
# *PHENIX results in small collision systems*

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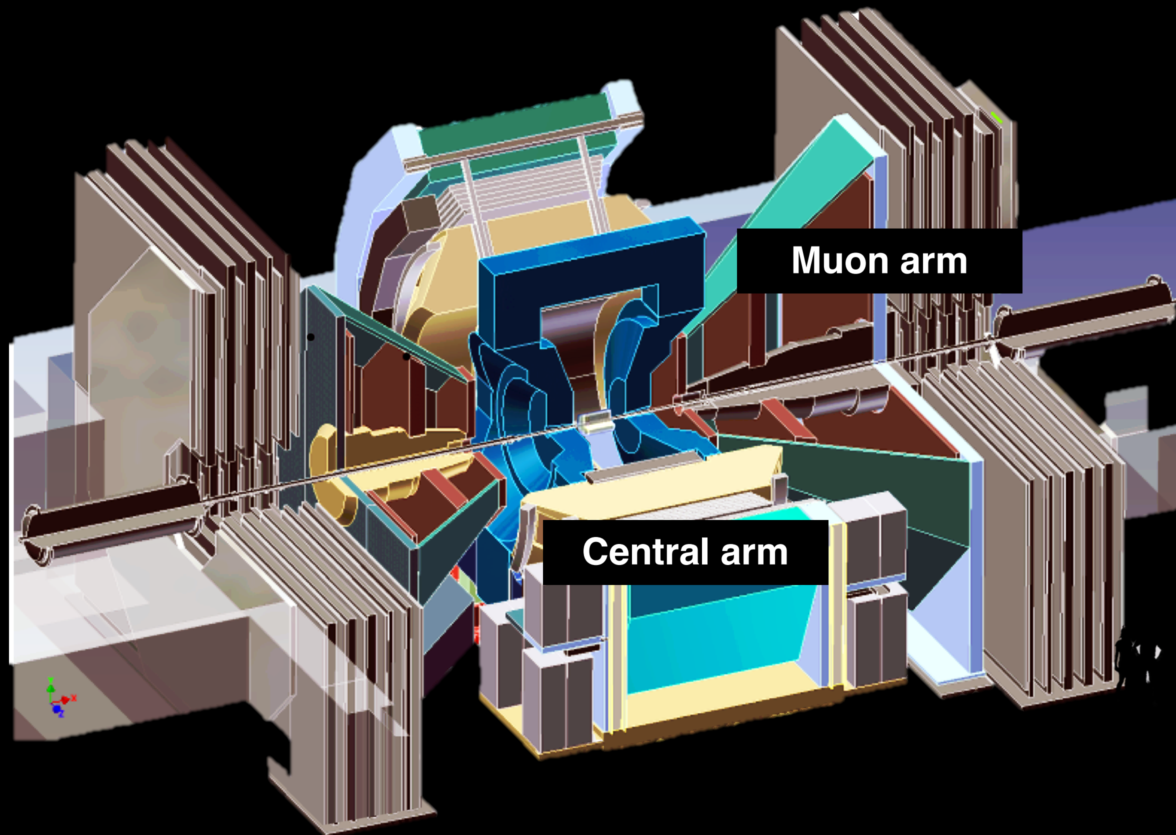
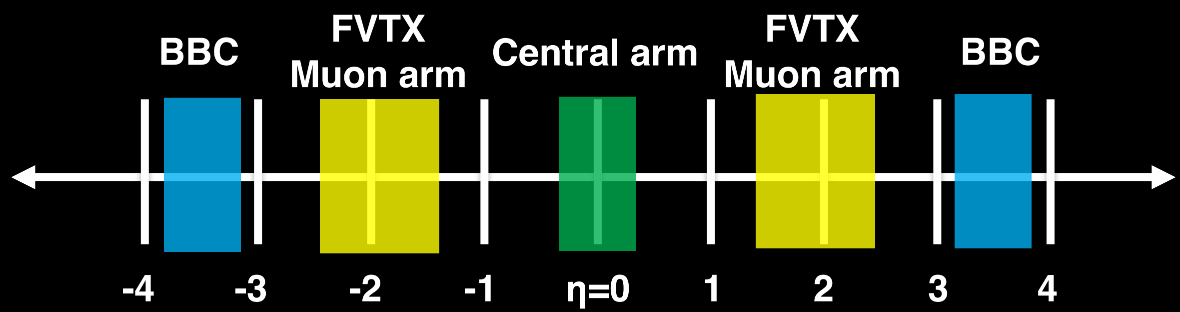
**University of Colorado Boulder**
**for the PHENIX collaboration**

University of Colorado **Boulder**

PHENIX

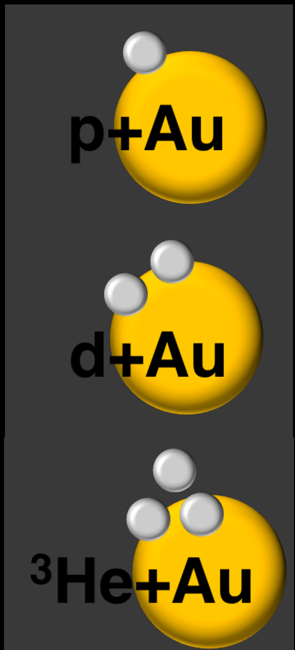


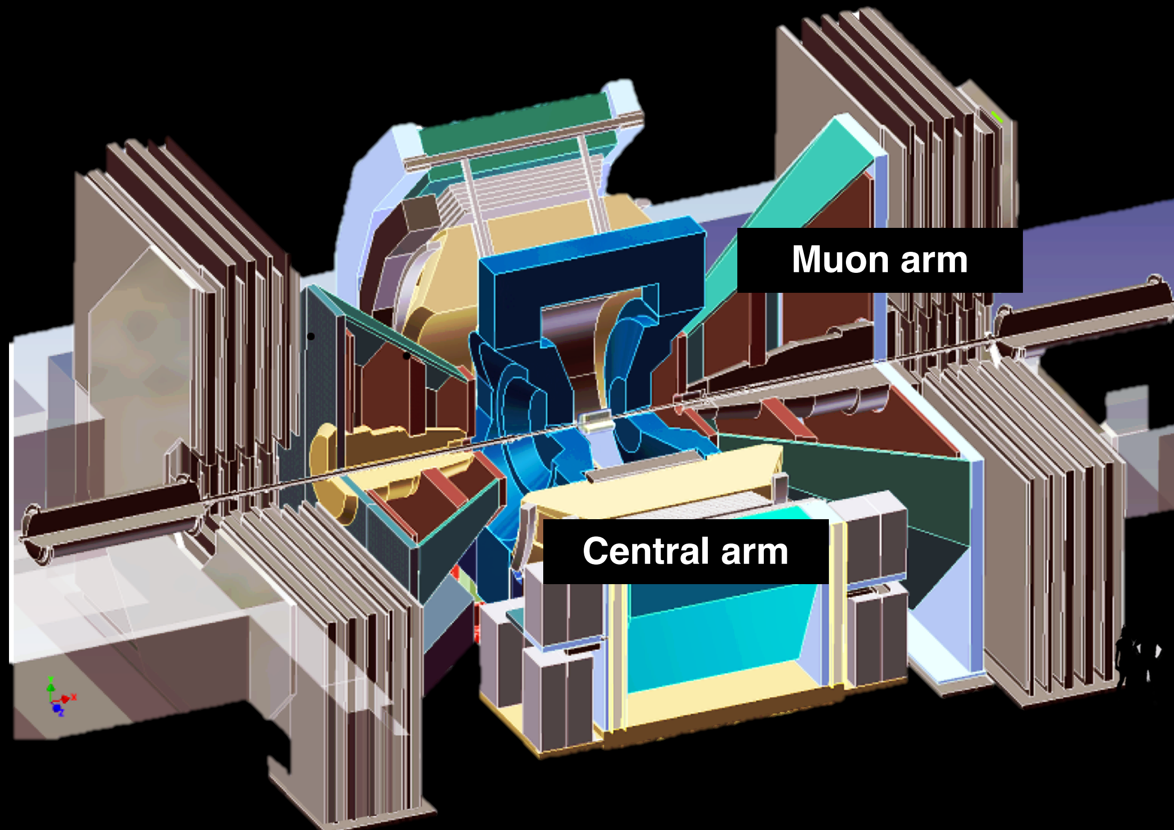




***Large Rapidity Coverage***

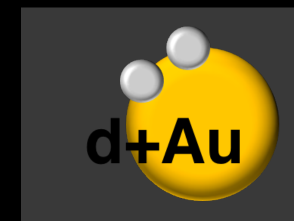
# *Study of small collision systems in PHENIX*

**Initial geometry**



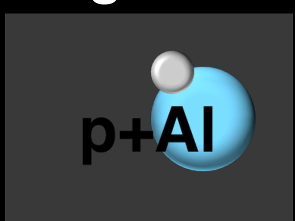




**Beam energy**

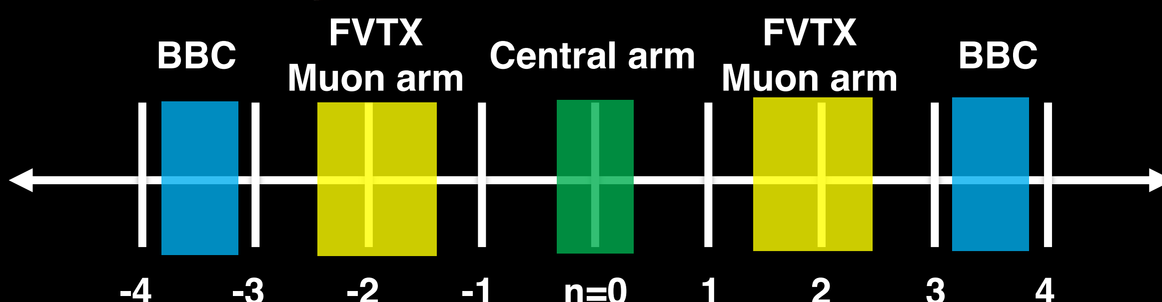



200 GeV
62.4 GeV
39 GeV
19.6 GeV

**Target size**




200 GeV



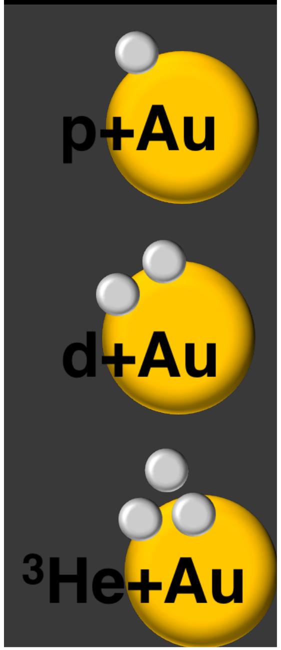

Event centrality

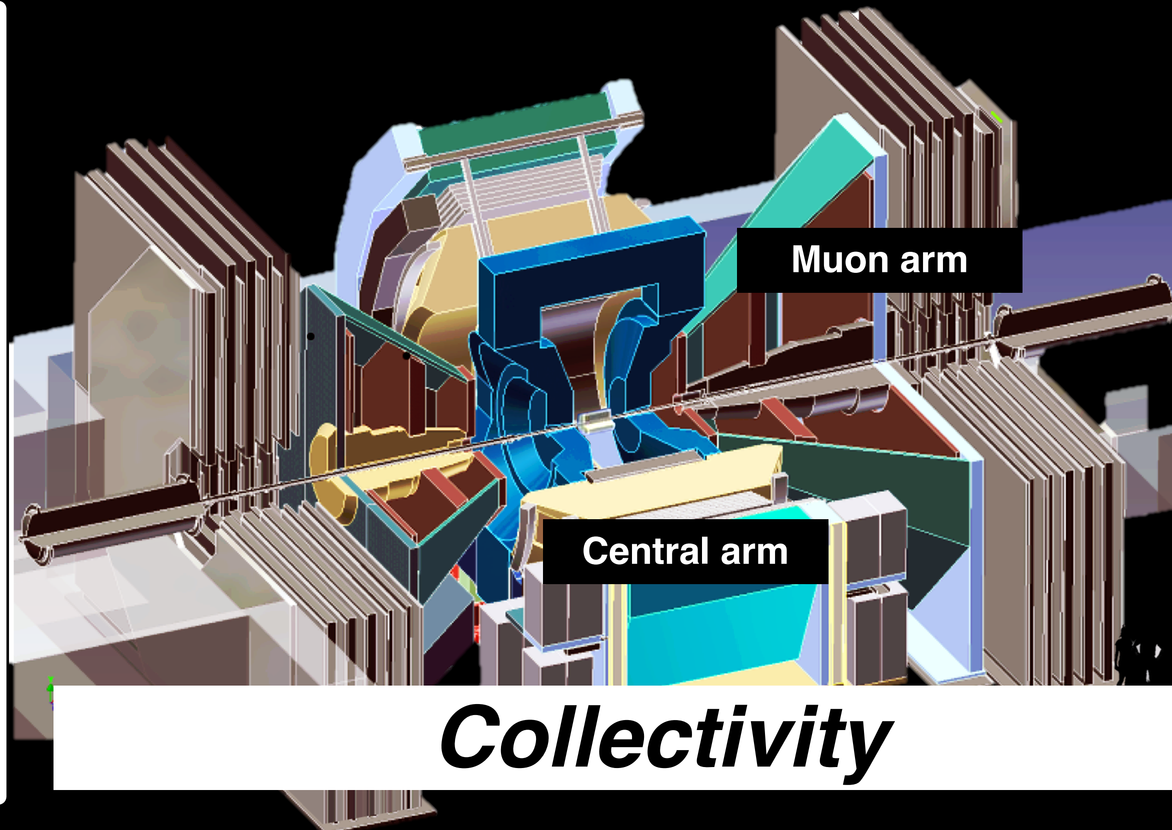
Au/Al going

p/d/$^3$He going

# *Study of small collision systems in PHENIX*

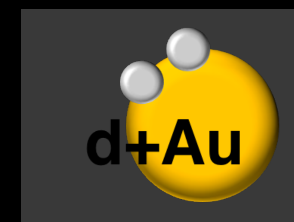
**Initial geometry**




## *Collectivity*

**Beam energy**

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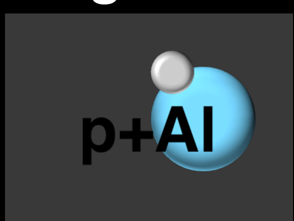
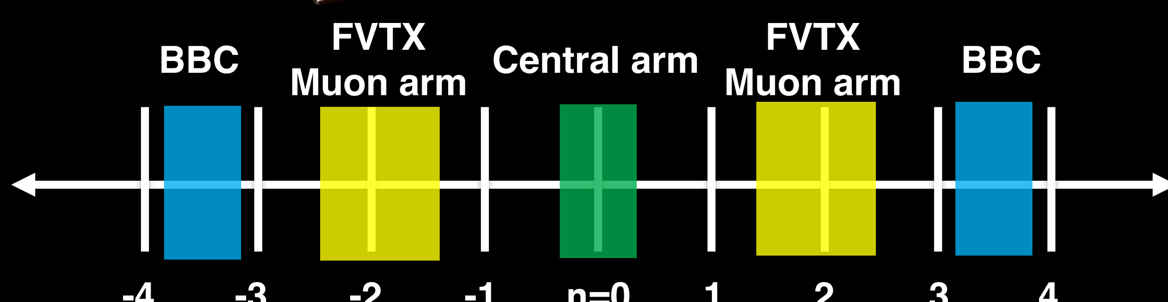



