PHENIX Experiment Highlights

Alexandre Lebedev (Iowa State University) for the PHENIX Collaboration

The XXIV International Workshop on
High Energy Physics and Quantum Field Theory
September 22 – September 29, 2019
Sochi, Russia

Huge amount of data collected by PHENIX

$\sqrt{s}$ [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								✓	

PHENIX at RHIC: 16 years of running, 9 collision species, 9 collision energies
196 papers published, 12 in the past year (2018)

Talk Outline

Spin physics (polarized proton beams)

- $W^{\pm}$ A_L results — Now published (Phys. Rev. D 98, 032007 (2018))
- h^{+} A_N results — Just submitted (arXiv:1903.07422)
- J/ψ A_N results — Now published (Phys. Rev. D 98, 012006 (2018))
- η A_N results — New!

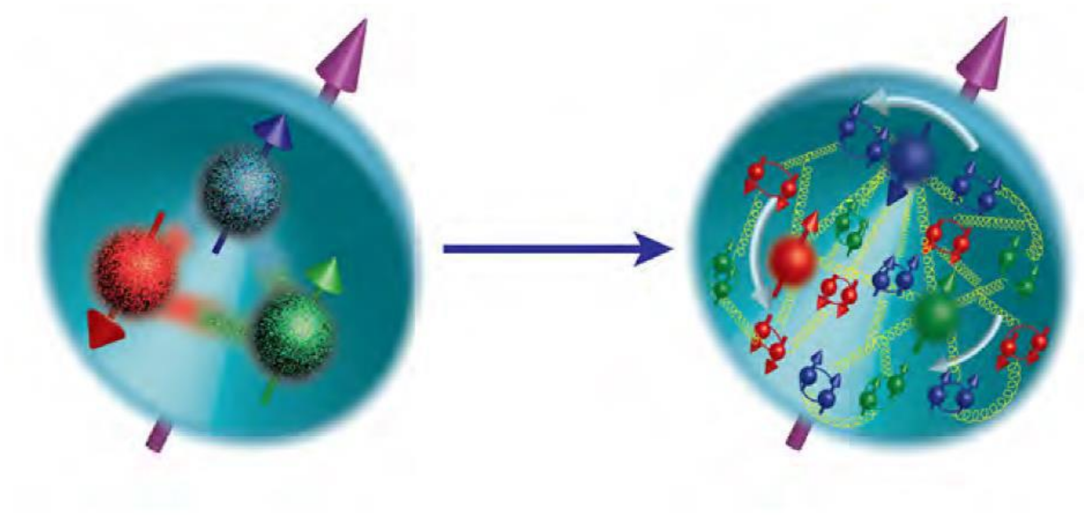
Small systems (p/d/3He + A)

- Longitudinal dynamics in small systems — Now published (Phys. Rev. Lett. 121, 222301 (2018))
- Small systems geometry scan — Now published (Nature Physics 15, 214-220 (2019))
- J/ψ in p+Al and p+Au and 3He+Au — New!
- ϕ meson nuclear modification factors — New!
- Drell-Yan measurement in p+p and p+Au — New!
- Direct photon measurements in p/d+Au — New!

Large systems (heavy ions)

- Single particle suppression: multiple species and collisions — New!
- Strangeness and nuclear modification factor — New!
- Spectra of charm and bottom in p+p — Now published (Phys. Rev. D 99, 092003 (2019))
- Flow of charm and bottom in Au+Au — New!

Spin Physics



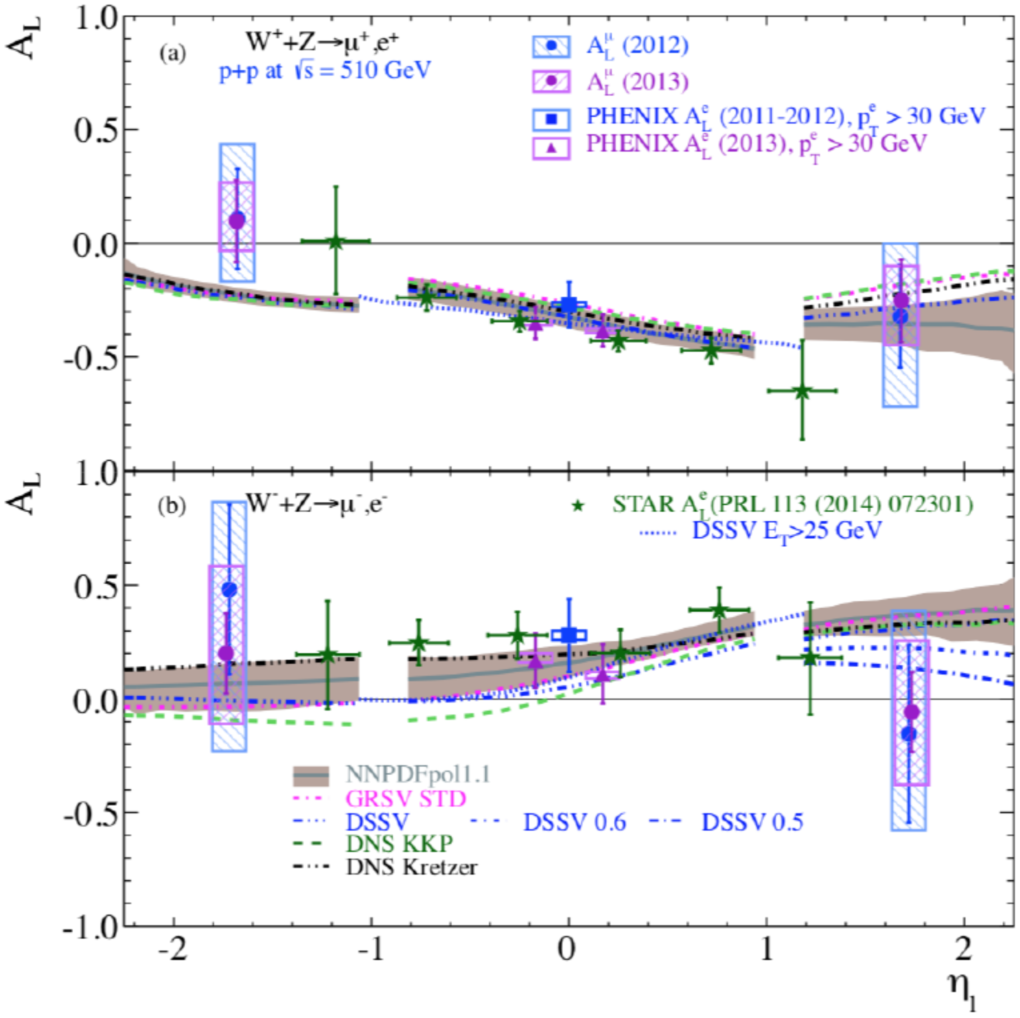
Proton spin is not just a sum of three valence quark spins

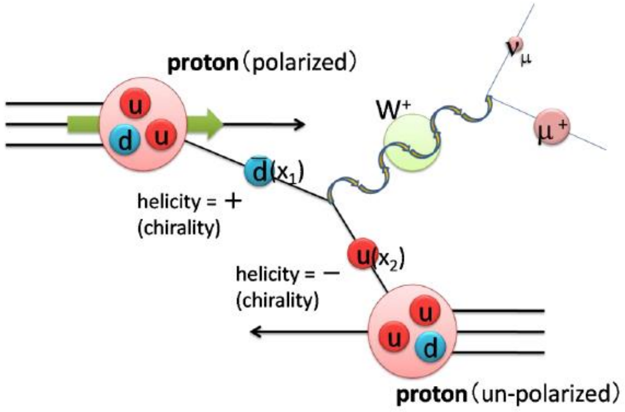
Jaffe-Manohar sum rule: $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$

PHENIX @ RHIC aims at both longitudinal spin structure and transverse spin phenomena

$W^{\pm}$ longitudinal single-spin asymmetry A_L

Phys. Rev. D 98, 032007 (2018)





$$A_L = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$A_L^{W+} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

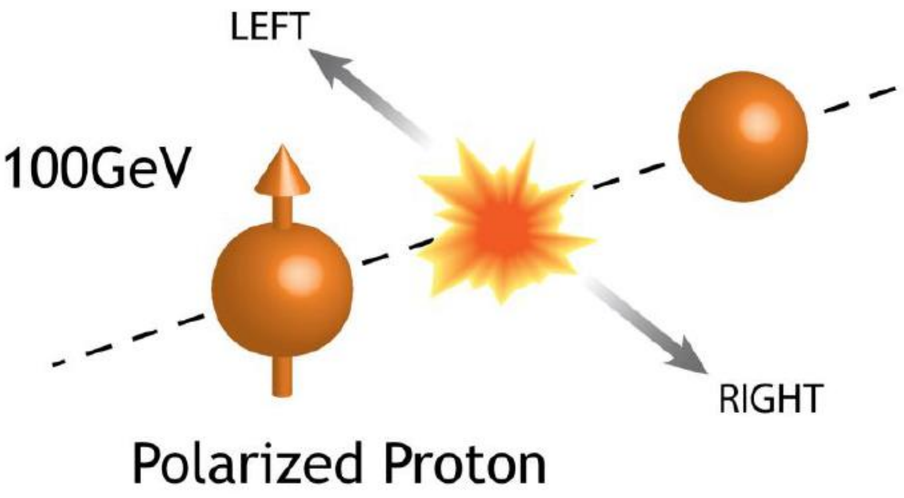
$$A_L^{W-} = \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

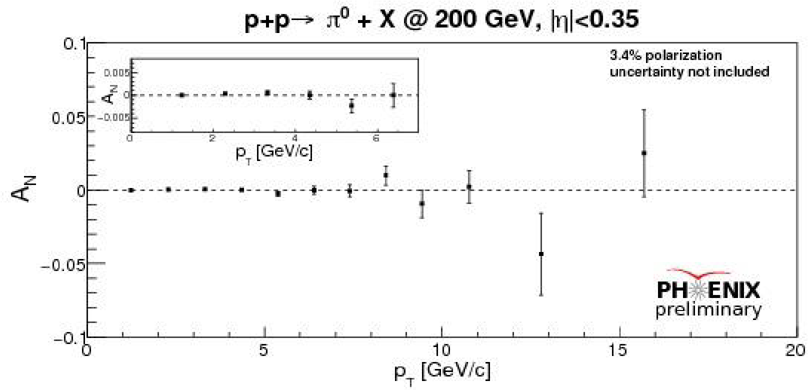
$$A_L^W = \frac{1}{P}\frac{N_+ - RN_-}{N_+ + RN_-}$$

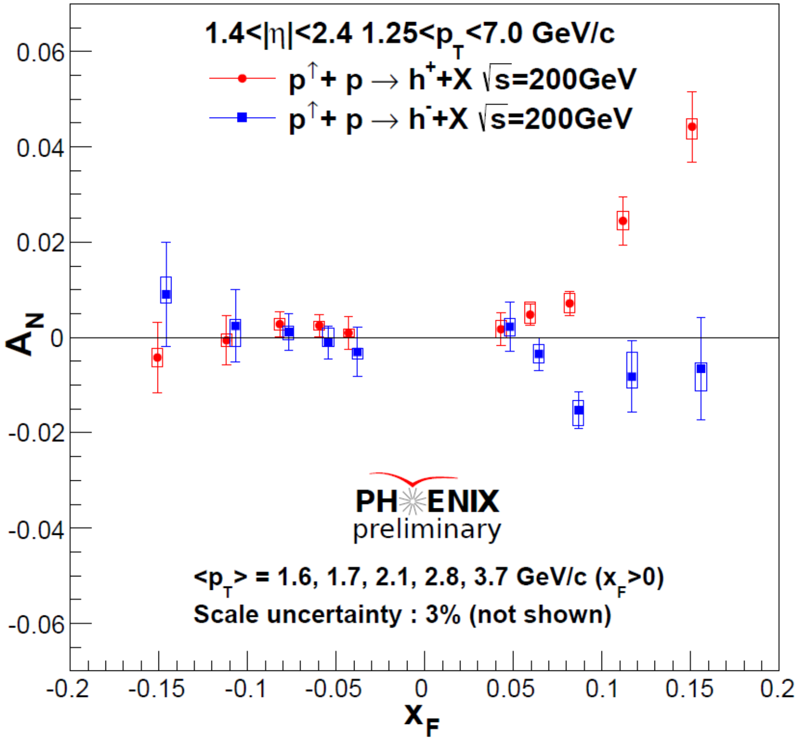
- P : avg. polarization of each beam
- $N+$ ($N-$) : yields in same (opposite) helicity
- $R = \frac{L++}{L+-}$: relative luminosity

A_L sensitive to light sea quarks.
Consistency between PHENIX, STAR, global fits

Transverse single-spin asymmetry A_N





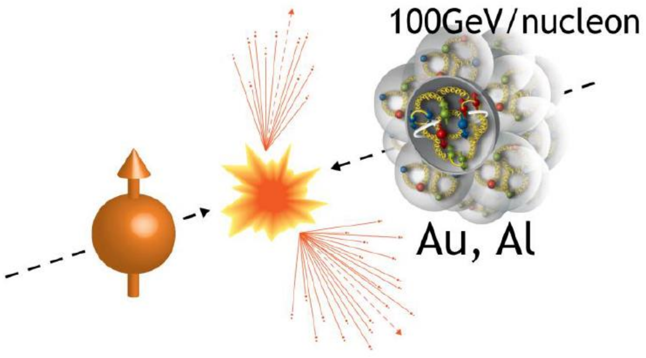


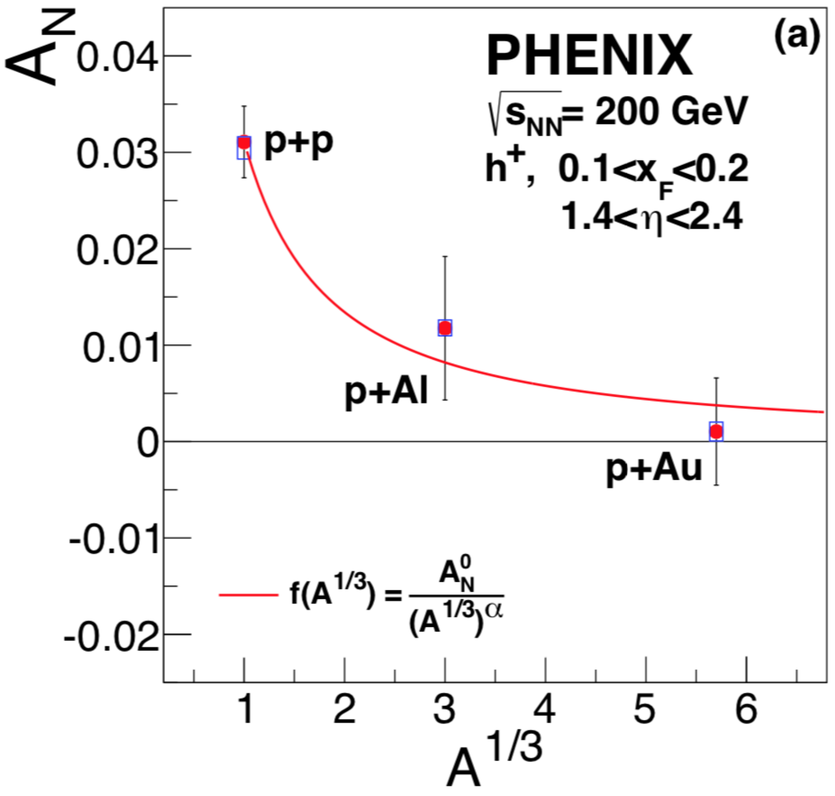
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{P} \times \frac{N_L - N_R}{N_L + N_R}, \quad X_F = \frac{2p_z}{\sqrt{s}} \sim (x_1 - x_2)$$

