Jets Measurements with PHENIX

Megan Connors
Georgia State University
for the PHENIX Collaboration

ZIMÁNYI SCHOOL 2022

Jets Measurements with PHENIX

And Other Recent

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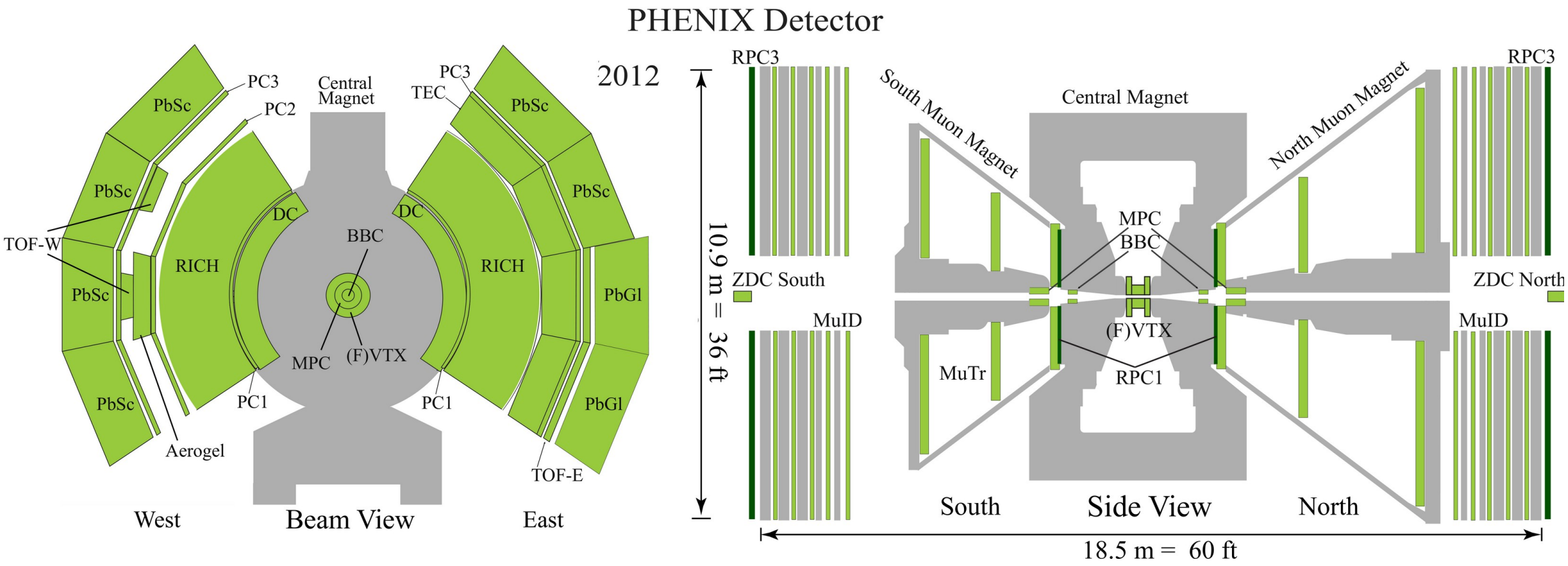
PHENIX Detector