200 GeV

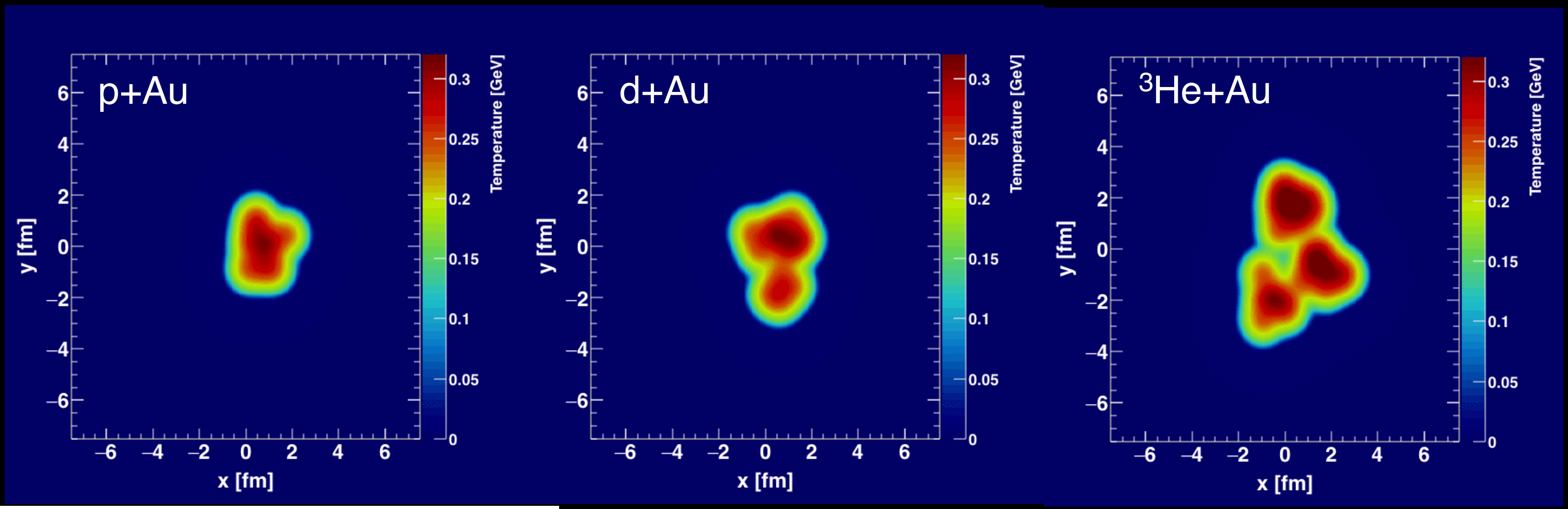


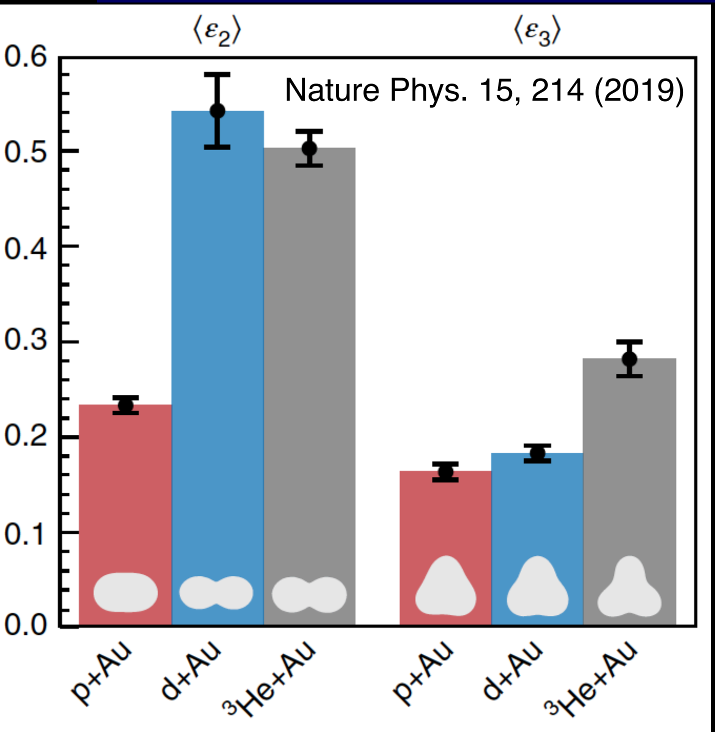

Event centrality

Au/Al going

p/d/$^{3}$He going

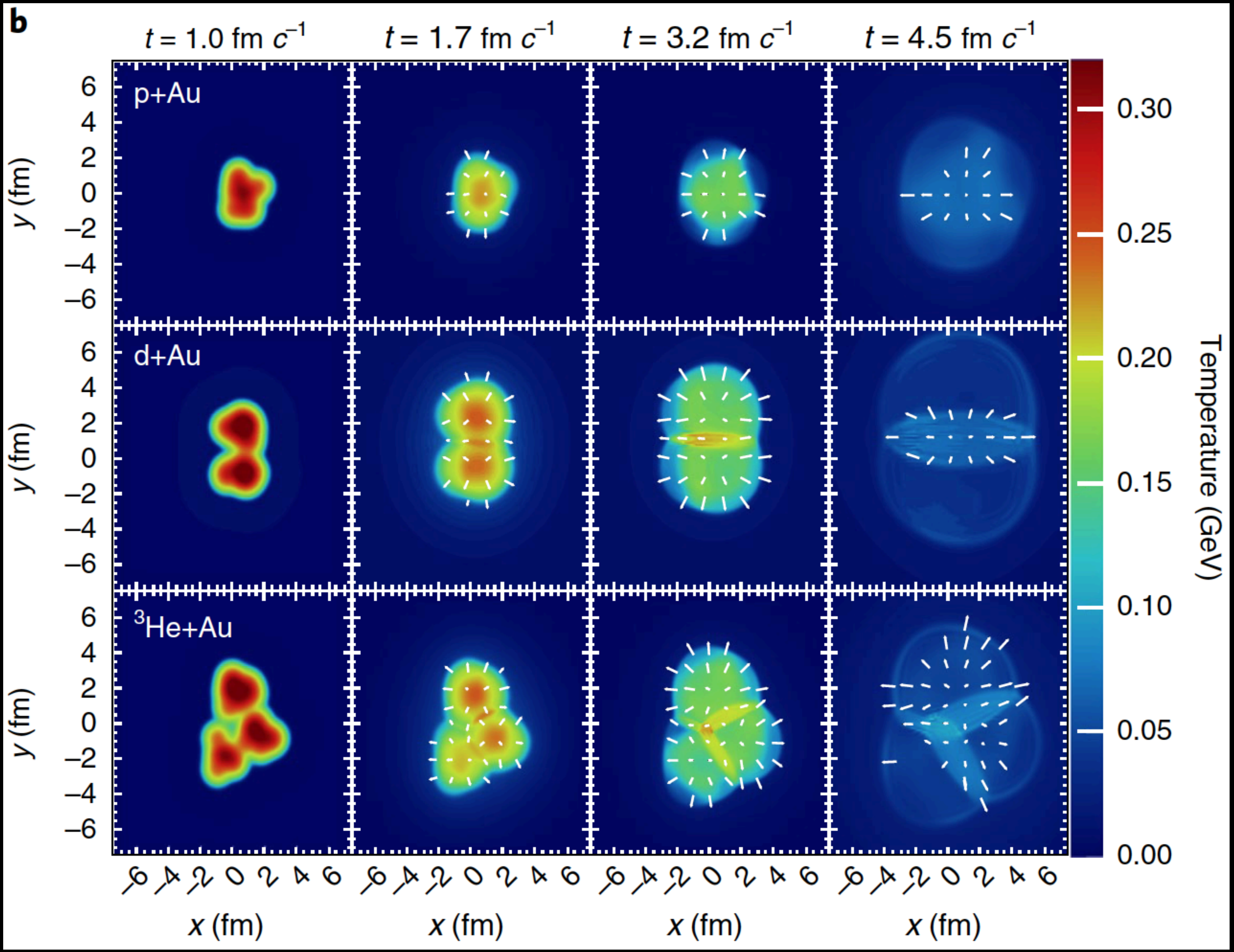
# *Control initial geometry*




- Clearly different initial collision geometry in p/d/$^3$He+Au collisions
  - Smaller $<\varepsilon_2>$ in p+Au collisions
  - Larger $<\varepsilon_3>$ in $^3$He+Au collisions

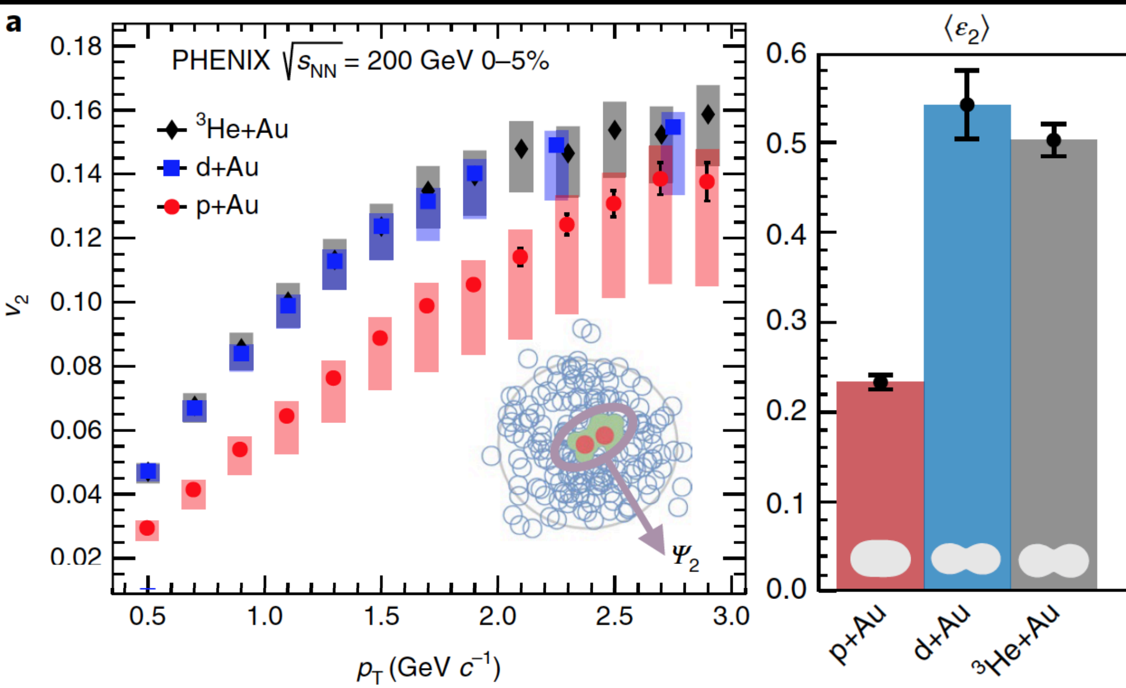
# *Translation of geometry in hydrodynamics*




Event display from SONIC

Nature Phys. 15, 214 (2019)

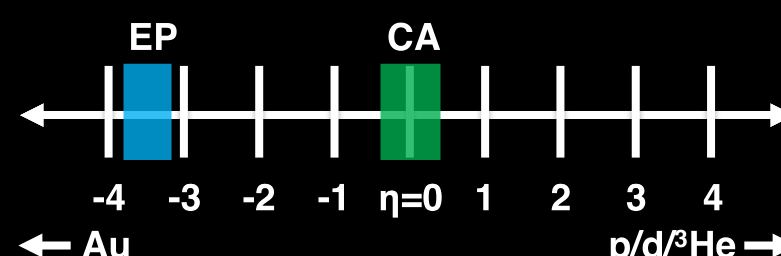
# *How about in data?*



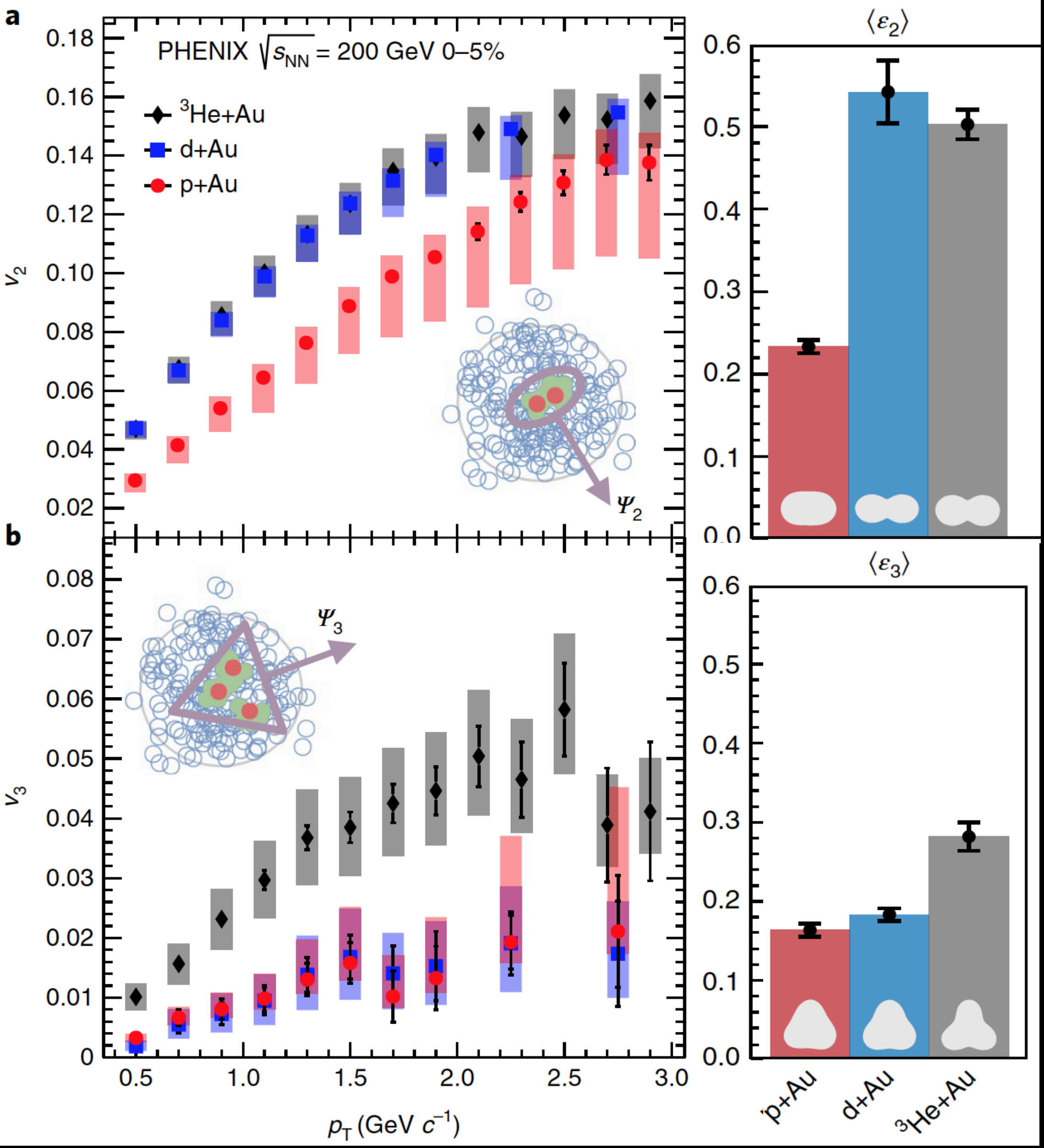

Nature Phys. 15, 214 (2019)

Smaller $\langle \varepsilon_2 \rangle$ in p+Au

Smaller $v_2$ in p+Au



# How about in data?




Smaller $<\varepsilon_2>$ in p+Au

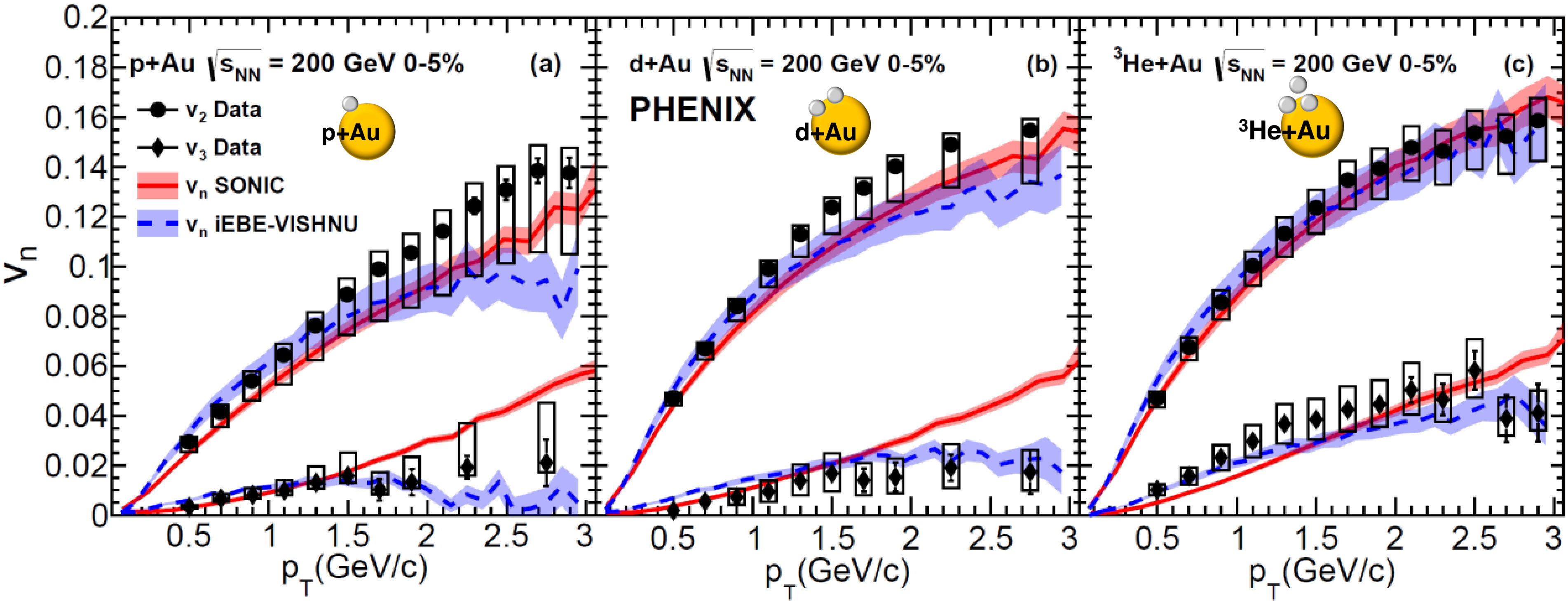
Smaller $v_2$ in p+Au

Larger $<\varepsilon_3>$ in $^3$He+Au

Larger $v_3$ in $^3$He+Au

Nature Phys. 15, 214 (2019)

# Model description (Hydrodynamic model)

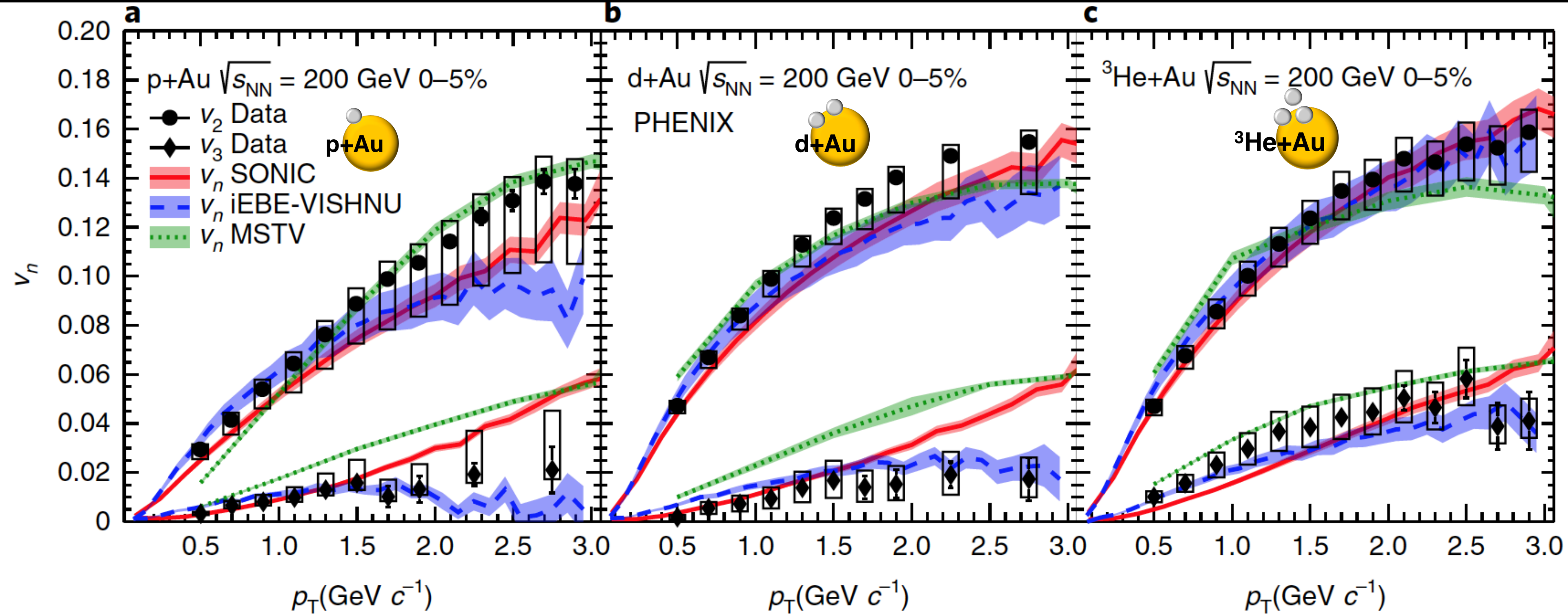



Nature Phys. 15, 214 (2019)

SONIC: Eur. Phys. J. C 75, 15 (2015)
iEBE-VISHNU: Phys. Rev. C 95, 014906 (2017)

Good agreement with $v_2$ and $v_3$
from hydrodynamic models in all three systems

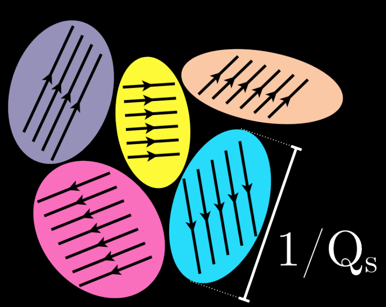
# Alternative model description ?