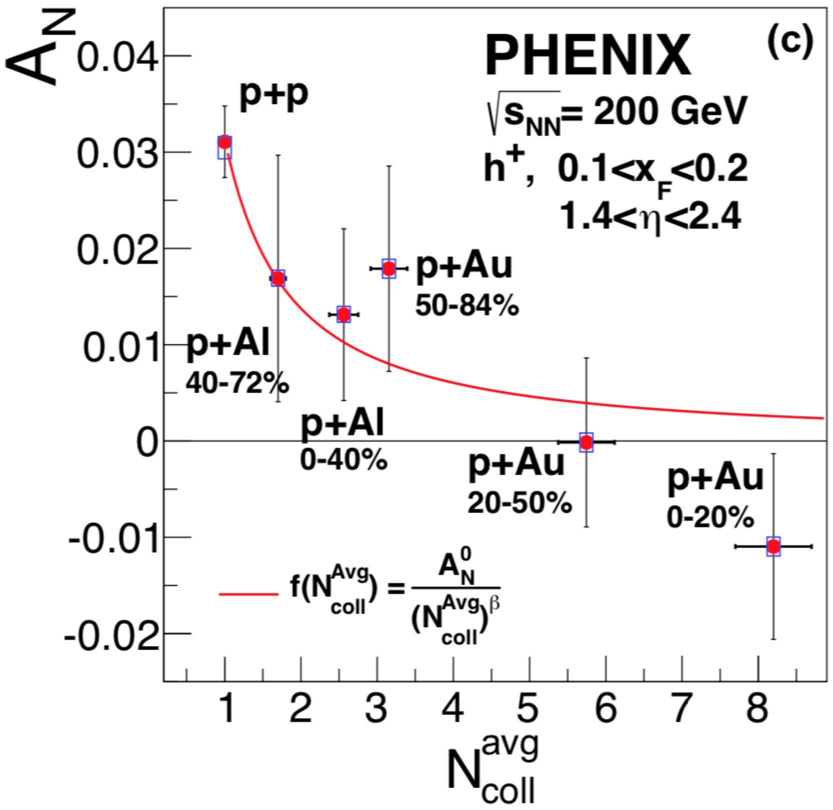
A_N expected to be small in conventional pQCD calculations

Transverse single-spin asymmetry for h^+ in p+A

arXiv:1903.07422 (submitted to PRL)







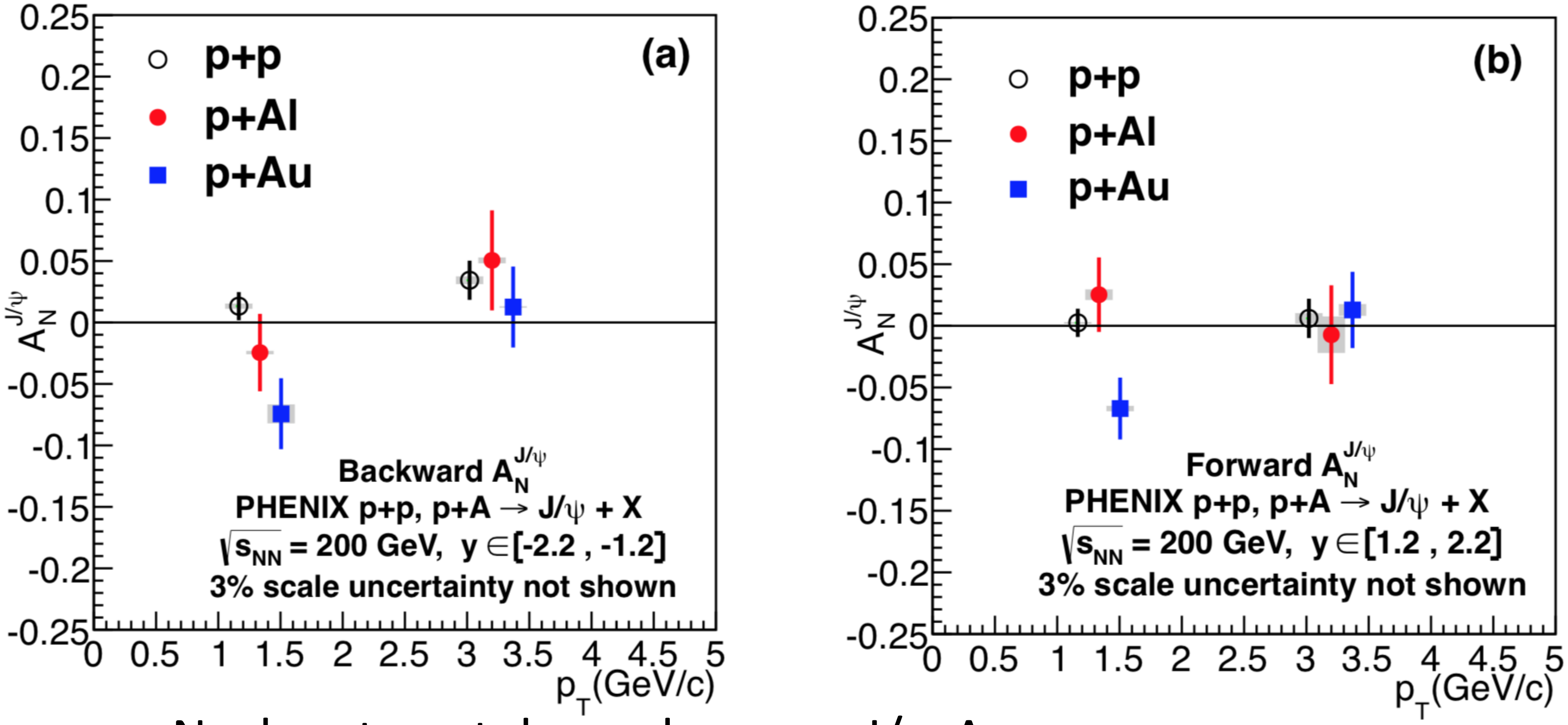
- PDF modification in nuclei (nuclear shadowing)
- Gluon saturation (CGC)
- Multiple scattering

Clear and strong dependence on nuclear target size $A^{1/3}$ (α = 1.21)

Very similar dependence on N_{coll} (centrality) (β = 1.19)

J/ψ transverse single-spin asymmetry

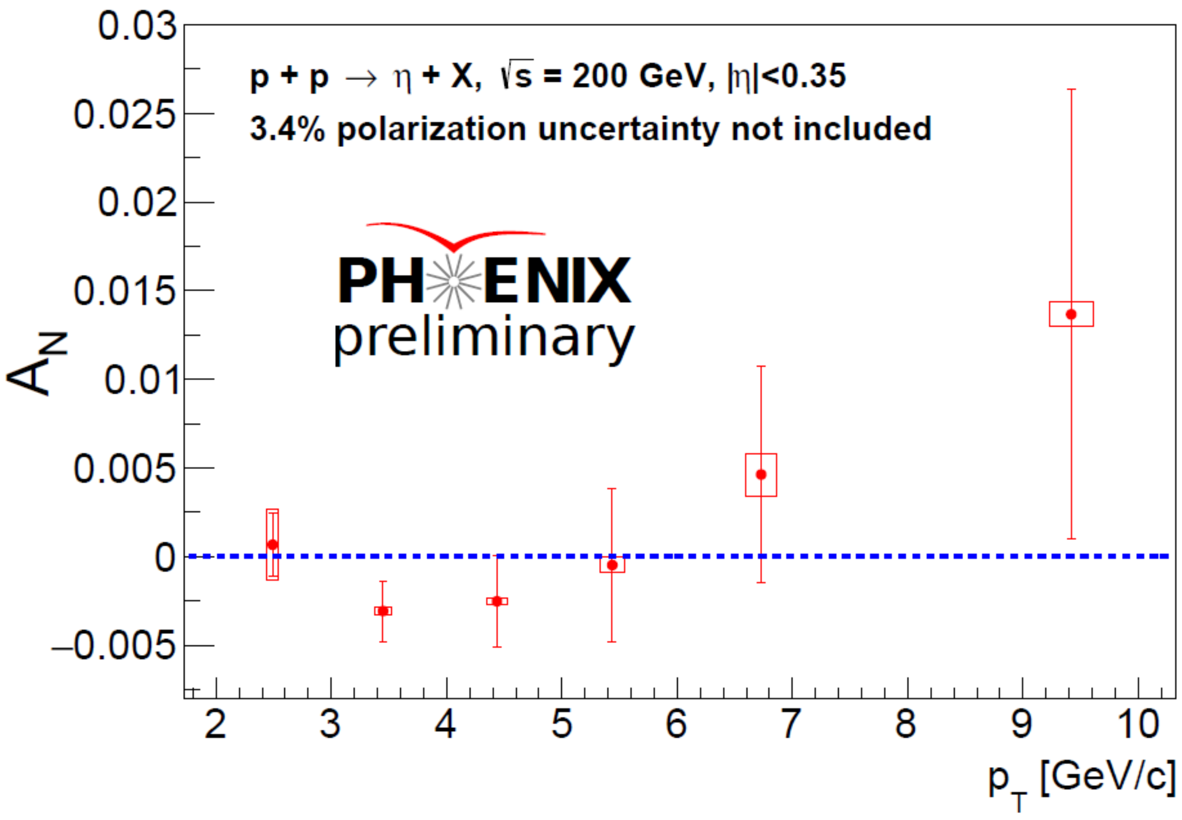
Phys. Rev. D 98, 012006 (2018)

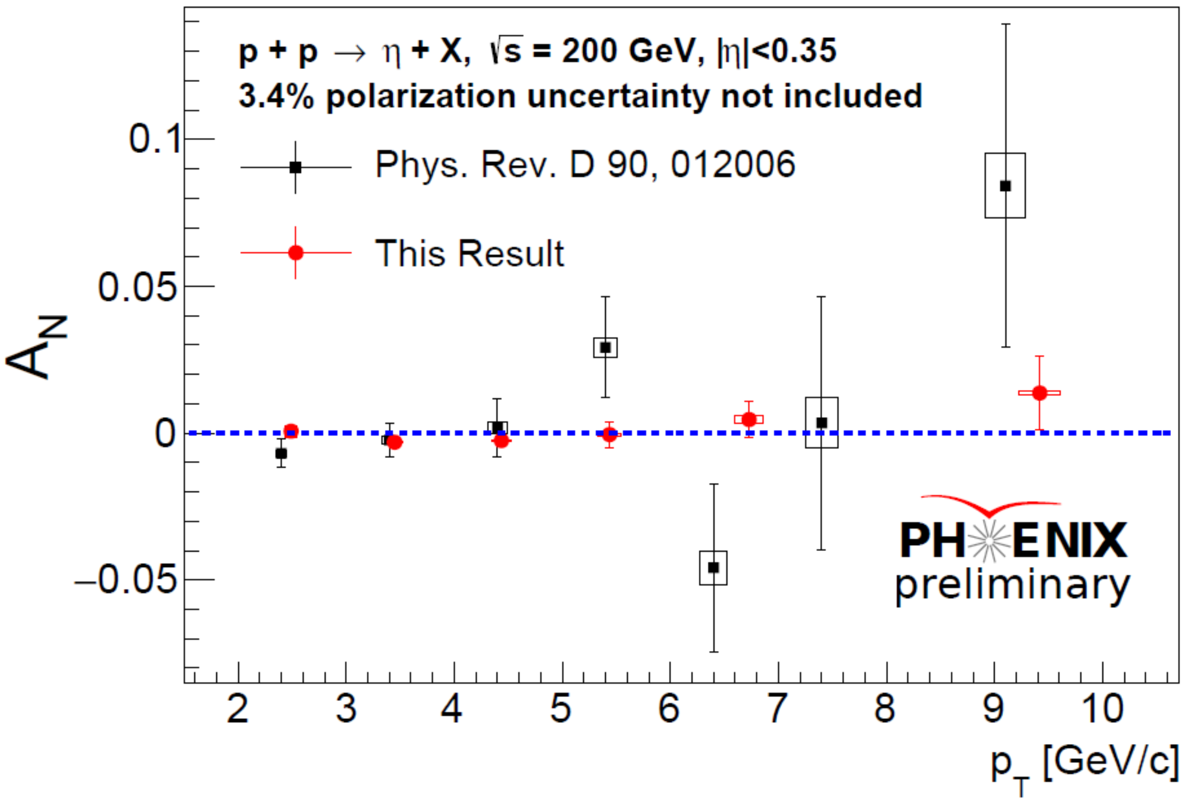


Nuclear target dependence on J/ψ A_N

What's the origin of the asymmetry at low p_T in p+Au?

η transverse single-spin asymmetry





η A_N is consistent with zero (but noticeable structure)
Dramatic improvement in statistical and systematic uncertainties over previous result

Spin Physics Summary

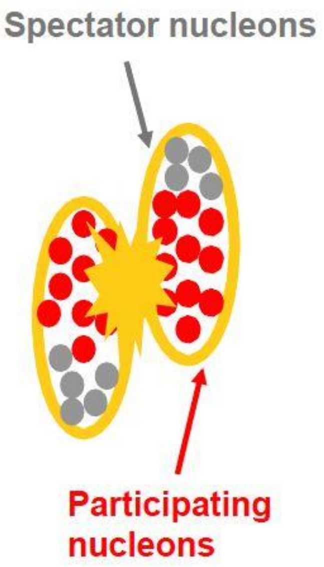
- $W^{\pm}$ A_L now published
- h^{+} A_N just submitted to PRL
  - Clear dependence of asymmetries on nuclear target, both $A^{1/3}$ and N_{coll}
- New results on η A_N
  - Dramatic improvement in statistical and systematic precision over previous results
  - Results consistent with zero with some noticeable structure
- J/ψ A_N now published
  - Illustrates importance of changing nuclear target in spin physics
  - Why is J/ψ A_N non-zero in p+Au?

