

Recent Results from

PH<sup>\*</sup>ENIX

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**SQM2022**

The 20th International Conference on Strangeness in Quark Matter  
13-17 June 2022 Busan, Republic of Korea

# Introduction

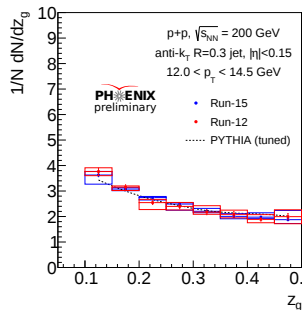
## PHENIX at SQM22

- Rachid Nouicer, PHENIX Probing QCD Matter Through Heavy Flavor and Quarkonium at RHIC, [PA-HF 2022-06-15 at 9am KST](#)
- László Kovács, Charge kaon femtoscopy with Lévy sources in  $\sqrt{s_{NN}} = 200$  GeV Au+Au collisions at PHENIX, [POS-BLK-21](#)
- Krista Smith,  $J/\psi$  in small systems with PHENIX, [POS-HF-14](#)

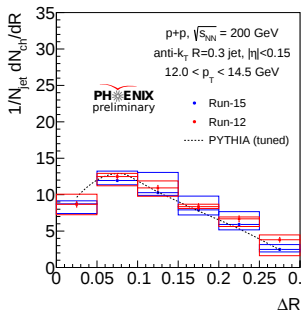
## PHENIX papers recently submitted

- [arXiv:2203.17058](#) Charm and bottom quark production in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV
- [arXiv:2203.17187](#) Non-prompt direct photon production in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV
- [arXiv:2203.12354](#) Low- $p_T$  direct-photon production in Au+Au collisions at 39 and 62.4 GeV
- [arXiv:2203.09894](#) Measurements of second-harmonic Fourier coefficients from azimuthal anisotropies in  $p+p$ ,  $p+Au$ ,  $d+Au$ , and  $^3He+Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV
- [arXiv:2203.06087](#) Study of  $\phi$  meson production in  $p+Al$ ,  $p+Au$ ,  $d+Au$ , and  $^3He+Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV
- [arXiv:2202.03863](#) Measurement of  $\psi(2S)$  nuclear modification at backward and forward rapidity in  $p+p$ ,  $p+Al$ , and  $p+Au$  collisions at  $\sqrt{s_{NN}} = 200$  GeV

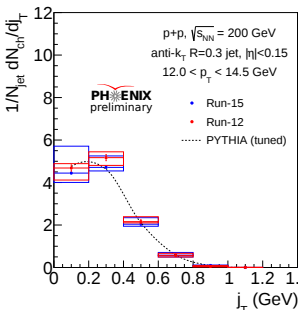
# Jet substructure in $p+p$



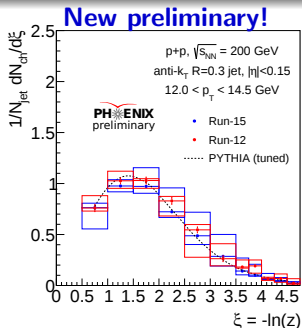
Jet splitting function



Radial profile



Transverse fragmentation

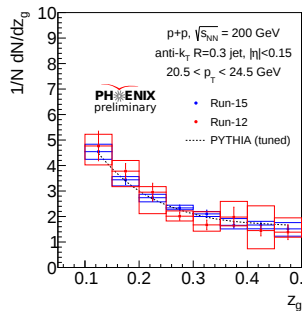


Longitudinal fragmentation

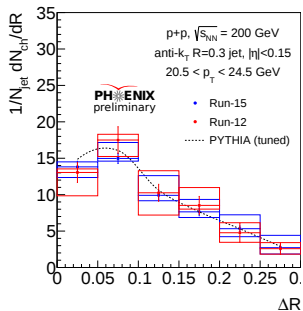
New preliminary!

- New analysis of jet substructure  
 —  $R = 0.3$   
 —  $12.0 \text{ GeV}/c < p_T < 14.5 \text{ GeV}/c$
- Analysis ongoing with  $p+\text{Au}$ , results coming soon!

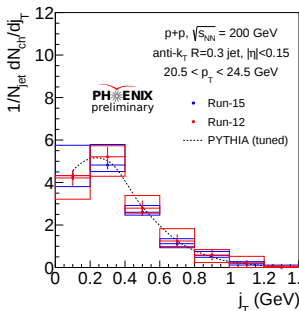
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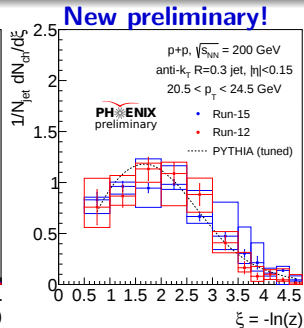
Jet splitting function



Radial profile



Transverse fragmentation



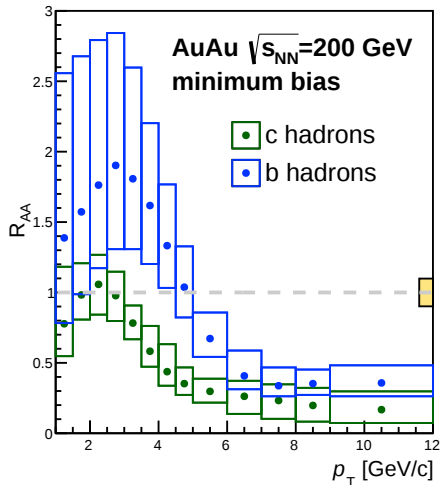
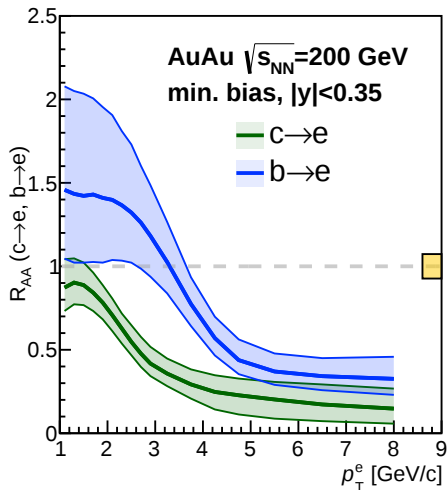
Longitudinal fragmentation

- New analysis of jet substructure  
 —  $R = 0.3$   
 —  $20.5 \text{ GeV}/c < p_T < 24.5 \text{ GeV}/c$
- Analysis ongoing with  $p+\text{Au}$ , results coming soon!

# $c$ and $b$ in large systems

arXiv:2203.17058 (submitted to Phys. Rev. C)

Recently submitted!

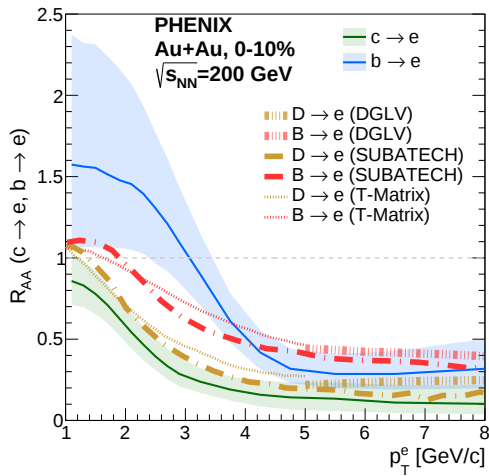
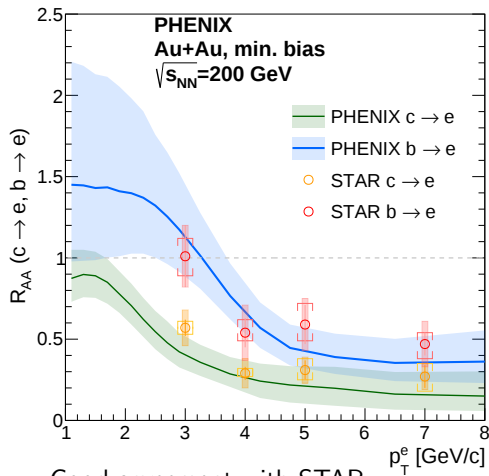


- Bottom shows less suppression than charm

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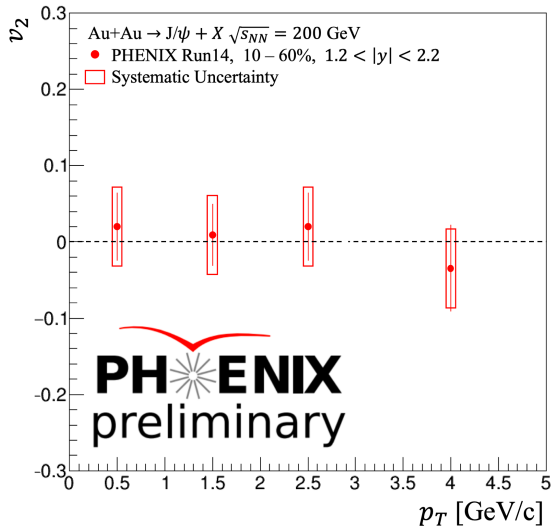
Recently submitted!



- Good agreement with STAR
- Good agreement with models (all  $p_T$  for  $c$ ,  $p_T > 4$  GeV/c for  $b$ )

# $J/\psi$ $v_2$ in large systems

New preliminary!