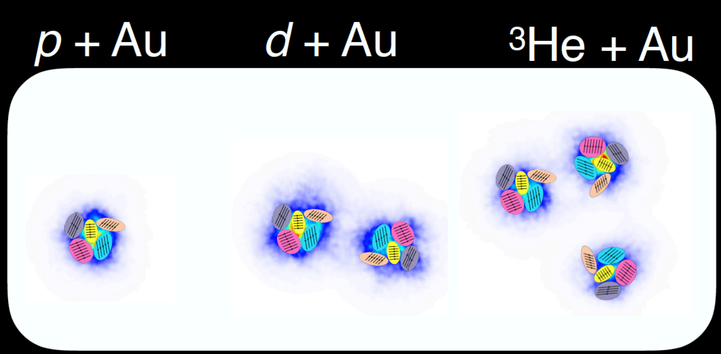



Nature Phys. 15, 214 (2019)

MSTV: Phys. Rev. Lett. 121, 052301 (2018)

A model considering initial-state correlation from color domain claimed to describe the order of $v_2$ in three systems



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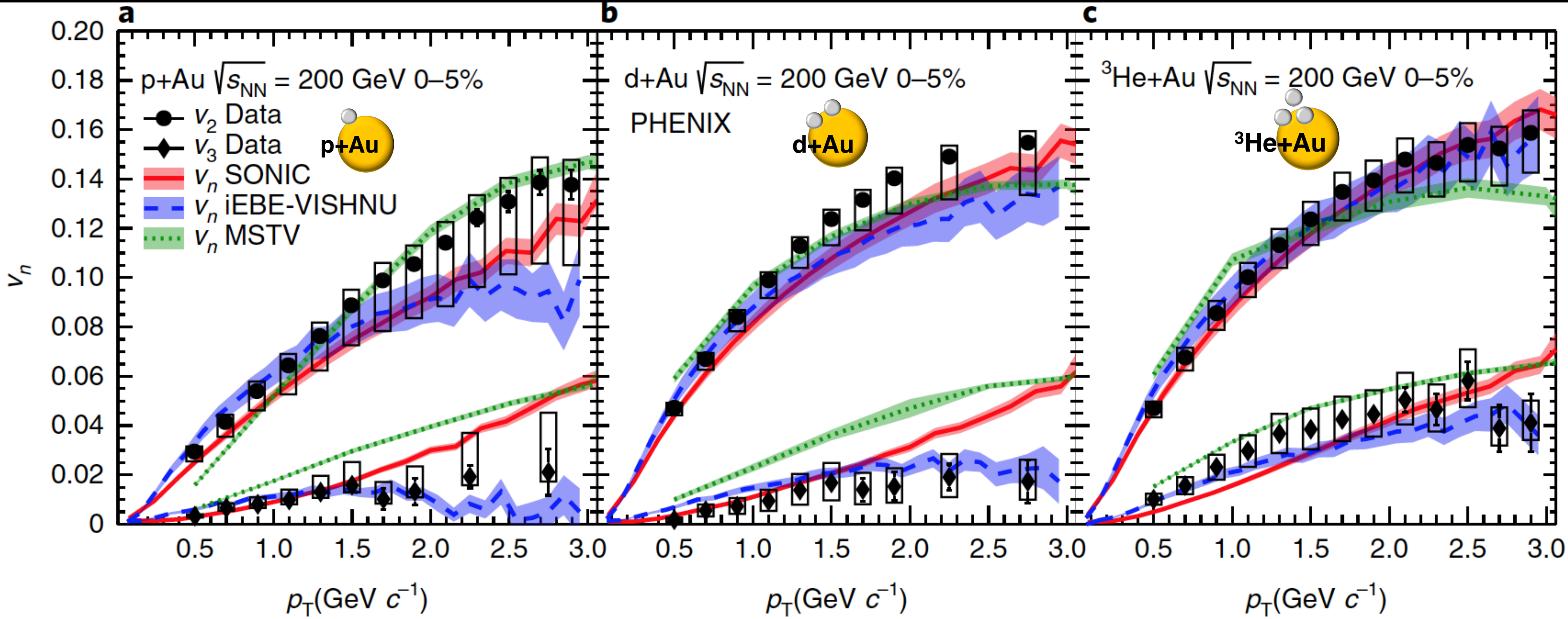



Nature Phys. 15, 214 (2019)

MSTV: Phys. Rev. Lett. 121, 052301 (2018)

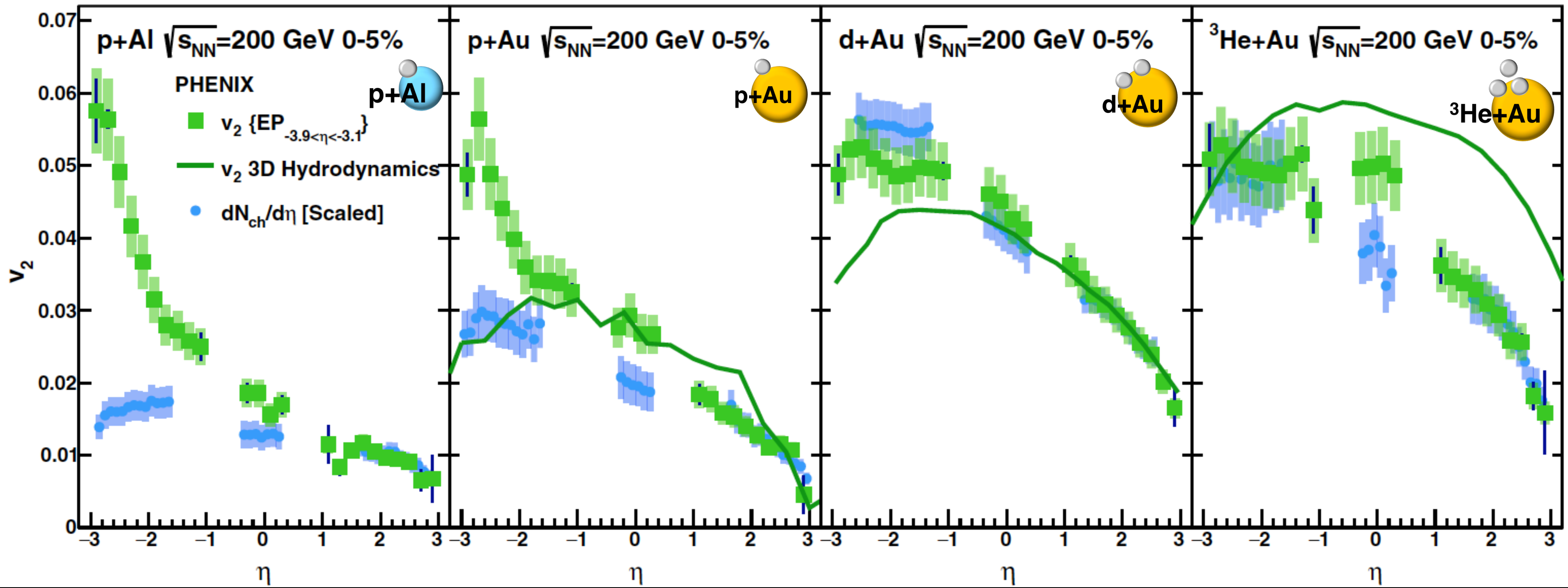
MSTV recently reported a bug such that the momentum scale is changed by $\hbar c$

With correction: $v_2$ in p+Au > $v_2$ in d+Au

Initial-state correlations are ruled out as the entire explanation

slides from Mark Mace: http://www.int.washington.edu/talks/WorkShops/int_19_1b/People/Mace_M/Mace.pdf

# Collectivity in η

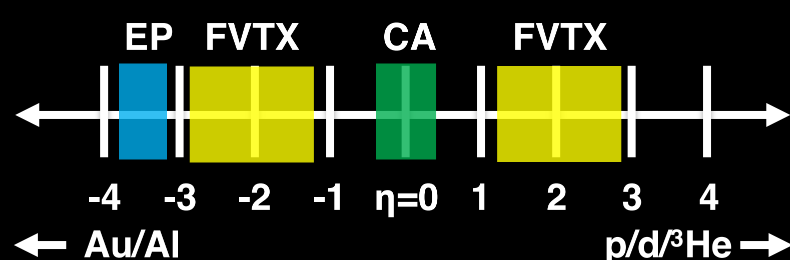



Phys. Rev. Lett. 121, 222301 (2018)

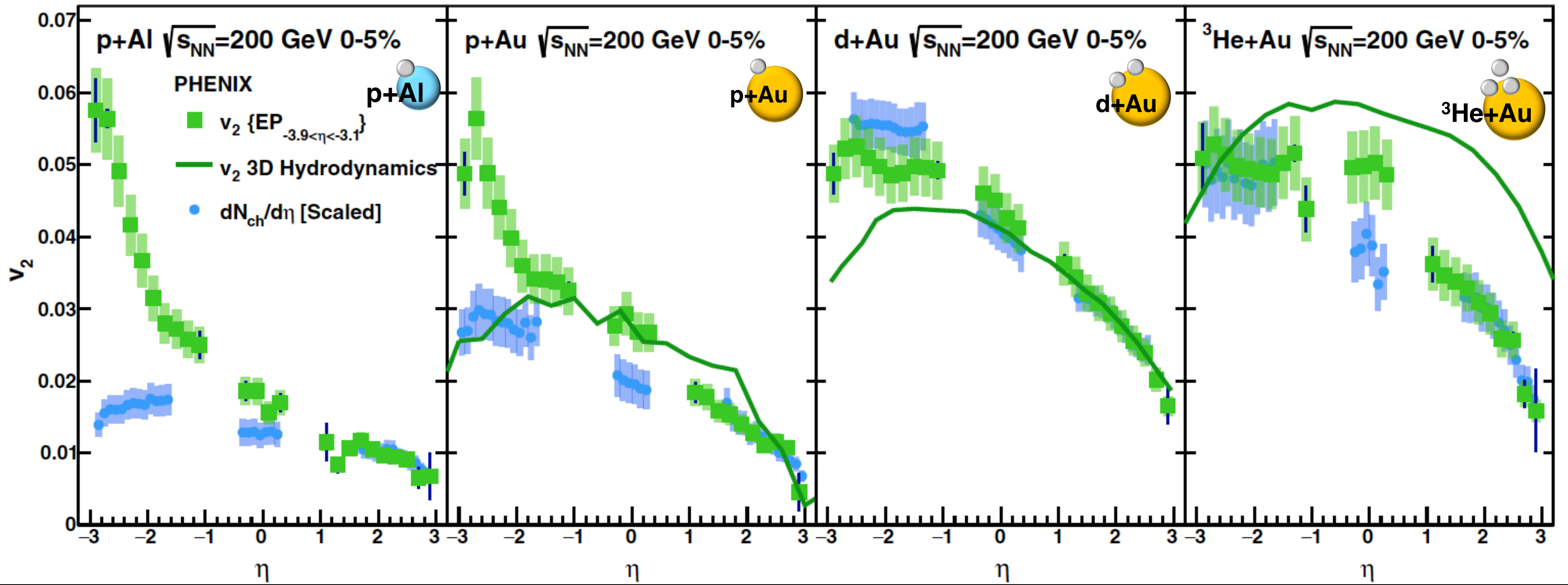
Phys. Lett. B 739 (2014) for 3D hydro

$v_2(\eta)$ in d+Au and $^3$He+Au scales with $dN_{ch}/d\eta$

Sharp sudden rise in $v_2$ at backward in p+Al and p+Au likely from non-flow



# *Collectivity in η*

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$v_2(\eta)$ in d+Au and $^3$He+Au scales with $dN_{ch}/d\eta$

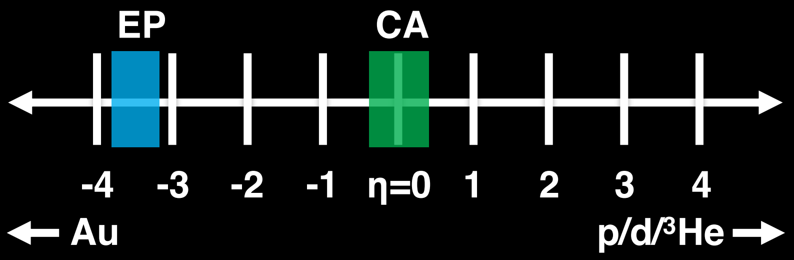
Sharp sudden rise in $v_2$ at backward in p+Al and p+Au likely from non-flow

Good agreement with 3D hydrodynamics model in p+Au and d+Au

but overpredicts $v_2$ at forward in $^3$He+Au

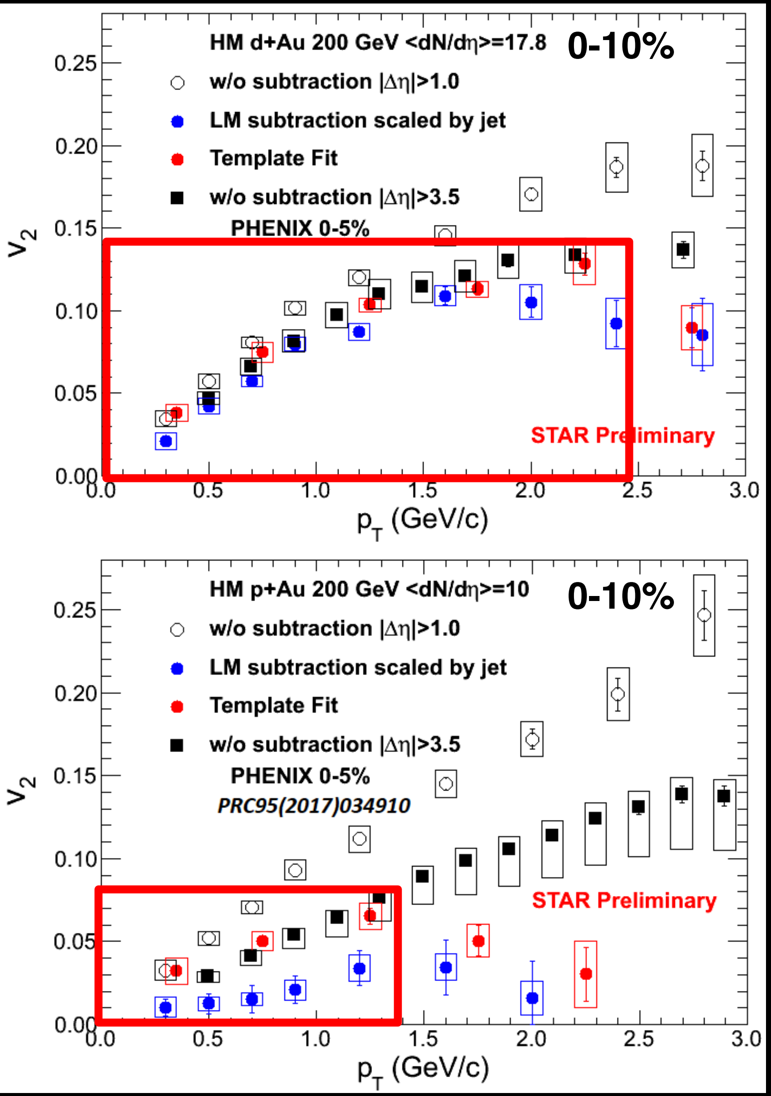
## *Non-flow effect*

- Non-flow contribution is expected to be more significant in smaller collision systems
  - larger in p+Au than d+Au
- PHENIX results using EP with $|\Delta\eta|>2.5$




  - Systematic uncertainty on the non-flow contribution is evaluated using p+p data

# Non-flow effect




Plots from Shengli Huang's presentation at 2019 RHIC & AGS AUM

- Non-flow contribution is expected to be more significant in smaller collision systems
  - larger in p+Au than d+Au
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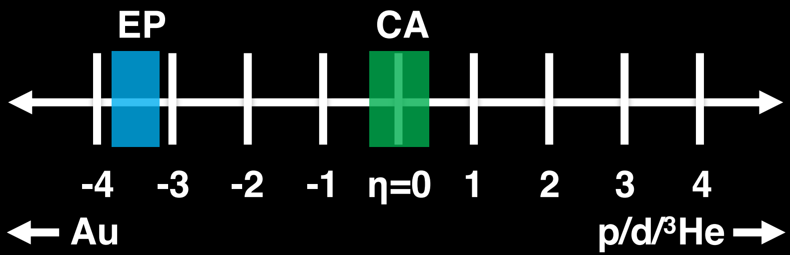
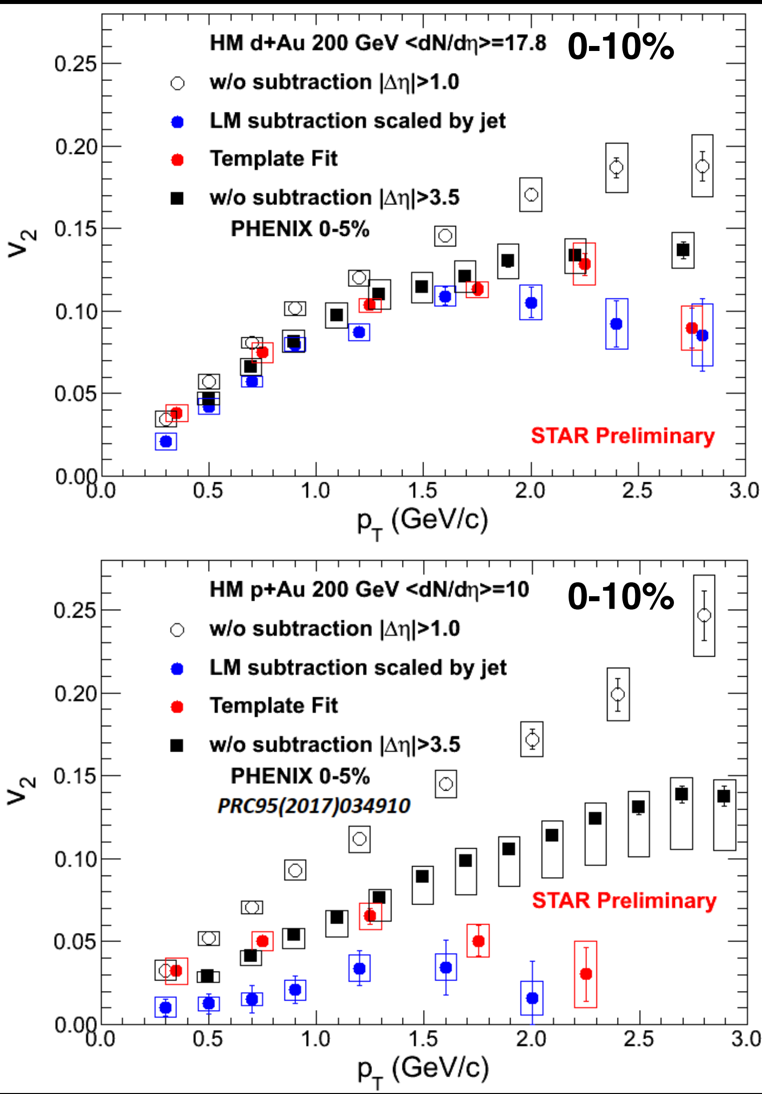


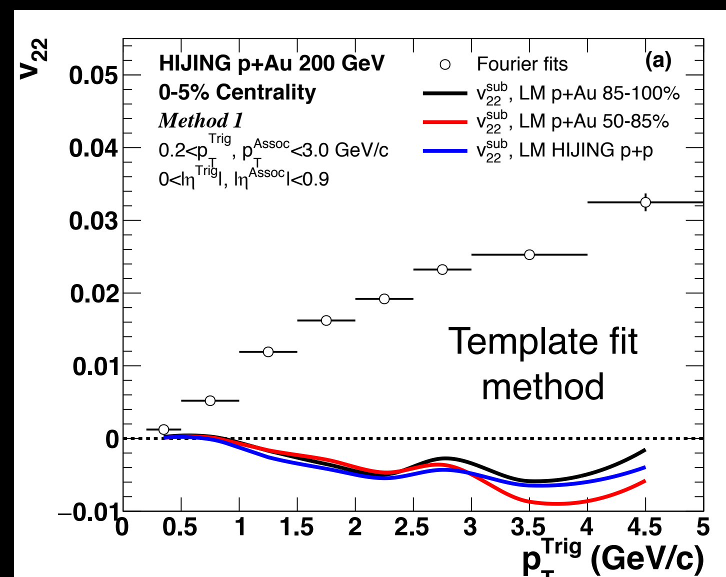

  - Systematic uncertainty on the non-flow contribution is evaluated using p+p data
- STAR preliminary template fit results agree with PHENIX published results
  for $p_T$<2.5 GeV/c in d+Au
  for $p_T$<1.5 GeV/c in p+Au

# *Non-flow effect*



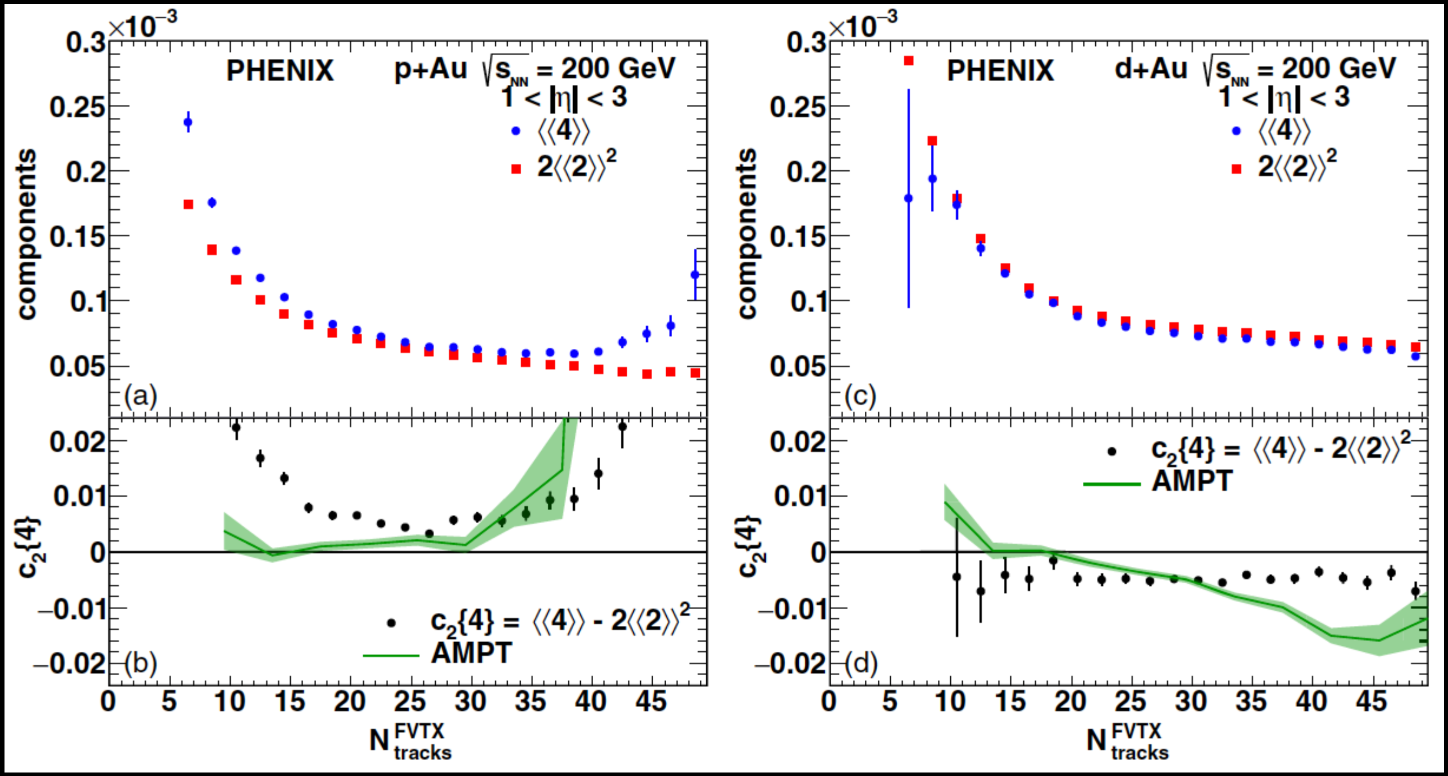

Plots from Shengli Huang's presentation at 2019 RHIC & AGS AUM

- On-going efforts in PHENIX to better understand the non-flow effect
  - Need careful studies because of the possibility of non-closure
  - Possible over-subtraction at higher $p_T$ based on the study with HIJING and AMPT




arXiv:1902.11290

# *Multiparticle correlation*



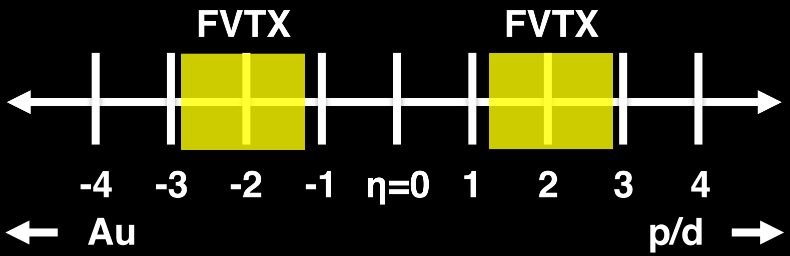

Phys. Rev. Lett. 120, 062302 (2018)

