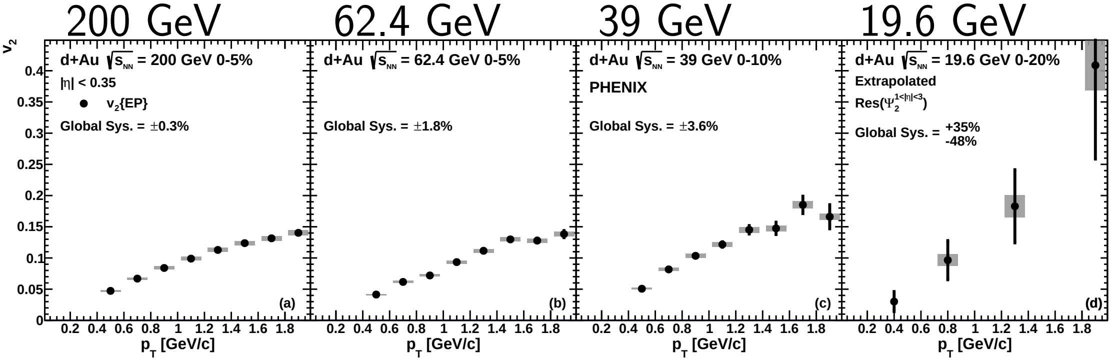


Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

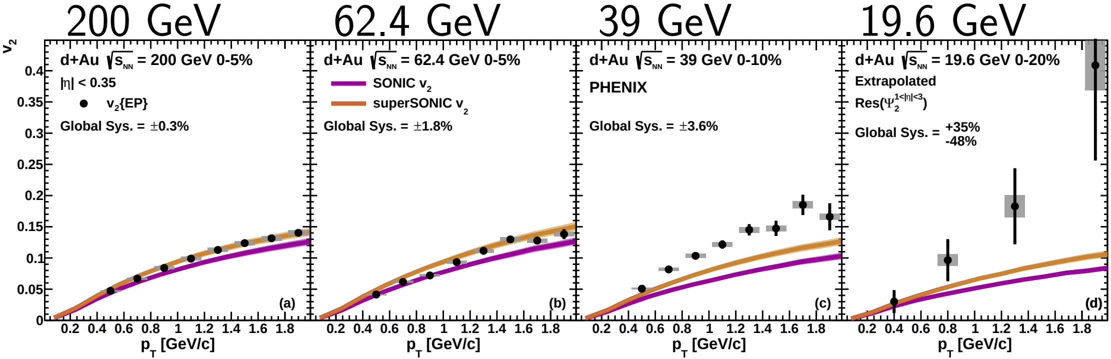
Phys. Rev. C 96, 064905 (2017)



Event plane v_2 vs p_T measured for all energies

d+Au beam energy scan

Phys. Rev. C 96, 064905 (2017)



Event plane v_2 vs p_T measured for all energies

Hydro theory agrees with higher energies very well, underpredicts lower energies—nonflow?

d+Au beam energy scan

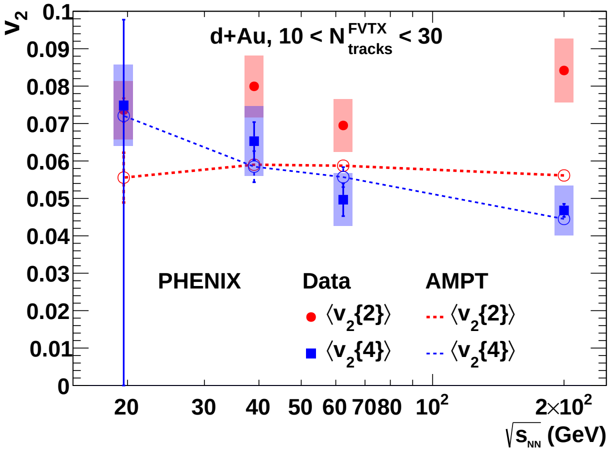
Phys. Rev. Lett. 120, 062302 (2018)