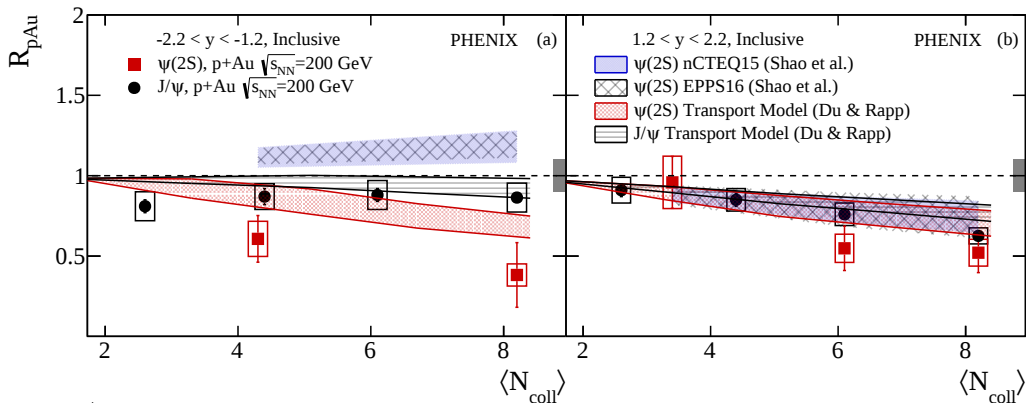
$J/\psi$   $v_2$  is consistent zero at forward rapidity, different from the LHC results

May indicate absence of charmonium regeneration in the forward rapidity region at RHIC energies

# $J/\psi$ and $\psi(2S)$ in small systems

arXiv:2202.03863 (submitted to Phys. Rev. C)

Recently submitted!

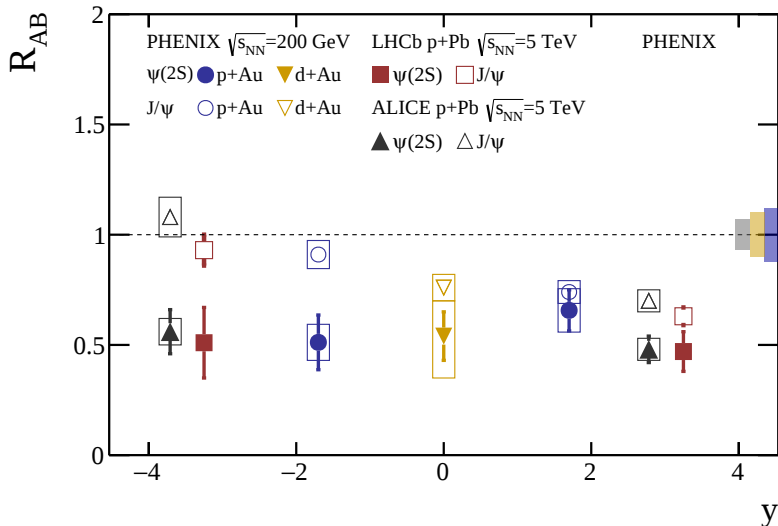


- $J/\psi$  modification consistent with initial state effects alone at forward and backward rapidity
- $\psi(2S)$  modification indicates presence of final state effects at backward rapidity
  - Presence of co-movers? QGP?

# $J/\psi$ and $\psi(2S)$ in small systems

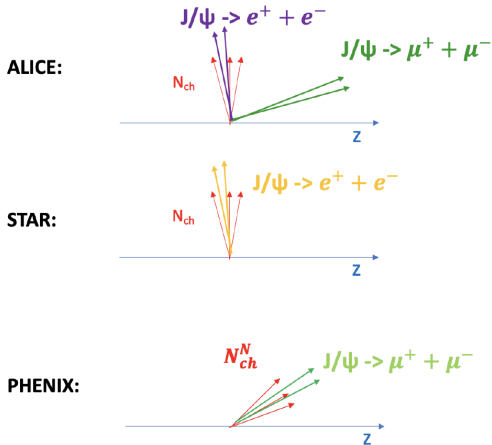
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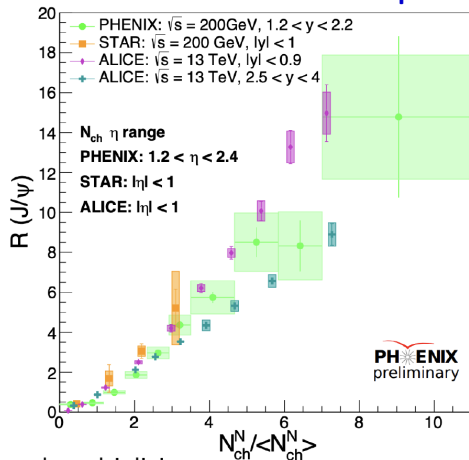
Similar patterns for  $J/\psi$  and  $\psi(2S)$  found at RHIC and LHC

# $J/\psi$ yield in $p+p$



- $J/\psi$  yield exhibits large dependence on local track multiplicity  
—Usually attributed to multi-parton interactions

New preliminary!

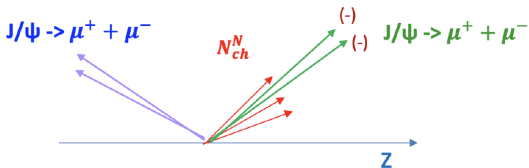


# $J/\psi$ yield in $p+p$

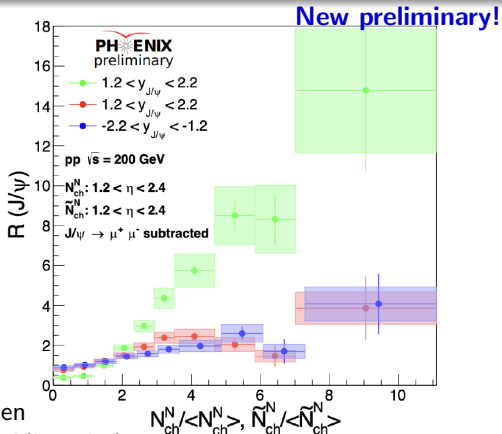
$J/\psi$  and tracks in the same rapidity

$J/\psi$  and tracks in the opposite rapidity

$J/\psi$  and tracks in the same rapidity, tracks from  $J/\psi$  removed from track count



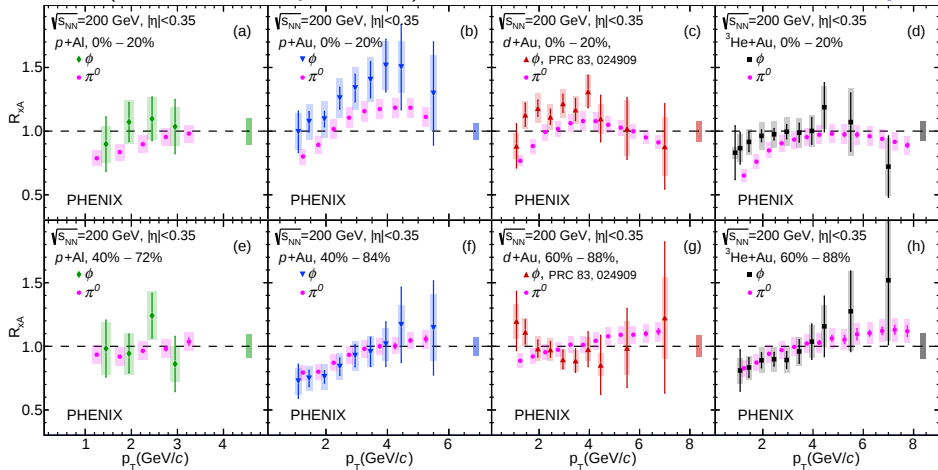
- $J/\psi$  yield vs multiplicity significantly reduced when
  - Looking at  $J/\psi$  and multiplicity in separate rapidity windows
  - Looking at  $J/\psi$  and multiplicity in the same rapidity window but removing the  $\mu^+\mu^-$  from the multiplicity
- Important implications for MPI picture



# $\phi$ meson in small systems

arXiv:2203.06087 (submitted to Phys. Rev. C)

Recently submitted!

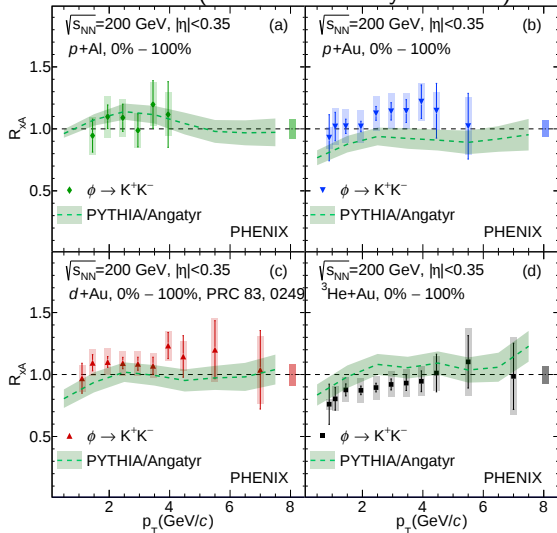


- $\phi$  similar to  $\pi^0$  with a few hints of a slight enhancement relative to  $\pi^0$

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arXiv:2203.06087 (submitted to Phys. Rev. C)

Recently submitted!