Small Systems (p/d/^{3}He + A)

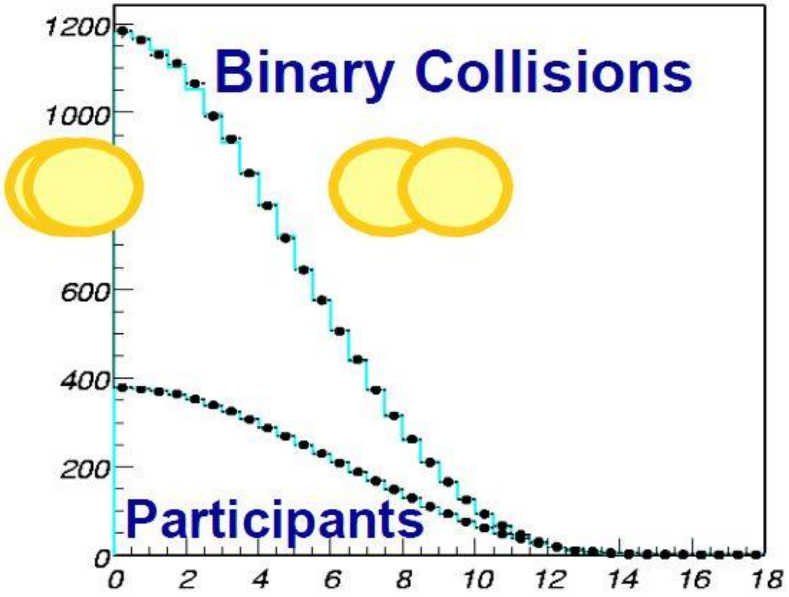
Nuclear Modification Factor R_{AA}

$$R_{AA} = \frac{dN_{AA}^{J/\psi}/dy}{N_{coll}\, dN_{pp}^{J/\psi}/dy}$$

Yield in nucleus-nucleus collisions divided by p+p yields and scaled by the appropriate number of binary collisions N_{COLL}, which is calculated using Glauber model.



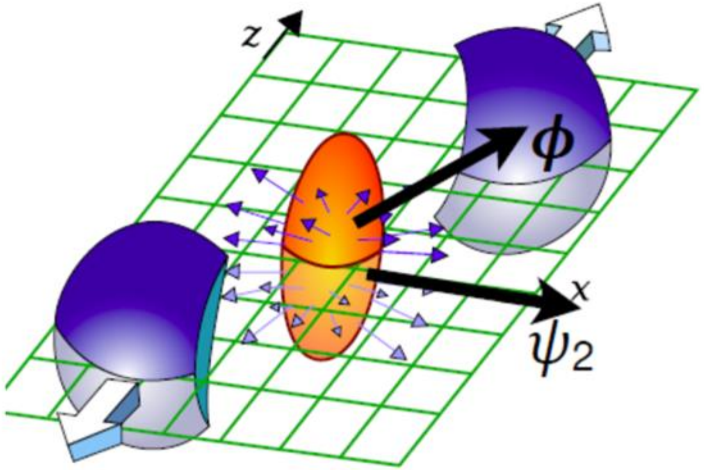
Centrality of collision is described by the number of participant nucleons N_{PART} or number of binary collisions N_{COLL}



Impact parameter [fm]

Intermission: some nuclear physics concepts

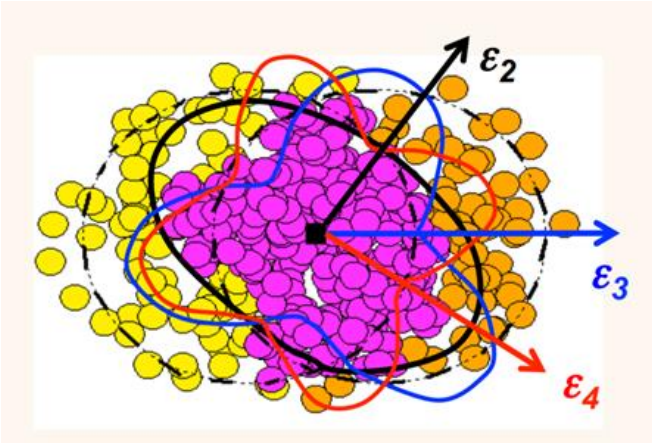
Collective Flow



In general, azimuthal distribution of the final state particles can be decomposed into Fourier series

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + \sum_n 2v_n\left(p_\mathrm{T}\right)\cos\left(n\left(\phi - \psi_n\right)\right)$$

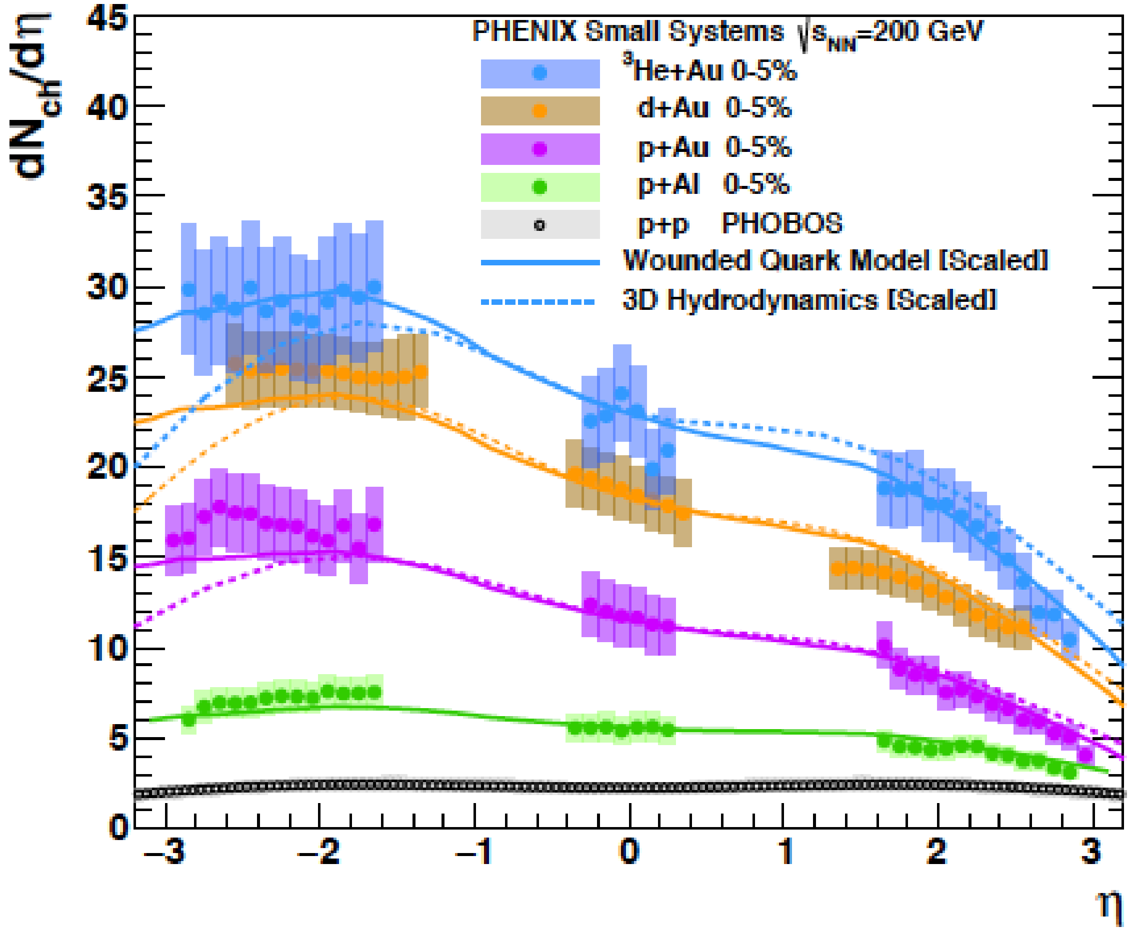
Spatial asymmetry represented by eccentricity



$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

translates into momentum flow described by Fourier coefficients v_n

Longitudinal dynamics in small systems ($dN_{ch}/d\eta$)



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

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

Good agreement with Wounded Quark Model

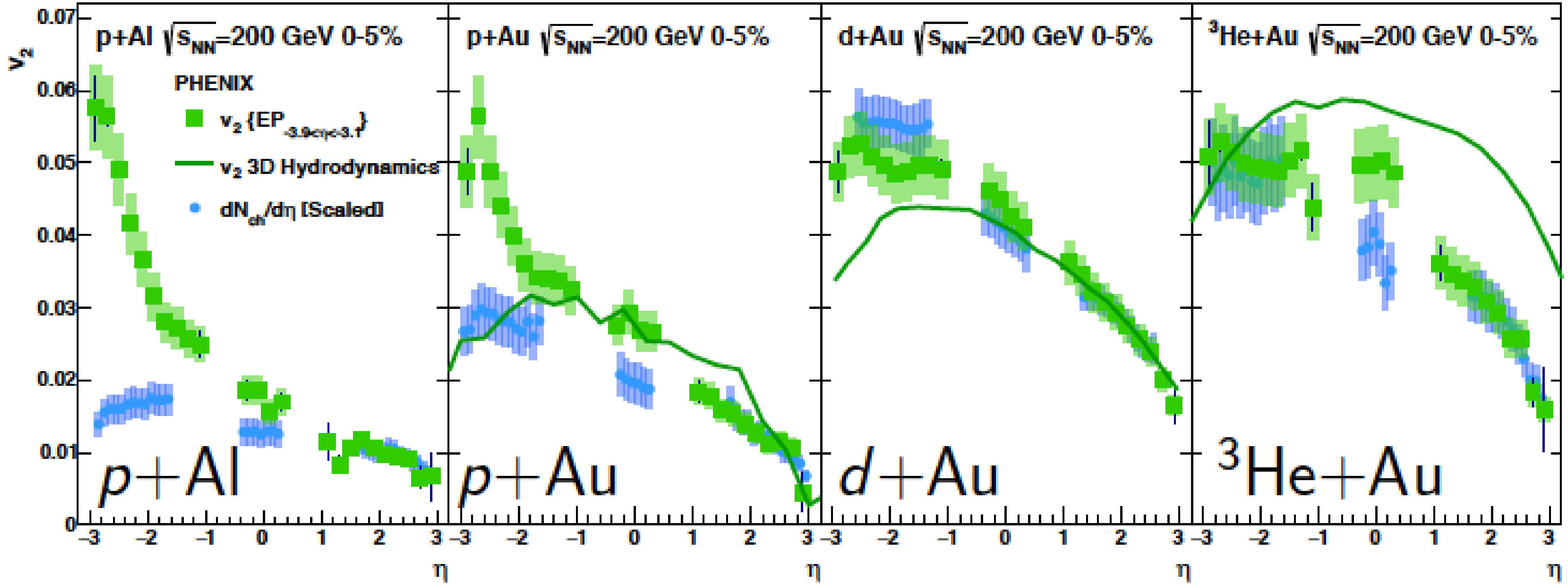
(M. Barej, A. Bzdak,and P. Gutowski Phys. Lett. B739, 308,2014).

and 3-D Hydrodynamics

(P. Bozek and W.Broniowski, Phys. Lett. B739, 308, 2014).

Longitudinal dynamics in small systems (flow)

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

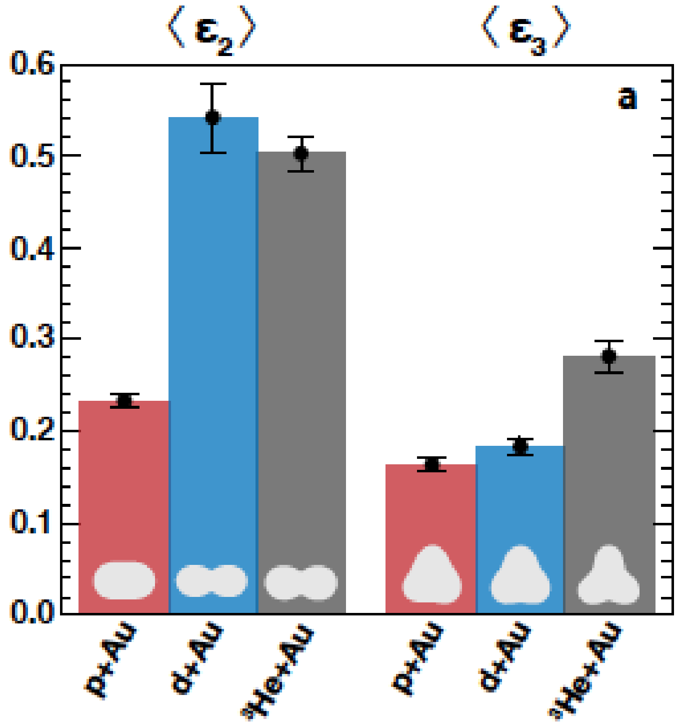


v_2 agrees with 3-D hydro for p+Au and d+Au

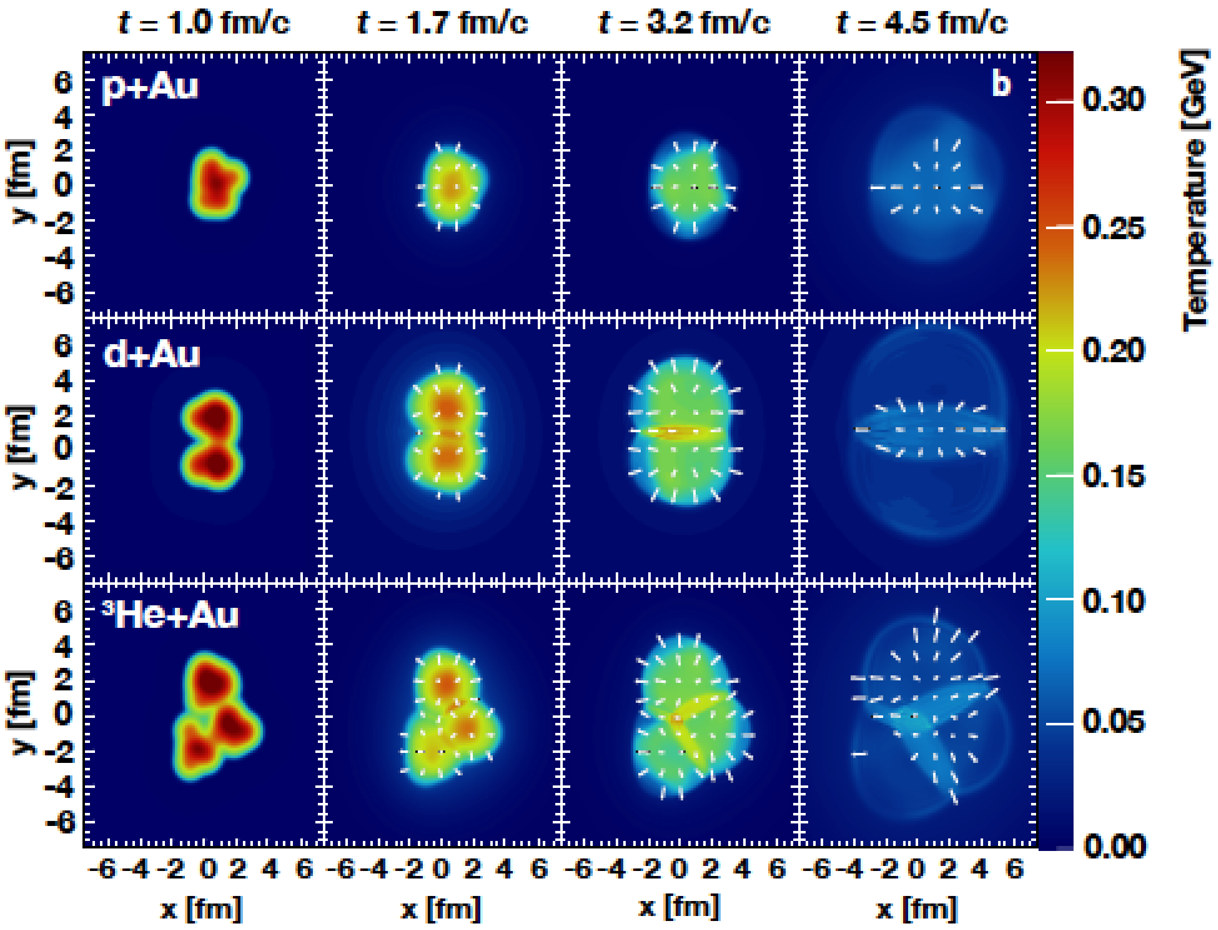
In ^{3}He+Au, 3-D hydro overpredicts the forward rapidity