Central detectors $|\eta|<0.35$

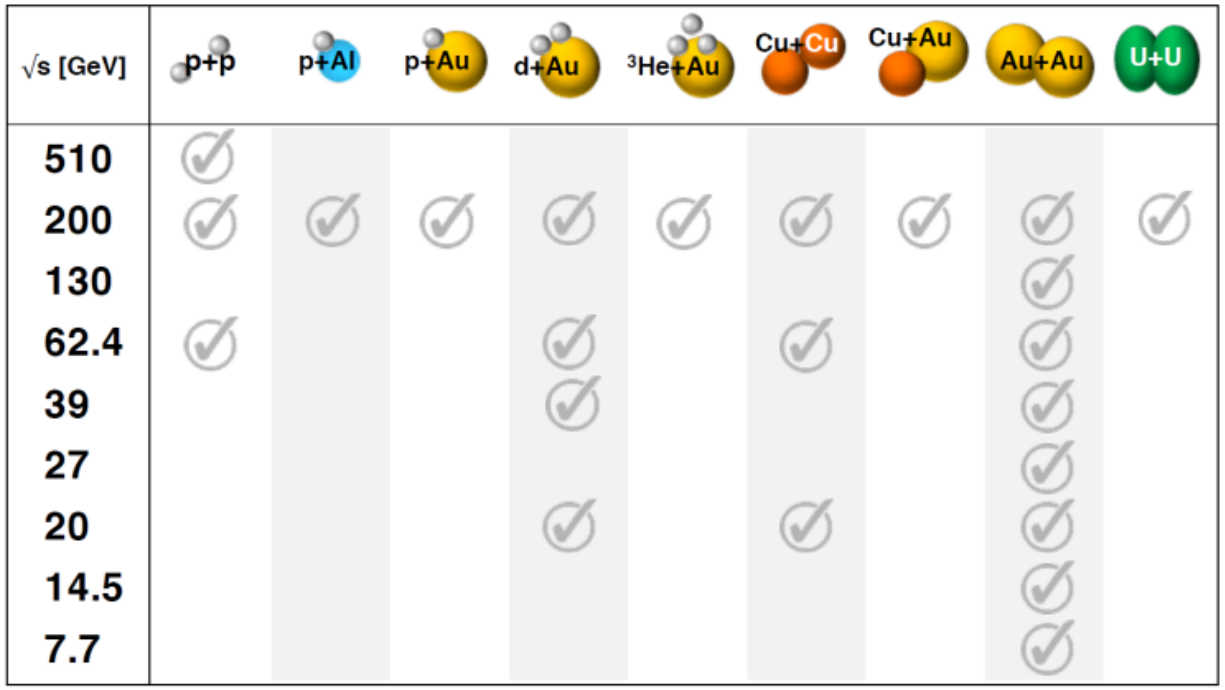
Forward/backward detectors

Muon Arms

PHENIX Highlights

Other PHENIX talks:
Mon. 12/5: J/ψ in pp *Zhaozhong Shi*

Thurs. 12/8:
HBT correlations *Marton Nagy*
π^0 in Au+Au *Nour Abdulameer*



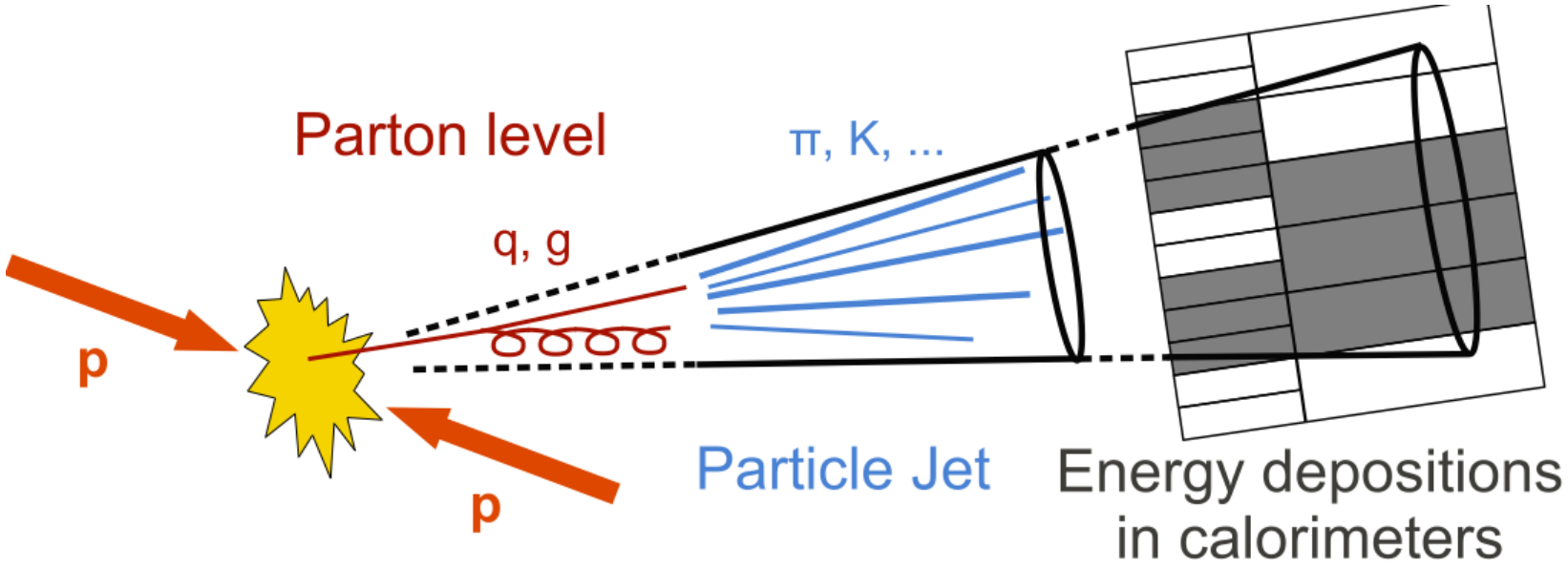
- Hard Probes
  - Jets
  - Jet like correlations
  - Heavy Flavor
  - High p_T hadrons
- Bulk Measurements
  - Flow
  - Thermal photons

**Focus on Heavy-Ion related results*

Recent Papers:

arXiv:2207.10745 ϕ meson production in Cu+Au and U+U collisions
arXiv:2203.17058 Charm and bottom quark production in 200 GeV Au+Au collisions
arXiv:2203.17187 Non-prompt direct photon production in Au+Au collisions
arXiv:2203.12354 Low-p_T direct-photon production in Au+Au collisions at 39 and 62.4 GeV
arXiv:2203.09894 Second-harmonic Fourier coefficients from azimuthal anisotropies in p+p, p+Au, d+Au, & ^{3}He+Au collisions
arXiv:2203.06087 Study of ϕ meson production in p+Al, p+Au, d+Au, and ^{3}He+Au collisions
arXiv:2202.03863 ψ(2S) nuclear modification at backward and forward rapidity in p+p, p+Al, and p+Au collisions at 200 GeV