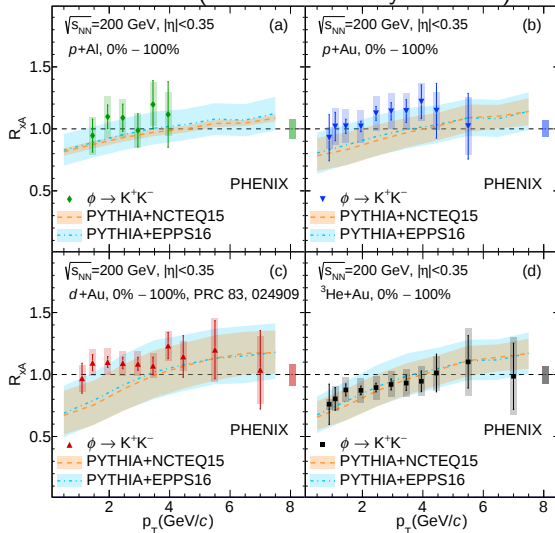


$\phi$  nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed

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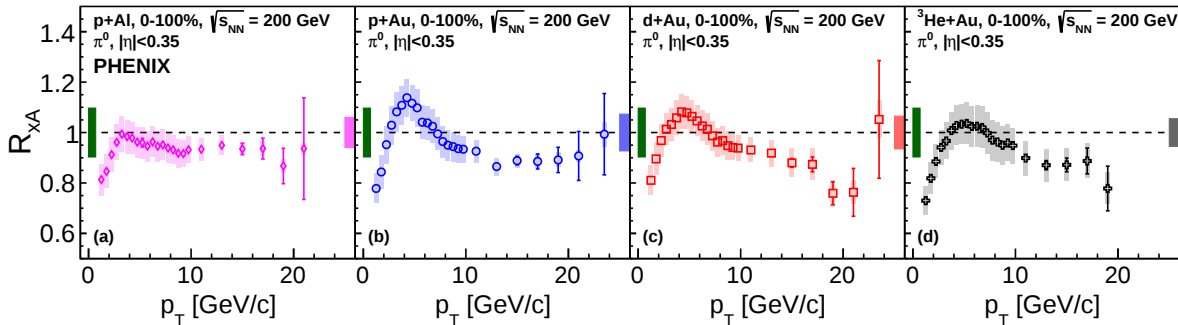
$\phi$  nuclear modification reasonably well-described by PYTHIA/Angantyr, but overall system size ordering is missed

Also reasonably well-described by PYTHIA with nPDFs, but overall system size ordering is missed

# Nuclear modification of $\pi^0$ in small systems

Phys. Rev. C 105, 064902 (2022)

Recently published!

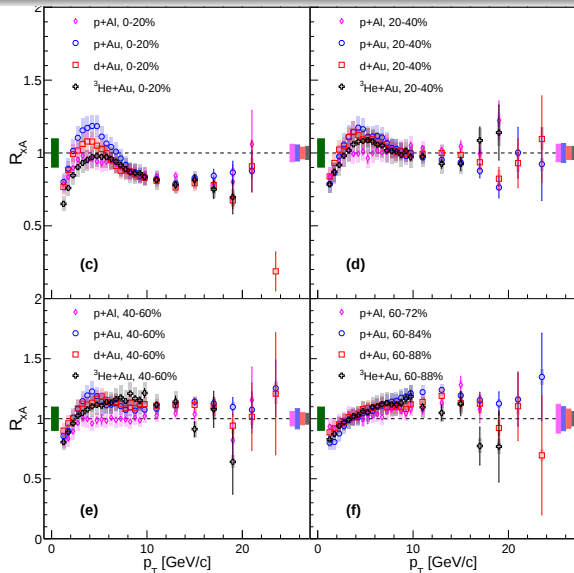


- Minimum bias collisions shown
- Cronin enhancement at intermediate  $p_T$ 
  - Lighter target shows smaller enhancement ( $p+Al < p+Au$ )
  - Heavier projectile shows smaller enhancement ( $^3He+Au < d+Au < p+Au$ )

# Nuclear modification of $\pi^0$ in small systems

Phys. Rev. C 105, 064902 (2022)

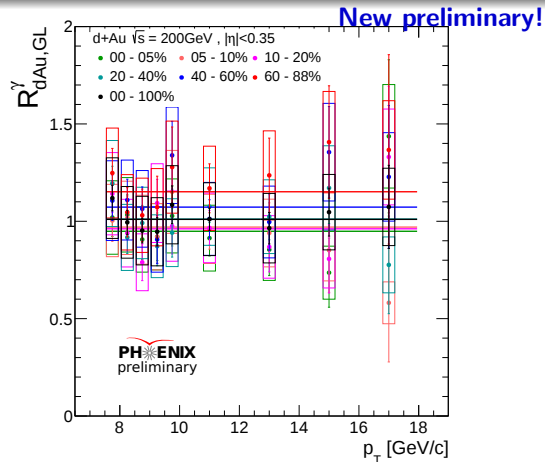
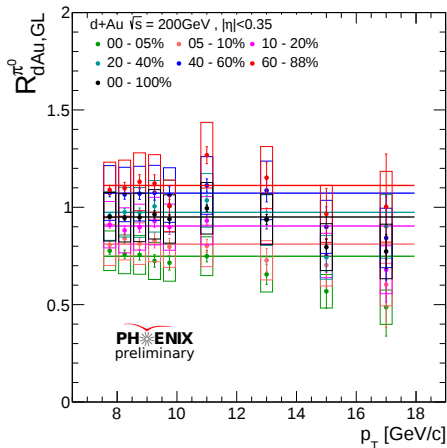
**Recently published!**



Considerable centrality dependence—suppression in central, enhancement in peripheral

Peripheral enhancement not new, but still difficult to understand...

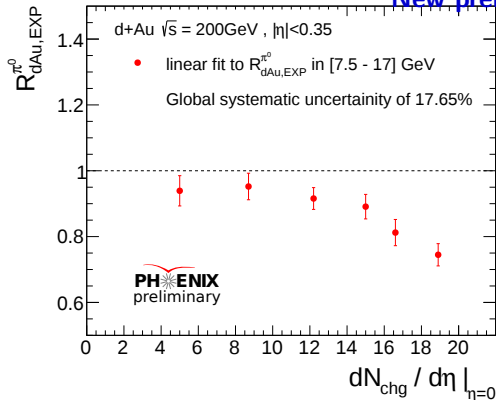
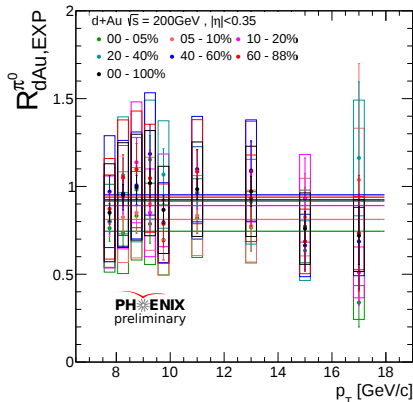
# Direct photons and $\pi^0$ in small systems



- Long-known (and somewhat mysterious) centrality dependence of  $R_{dA}$  of  $\pi^0$
- New measurement of direct photons shows similar centrality dependence, but should be unity—mean free path  $\sim 50$  times larger than nuclear size

# Direct photons and $\pi^0$ in small systems

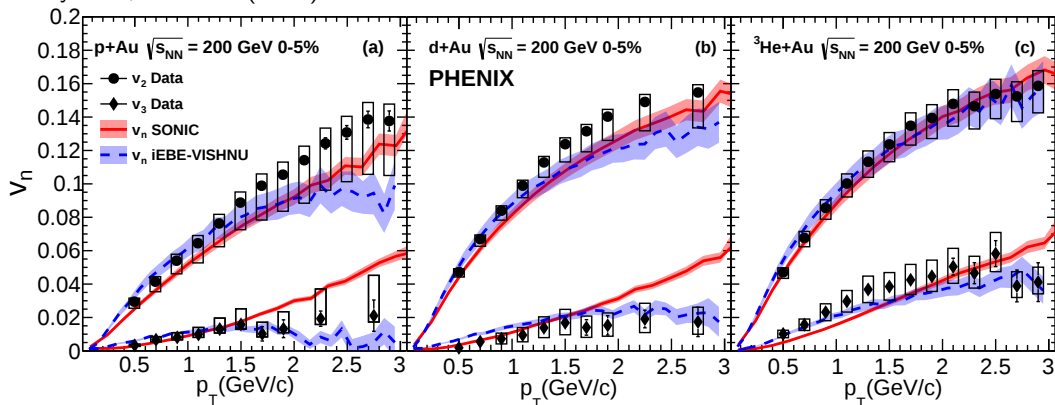
New preliminary!



- Can use non-modification of photons to correct for bias in  $N_{coll}$  determination
- Resolves a decade-long mystery of apparent enhancement in peripheral collisions
- Small but non-negligible suppression in central collisions  
—EMC effect? QGP?

# $v_n$ in small systems

Nat. Phys. 15, 214–220 (2019)

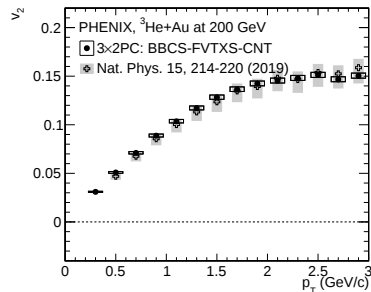
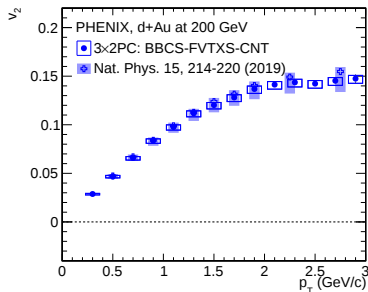
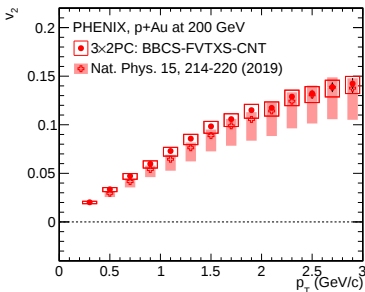


- $v_2$  and  $v_3$  vs  $p_T$  predicted or described very well by hydrodynamics in all three systems
  - All predicted (except  $v_2$  in  $d+\text{Au}$ ) in J.L. Nagle et al, PRL 113, 112301 (2014)
  - $v_3$  in  $p+\text{Au}$  and  $d+\text{Au}$  predicted in C. Shen et al, PRC 95, 014906 (2017)

# $v_n$ in small systems

Phys. Rev. C 105, 024901 (2022)

Recently published!