Testing hydrodynamic models by controlling geometry

p+Au, d+Au and 3He+Au collisions have different elliptic and triangular eccentricities (ε_2 and ε_3)

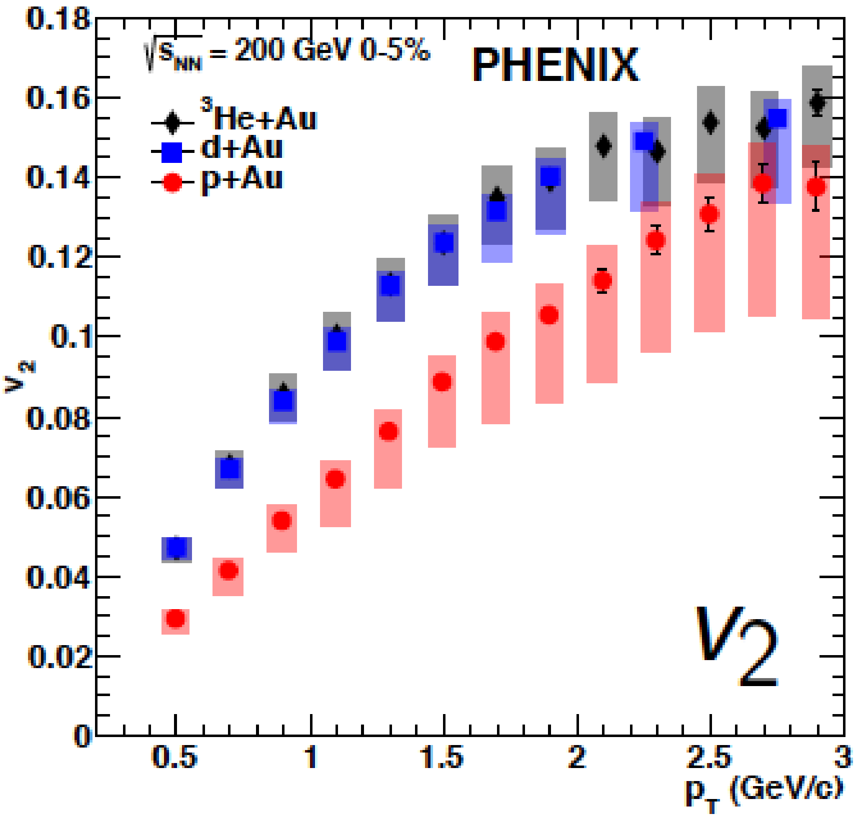


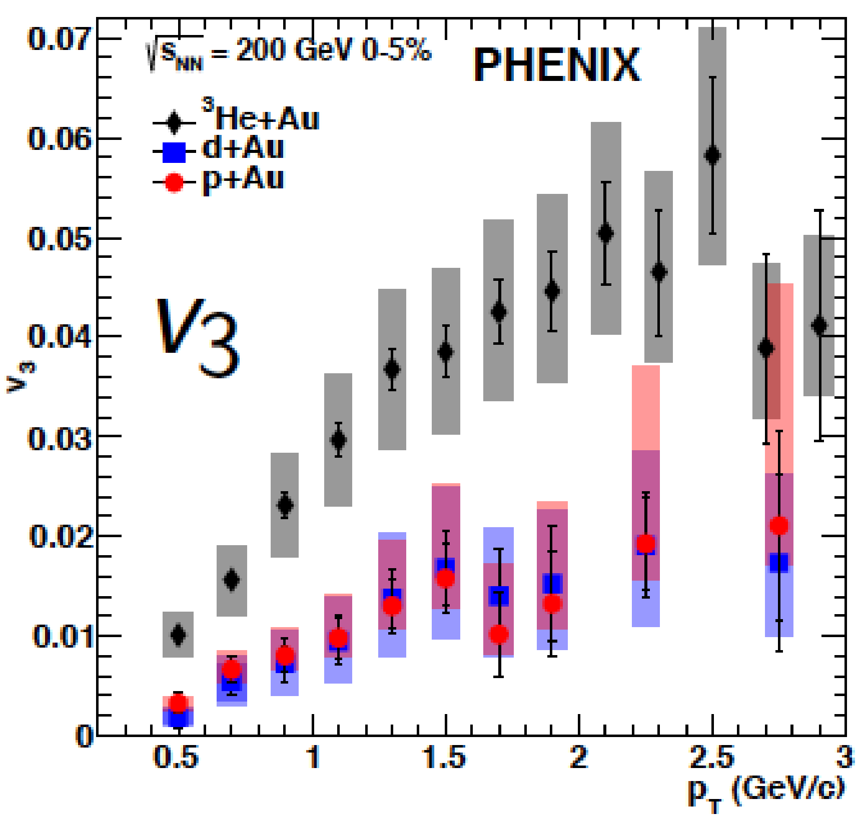
Nature Physics 15, 214-220 (2019)

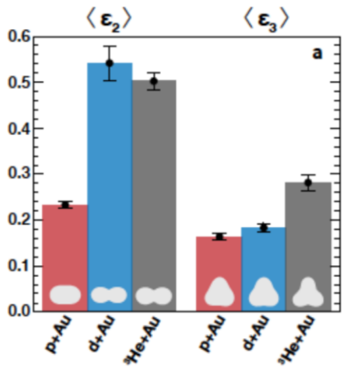


SONIC model: Habich, M., Nagle, J. L. & Romatschke, Eur. Phys. J. C 75, 15 (2015).

v_2 and v_3 ordering



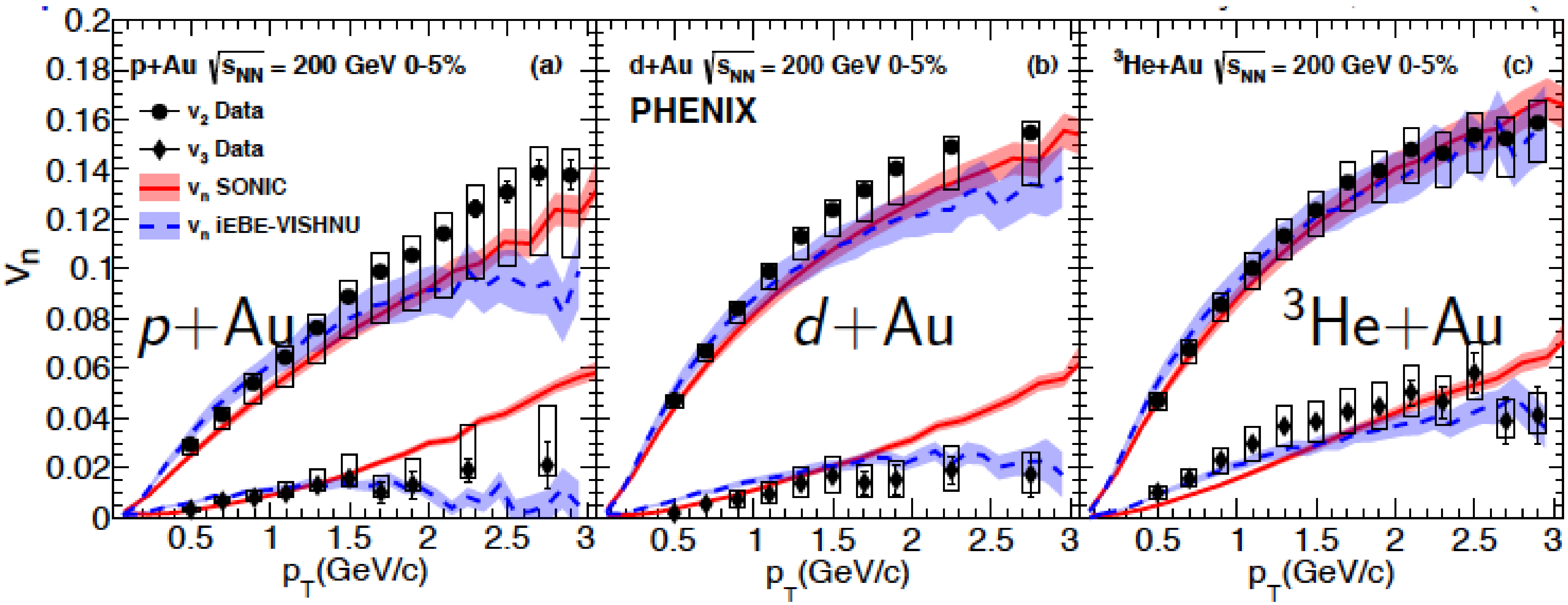




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all systems
- Regardless of the mechanism, the correlation is geometrical

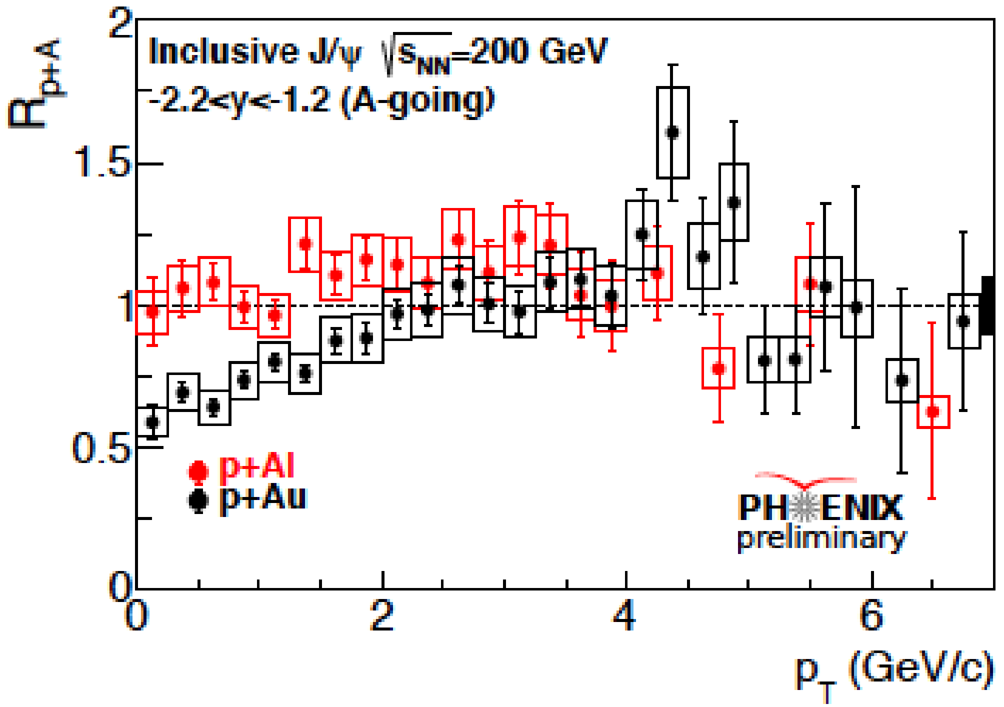
Theory comparison

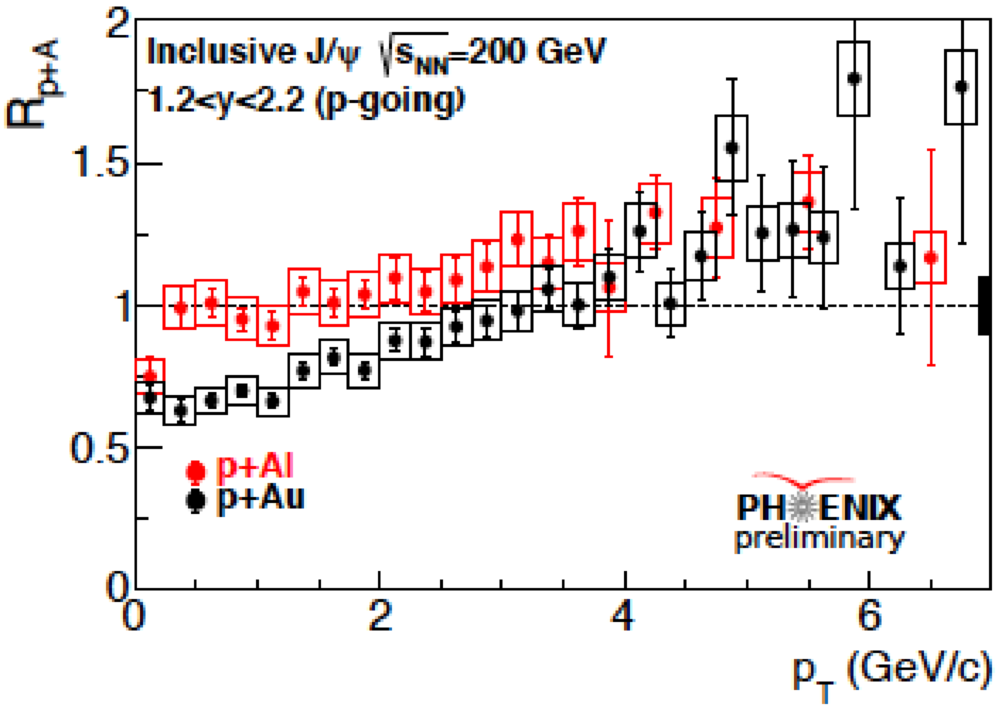
v_2 and v_3 vs p_T described very well by hydro in all three systems