Jet Reconstruction in PHENIX



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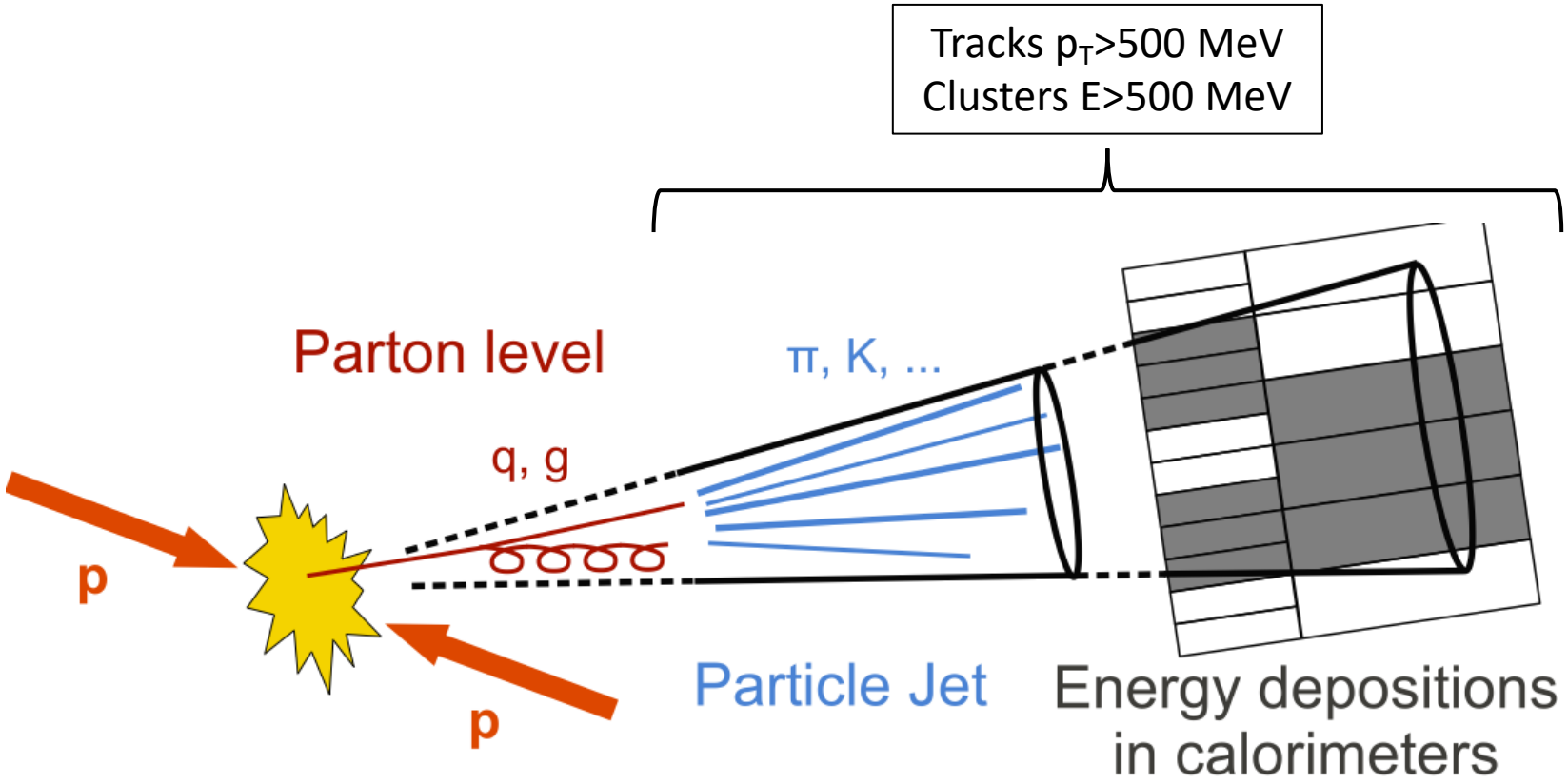
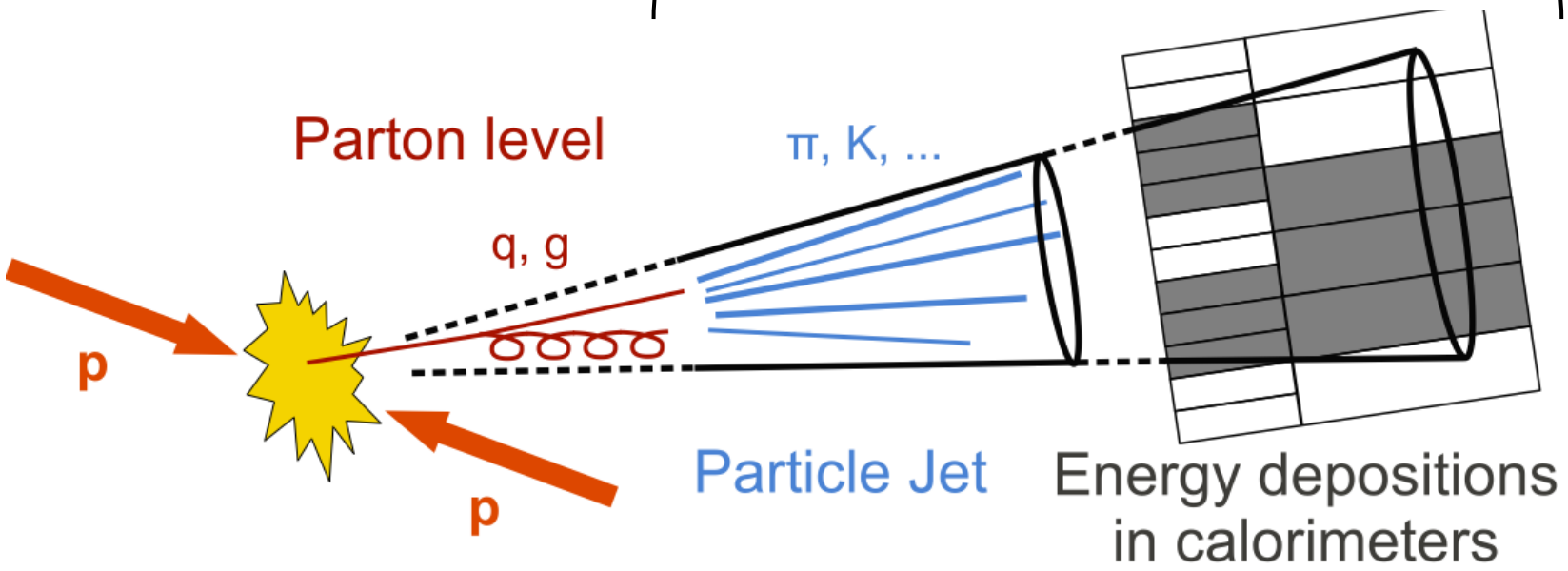


Jet Reconstruction in PHENIX

Tracks p_T>500 MeV
Clusters E>500 MeV

FastJet
anti-k_T algorithm
(R=0.2,0.3):

$$d_{ij} = min(\frac{1}{k_{T,i}^2}, \frac{1}{k_{T,j}^2})\frac{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}{R^2}$$