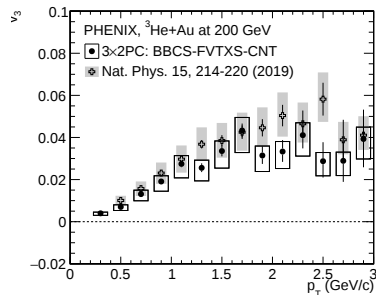
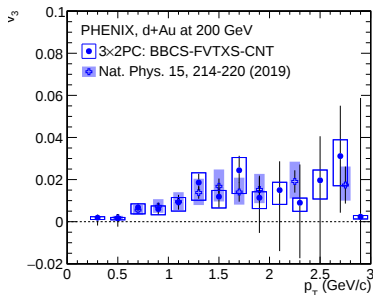
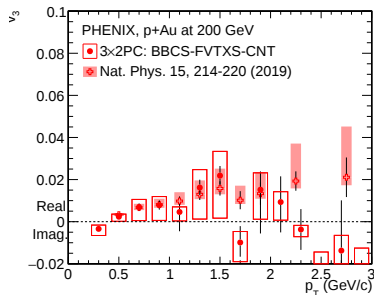


- All new analysis using two-particle correlations with event mixing instead of event plane method used in Nature Physics publication  
—Very different sensitivity to key experimental effects (beam position, detector alignment)
- Uses same detector combination as used in Nature Physics publication

# $v_n$ in small systems

Phys. Rev. C 105, 024901 (2022)

Recently published!

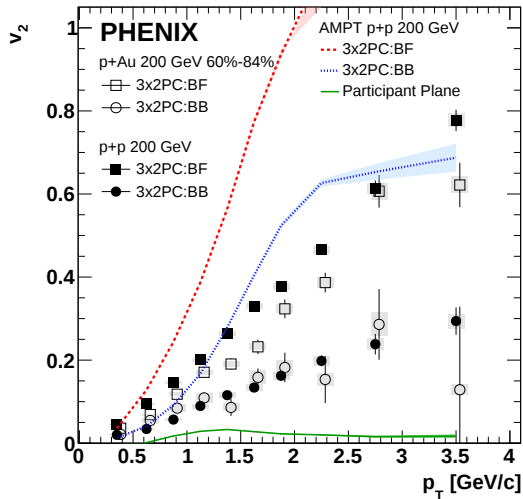


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# $v_2$ in small systems

arXiv:2203.09894 (submitted to Phys. Rev. C)

Recently submitted!



Systematic study of  $v_2$  in small systems

—  $p+p$ ,  $p+Au$ ,  $d+Au$ ,  $^3\text{He}+Au$

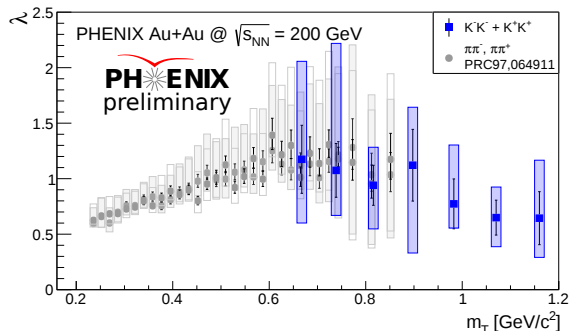
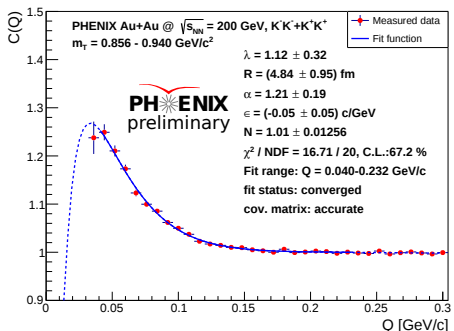
— Centrality dependence

— Multiple detector combinations

AMPT exhibits little or no collectivity  
but large  $v_2$  due to non-flow correlations  
Also shows similar relative pattern  
between backward-backward (BB) and  
backward-forward (BF)

# Kaon femtoscopy in large systems

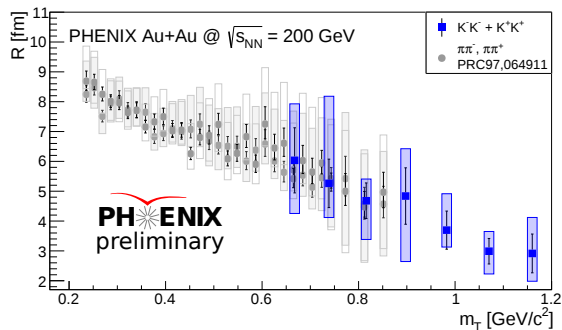
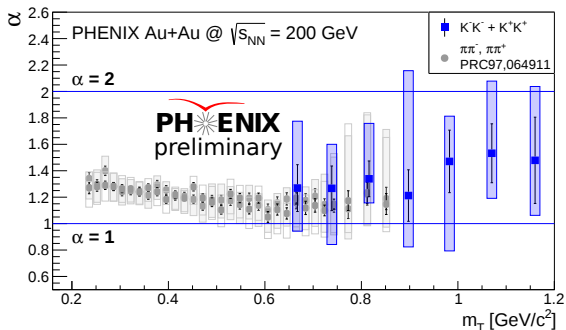
New preliminary!



- Femtoscopy with  $K^\pm$  and assuming Lévy source
- $\lambda$  describes strength of correlation
- $\alpha$  describes shape of distributions— $\alpha = 2$  is Gaussian,  $\alpha = 1$  is Cauchy
- $R$  is width parameter (similar to but not same as standard Gaussian radius)

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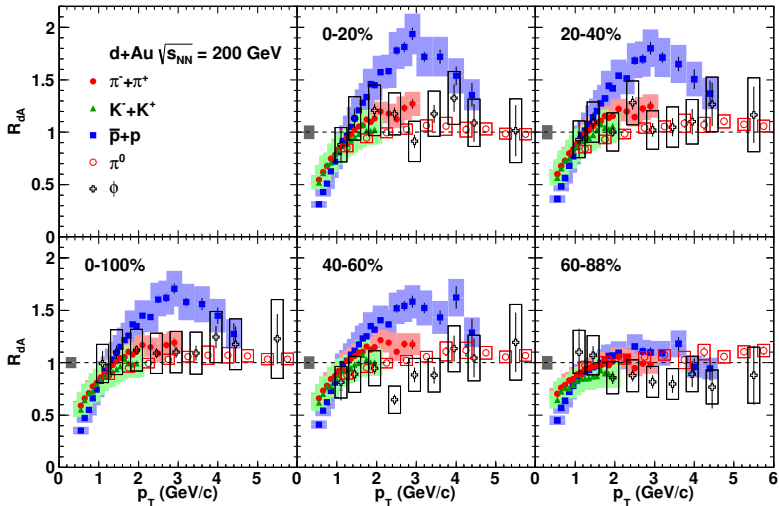
## Brief summary and outlook

- Jet substructure measurements done in  $p+p$ ,  $p+\text{Au}$  and  $\text{Cu}+\text{Au}$  coming soon
- Evidence of final state effects in charmonium production in small systems at RHIC
- Evidence of centrality determination bias in high- $p_T$  particle  $R_{xA}$  in small systems, can use direct photons to correct for this bias
  - No enhancement in peripheral collisions
  - Suppression in central collisions
- Comprehensive set of small systems flow measurements
- New results on femtoscopy with charged kaons
- Many more interesting and important measurements from PHENIX coming soon!