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

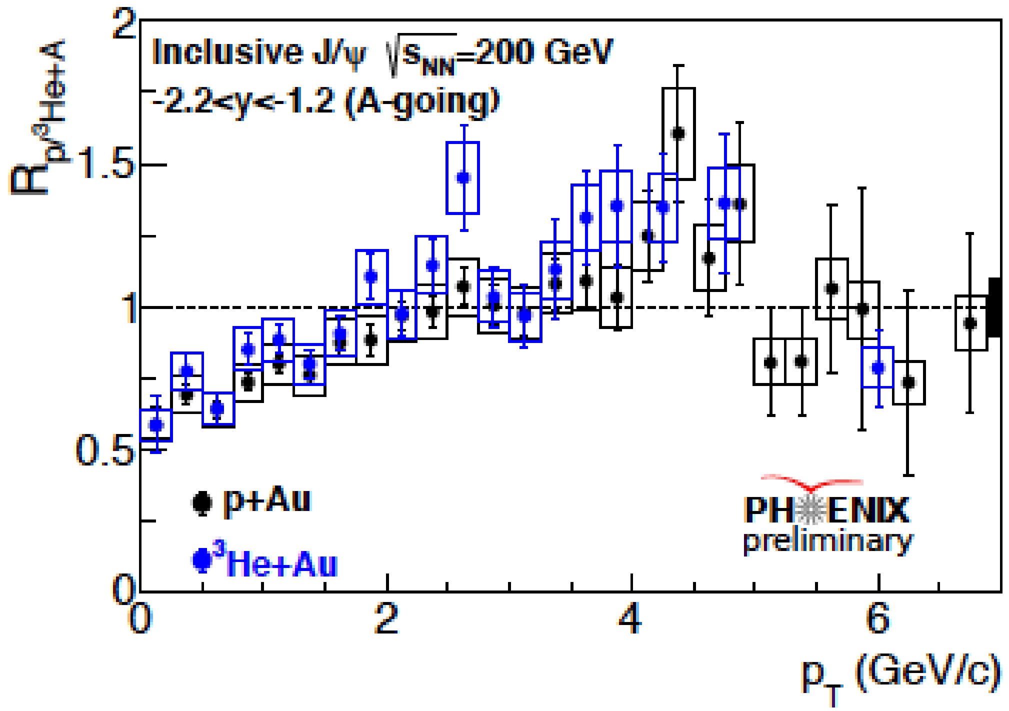
J/ψ in p+Al and p+Au

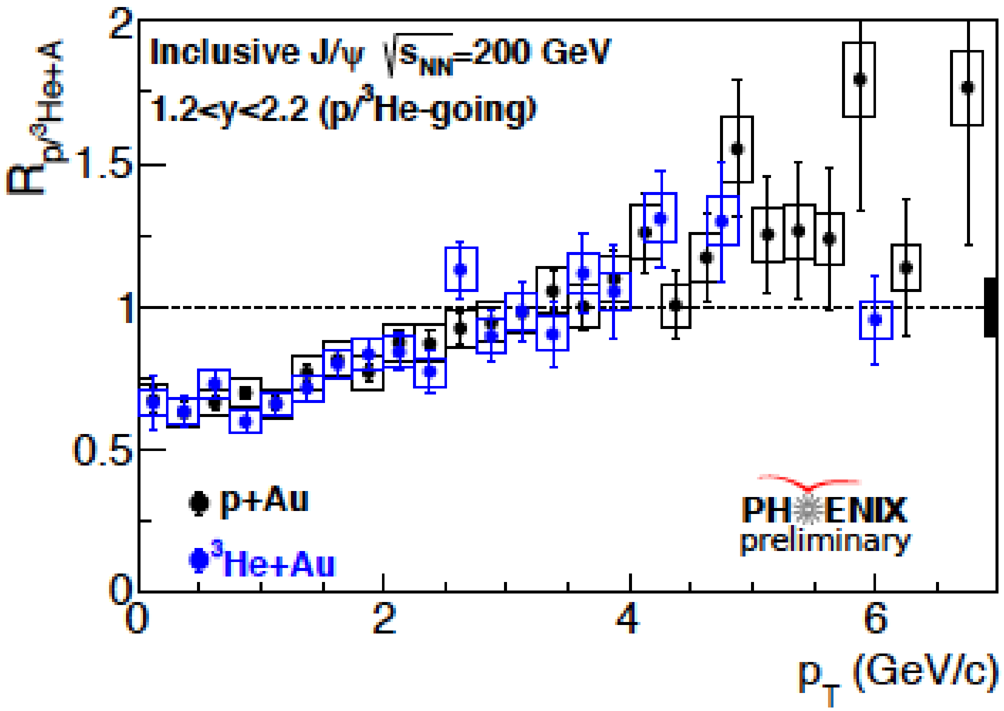




- Almost no modification in p+Al
- Significant suppression at low p_T in p+Au in both directions.

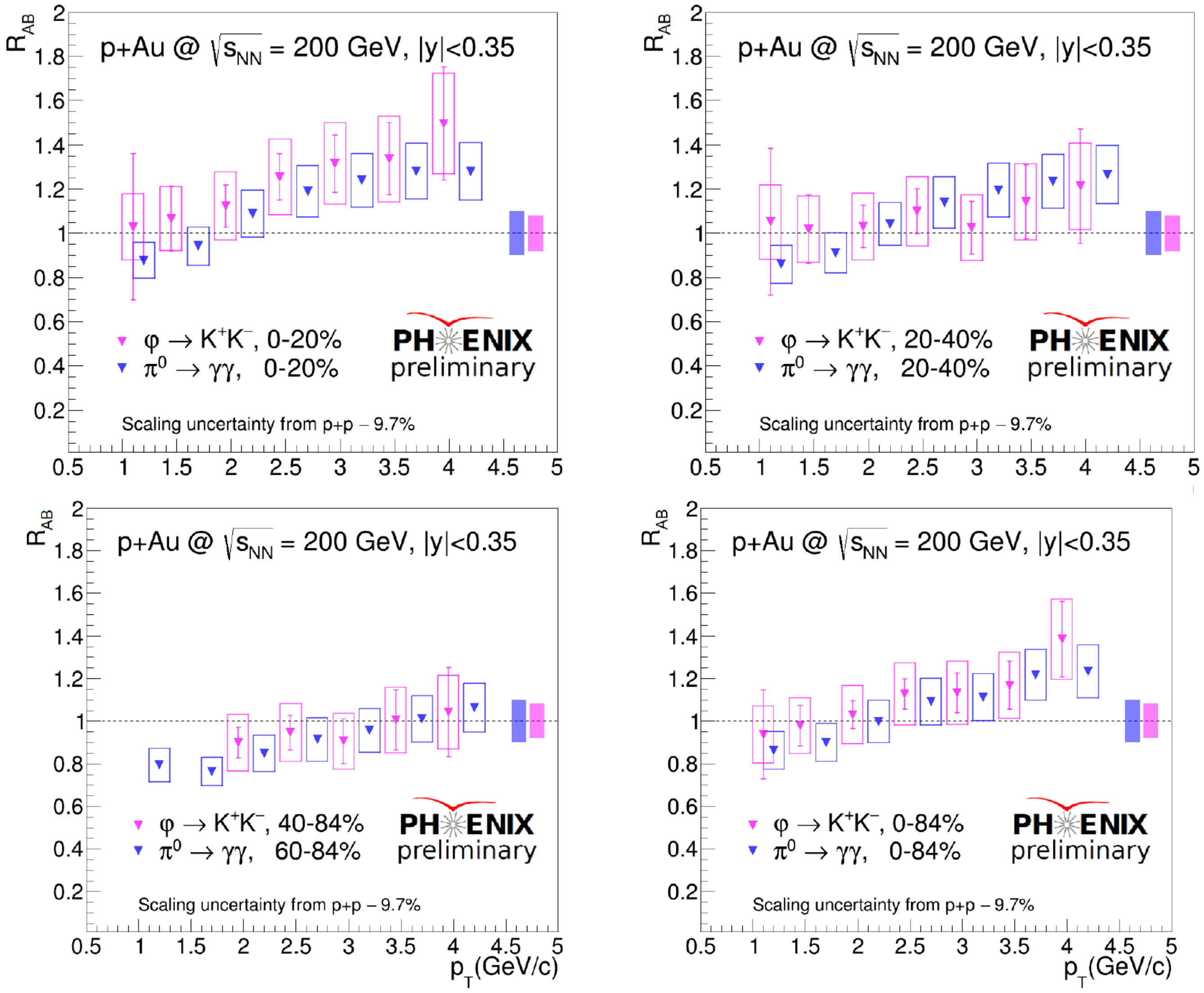
J/ψ in ^{3}He+Au





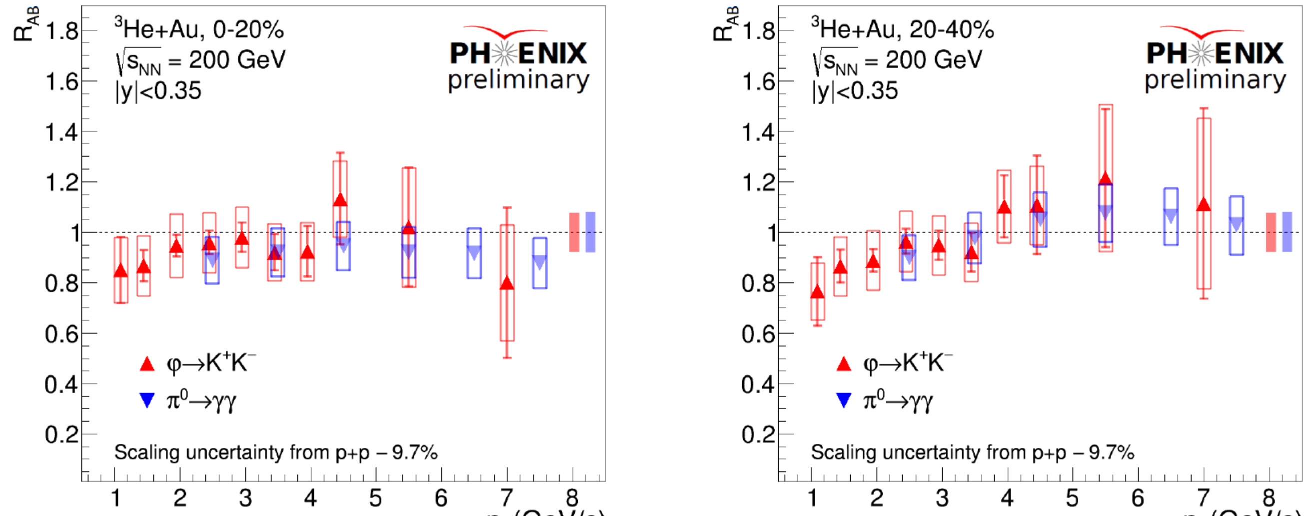
No difference with increasing projectile size.

ϕ mesons in p+Au

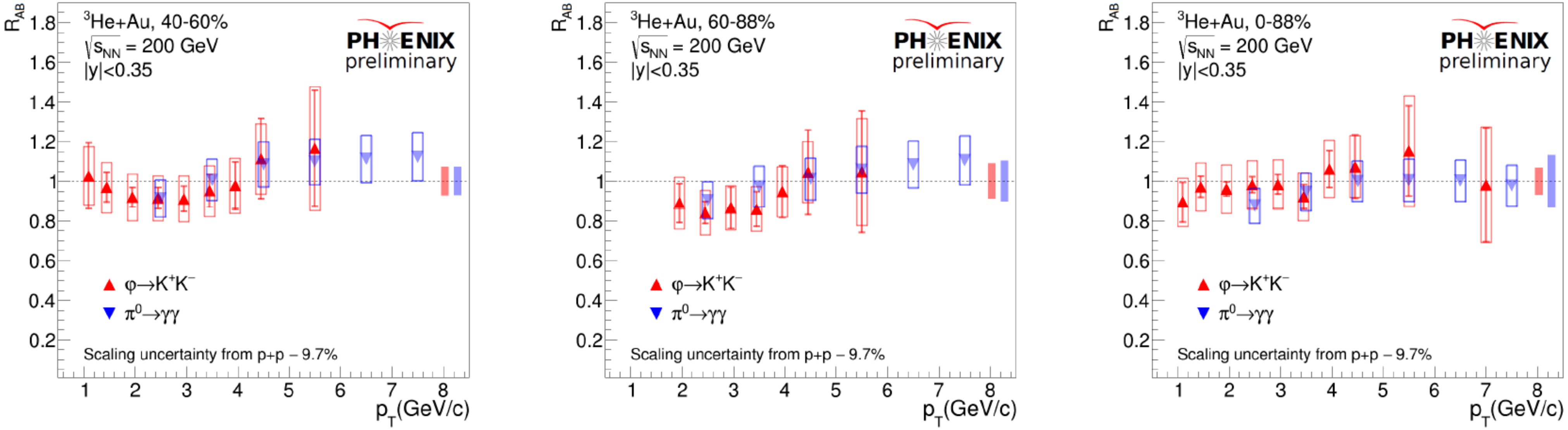


Despite mass difference and strangeness, in p+Au collisions ϕ shows similar modification to π^0