Reco jet-level cuts:
- $0.3 < c_f < 0.7$
- n_C>=3
- p_T^{reco}>5 GeV

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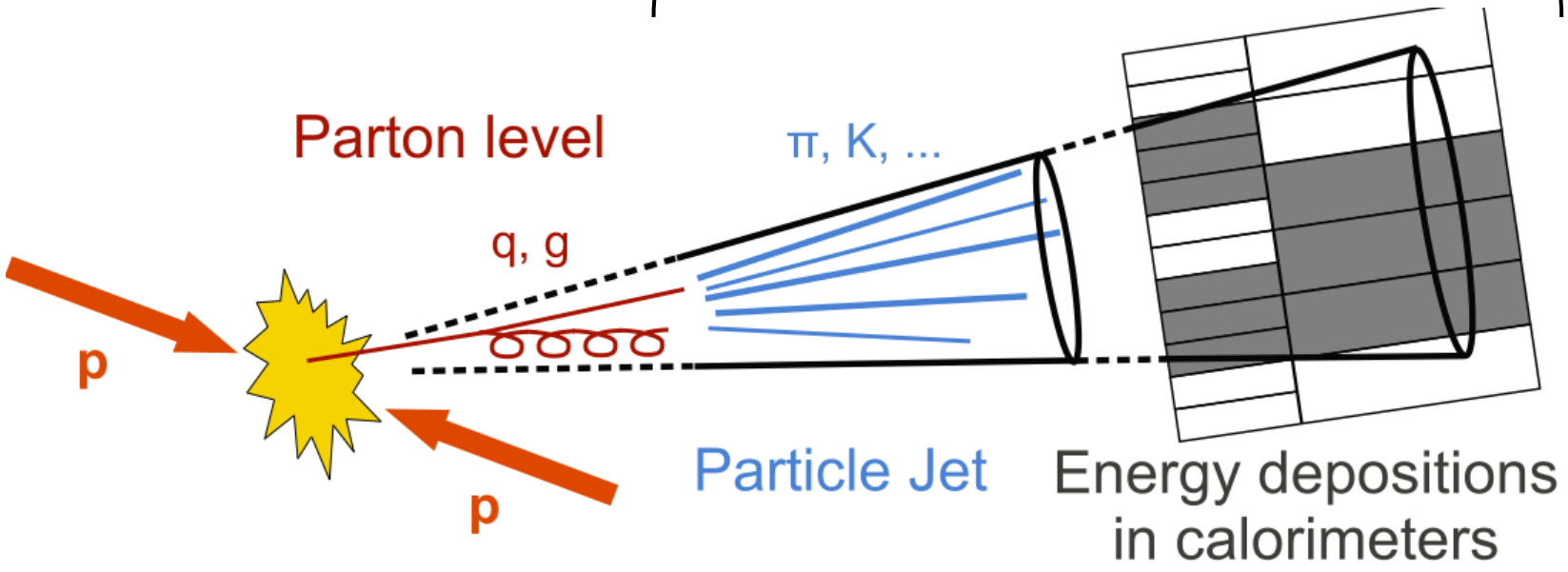

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Bayesian Unfolding:
- Missing energy
- Bin migration (resolution)
- Trigger Efficiency
- Fake Subtraction (UE)

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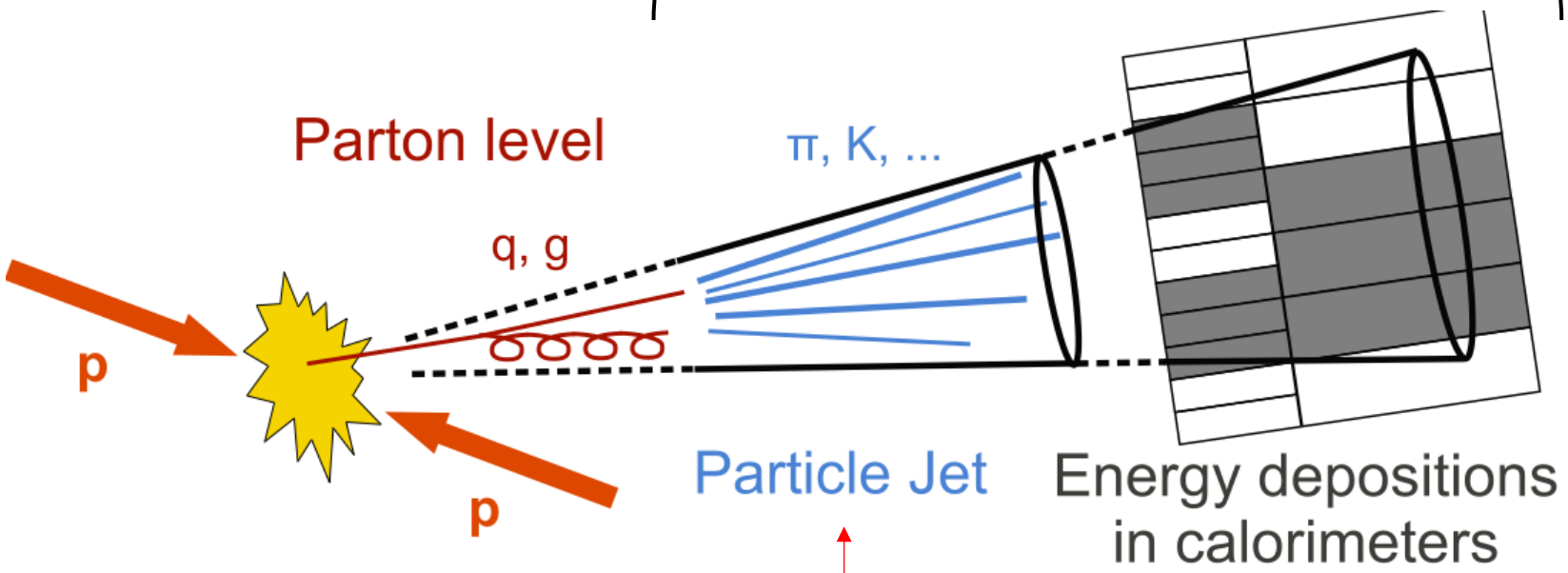