Select $10 < N^{\text{FVTX}}_{\text{tracks}} < 30$, integrate

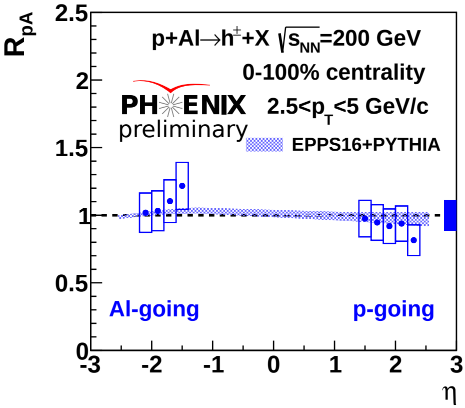
AMPT sees similar trend

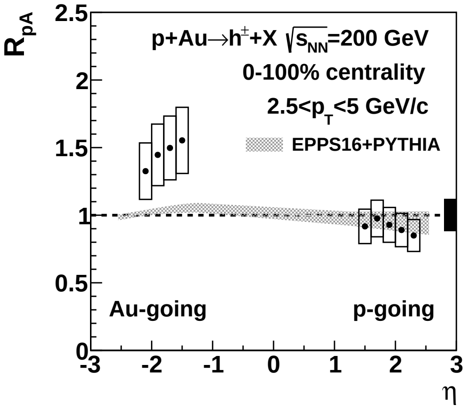
Fluctuations?

- Not Bessel-Gaussian
- Not small-variance limit
- Need to understand fluctuations better



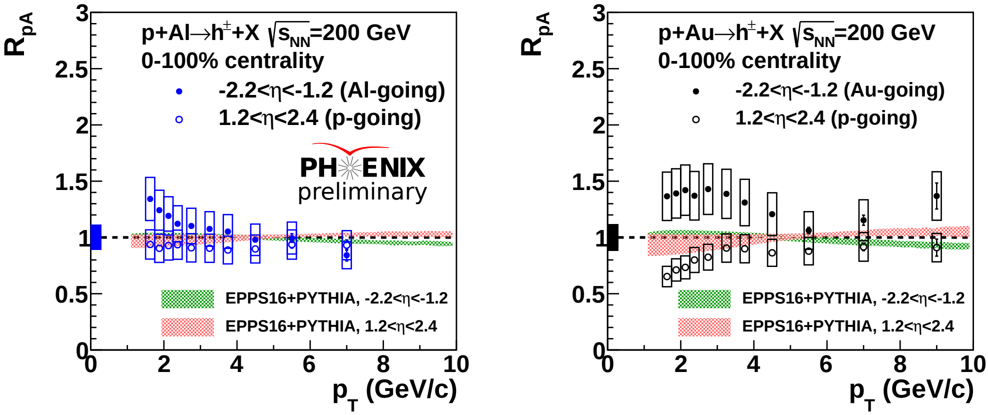
Small systems nuclear modification





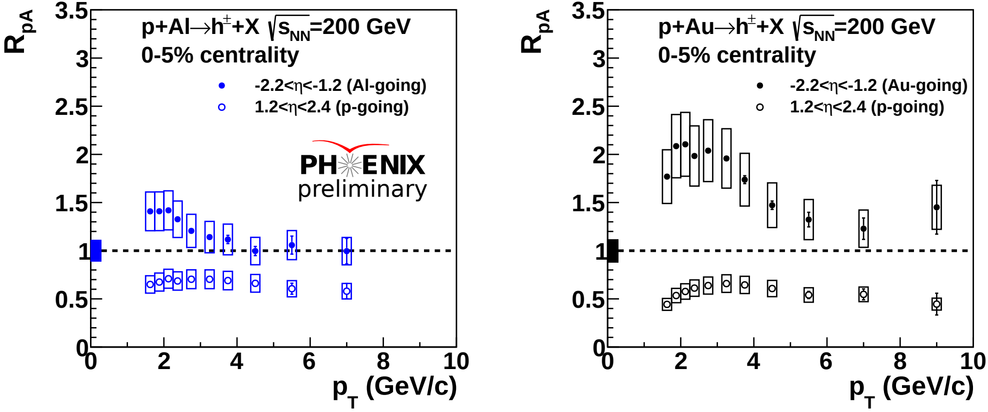
Forward modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