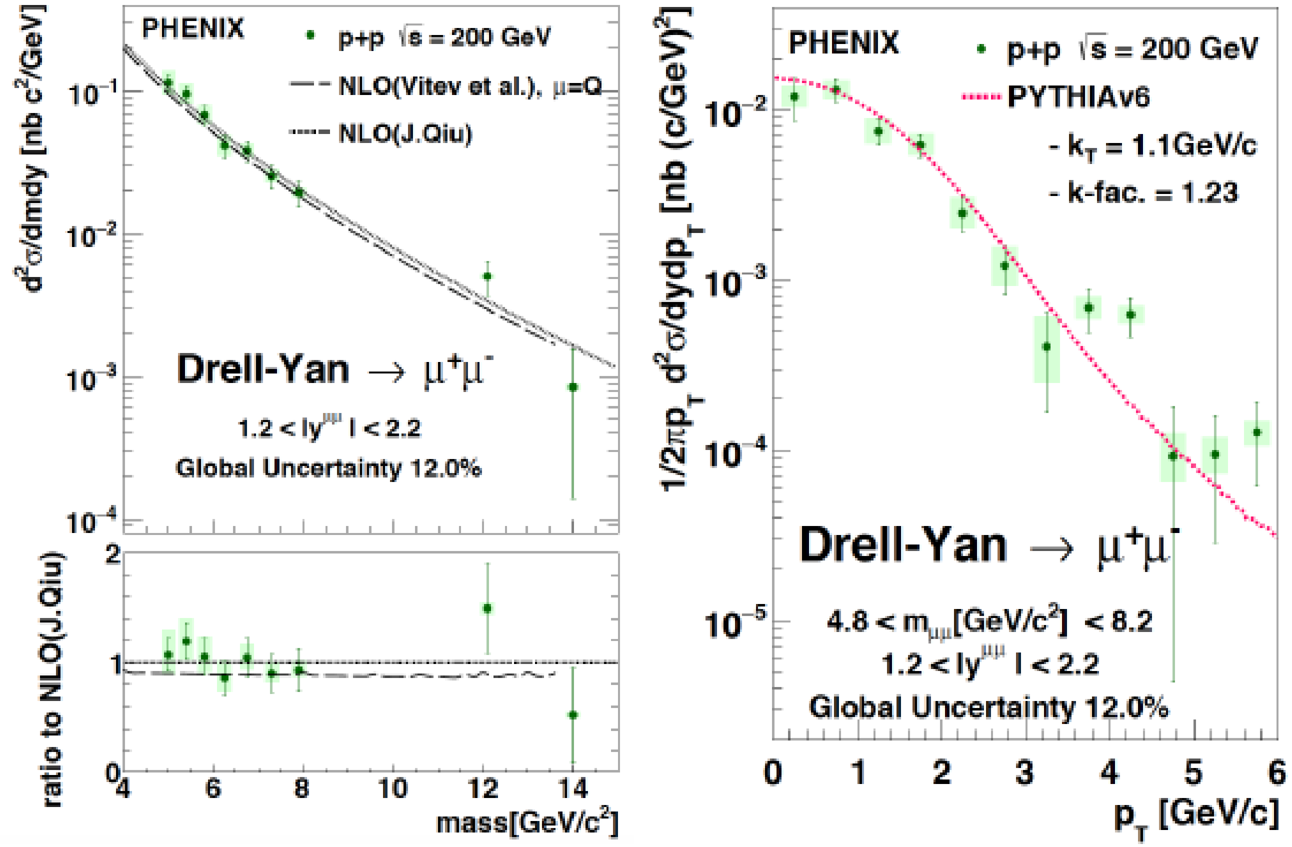
ϕ meson in ^{3}He+Au



Again, ϕ shows similar modification to π^0



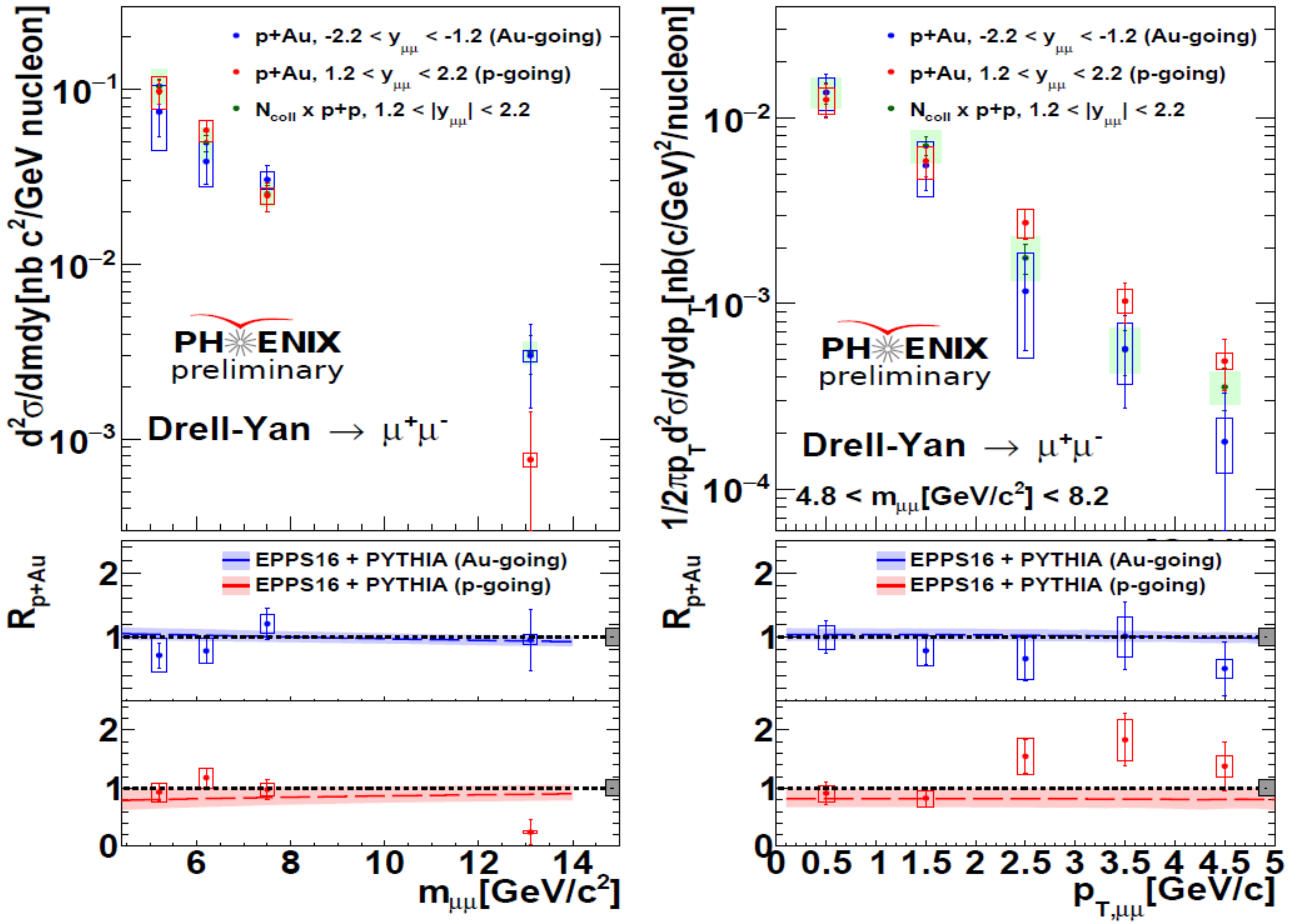
Drell-Yan in p+p from μ-μ angular correlations



arXiv:1805.04075
arXiv:1805.02448

Well described by PYTHIA and NLO

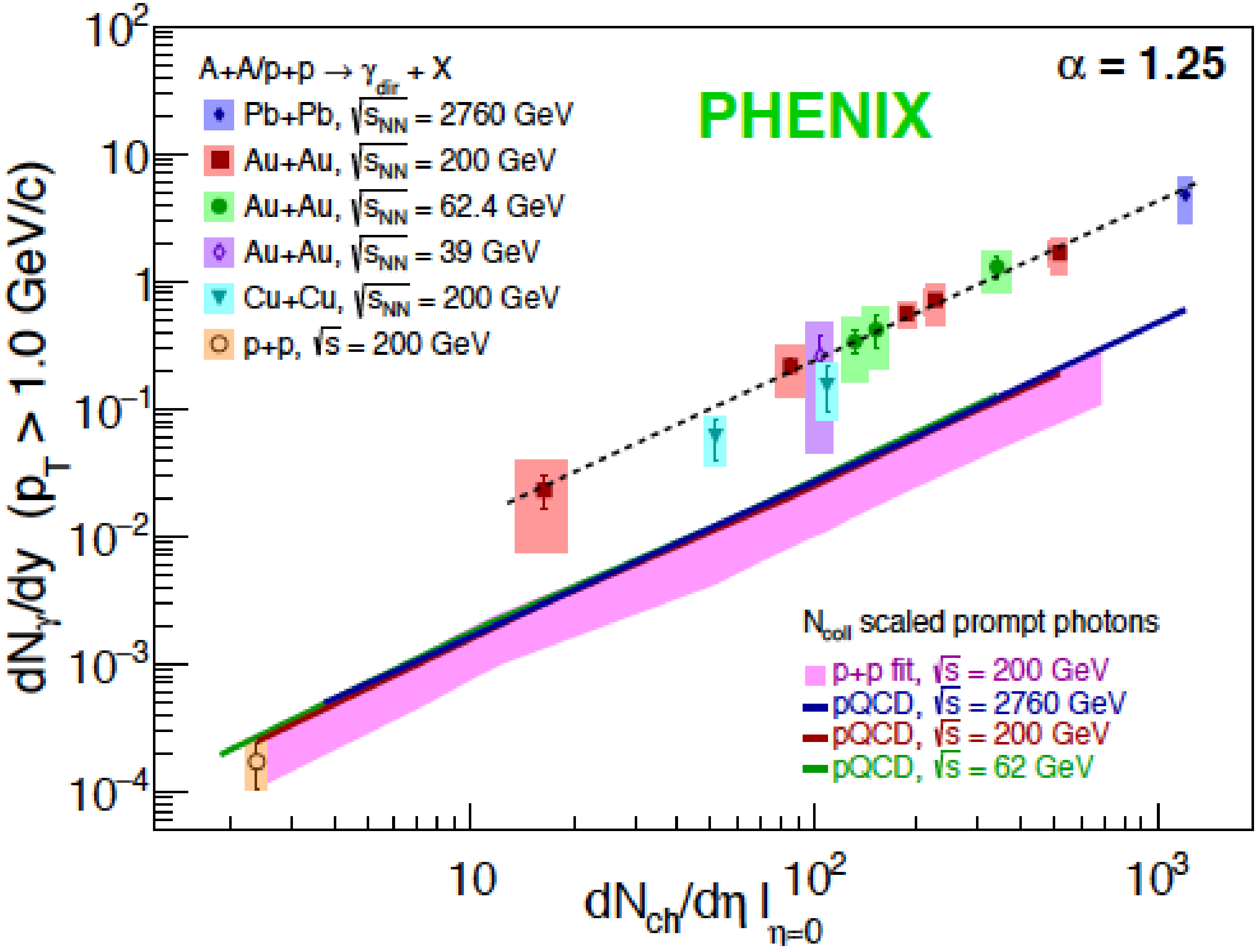
Drell-Yan in p+Au



Hint of modification of Drell-Yan in p+Au, although large uncertainties prevent a firm conclusion

Direct Photon Yields in p+p and A+A

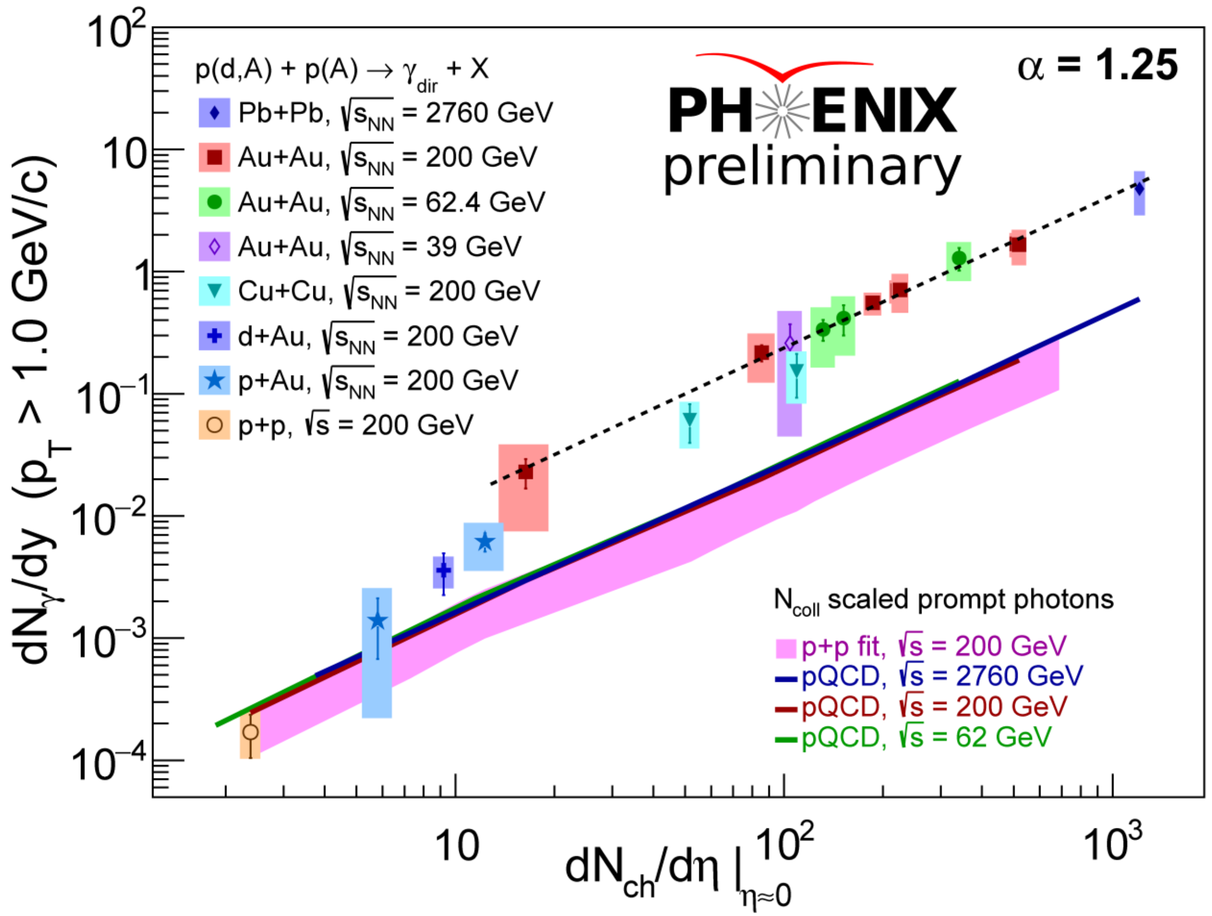
arXiv:1805.04084, accepted by Phys. Rev. Lett. 123, 022301 (2019)



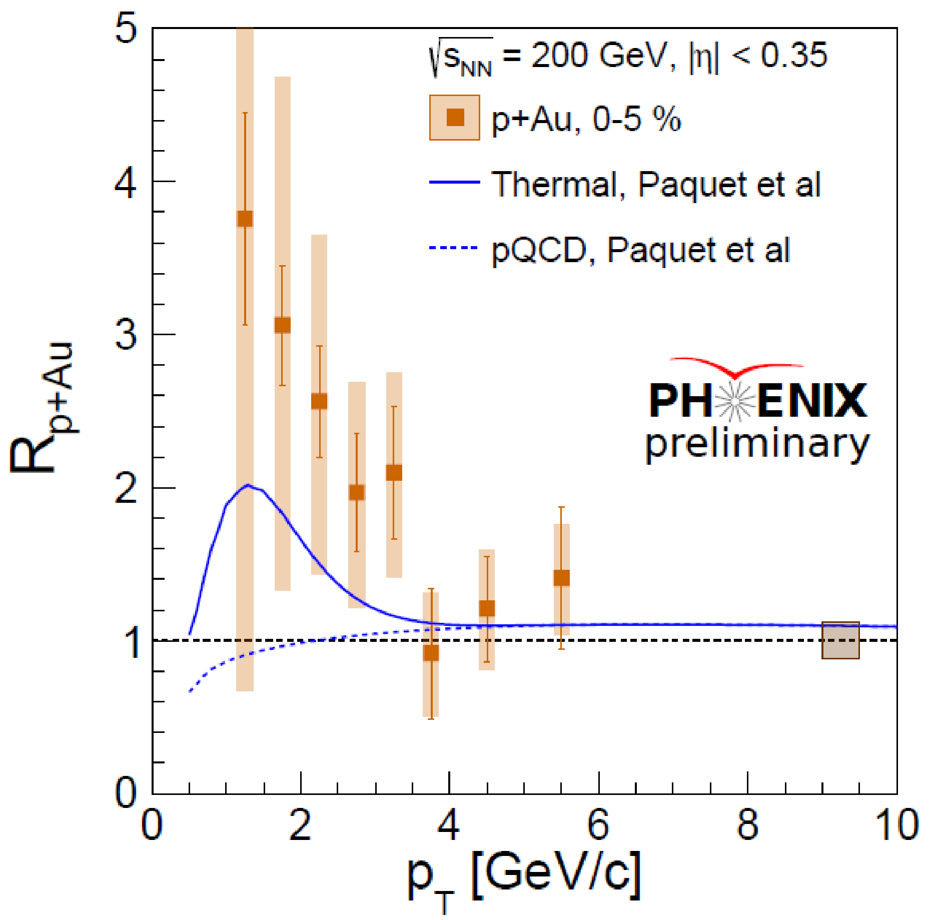
Common scaling independent of collision energy or centrality for Au+Au and Pb+Pb at different energies;

Very different from N_{coll}-scaled p+p

Direct Photons in p/d + Au



p+Au and d+Au data fill the gap smoothly between A+A and p+p collisions.