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Unfold to hadron jet
(Pythia prior)

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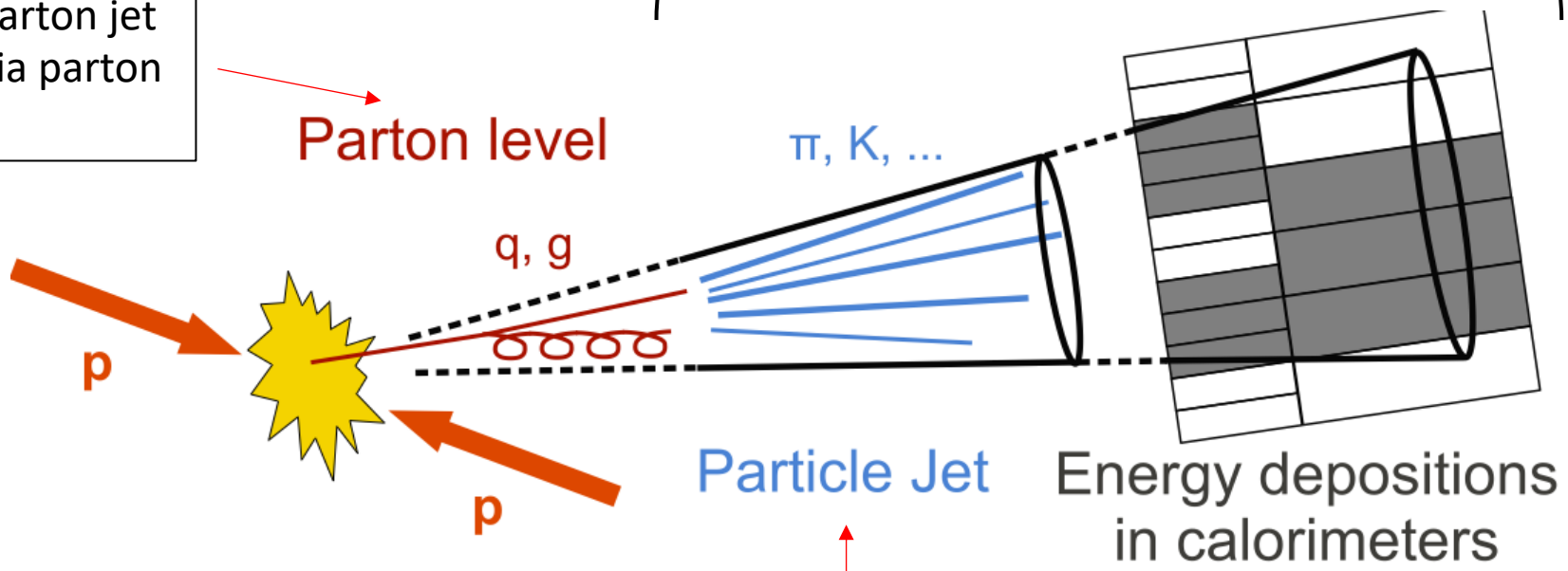
Unfold to parton jet (using Pythia parton shower)



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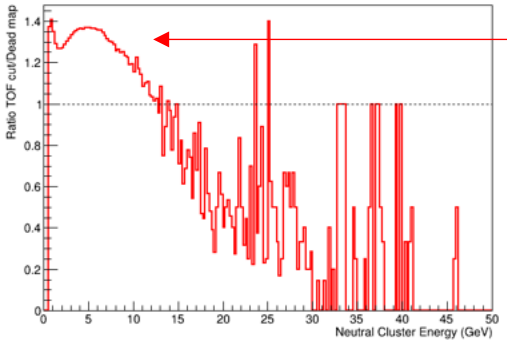
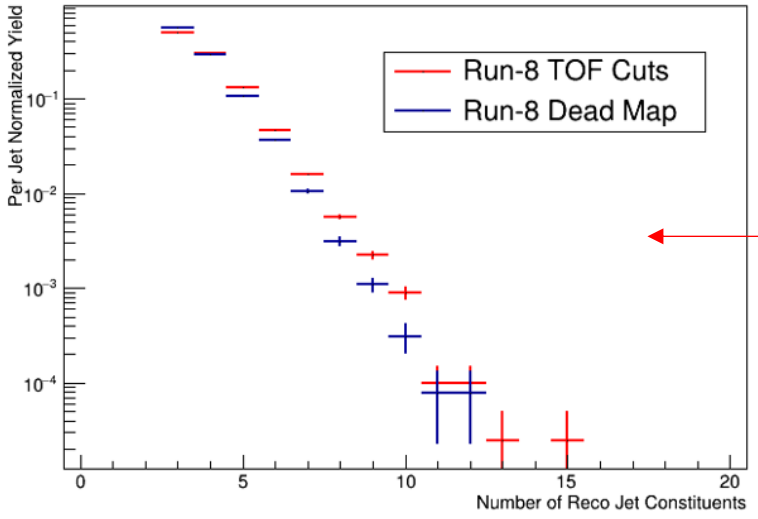
Unfold to hadron jet (Pythia prior)