Positive $c_2\{4\}$ in p+Au and negative $c_2\{4\}$ in d+Au

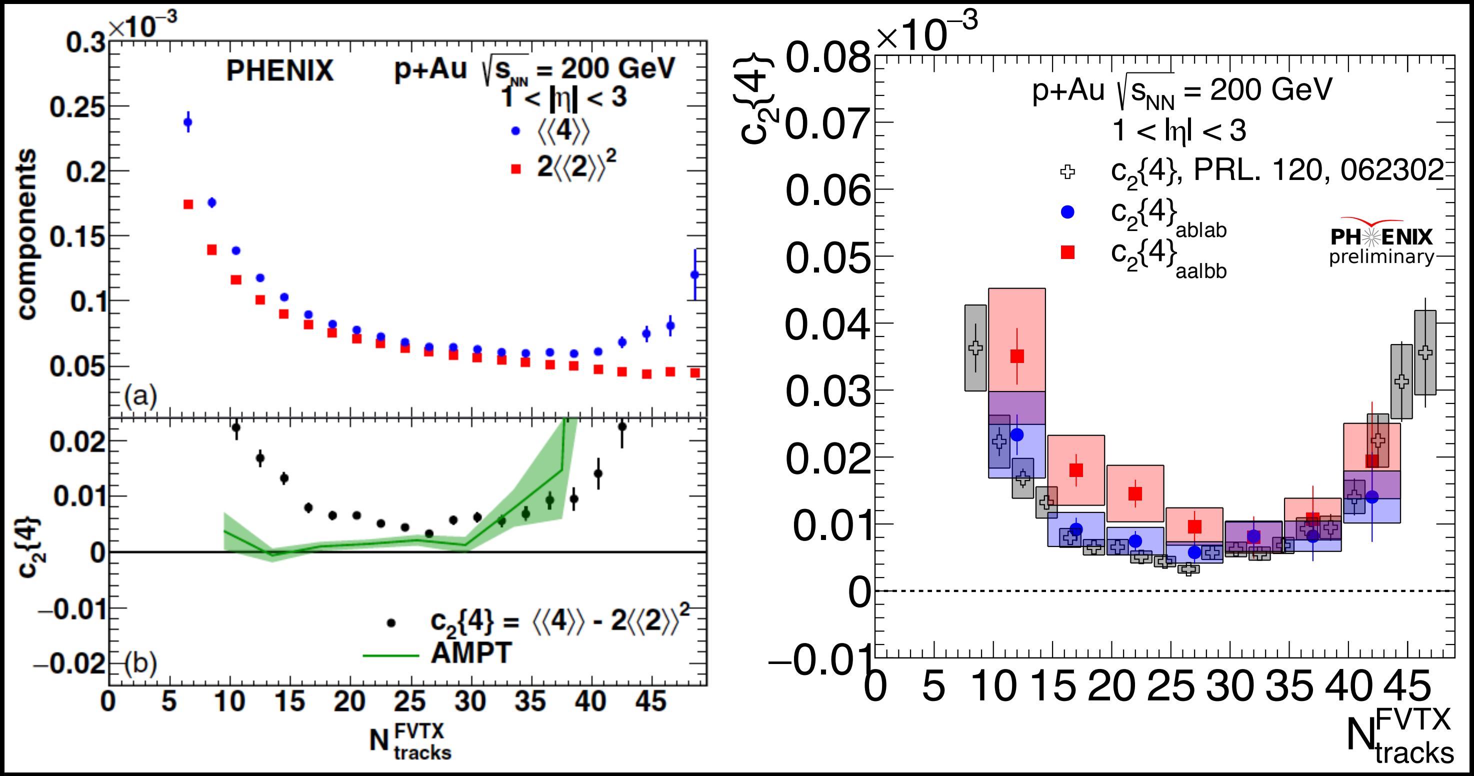
Positive $c_2\{4\}$ in p+Au from large fluctuation? remaining non-flow?

$$v_2\{2\} = (c_2\{2\})^{1/2} \approx (v_2^2 + \sigma^2)^{1/2}$$

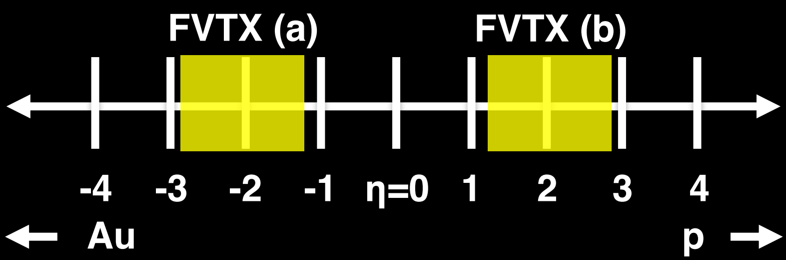
$$v_2\{4\} = (-c_2\{4\})^{1/4} \approx (v_2^2 - \sigma^2)^{1/2}$$



# *Multiparticle correlation*




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

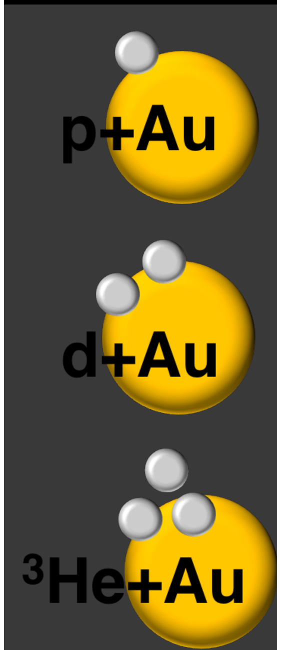



Confirm positive $c_2\{4\}$ in p+Au with sub-event method (ablab) and (aalbb)

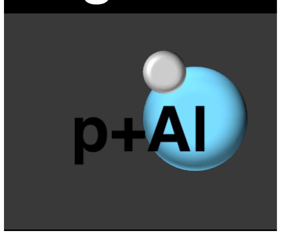
More results in d+Au beam energy scan data will come

# *Study of small collision systems in PHENIX*

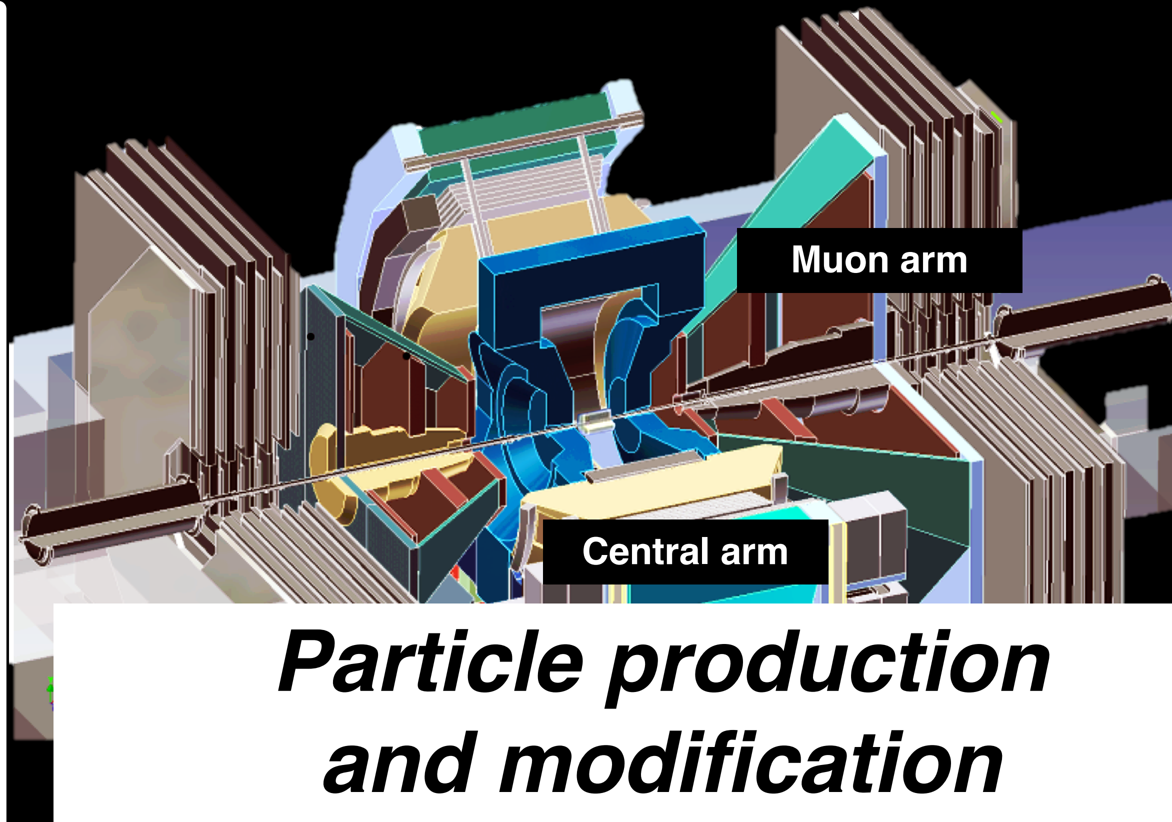
Initial geometry




Target size

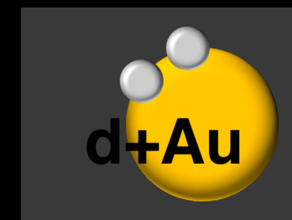



200 GeV




***Particle production and modification***

Beam energy

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62.4 GeV
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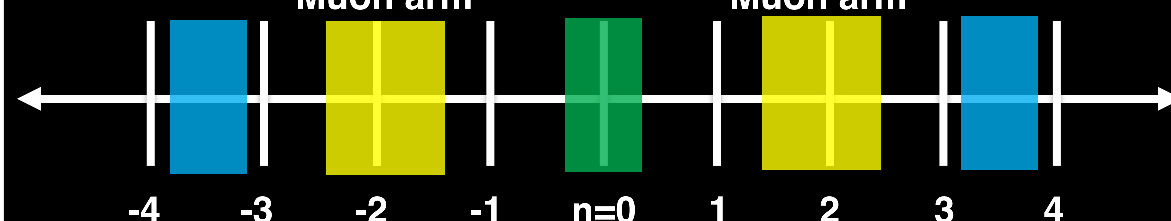
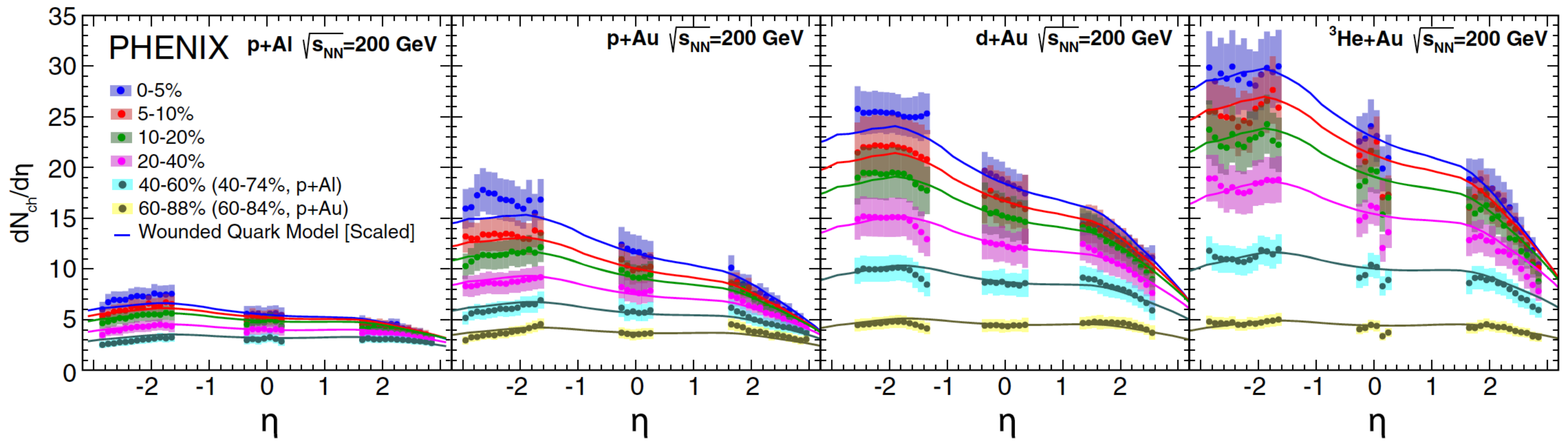



Event centrality

Au/Al going

p/d/$^3$He going

# *Particle production in small systems*

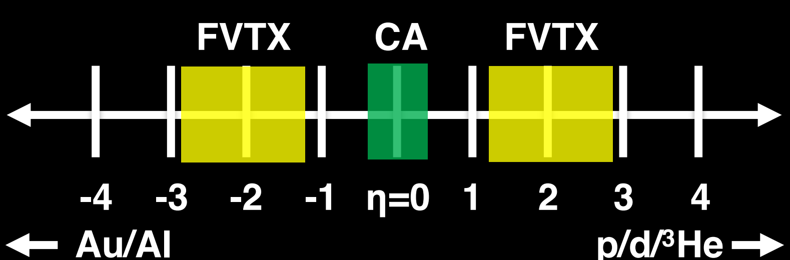



Phys. Rev. Lett. 121, 222301 (2018)

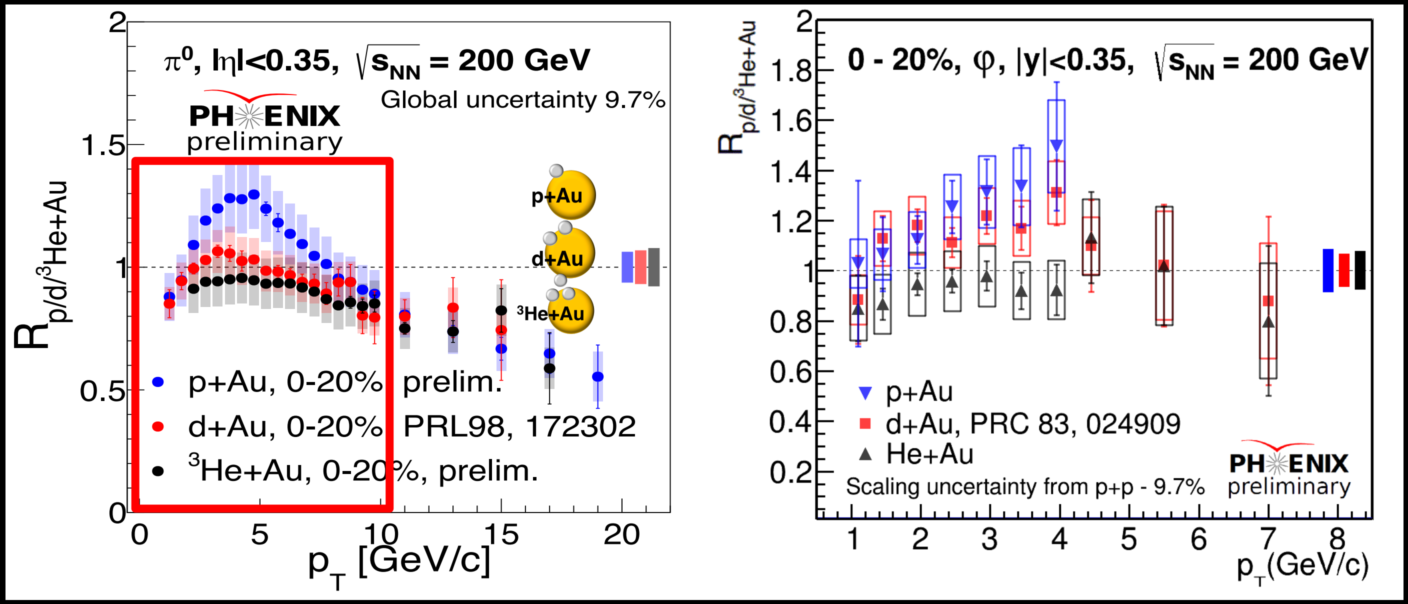
Phys. Rev. C 97, 034901 (2018) for the model

$dN_{ch}/d\eta$ increases with system size

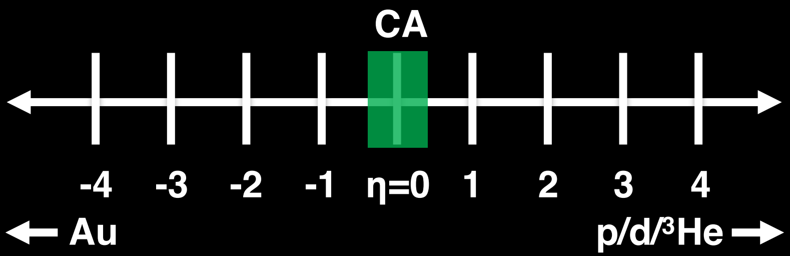
Wounded quark model can describe the $dN_{ch}/d\eta$ shapes
in all centrality bins of different collision systems
with a common wounded quark emission function extracted from PHOBOS d+Au data



# $\pi^0$ and $\phi$ in small systems




Clearly different modification of $p_T$ distribution for $p_T$<7 GeV/c in three systems