Extra material

# Particle species dependence of “Cronin enhancement”

PHENIX, Phys. Rev. C 88, 024906 (2013)



$\pi^+$ ,  $\pi^-$ ,  $\pi^0$ ,

$K^+$ ,  $K^-$ ,

$p$ ,  $\bar{p}$ ,

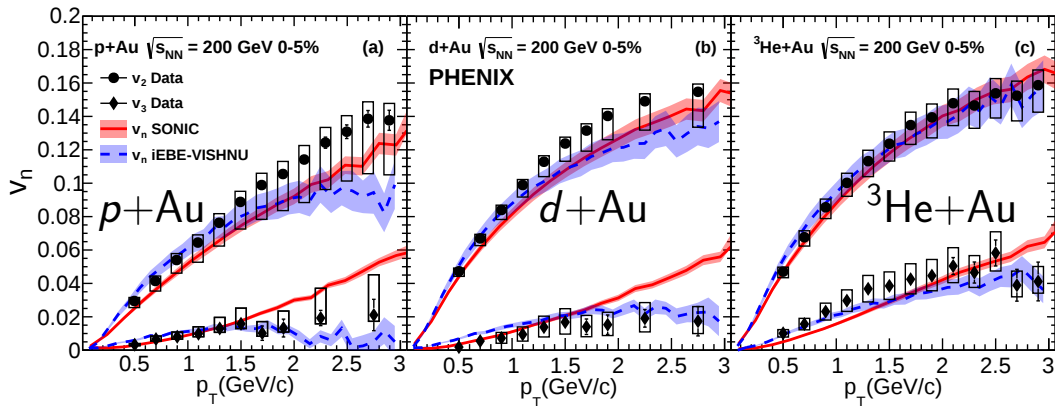
$\phi$

Protons much more strongly  
modified than pions

$\phi$  mesons similar to pions

# $v_n$ in small systems

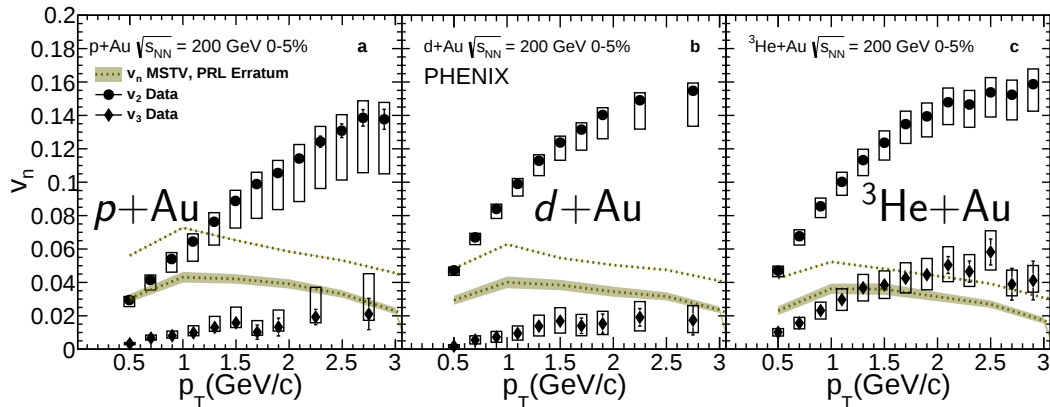
Nat. Phys. 15, 214–220 (2019)



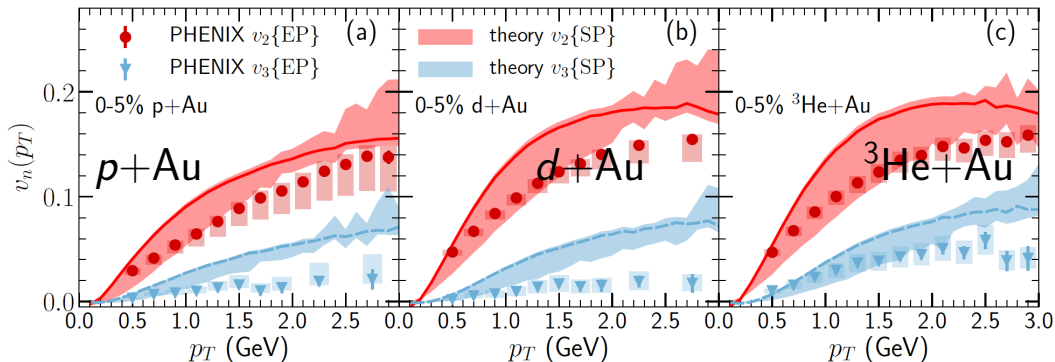
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# $v_n$ in small systems

Nat. Phys. 15, 214–220 (2019)



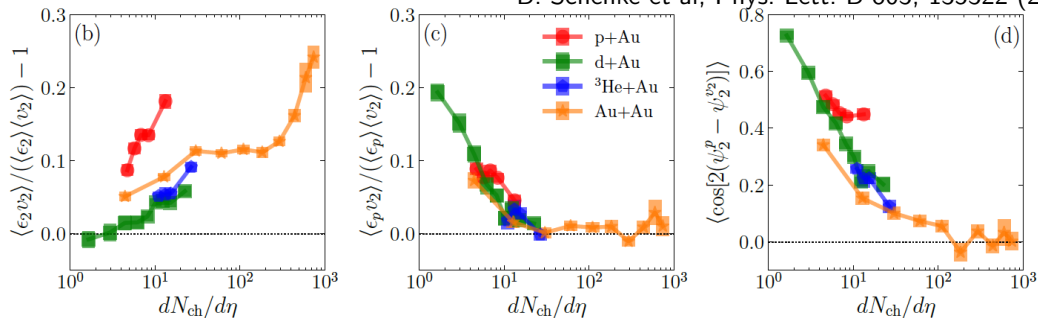
- Initial state effects alone do not describe the data  
—Phys. Rev. Lett. 123, 039901 (Erratum) (2019)



- Inclusion of initial state effects is important, but not a big contribution for central collisions —B. Schenke et al, Phys. Lett. B 803, 135322 (2020)

# $v_n$ in small systems

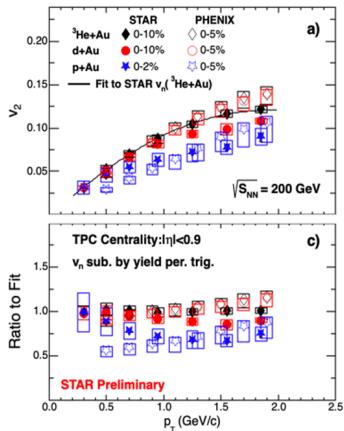
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- For central  $p+\text{Au}$ , modest correlation between  $\epsilon_p$  and  $v_2$  but fairly strong correlation between  $\psi_2^p$  and  $\psi_2^{v_2}$
- For central  $d+\text{Au}$  and  $^3\text{He}+\text{Au}$ , no correlation between  $\epsilon_p$  and  $v_2$ , modest correlation between  $\psi_2^p$  and  $\psi_2^{v_2}$

# $v_n$ in small systems

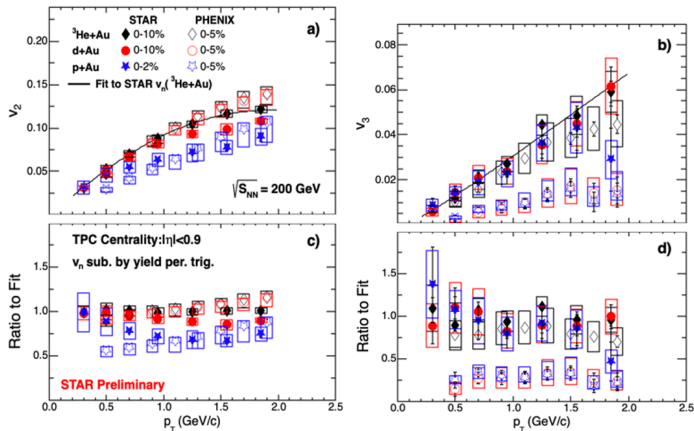
STAR, Quark Matter 2019



Good agreement between STAR and PHENIX for  $v_2$

# $v_n$ in small systems

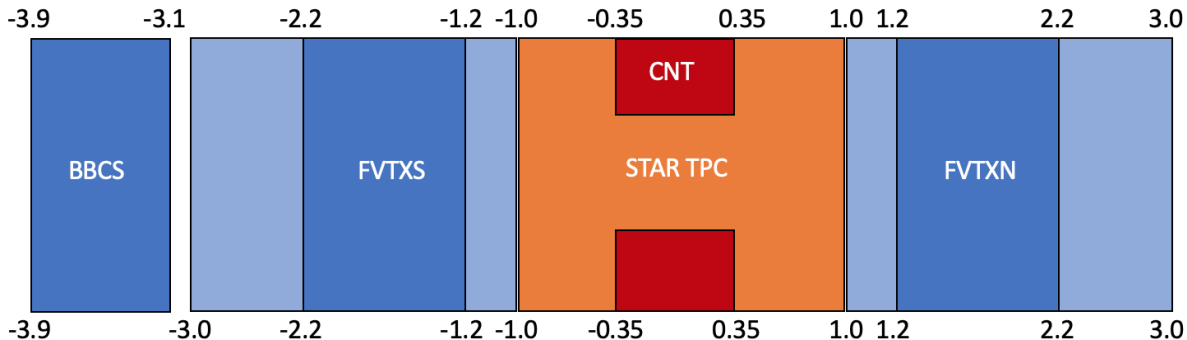
STAR, Quark Matter 2019



Good agreement between STAR and PHENIX for  $v_2$

Large discrepancy between STAR and PHENIX for  $v_3$

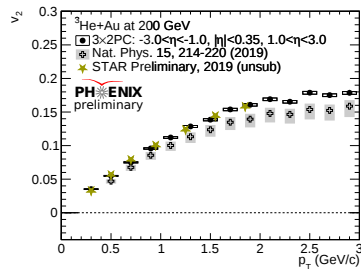
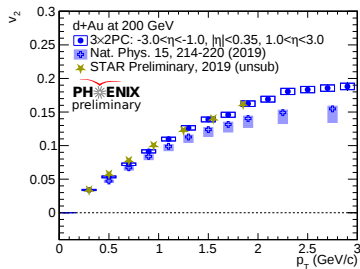
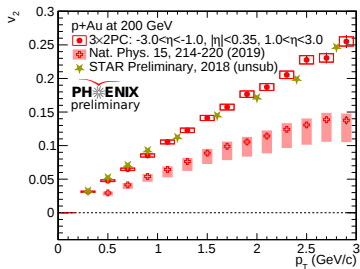
## $v_n$ in small systems



- The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination  
—Very different kinematic acceptance compared to STAR
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR  
—Closer, and “balanced” between forward and backward