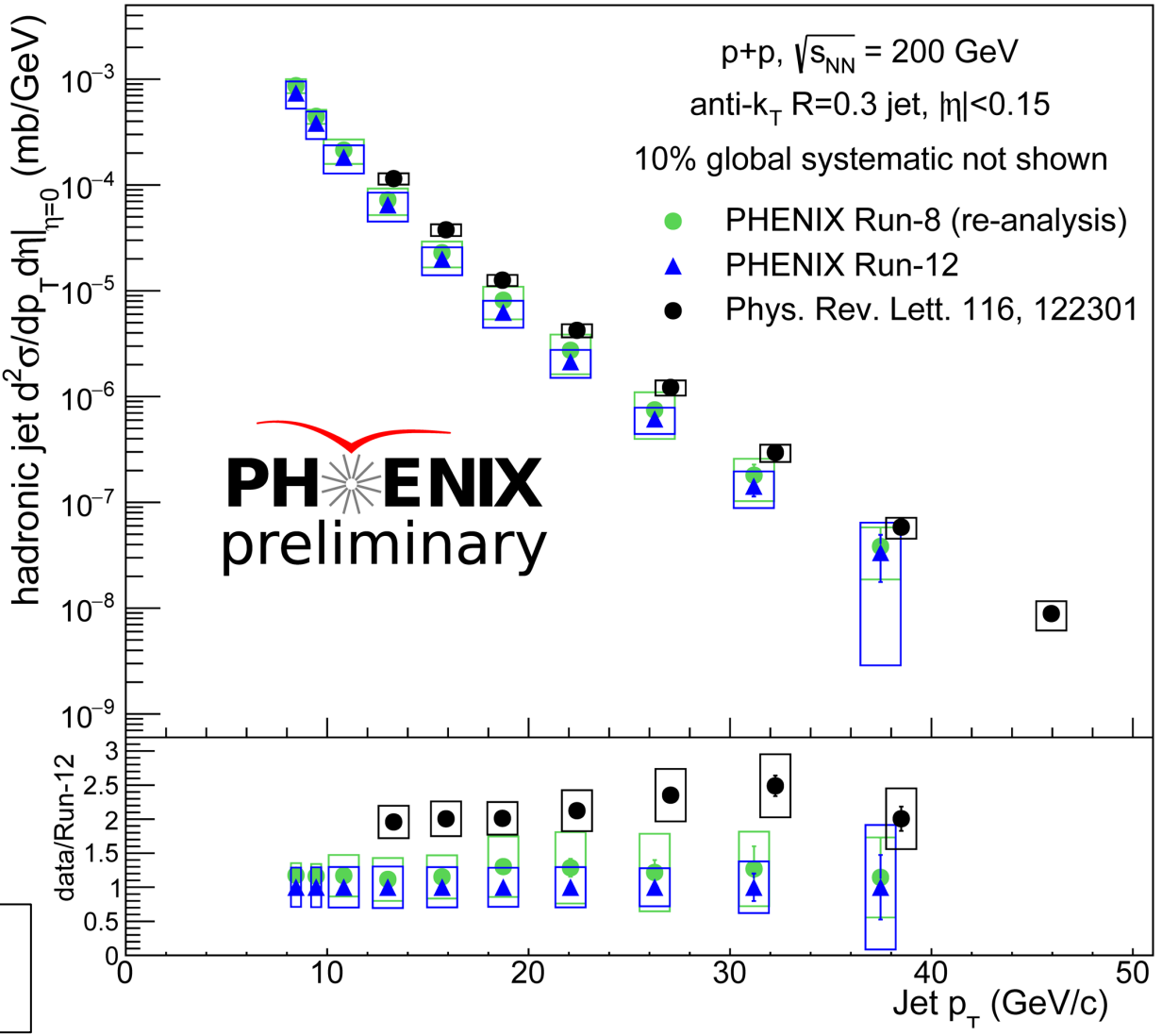
200 GeV p+p R=0.3 Jet Cross Section



Prior analysis used TOF cuts to suppress noisy EMCal towers, but this still exhibits an excess of low energy clusters compared to eliminating those towers.



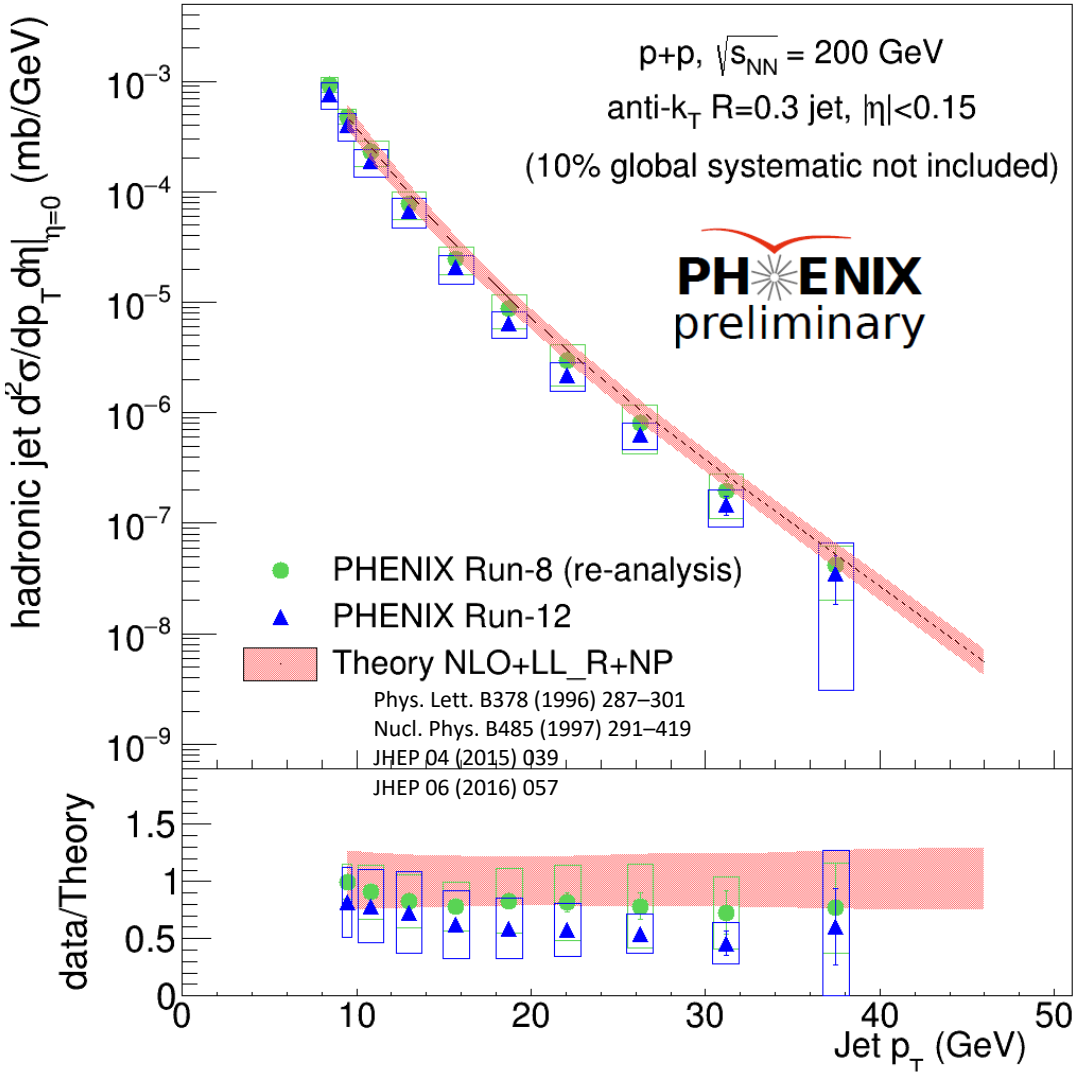
The number of jet constituents is a steeply falling function – addition of a small amount of noise (not in simulation) in the EMCal can dramatically increase jet yield!