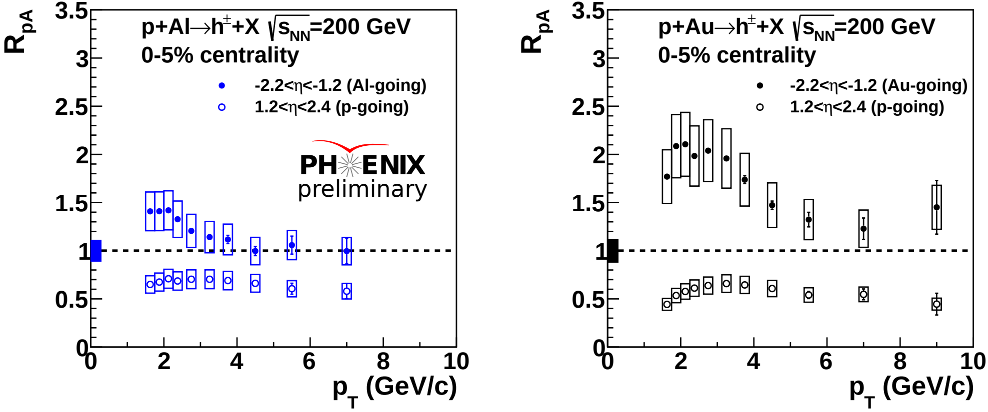
High-p_T modification consistent with nPDF effects (EPPS16)