Thermal photons in p+Au?

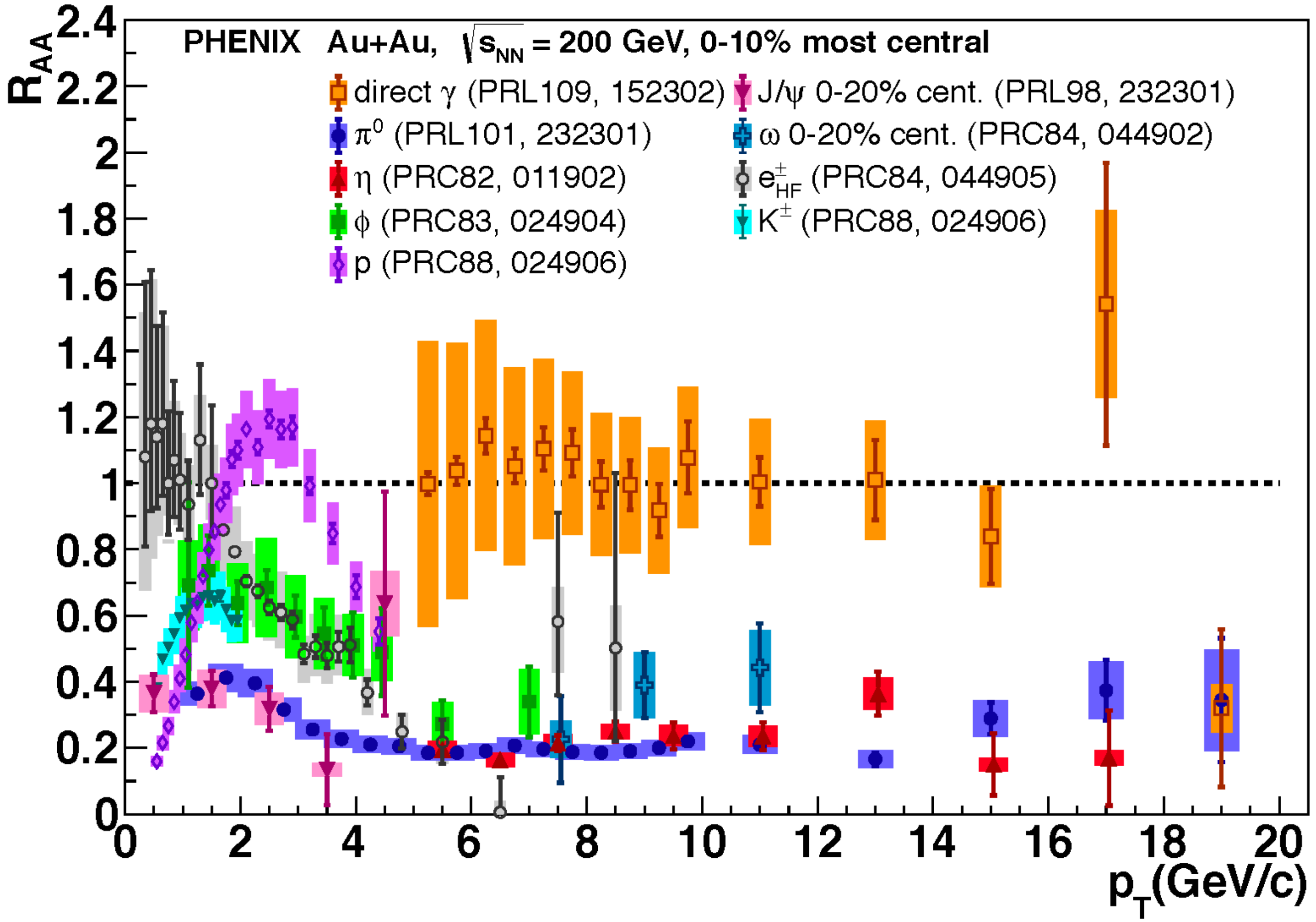
Theory: Phys. Rev. C 95, 014906 (2017)

Small systems summary

- Comprehensive set of measurements of longitudinal dynamics
  - Good support for wounded quark model and 3D hydro
- Geometry scan results published in Nature Physics
  - Only hydro can describe all the data
- J/ψ in p/d/3He + A
  - Modification depends on target size, but not projectile size
- Modification of ϕ meson is very similar to that of π^0 despite differences in mass and strangeness content
- First measurement of Drell-Yan in small systems at RHIC
  - Hint of enhancement but no firm conclusions
- Photon enhancement in small systems is an important additional evidence in support of QGP droplet formation in small systems

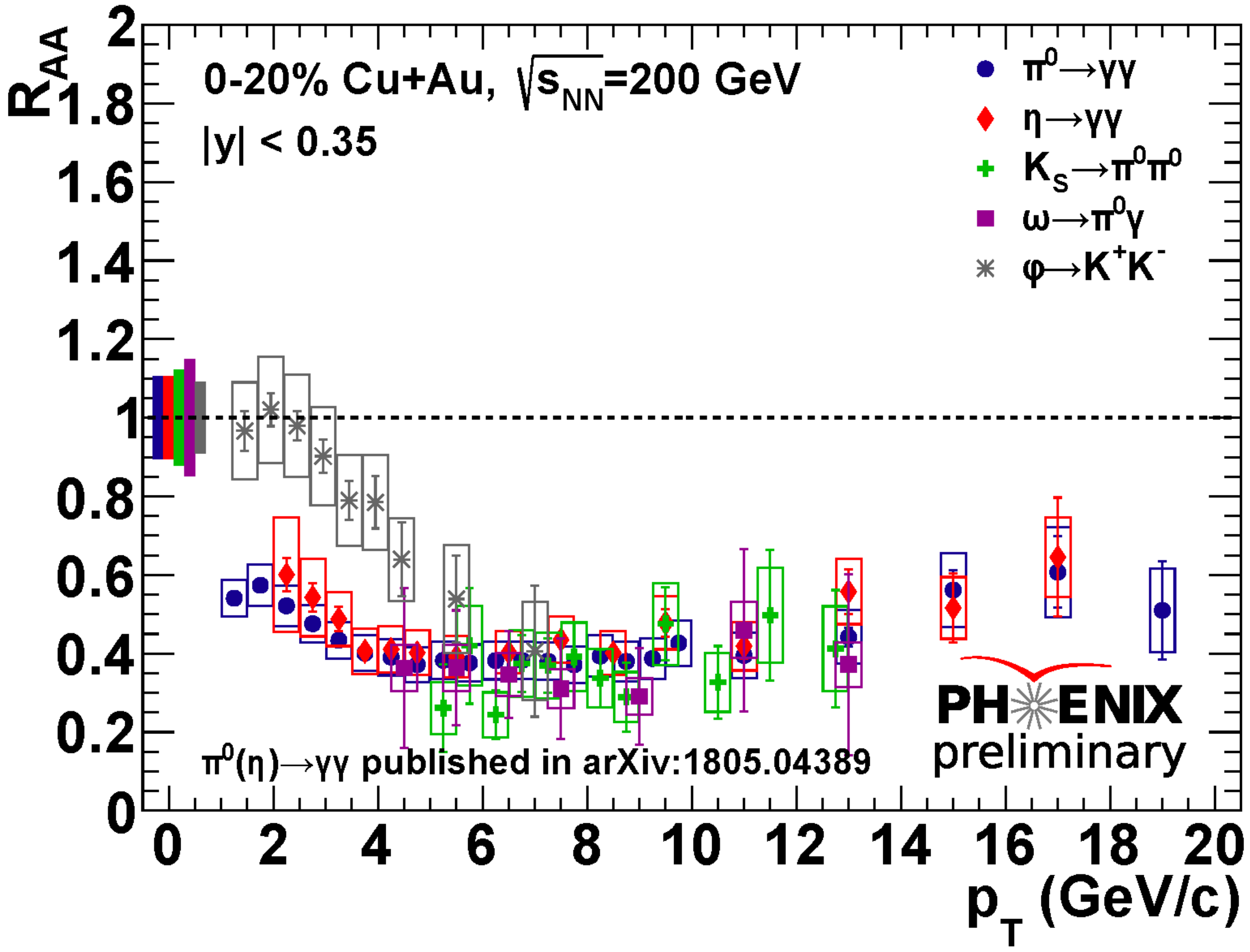
Heavy Ions

Summary of suppression in Au+Au



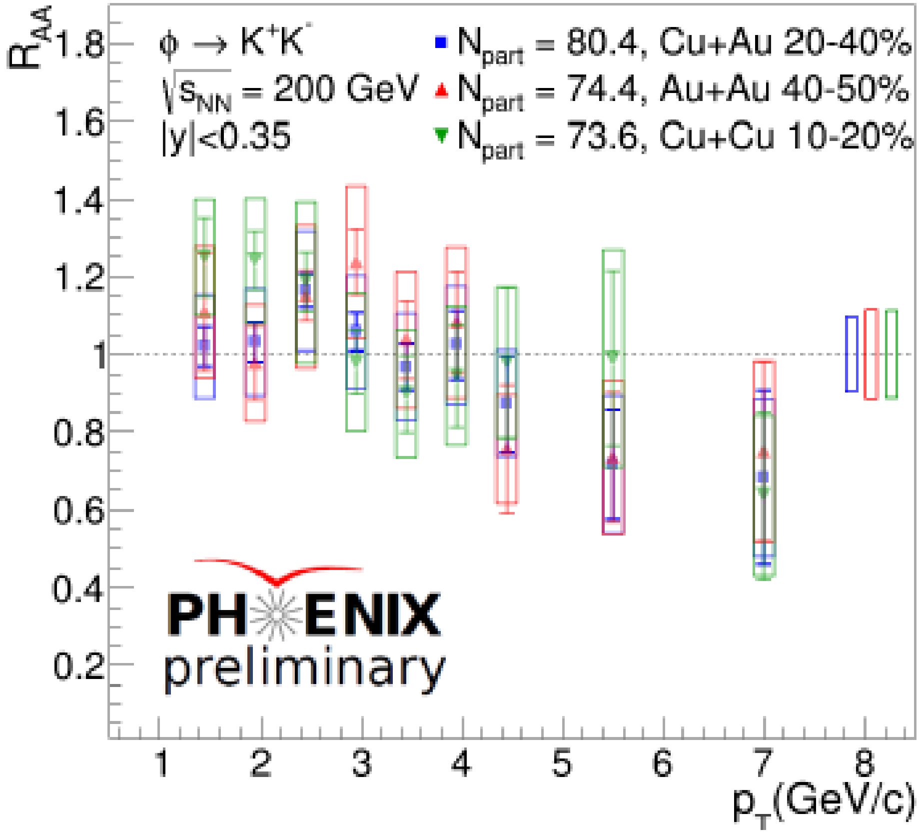
- Photons unmodified
- Baryons are not suppressed at intermediate p_T
- ϕ is an outlier at low p_T

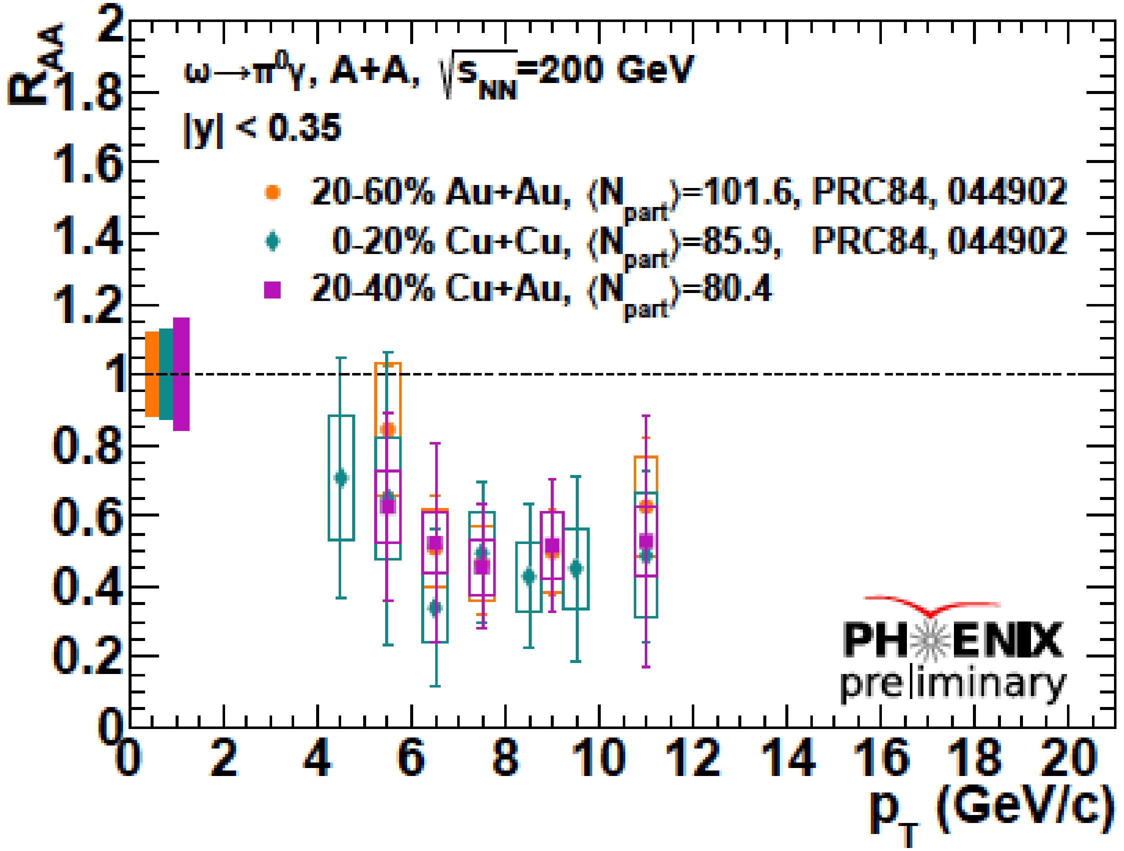
Nuclear suppression in Cu+Au



Again ϕ is an outlier at low p_T, but ω and K_S follow π^0 and η trend at high p_T