The new PHENIX Preliminary supersedes the previously published result (PRL 116, 122301, erratum in preparation).

Comparison with NLO pQCD

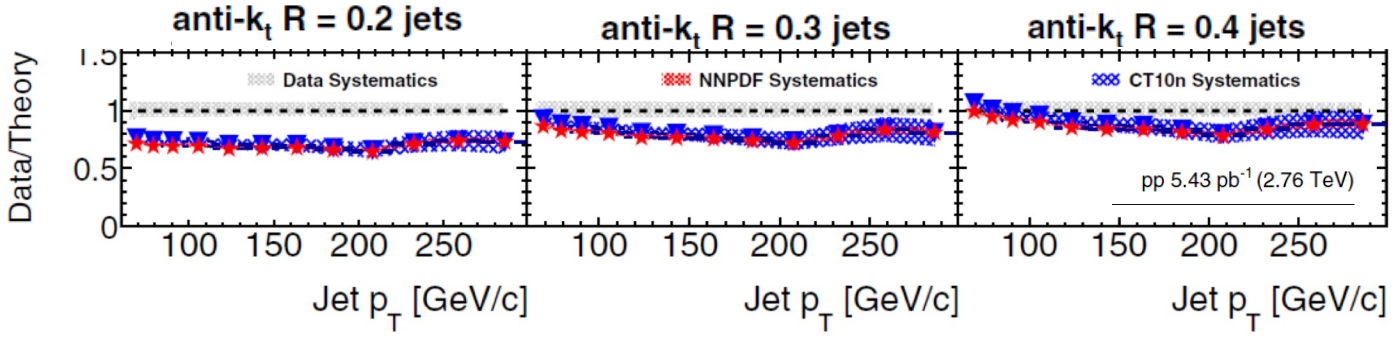
- R=0.3 anti-k_T jet cross section systematically lower than NLO prediction.