Small systems nuclear modification



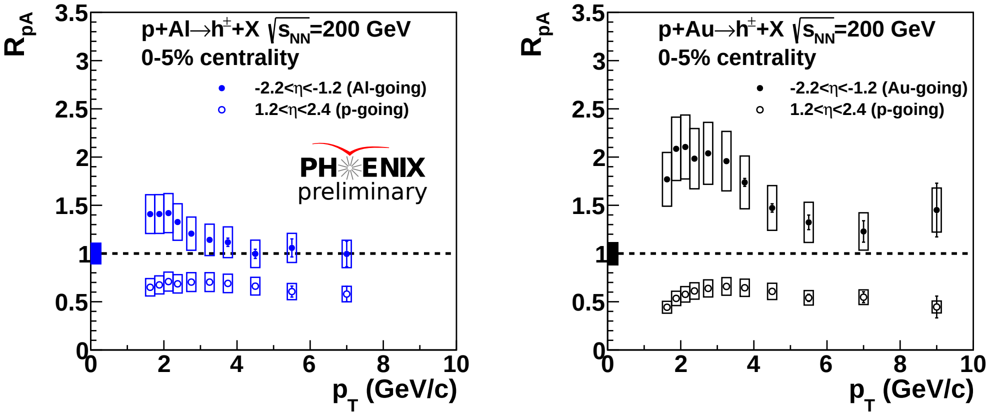
Stronger effects in central collisions

Small systems nuclear modification



Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification

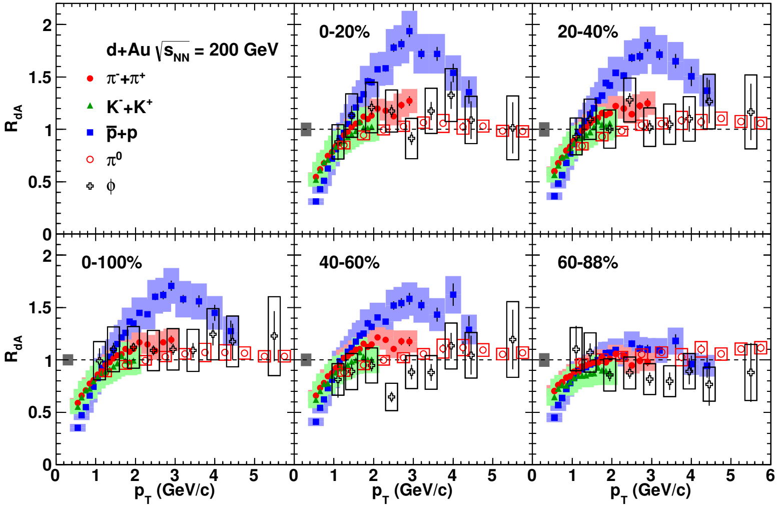


Strong enhancement for backward at intermediate p_T—why?

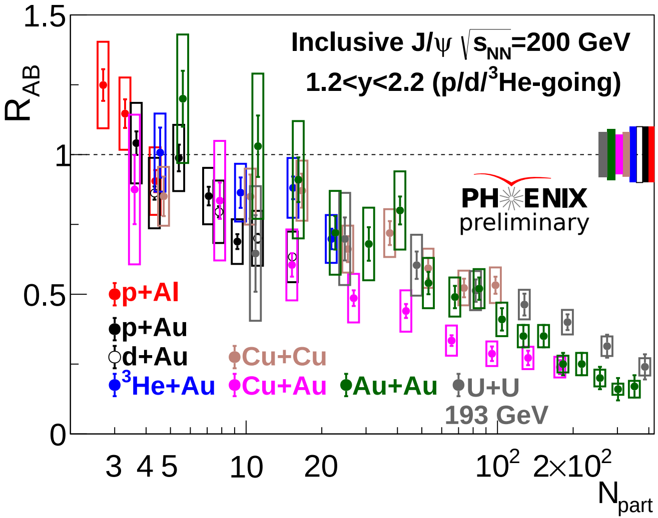
Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

Particle species dependence of “Cronin enhancement”

Phys. Rev. C 88, 024906 (2013)



J/ψ nuclear modification in all systems



Small systems:

p+Al, p+Au,

d+Au, ^{3}He+Au,

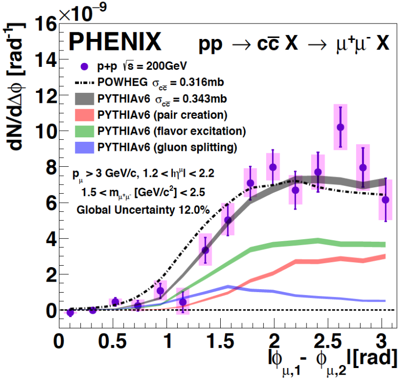
Large systems:

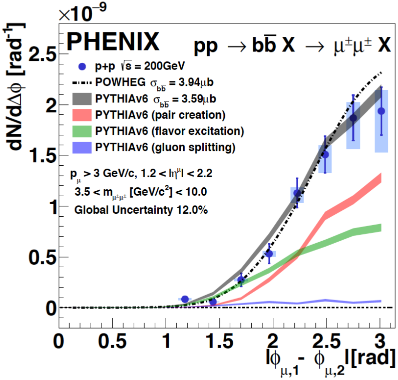
Cu+Cu, Cu+Au,

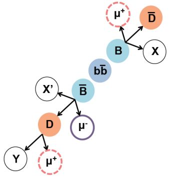
Au+Au, U+U,

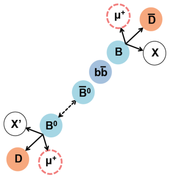
$c\bar{c}$ and $b\bar{b}$ from angular correlations in $p+p$

arXiv:1805.04075 (submitted to PRL)
arXiv:1805.02448 (submitted to PRD)