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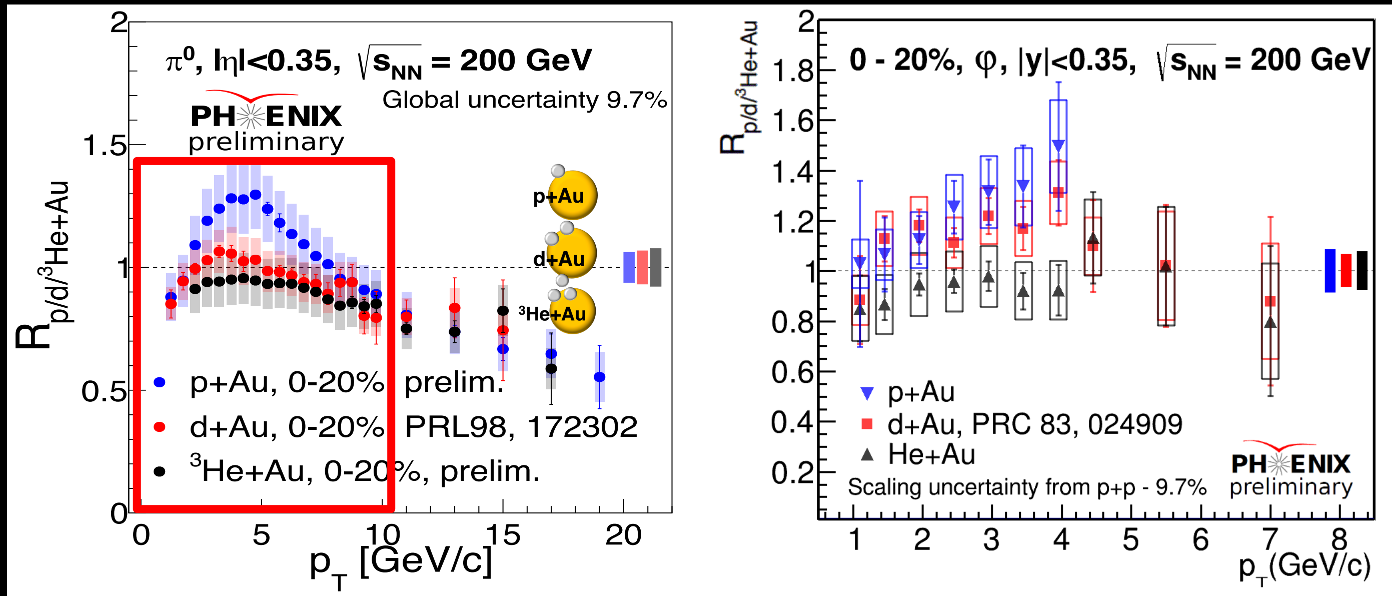
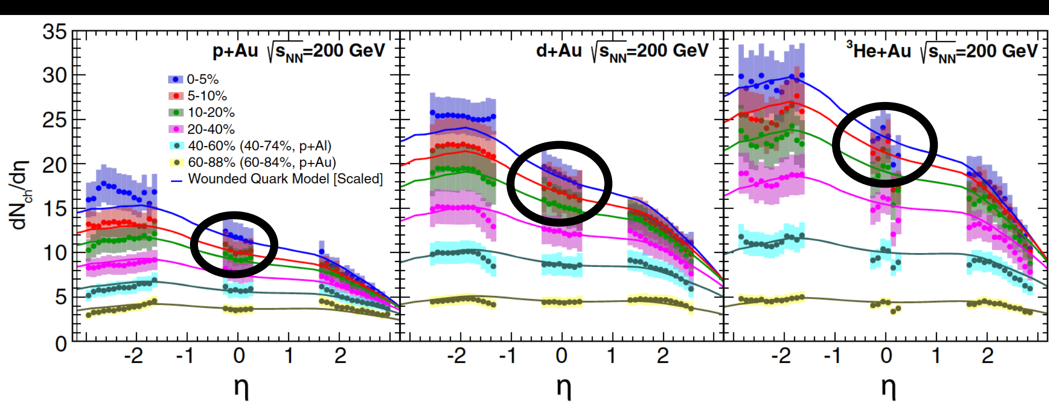


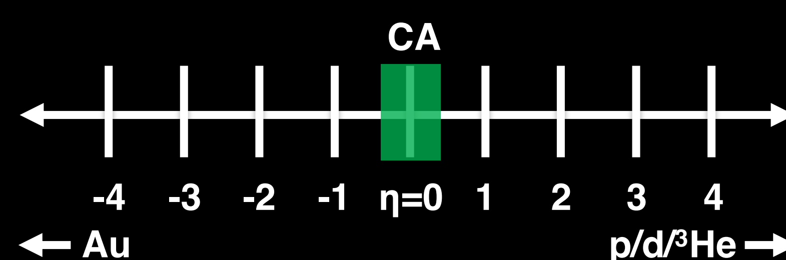

Stronger $p_T$ broadening in p+Au where multiplicity is smallest

*Larger initial $k_T$ due to more $\langle N_{coll} \rangle$ per projectile nucleon?*

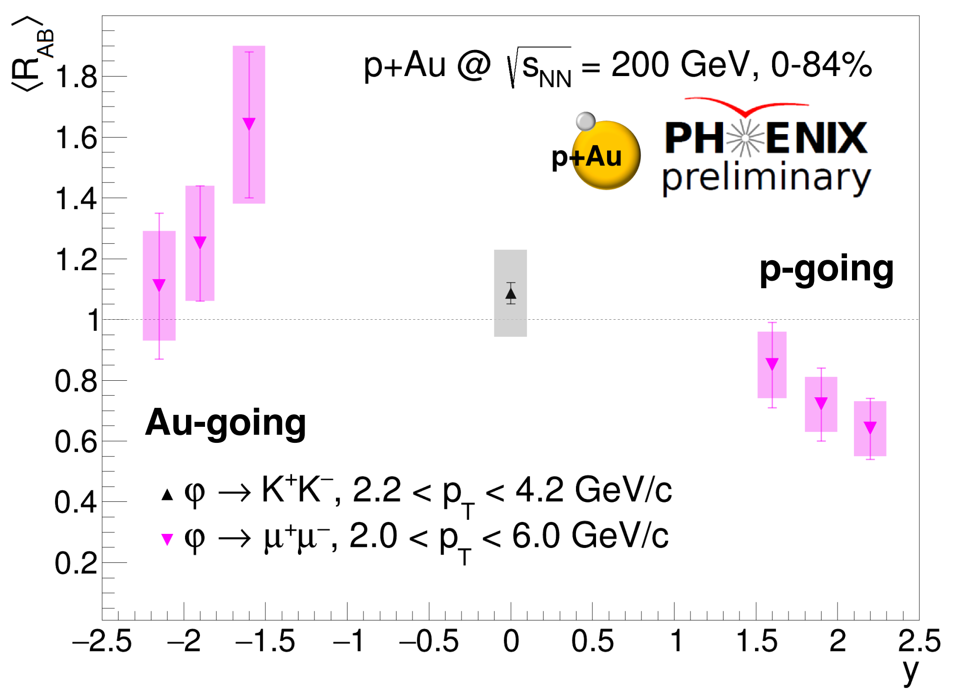
$\langle N_{coll} \rangle$: 9.7 in p+Au, 15.1 in d+Au, 22.3 in $^3$He+Au

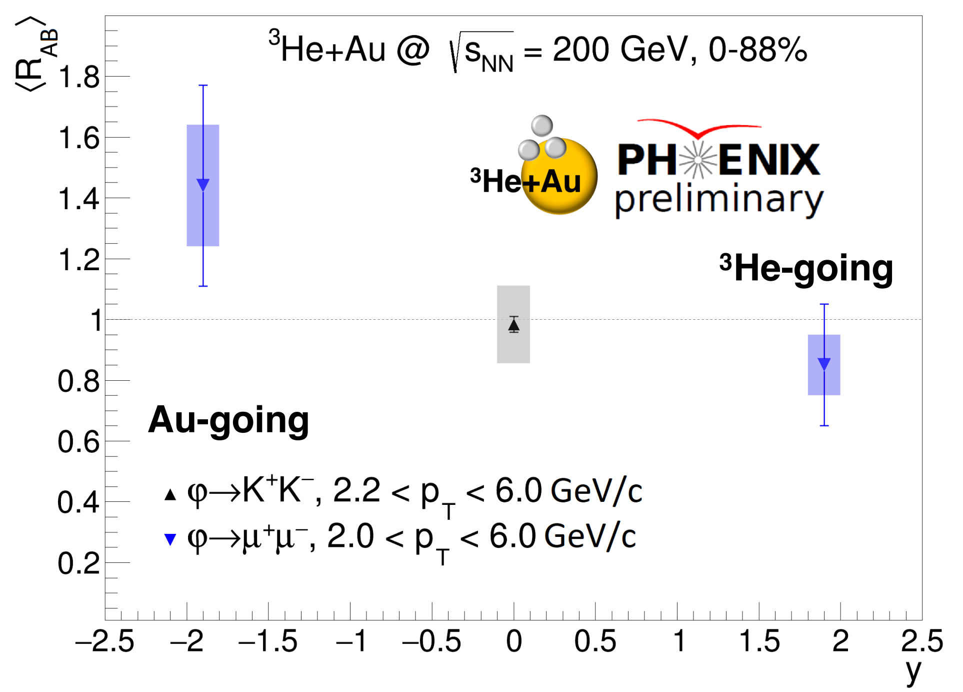
*Final-state effects in $^3$He+Au?*



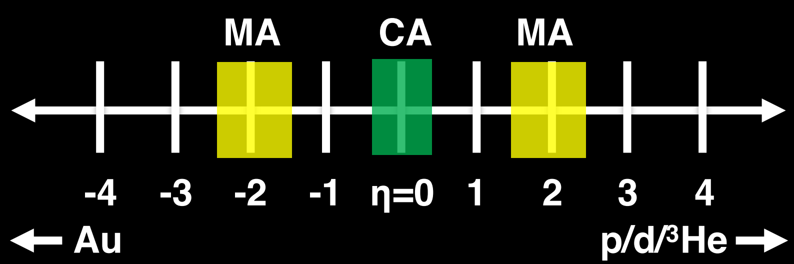



# Modification of φ at forward and backward

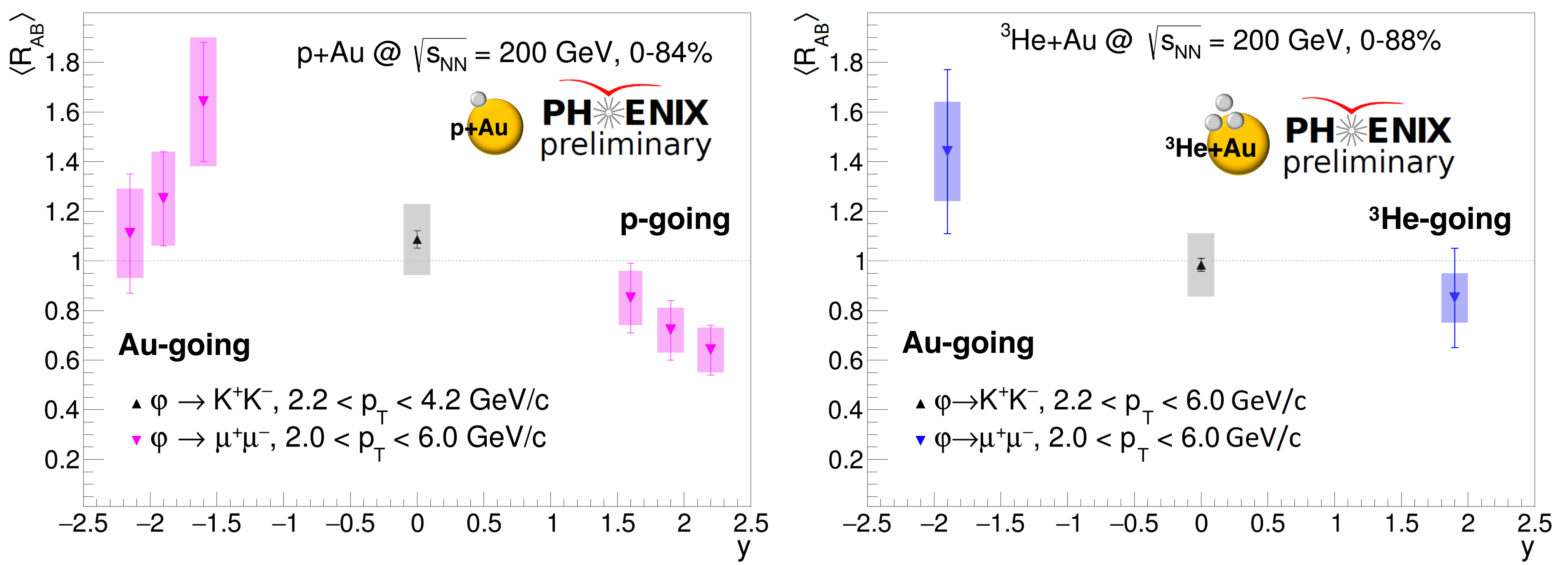



Observed enhancement at backward and suppression at forward indicate different nuclear effects dominate in different η ranges



# *Modification of φ at forward and backward*

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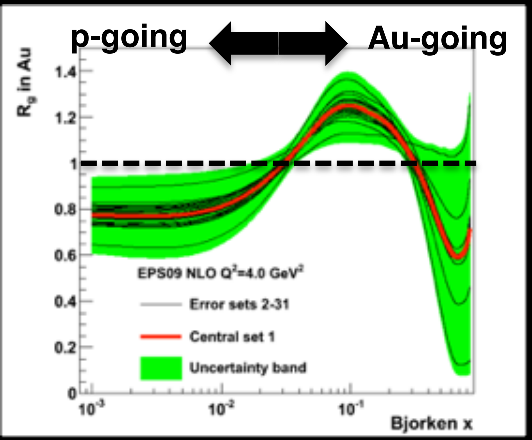


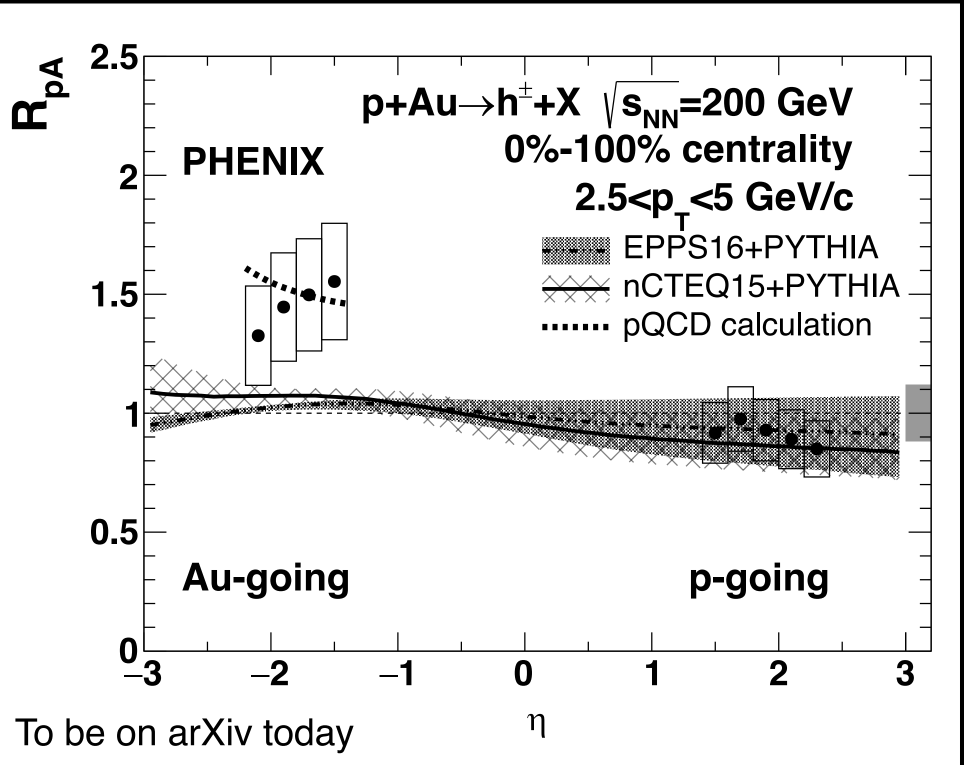

***Parton-x in nucleus?***

Sensitive to shadowing of low-x (anti-shadowing of high-x) partons in Au at forward (backward)

***Multiplicity effect?***

Larger particle density at backward

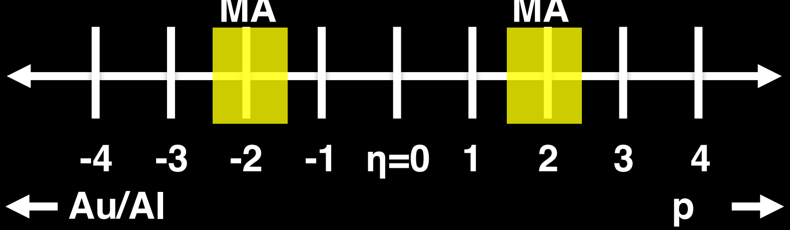
# Charged hadrons in p+A




pQCD calculation: Phys. Lett. B 740, 23 (2015)

In charged hadron production, very similar modification as the $\phi$ results

Modification based on nPDF sets can describe the forward results but underestimate the enhancement at backward



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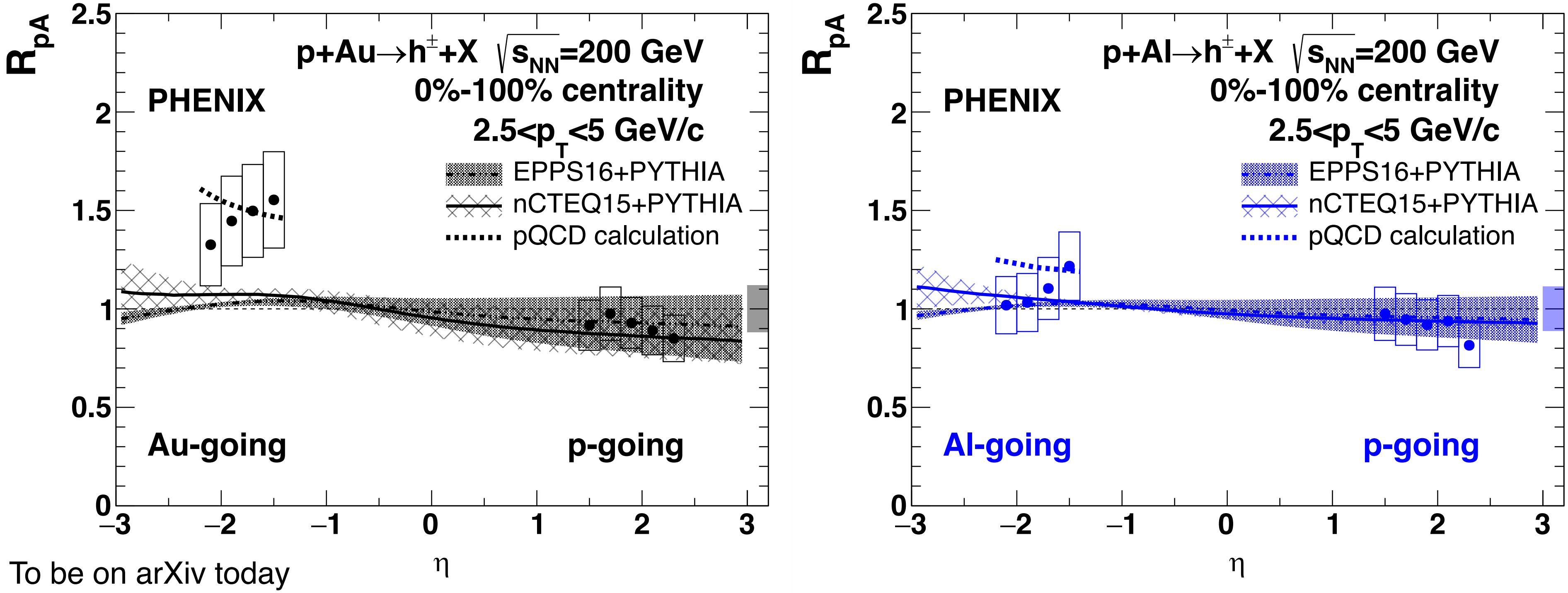



To be on arXiv today

pQCD calculation: Phys. Lett. B 740, 23 (2015)

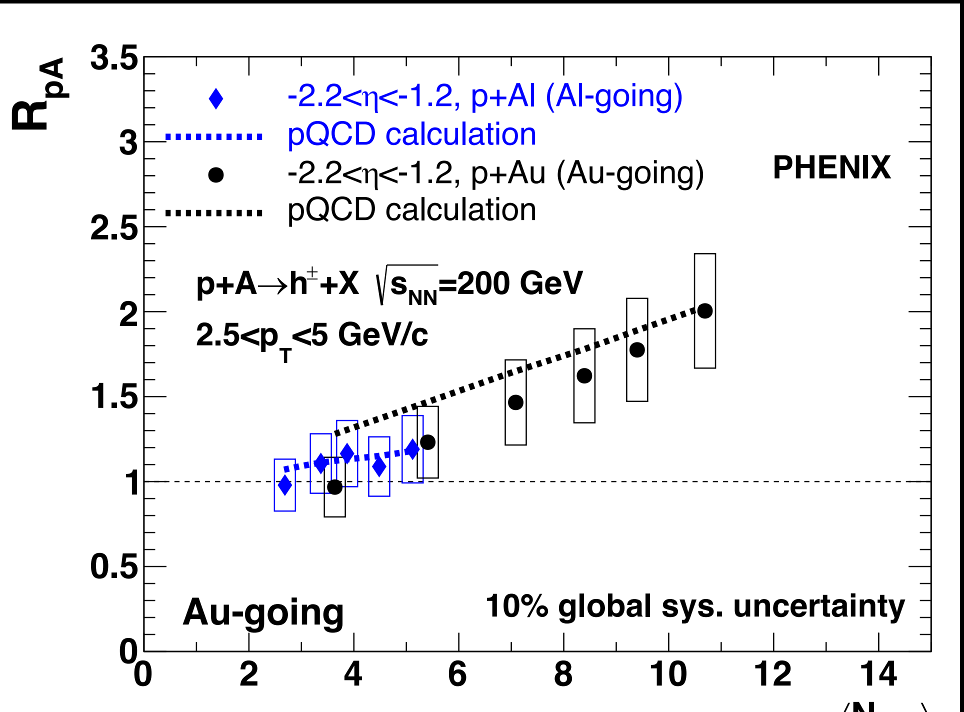
In charged hadron production, very similar modification as the $\phi$ results