# $v_n$ in small systems

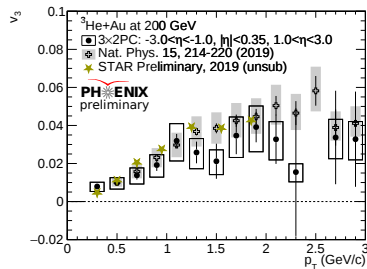
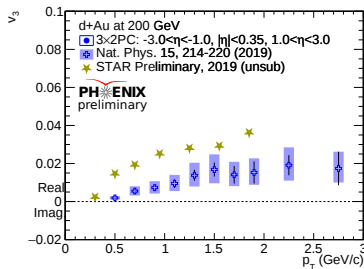
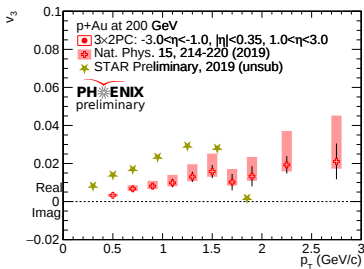
Phys. Rev. C 105, 024901 (2022)



- Good agreement with STAR for  $v_2$   
 —Similar physics for the two different pseudorapidity acceptances

# $v_n$ in small systems

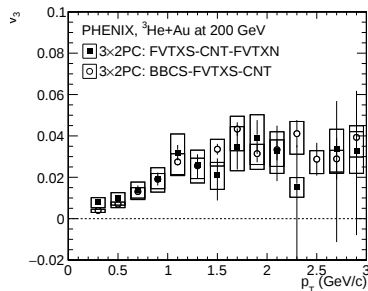
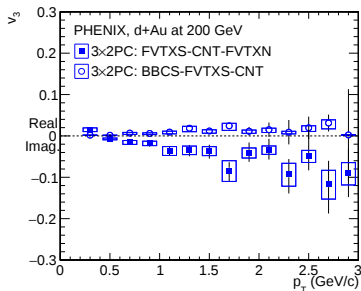
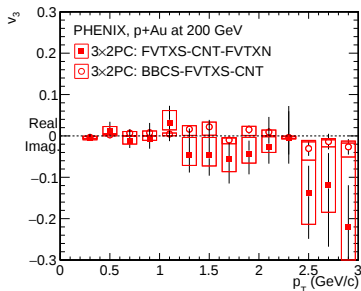
Phys. Rev. C 105, 024901 (2022)



- Good agreement with STAR for  $v_2$ 
  - Similar physics for the two different pseudorapidity acceptances
- Strikingly different results for  $v_3$ 
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  - Longitudinal effects much stronger for  $v_3$  than  $v_2$

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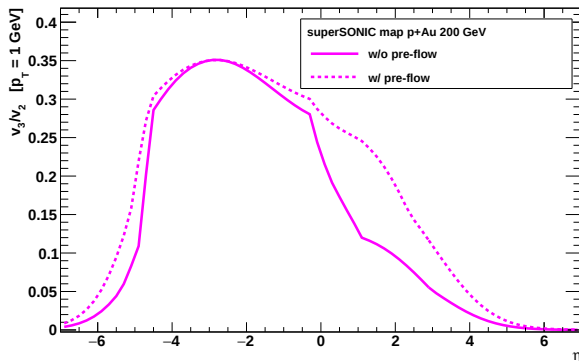
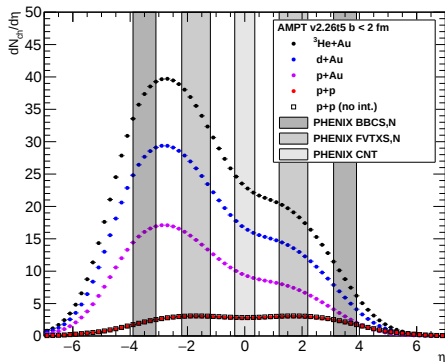
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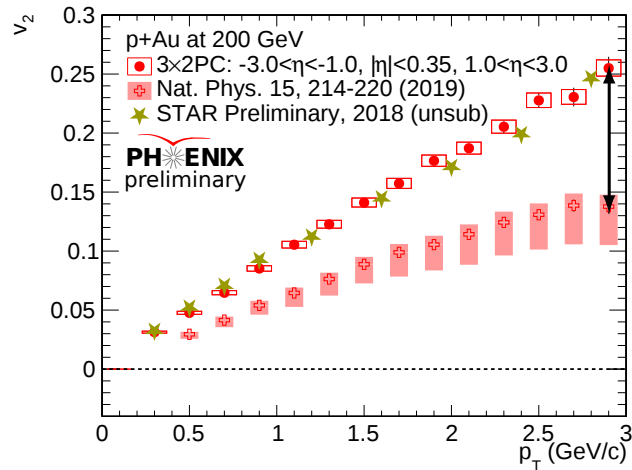
# $v_n$ in small systems

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



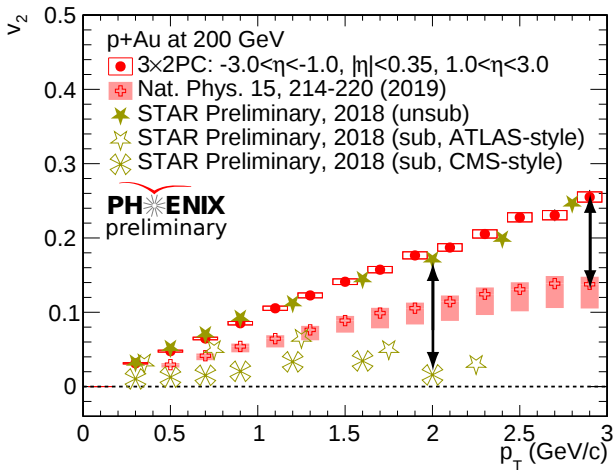
- $dN_{ch}/d\eta$  from AMPT,  $v_3(\eta)$  from (super)SONIC
- The likely much stronger pseudorapidity dependence of  $v_3$  compared to  $v_2$  is an essential ingredient in understanding different measurements

# Understanding the nonflow contribution: $v_2$ in $p$ +Au as a case study



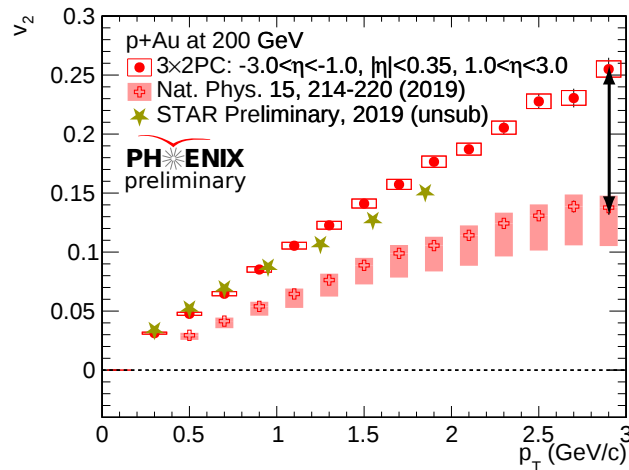
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# Understanding the nonflow contribution: $v_2$ in $p$ +Au as a case study



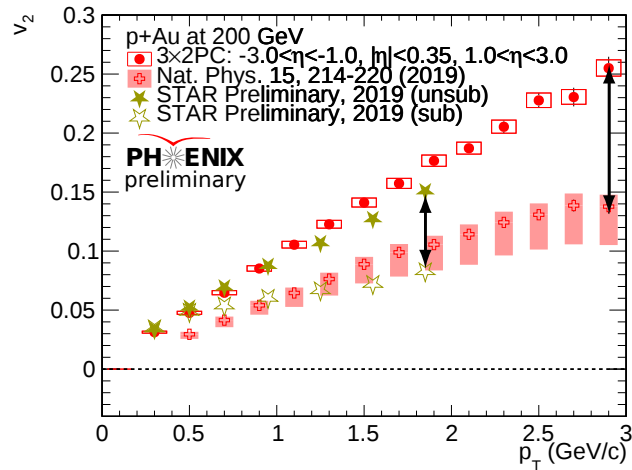
- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim et al, Phys. Rev. C 100, 024908 (2019)

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- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

# Additional non-flow studies using published data tables

## Checking Non-Flow Assumptions and Results via PHENIX Published Correlations in $p+p$ , $p+\text{Au}$ , $d+\text{Au}$ , $^3\text{He}+\text{Au}$ at $\sqrt{s_{NN}} = 200 \text{ GeV}$

J.L. Nagle,<sup>1</sup> R. Belmont,<sup>2</sup> S.H. Lim,<sup>3</sup> and B. Seidlitz<sup>1</sup>

<sup>1</sup>*University of Colorado, Boulder, Colorado 80309, USA*

<sup>2</sup>*University of North Carolina, Greensboro, North Carolina 27413, USA*

<sup>3</sup>*Pusan National University, Busan, 46241, South Korea*

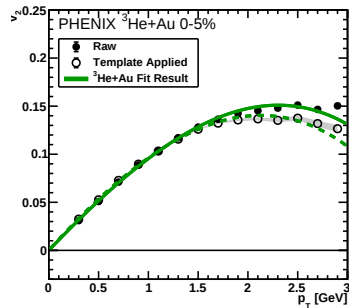
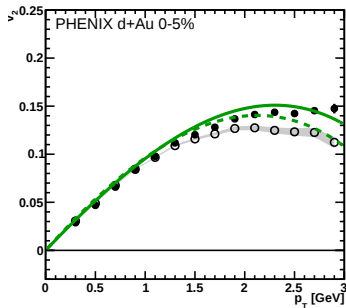
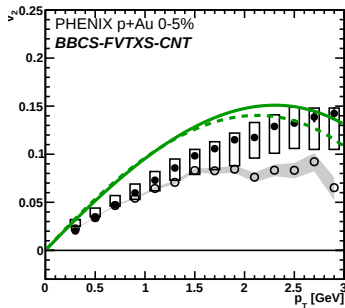
(Dated: July 16, 2021)