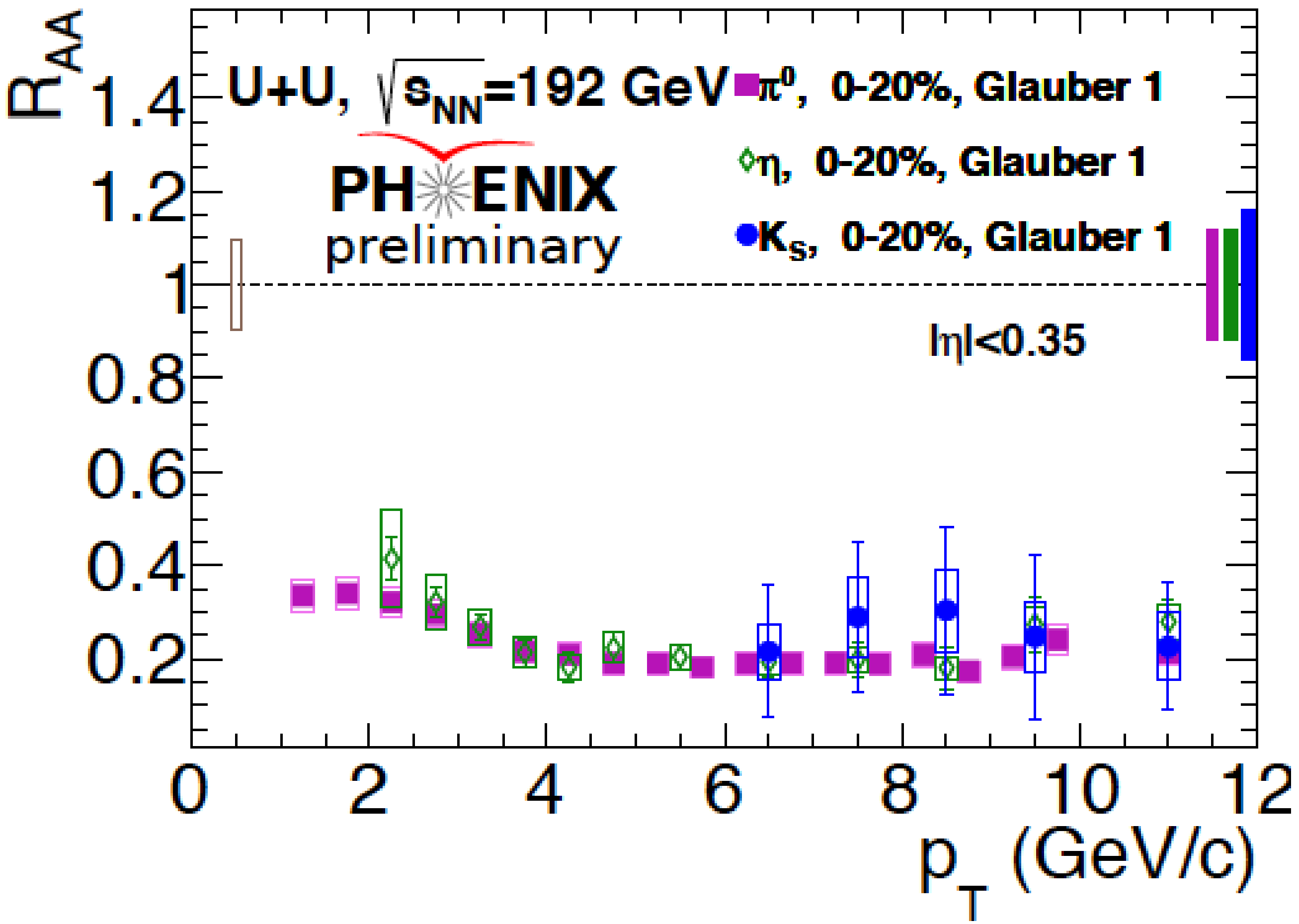
Strangeness for different collision species





ω and ϕ mesons behave similarly in Cu+Cu, Cu+Au, and Au+Au when selecting for similar N_{part}

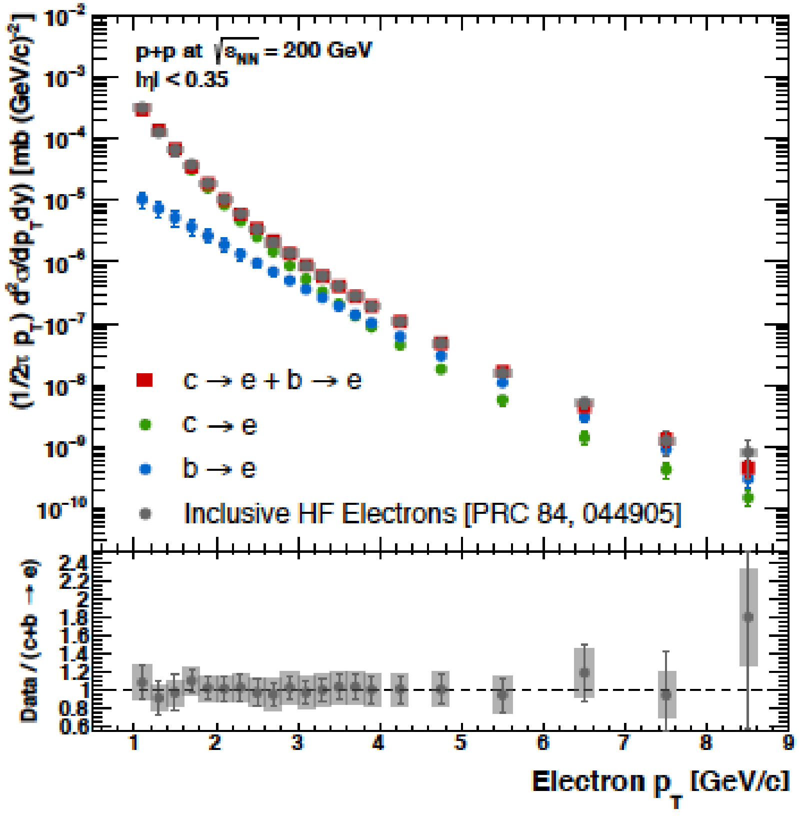
Strangeness in U+U

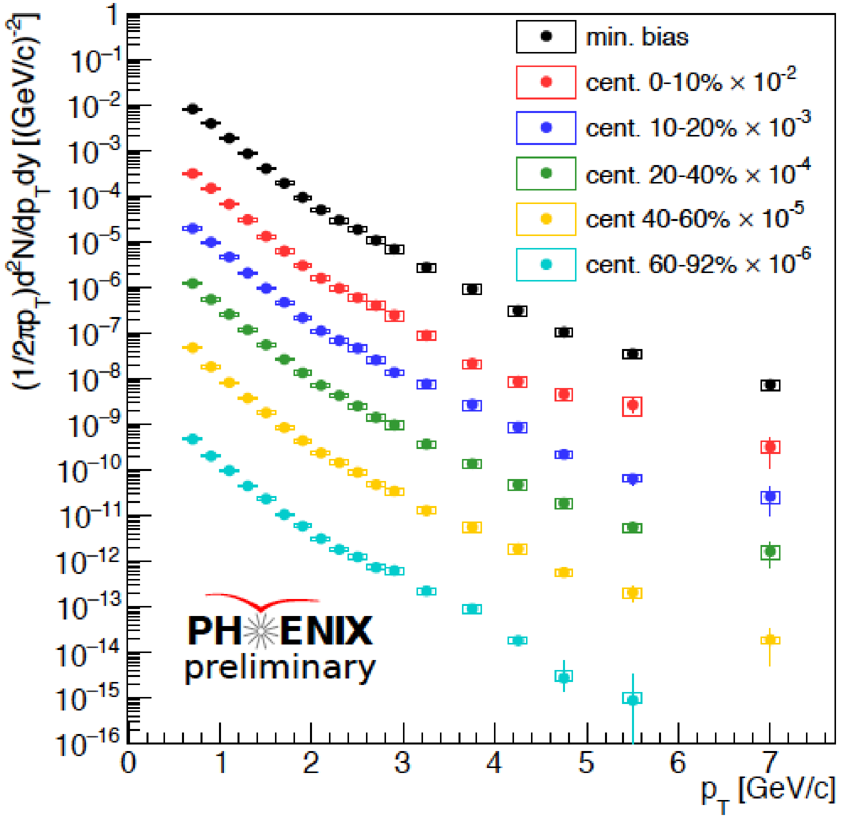


Suppression similar for all species including strange mesons at high p_T

c → e and b → e in p+p and Au+Au

Phys. Rev. D 99, 092003 (2019)

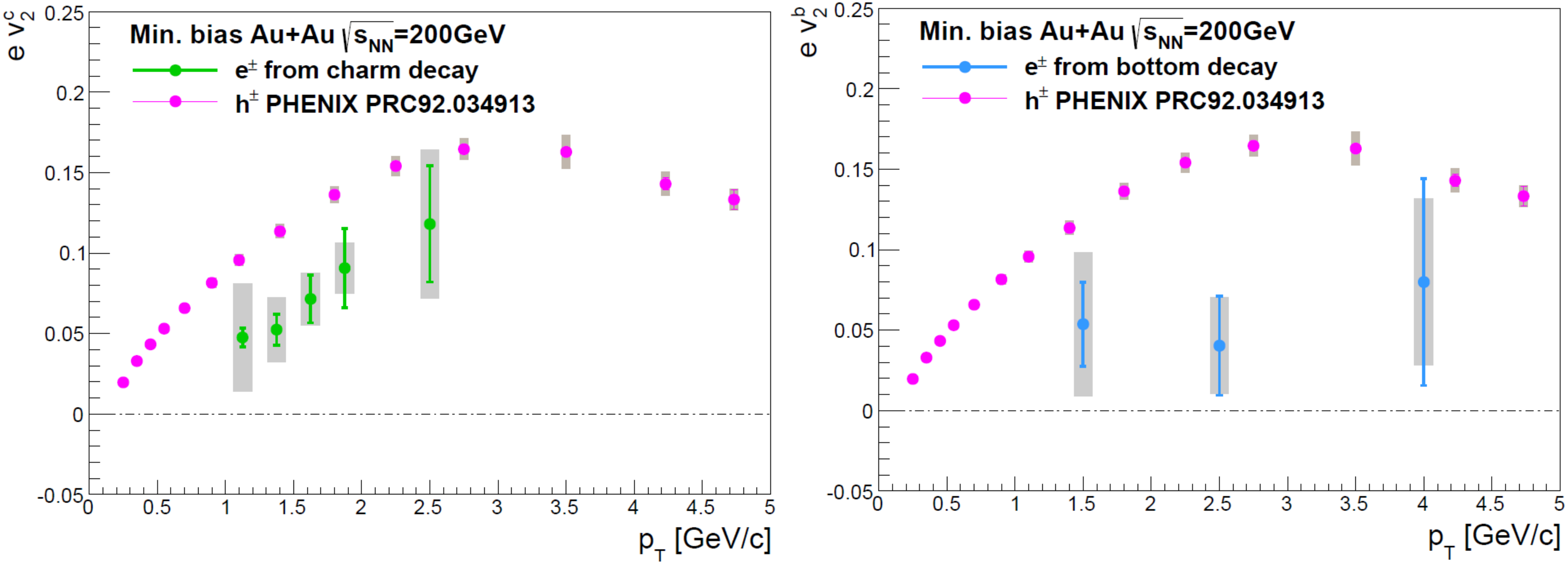




HF electron spectra, all centralities and using all available data

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

Charm and Bottom Flow in Au+Au



First bottom flow measurement at RHIC

Charm flows less than light-flavor hadrons, a hint of bottom flow

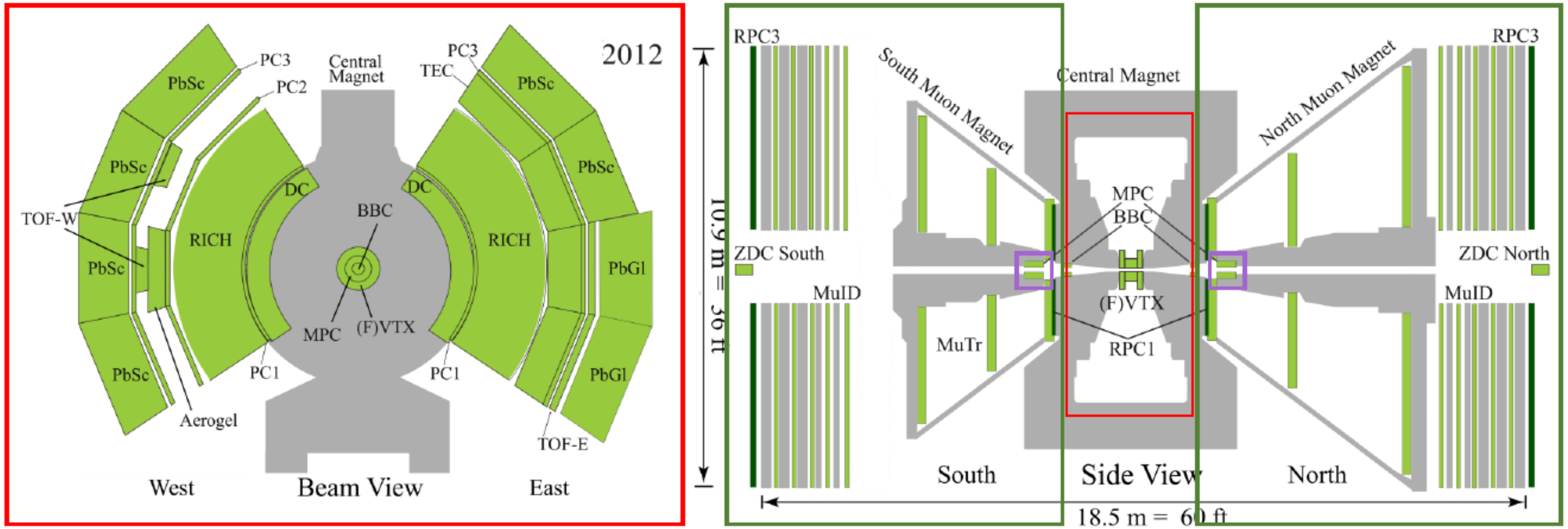
Heavy Ion Physics Summary

- Single particle R_{AA} independent of collision species when selecting for similar N_{PART}
- Strangeness appears to be important at low p_T but not at high p_T
- 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
  - Refinements and publication forthcoming

Thank you!

Backup Slides

The PHENIX Experimental Setup



- **Central Arms** ($|\eta| < 0.35$, $\Delta\phi = \frac{\pi}{2} \times 2$)
  - VTX (Si pixel and strip, from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbGl, PbSc

- **Muon Arms** ($1.2 < |\eta| < 2.2$ (S) or 2.4 (N), $\Delta\phi = 2\pi$)
  - FVTX (Si strip, from 2012)
  - Tracking: MuTr (CS chambers)
  - pID: MuID (steel interleaved Iarocci tubes), RPCs

- **MPC/MPC-Ex** ($3.1 < |\eta| < 3.8$, $\Delta\phi = 2\pi$)
  - EMCal ($PbWO_4$) / Preshower by W + Si minipads