Modification based on nPDF sets can describe the forward results but underestimate the enhancement at backward

In p+Al collisions, a clear A-dependence only at backward (*A-going direction*)

pQCD calculation considering incoherent multiple scattering can describe the difference between p+Au and p+Al collsions

# *A-dependent modification*



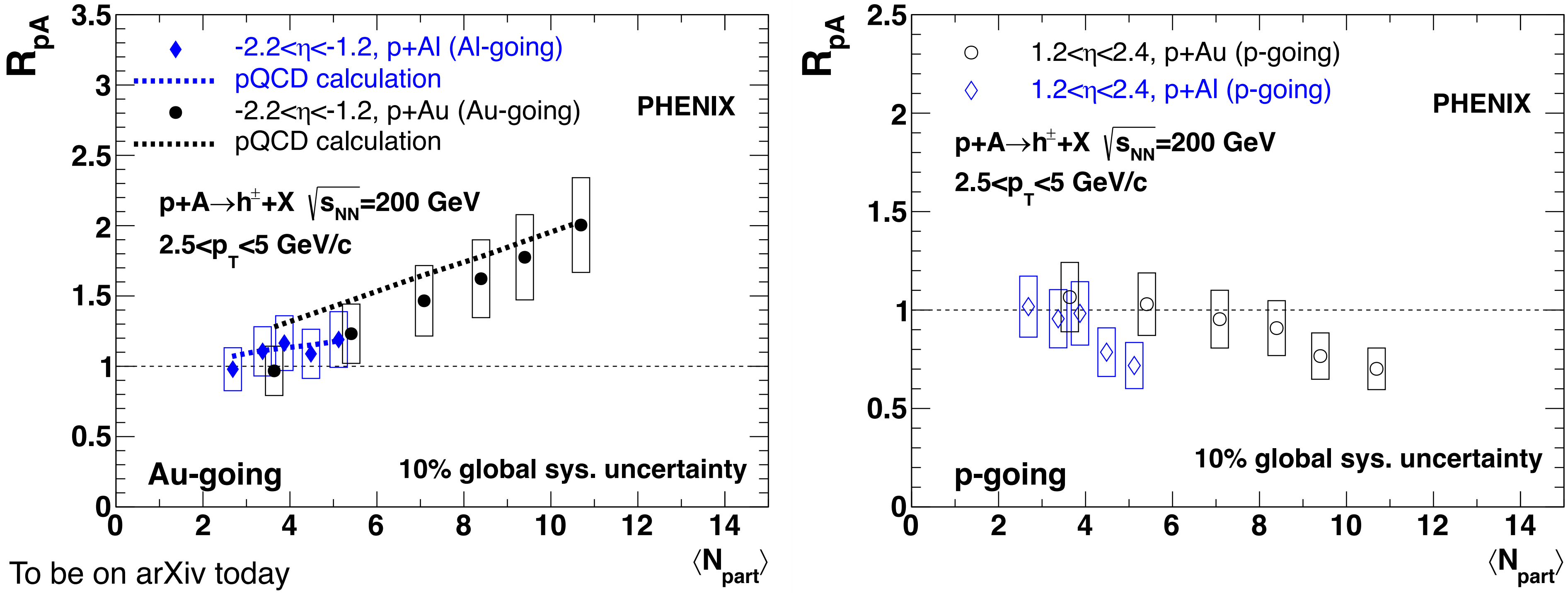

To be on arXiv today

pQCD calculation: Phys. Lett. B 740, 23 (2015)

At backward rapidity (*A-going direction*),

$R_{pA}$ in p+Au and p+Al follows the same trend of increasing with $\langle N_{part} \rangle$

# *A-dependent modification*




To be on arXiv today

pQCD calculation: Phys. Lett. B 740, 23 (2015)

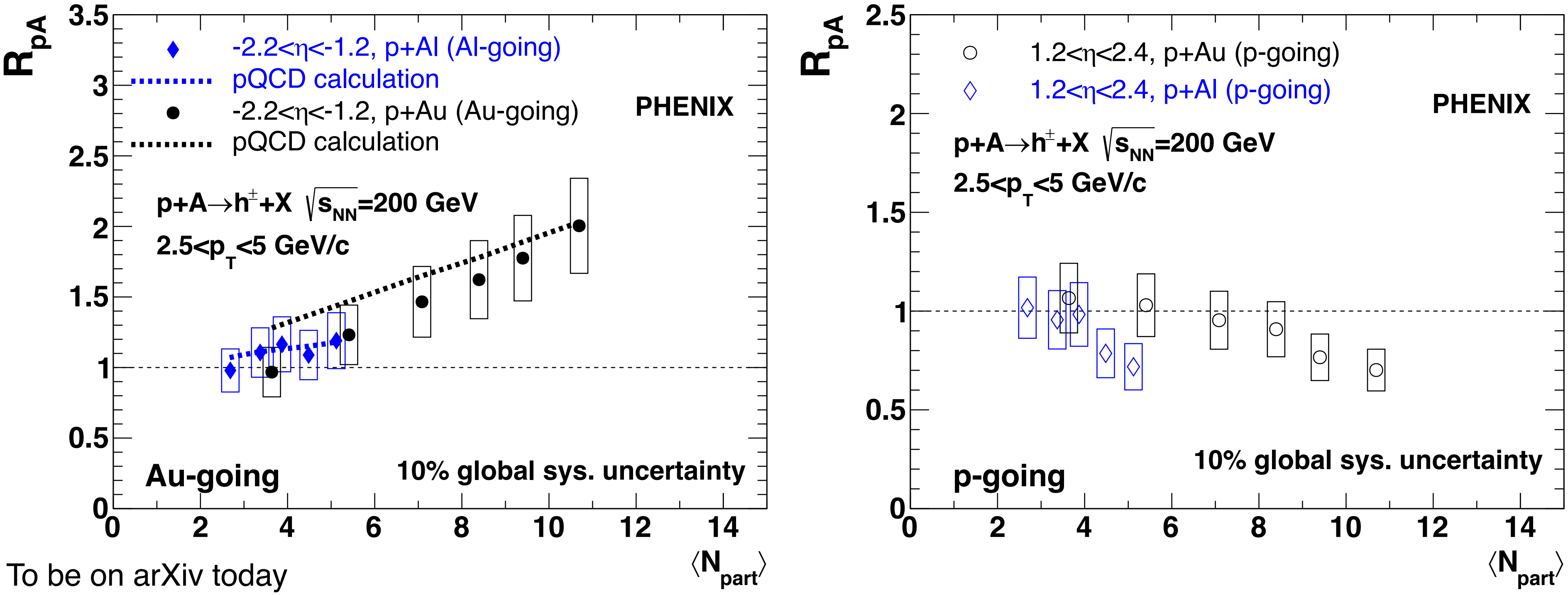
At backward rapidity (*A-going direction*),

$R_{pA}$ in p+Au and p+Al follows the same trend of increasing with $<N_{part}>$

At forward rapidity (*p-going direction*),

$R_{pA}$ in p+Au and p+Al show their own trend of decreasing with $<N_{part}>$

# *A-dependent modification*




To be on arXiv today

pQCD calculation: Phys. Lett. B 740, 23 (2015)

At backward rapidity (*A-going direction*),

$R_{pA}$ in p+Au and p+Al follows the same trend of increasing with $<N_{part}>$

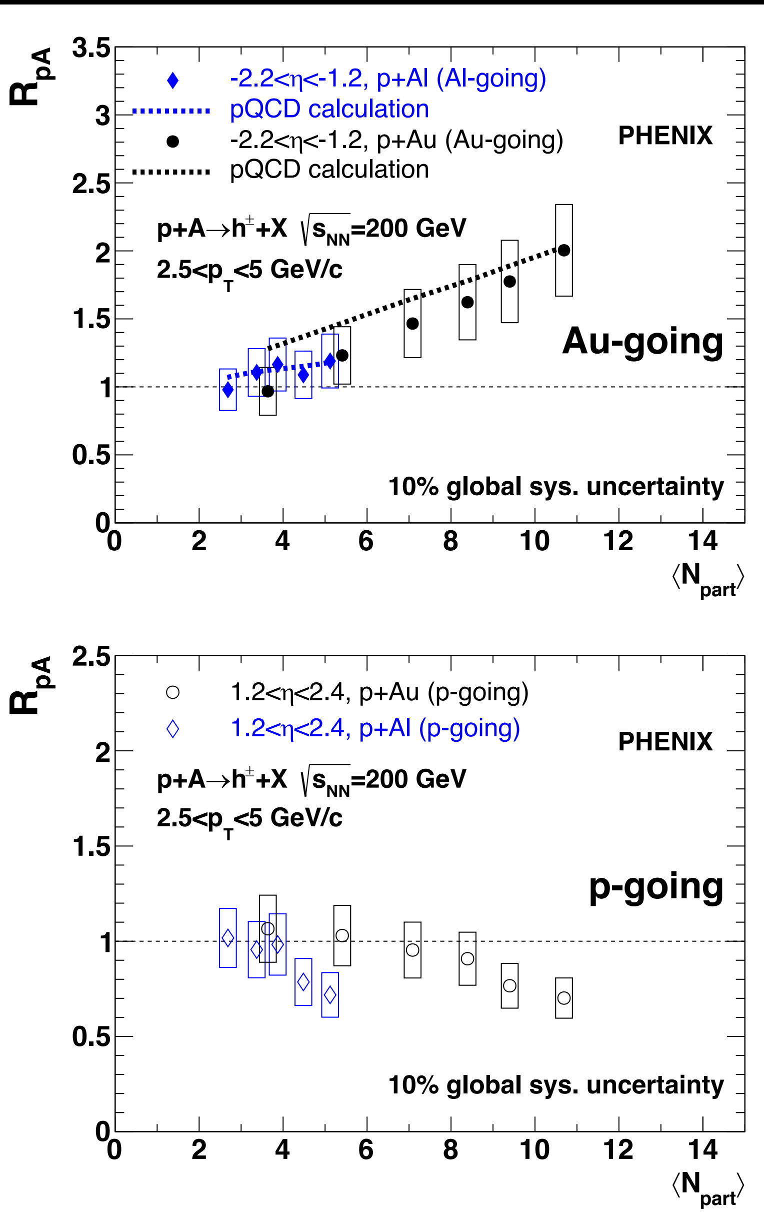
Dominated by final-state effects (multiplicity)?

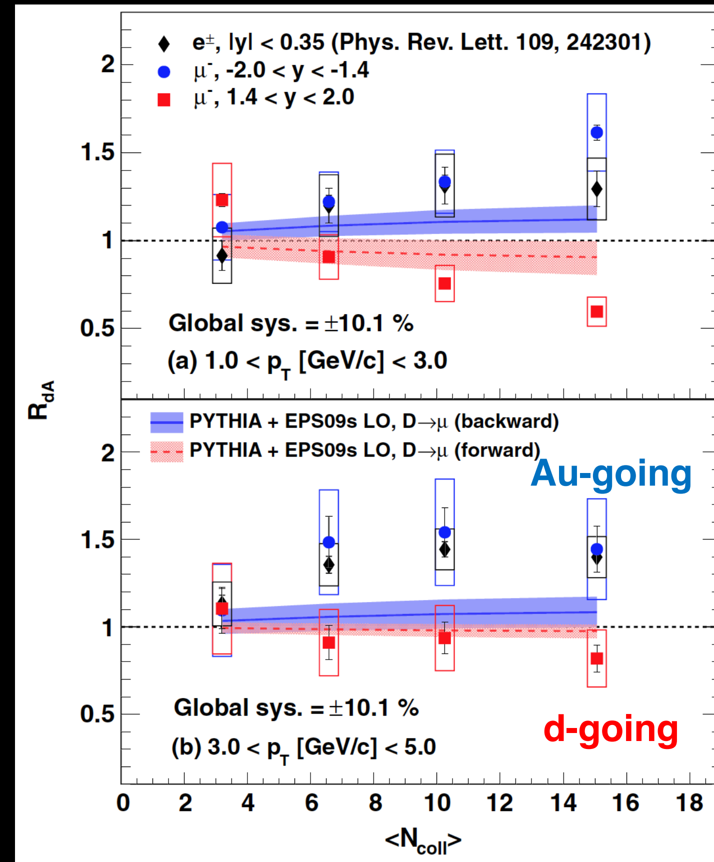
At forward rapidity (*p-going direction*),

$R_{pA}$ in p+Au and p+Al show their own trend of decreasing with $<N_{part}>$

Dominated by initial-state effects (impact parameter)?

# *Comparison with heavy-flavor*



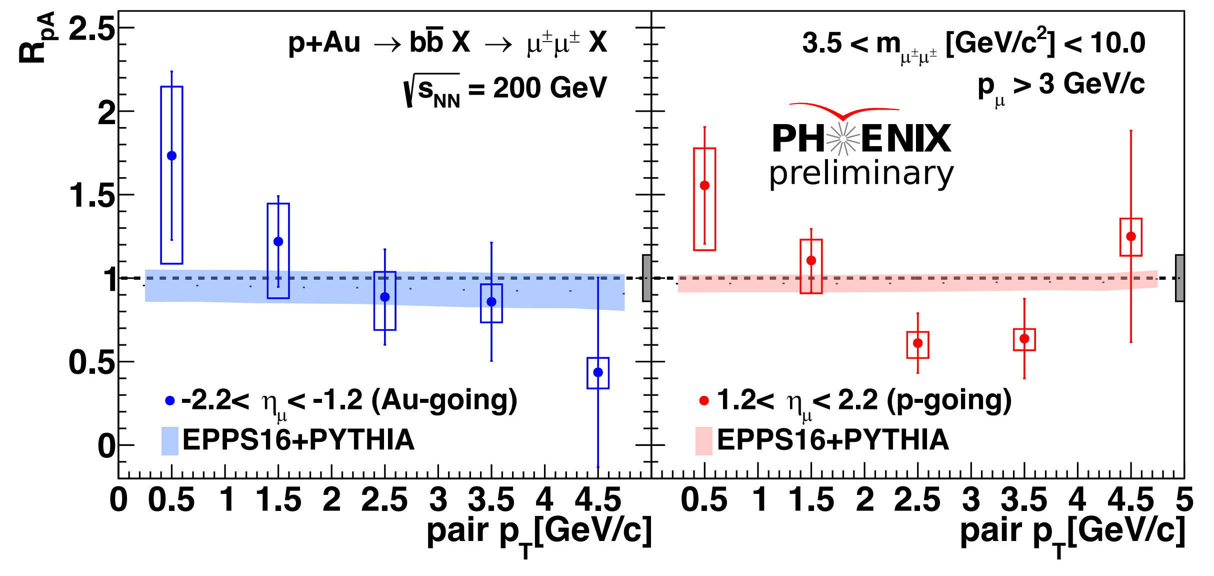

Phys. Rev. Lett. 112, 252301 (2014)

To be on arXiv today

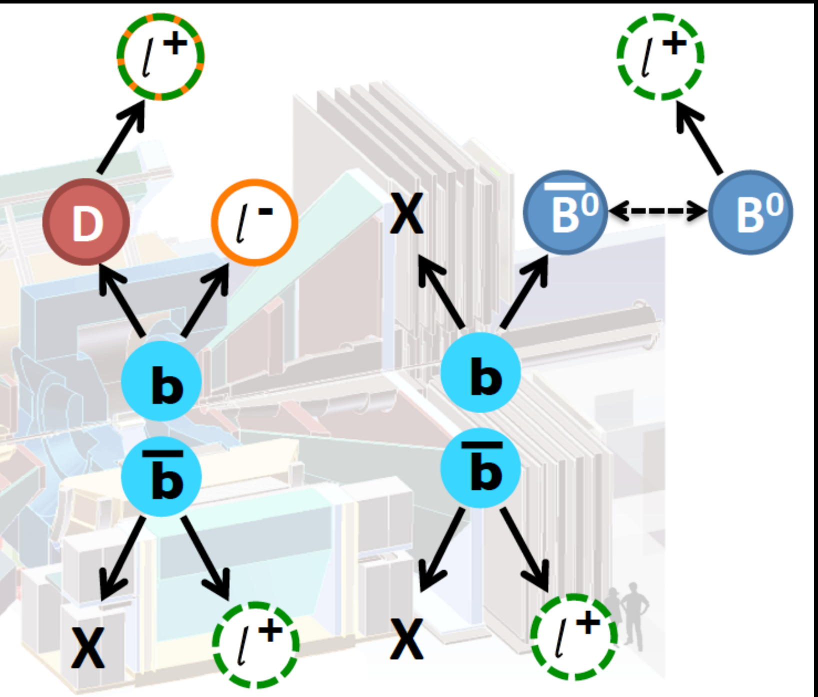
Similar modification in charged hadrons and heavy-flavor muons (dominated by charm) both at forward and backward

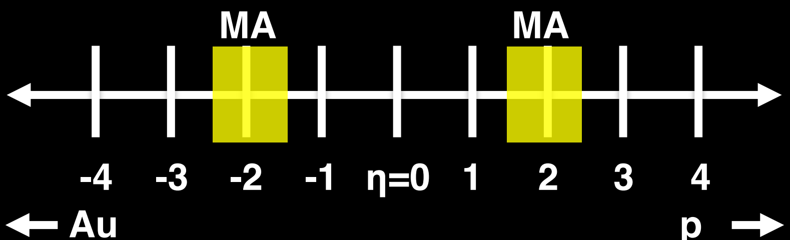
Common nuclear effects
for light and charm in small collision systems?

# *dimuons from bb*

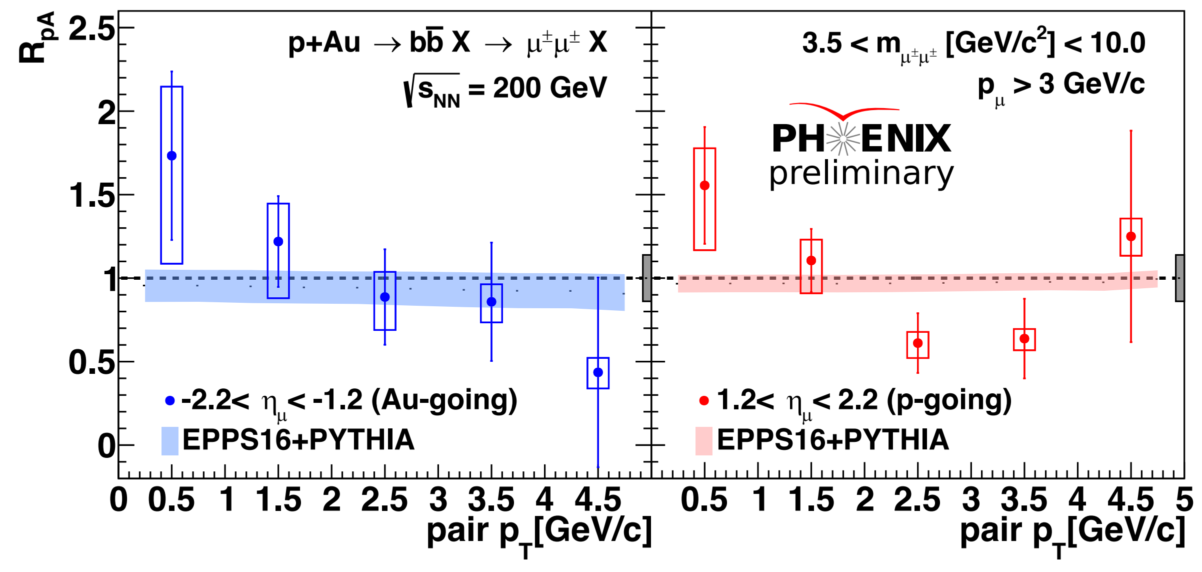



Indication of modification in pair $p_T$ of dimuon from bb at both forward and backward



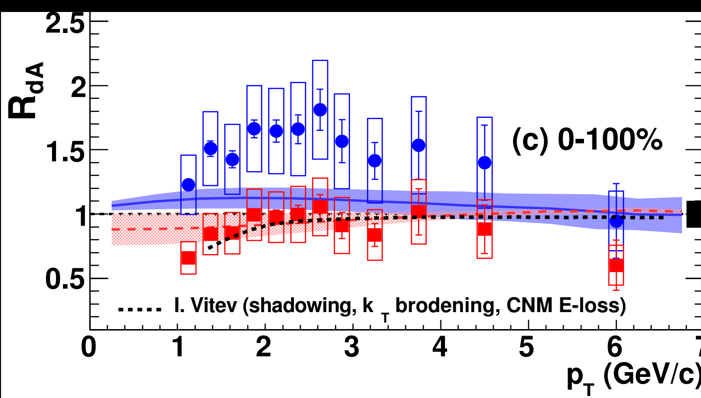
# *dimuons from bb*




Indication of modification in pair $p_T$ of dimuon from bb at both forward and backward

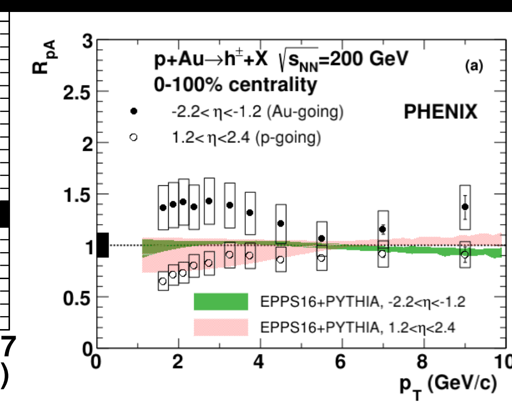
Similar with $p_T$ broadening of charged hadrons and heavy-flavor muons

**Heavy-flavor muon**




Phys. Rev. Lett. 112, 252301 (2014)

**Charged hadron**




To be on arXiv today

Common nuclear effects in small collision systems for bottom as well?