Pair creation at LO, flavor excitation and gluon splitting at NLO

PYTHIA suggests $b\bar{b}$ dominated by pair creation

$b\bar{b}$ from angular correlations in p+p

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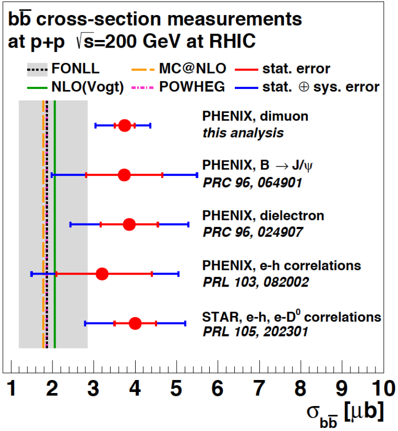
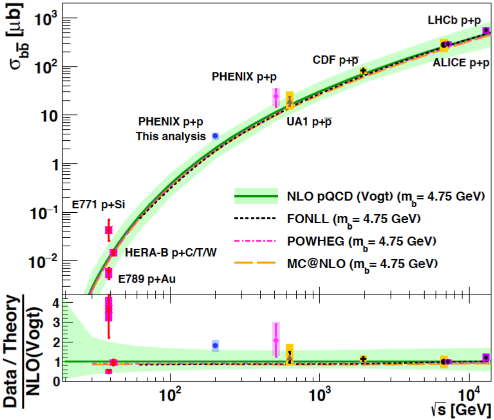
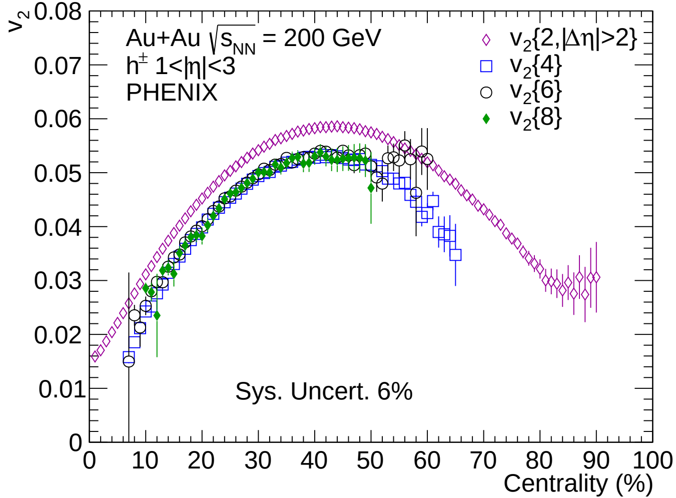




$b\bar{b}$ cross-section consistent with previous measurements, larger than FONLL

Collectivity in large systems

arXiv:1804.10024 (submitted to Phys Rev C)



$1 < |\eta| < 3$

$v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

Collectivity in large systems

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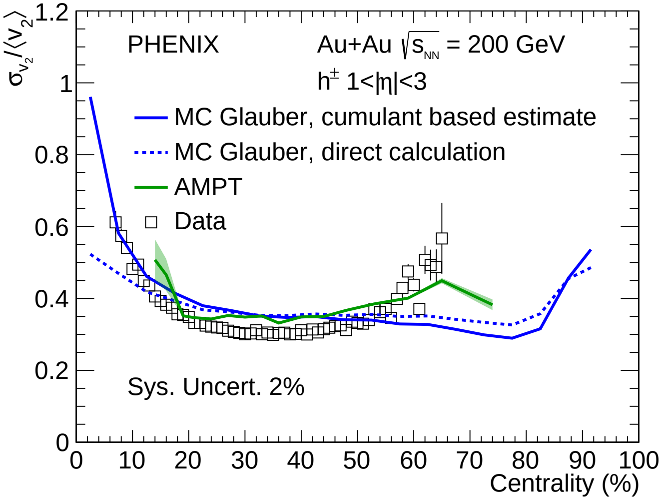