<https://arxiv.org/abs/2107.07287>

- To enable additional study, the new PHENIX publication (Phys. Rev. C 105, 024901 (2022)) includes the complete set of  $\Delta\phi$  correlations and extracted coefficients  $c_1$ ,  $c_2$ ,  $c_3$ ,  $c_4$
- A new paper uses these data tables to explore non-flow subtraction of these data as well as to assess the degree of (non-)closure of non-flow subtraction methods

# Additional non-flow studies using published data tables

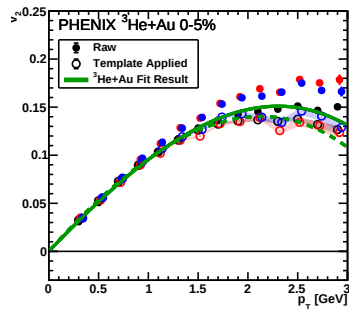
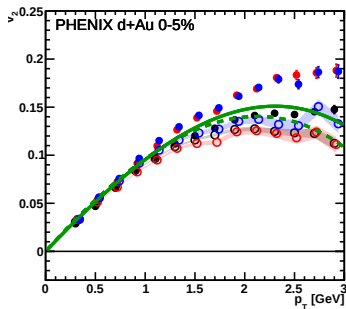
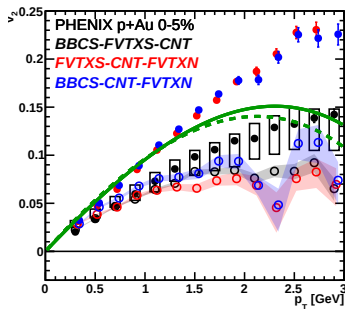
J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



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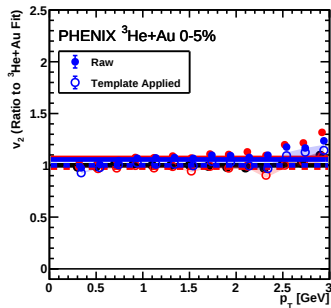
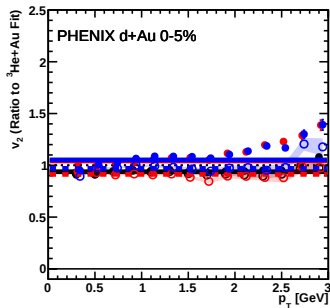
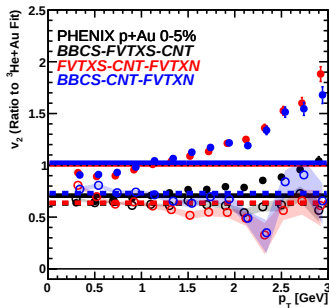
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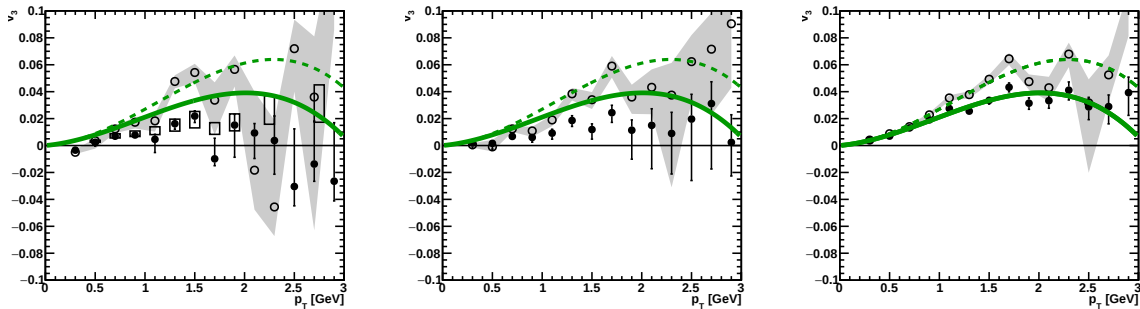
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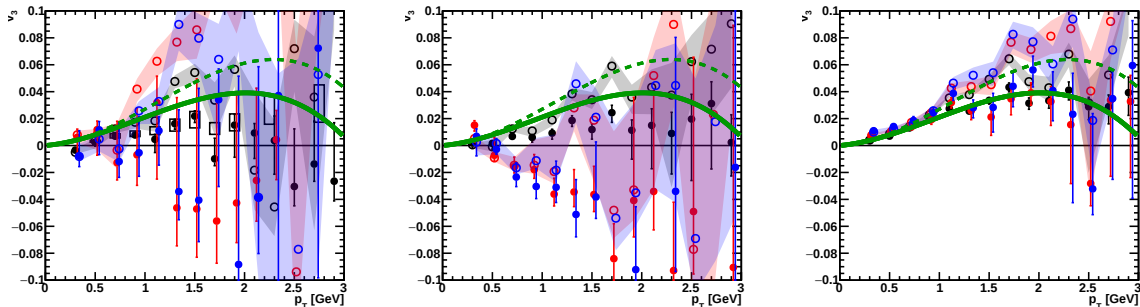
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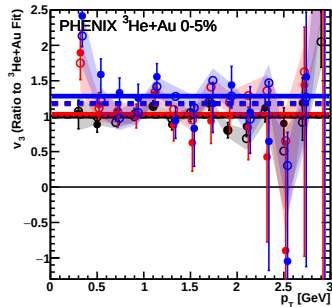
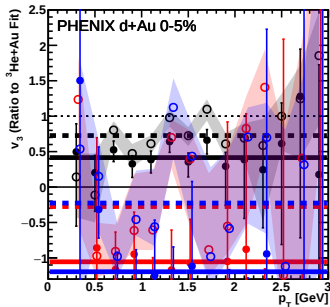
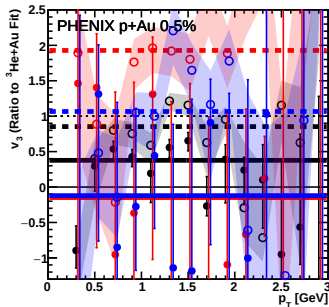
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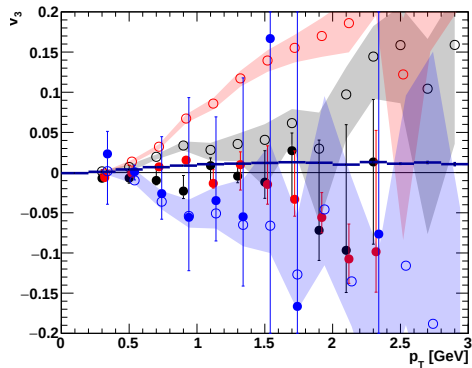
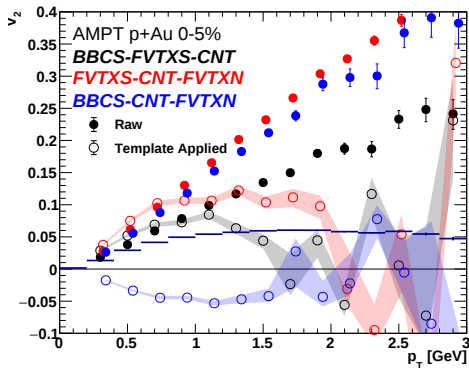
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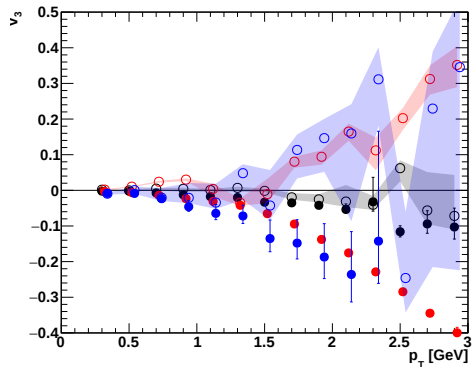
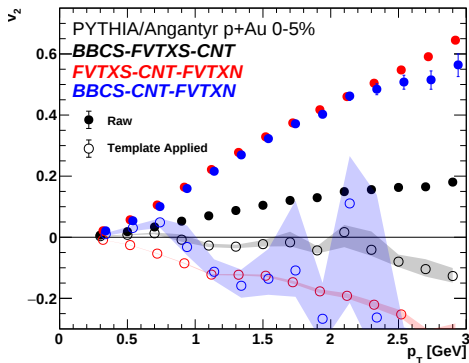
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• Closure is considerably violated in AMPT