# *PHENIX talks at Initial Stages 2019*

- *PHENIX measurements of muon pairs from cc, bb, and Drell-Yan in p+p and p+Au at 200 GeV*
  - Axel Drees (nPDF/CNM, June/25 TUE, PM 3:10)

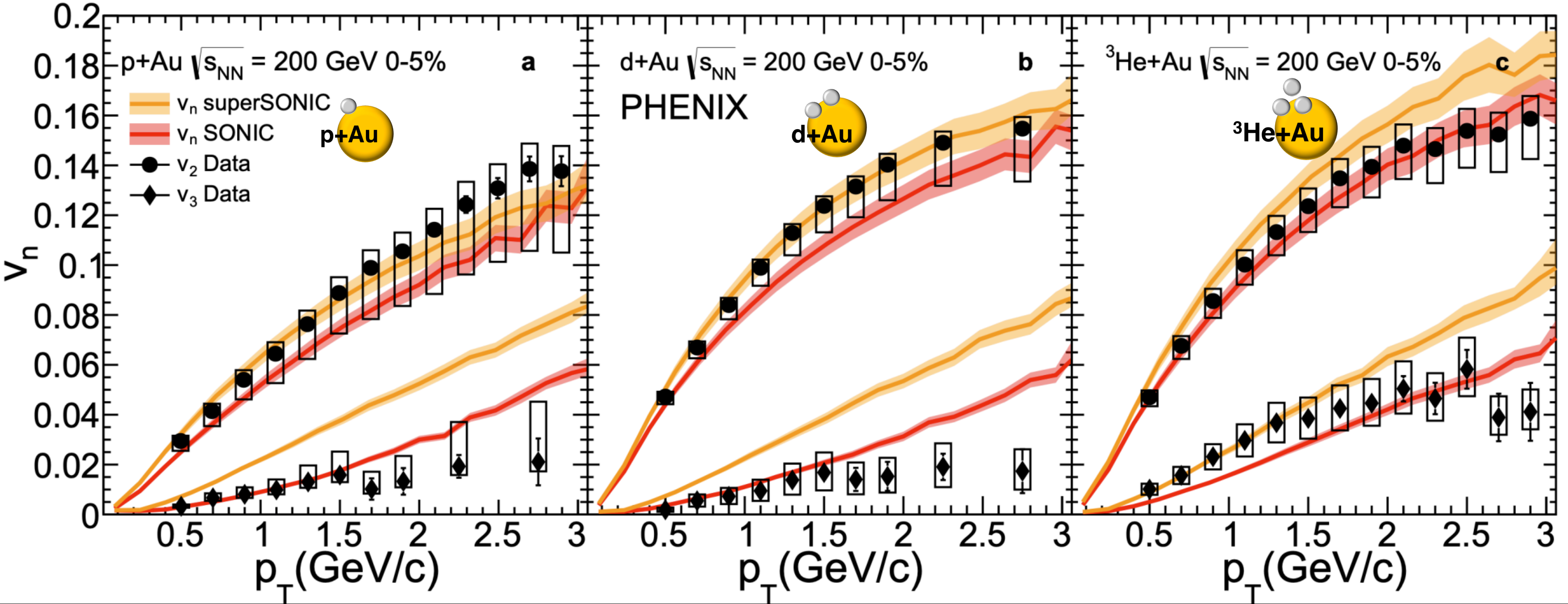
- *Probing collision dynamics of small system collisions via high $p_T$ hadrons and direct photons by the PHENIX experiment at RHIC*
  - Takao Sakaguchi (high $p_T$ probe of initial states, June/26 WED, PM 2:40)

- *Observation of collectivity in p+Au, d+Au, and $^3$He+Au collisions with PHENIX*
  - Qiao Xu (Collectivity in small systems, June/26 WED, PM 4:50)

## *Thank you*

# *BACKUP*

# Model description (Hydrodynamic model)



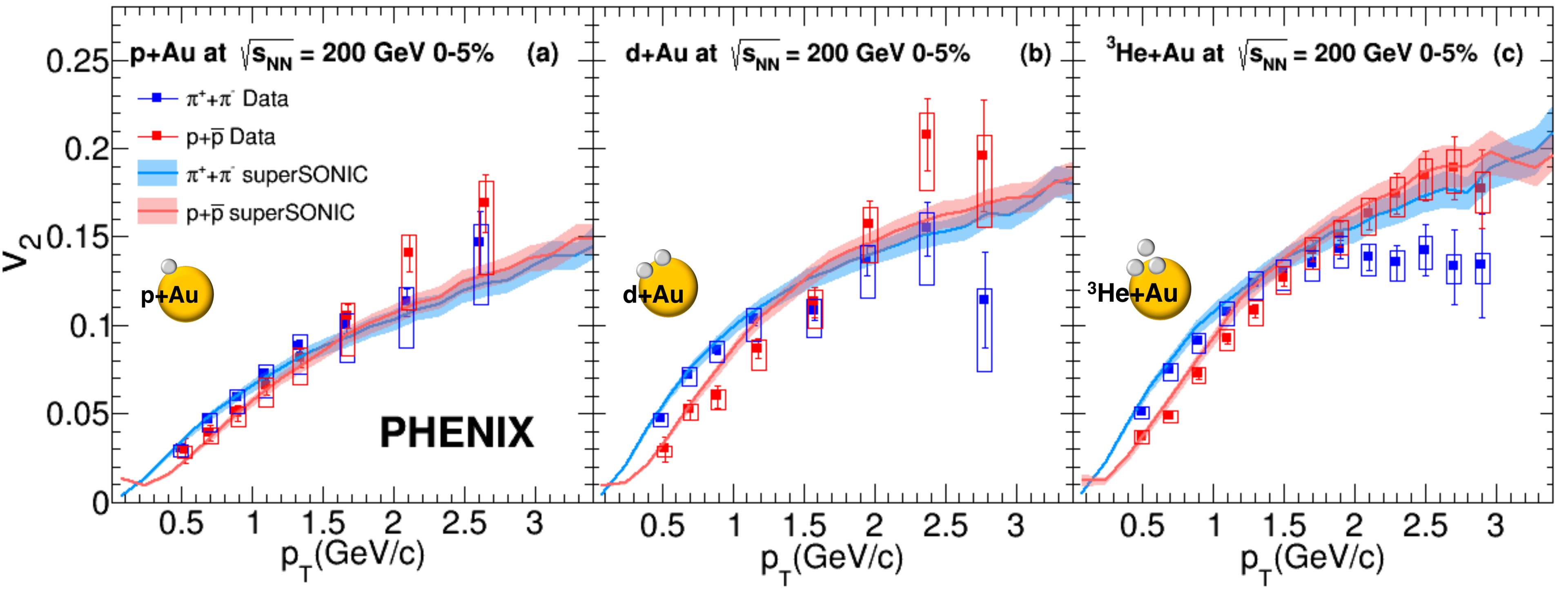

Nature Phys. 15, 214 (2019)

SONIC: Eur. Phys. J. C 75, 15 (2015)

Good agreement with $v_2$ and $v_3$ from hydrodynamic models in all three systems

Hydrodynamic model with pre-flow (superSONIC)
does not give as good agreement model without pre-flow (SONIC)

# *Identified particles*



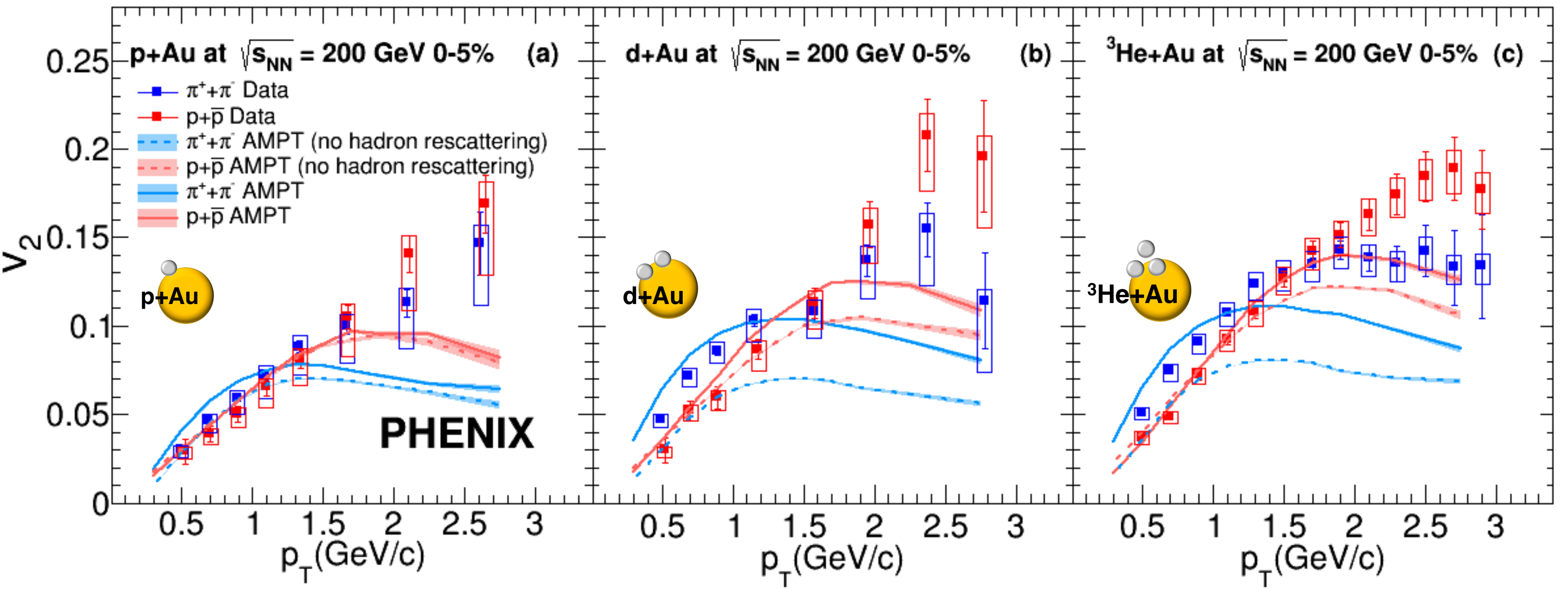

Phys. Rev. C 97, 064904 (2018)

Clear mass dependent $v_2$ in all three systems

$p_T$<1.5 GeV: Higher pion $v_2$

$p_T$>1.5 GeV/c: Higher proton $v_2$

Hydrodynamic model describes the mass ordering in $p_T$<1.5 GeV/c




Phys. Rev. C 97, 064904 (2018)

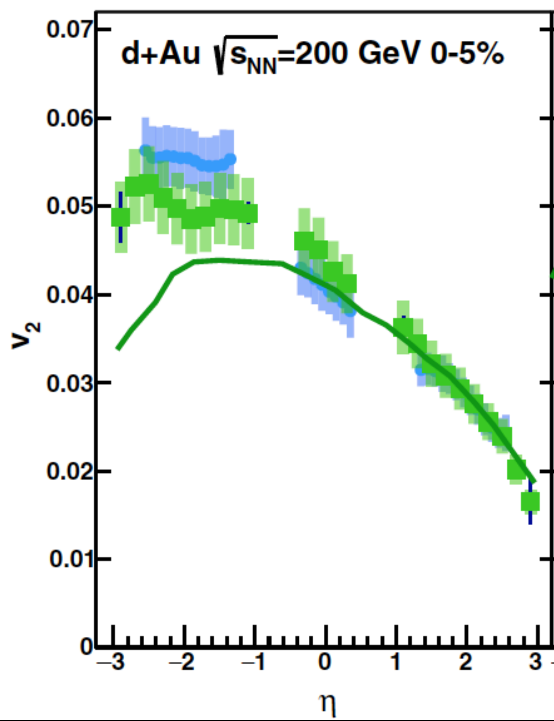
Clear mass dependent $v_2$ in all three systems

$p_T$<1.5 GeV: Higher pion $v_2$

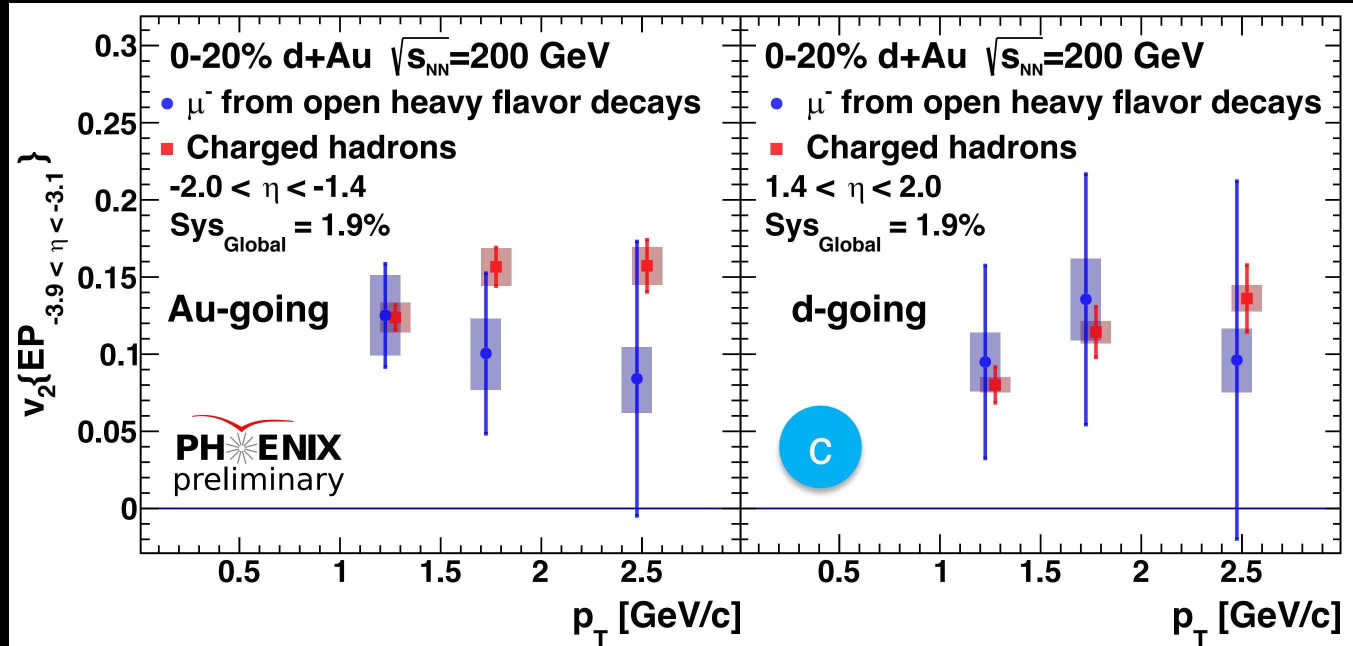
$p_T$>1.5 GeV/c: Higher proton $v_2$

AMPT with hadronic rescattering also describes the mass ordering in $p_T$<1.5 GeV/c
The splitting in $p_T$>1.5 GeV/c is also described by AMPT from coalescence

# *Heavy-flavor $v_2$*




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

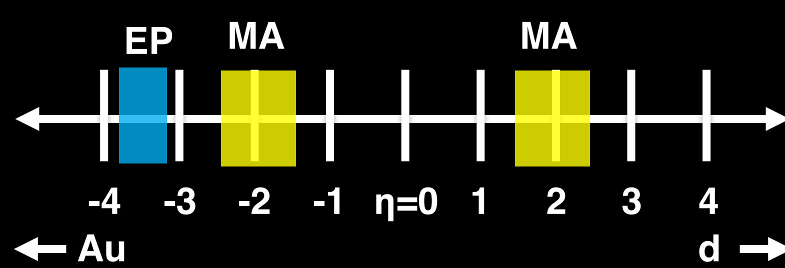



Non-zero $v_2$ of muons from heavy-flavor decays (mostly charm) at forward and backward in d+Au collisions

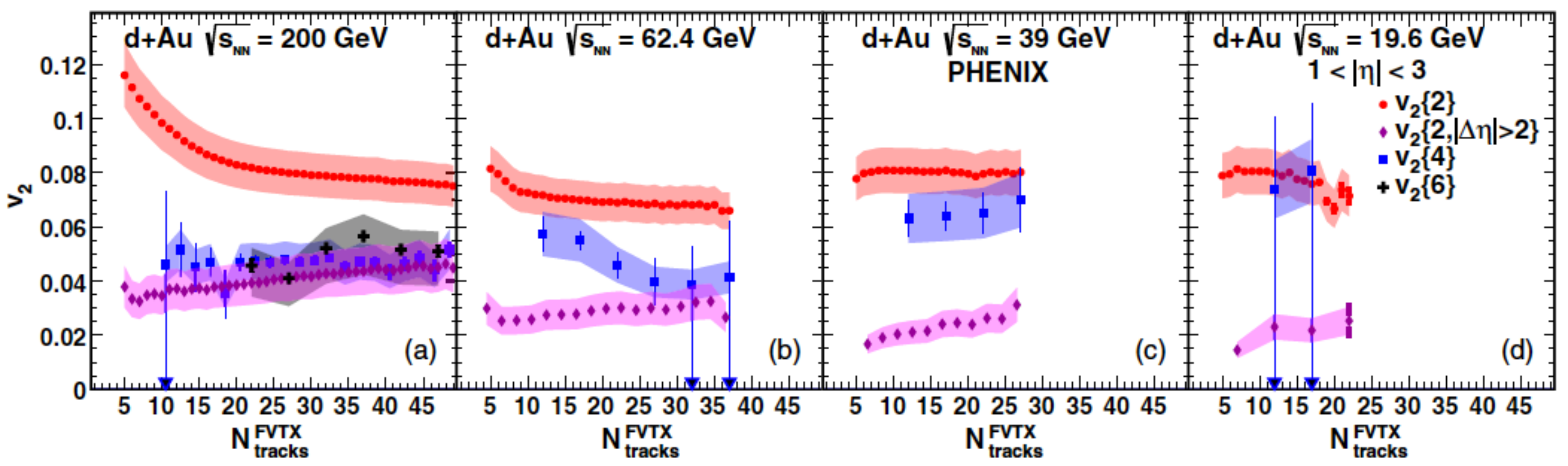
Finite $v_2$ for charm in p+Pb

CMS: Phys. Rev. Lett. 121, 082301 (2018)

ALICE: Phys. Rev. Lett.122, 072301 (2019)