$1 < |\eta| < 3$

$\sigma_{v_2}/\langle v_2 \rangle$

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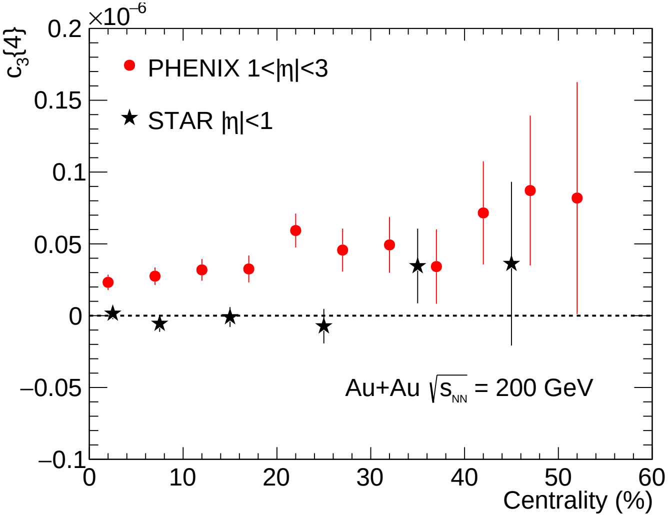

$1 < |\eta| < 3$

Cannot extract

$\sigma_{v_3} / \langle v_3 \rangle$

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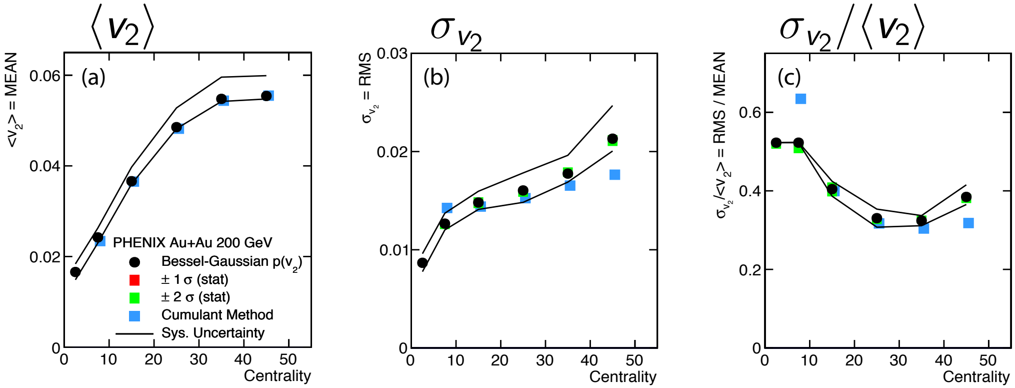

Can extract $\langle v_2 \rangle$ and σ_{v_2} separately using forward-fold

Collectivity in large systems

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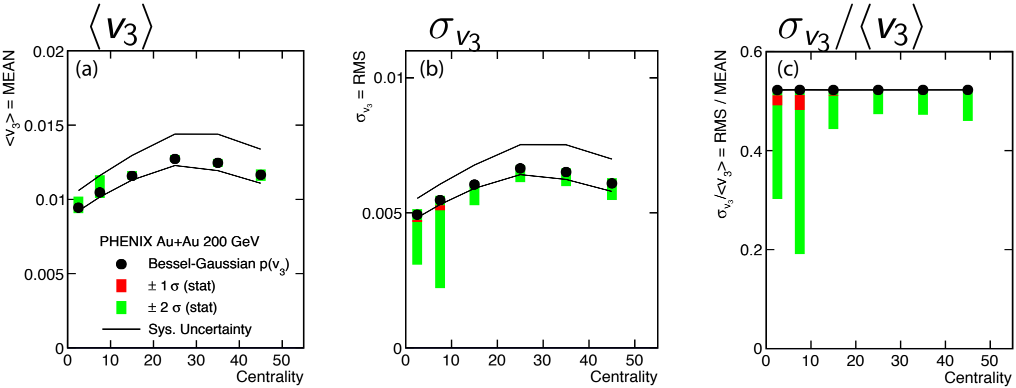

Can extract $\langle v_3 \rangle$ and σ_{v_3} separately using forward-fold