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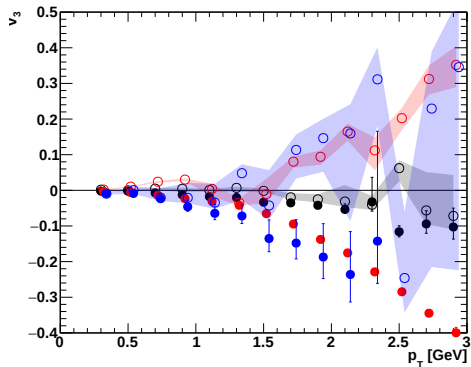
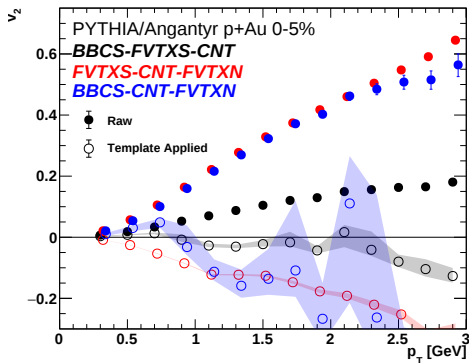
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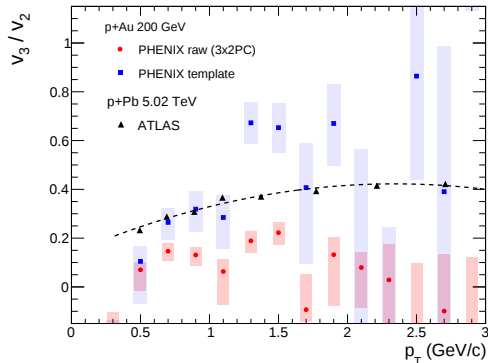
J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



- Closure is considerably violated in AMPT and PYTHIA/Angantyr
- Since AMPT has too much non-flow and PYTHIA doesn't have any flow, the degree of overcorrection in real data is likely not as bad as it is with these generators

# Additional non-flow studies using published data tables

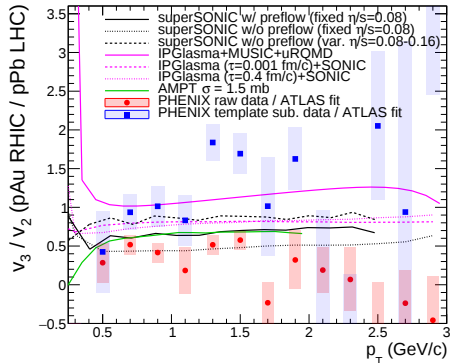
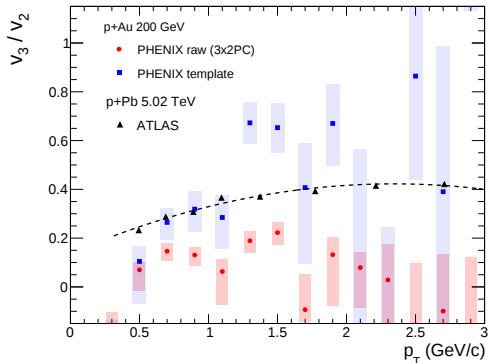
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- The standard PHENIX  $v_3/v_2$  is lower than the ATLAS, while the non-flow corrected is above

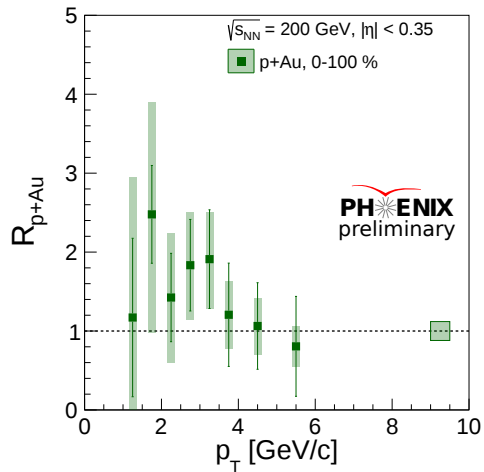
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J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)

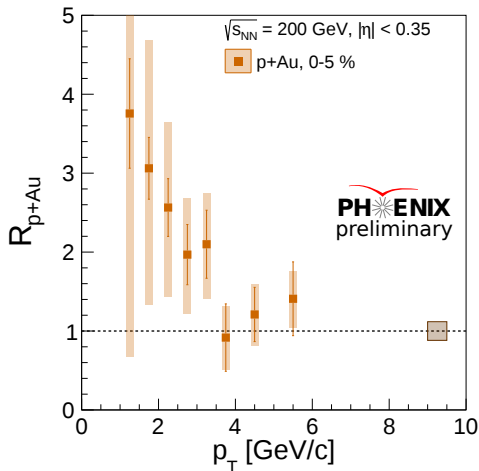
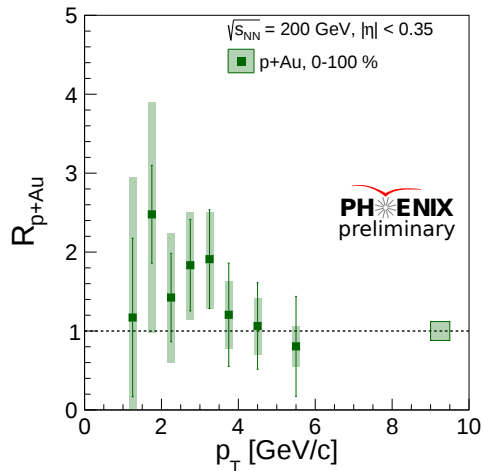


- The standard PHENIX  $v_3/v_2$  is lower than the ATLAS, while the non-flow corrected is above
- The ratio is expected to be lower for lower collision energies in almost all physics scenarios  
—Lower energy, shorter lifetime, more damping of higher harmonics

# Photons in small systems

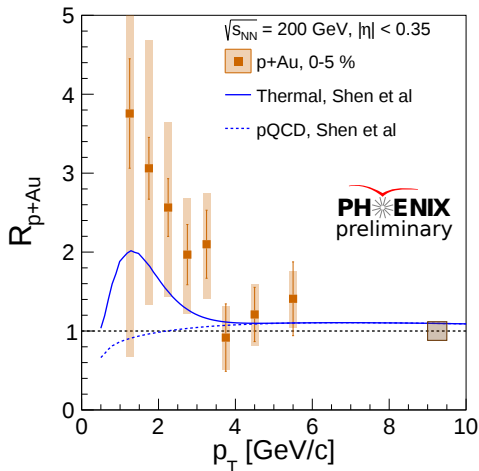
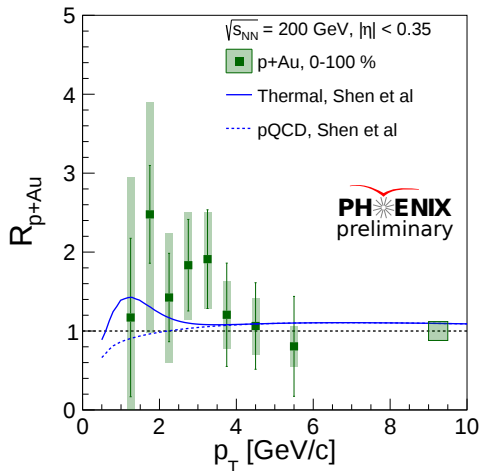


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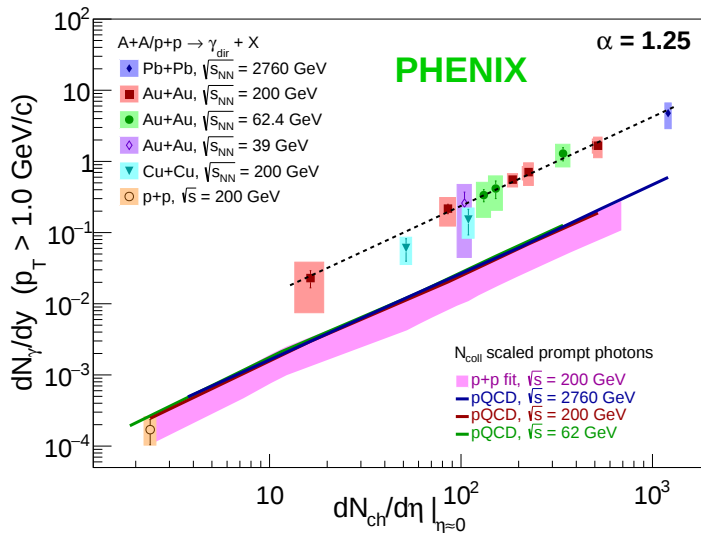
- Thermal photons in  $p+Au$ ?

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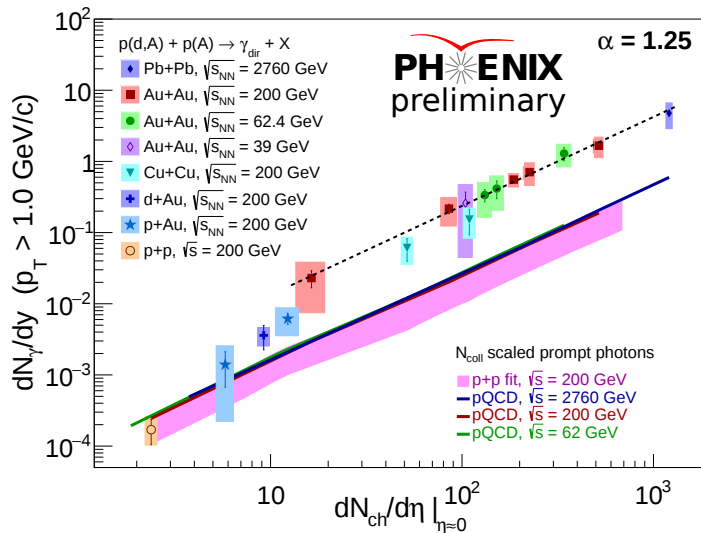
- Thermal photons in  $p+Au$ ? Theory from Phys. Rev. C 95, 014906 (2017)

# Photon yields



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

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$p+Au$  and  $d+Au$  in between