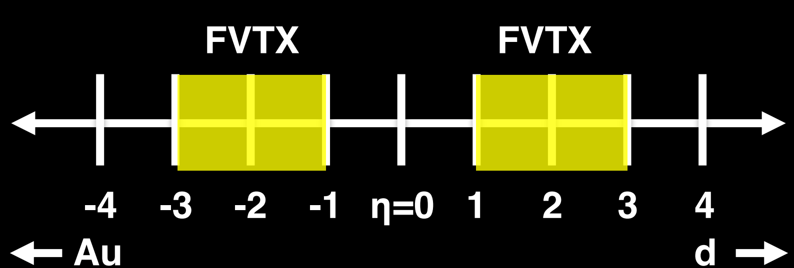
# Multiparticle correlation in d+Au



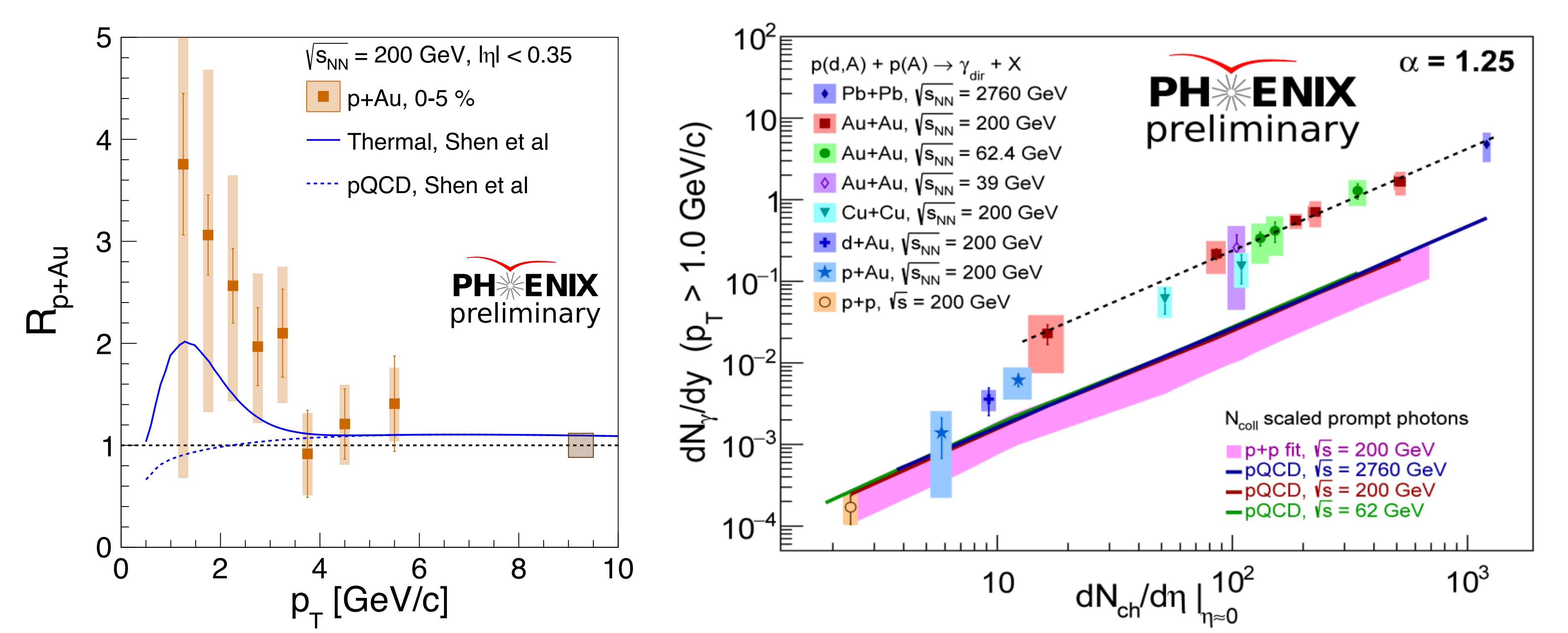

Phys. Rev. Lett. 120, 062302 (2018)

Non-zero $v_2\{4\}$ in d+Au collisions at all energies!

At 200 GeV, consistent $v_2\{2,|\Delta\eta|>2\}$, $v_2\{4\}$, and $v_2\{6\}$ indicate minimal non-flow effect



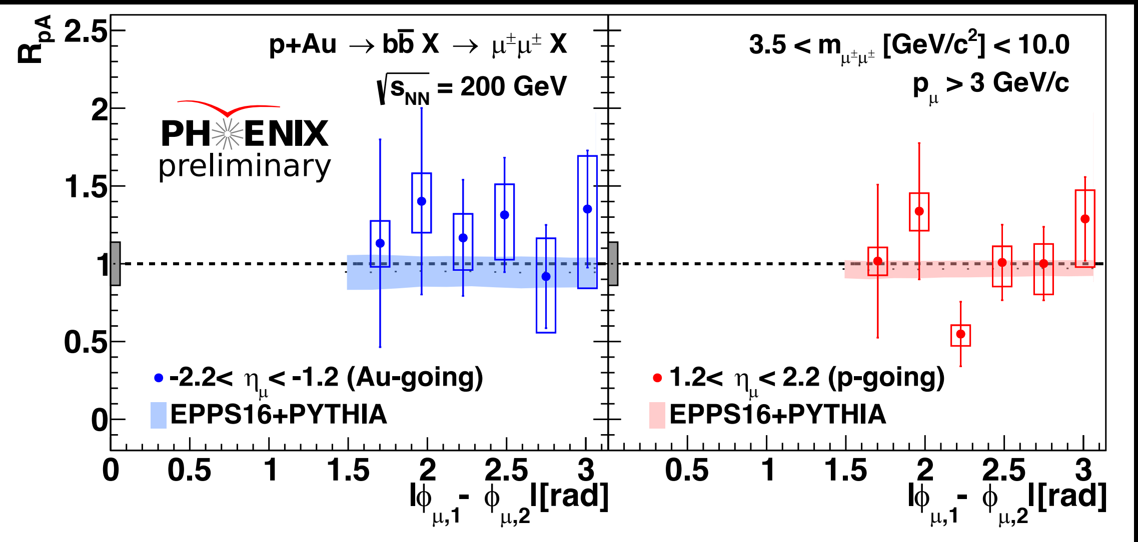
# Direct photons in p+Au




Direct photon yield in 0-5% p+Au collision is higher than the scaled p+p yield

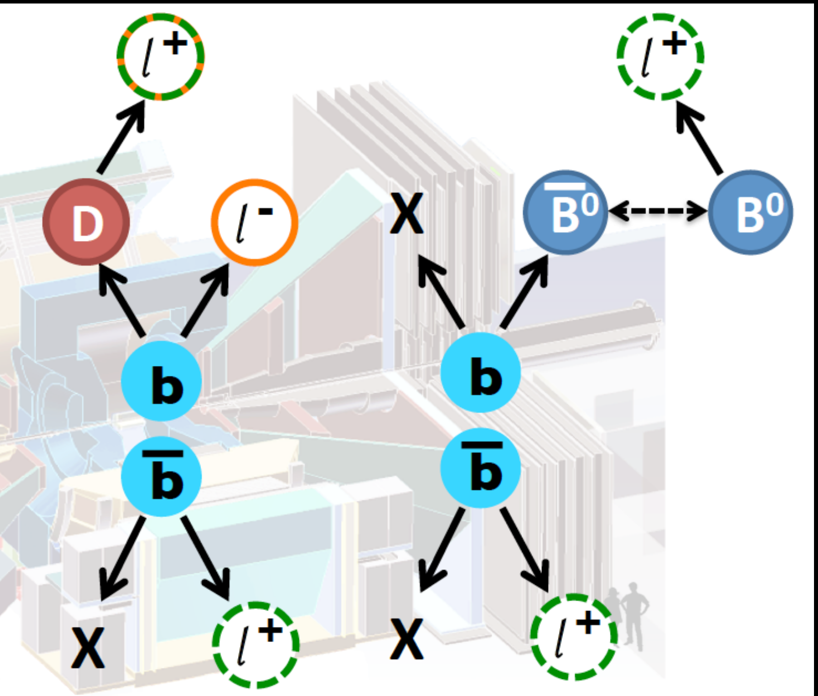
Integrated yields in p+Au and d+Au collisions fill the gap between p+p and A+A

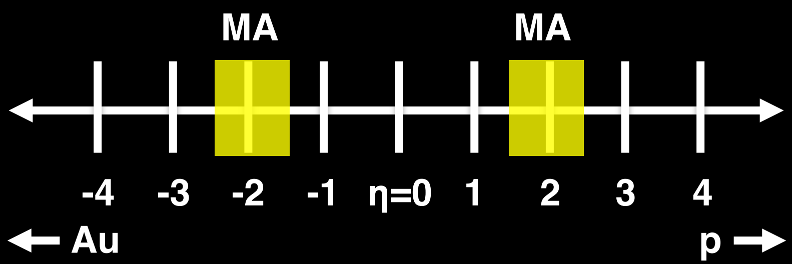
# *dimuons from bb*



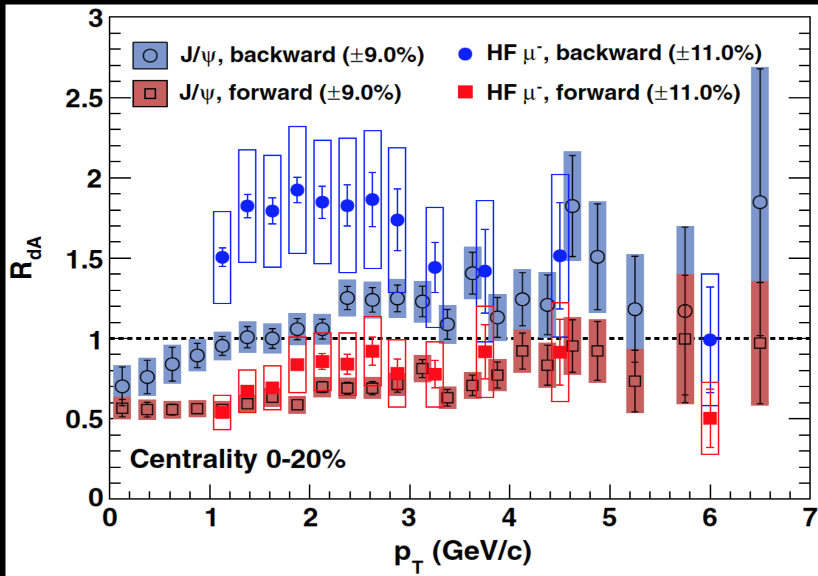

No overall modification in
Δϕ between dimuon from bb
both at forward and backward

Consistent with nPDF

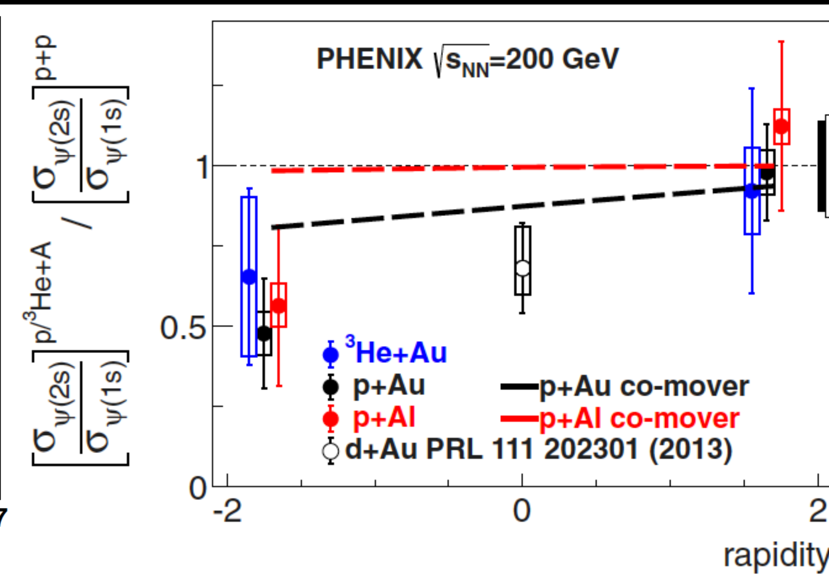


# J/ψ in small systems



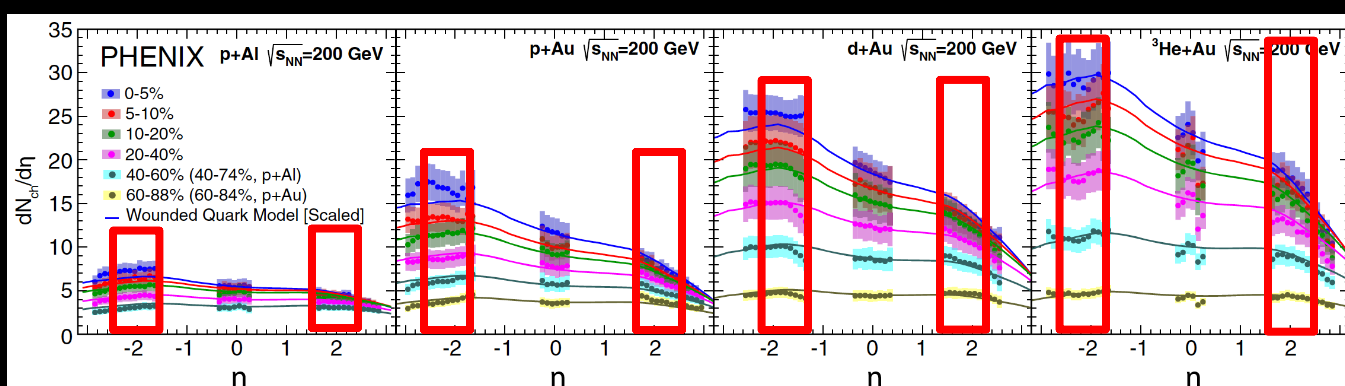

Phys. Rev. Lett. 112, 252301 (2014)




Phys. Rev. C 95, 034904 (2017)

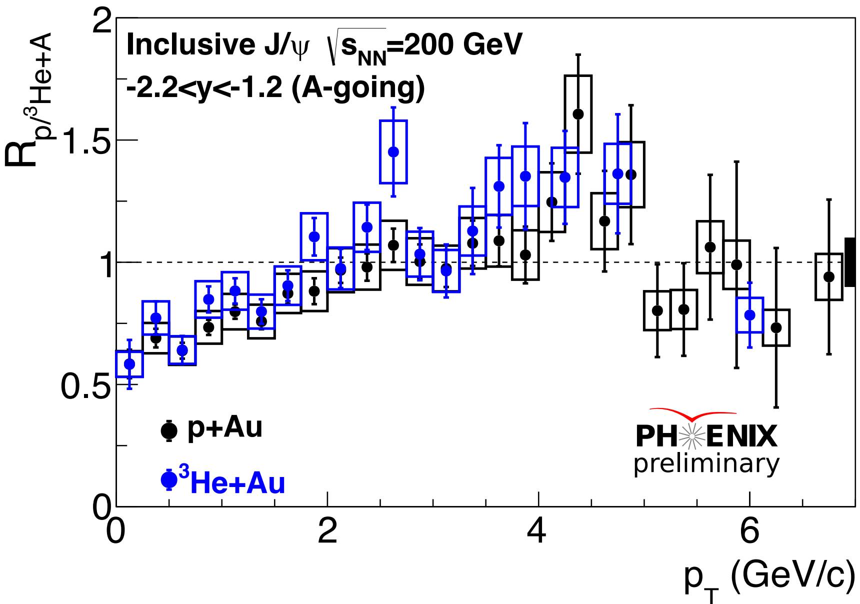
Initial-state effects are expected to be similar for open and hidden heavy-flavor

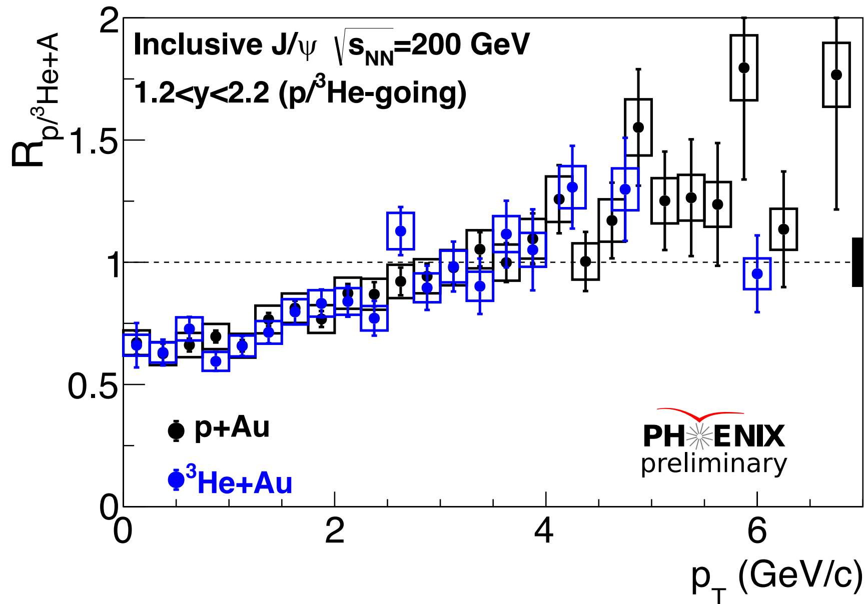
Clear indication of final-state effects at A-going direction




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

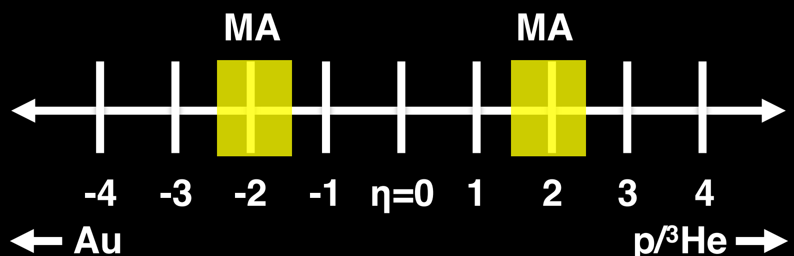
# *Modification of J/ψ*



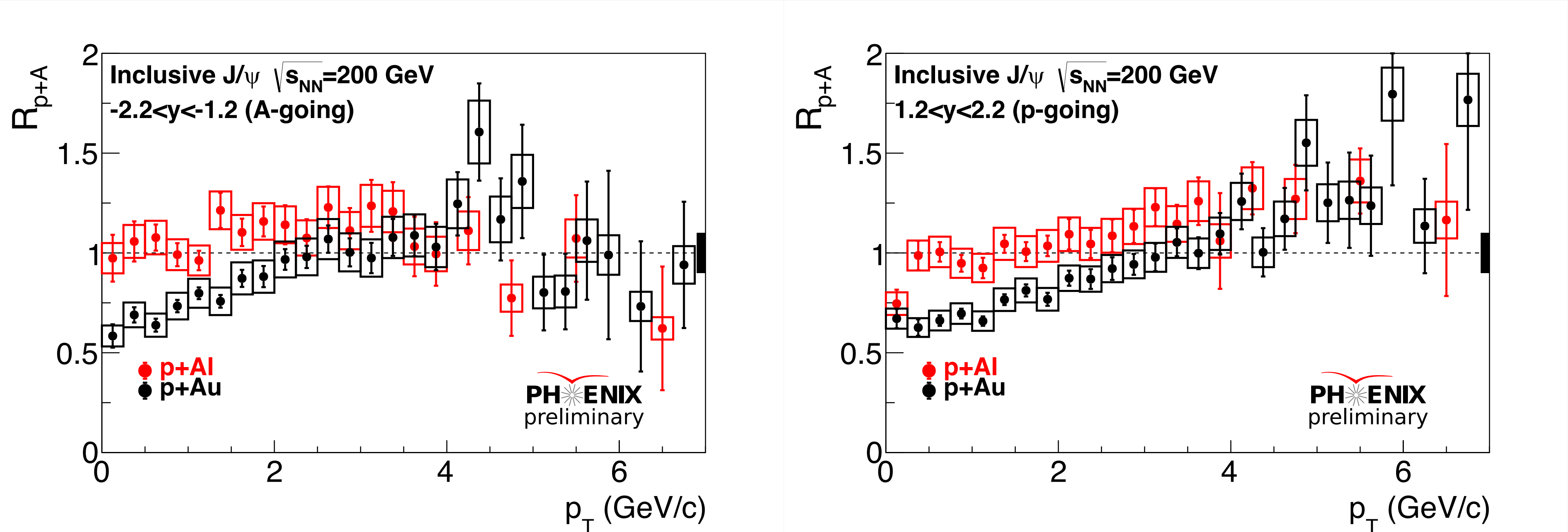




Similar modification of J/ψ in p+Au and $^3$He+Au both at forward and backward

No dependence on projectile



# Modification of J/ψ




Different modification of J/ψ in p+Al and p+Au both at forward and backward

Clear dependence on target size

Centrality dependence study in all small systems coming soon