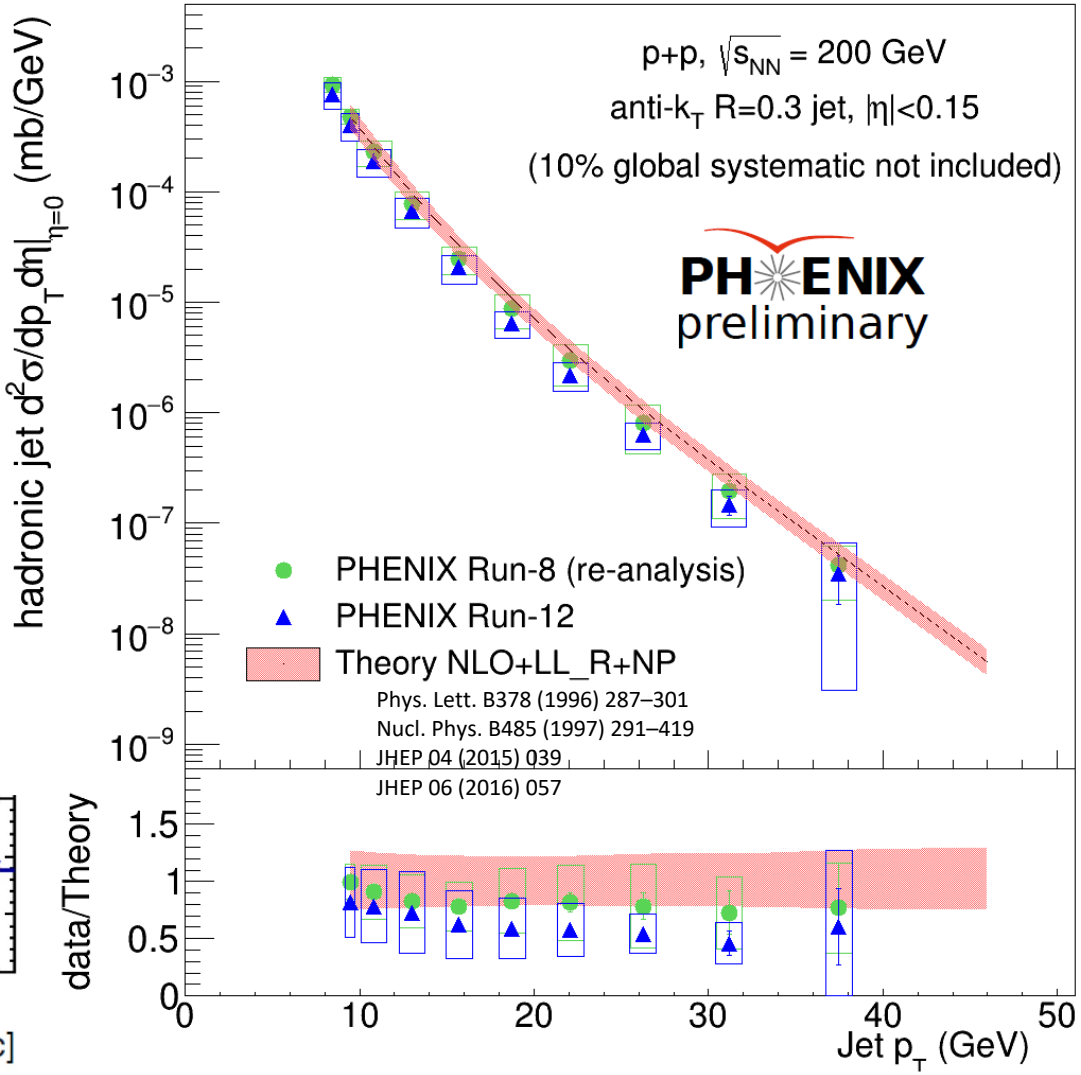


Comparison with NLO pQCD

- R=0.3 anti-k_T jet cross section systematically lower than NLO prediction.
- Small-R anti-k_T jet cross sections are systematically lower than NLO predictions. (Large R generally agrees better with NLO.)
- Suggests the distribution of particles in the jet is not accurately reproduced by NLO.
- Investigating a comparison with NNLO

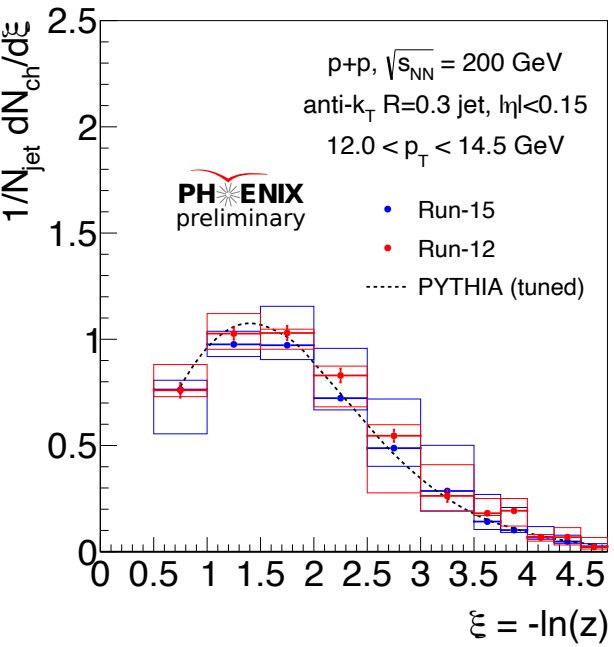
CMS PRC **96**, 015202 (2017)





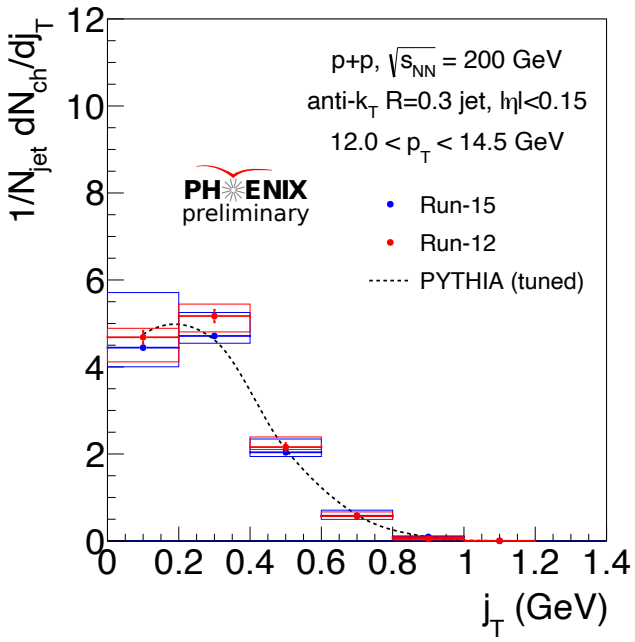
Jet substructure in p+p

Fragmentation Function



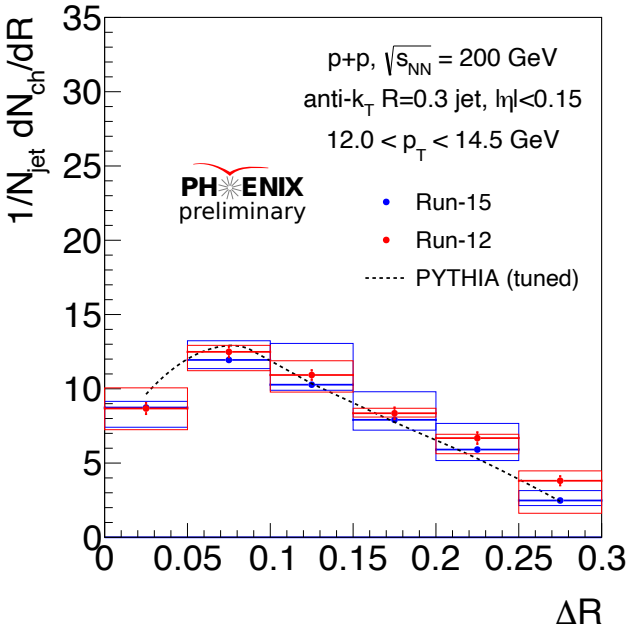
$\xi = -\ln(z) = \ln(p_{T,jet}/p_{Th})$

Transverse fragmentation



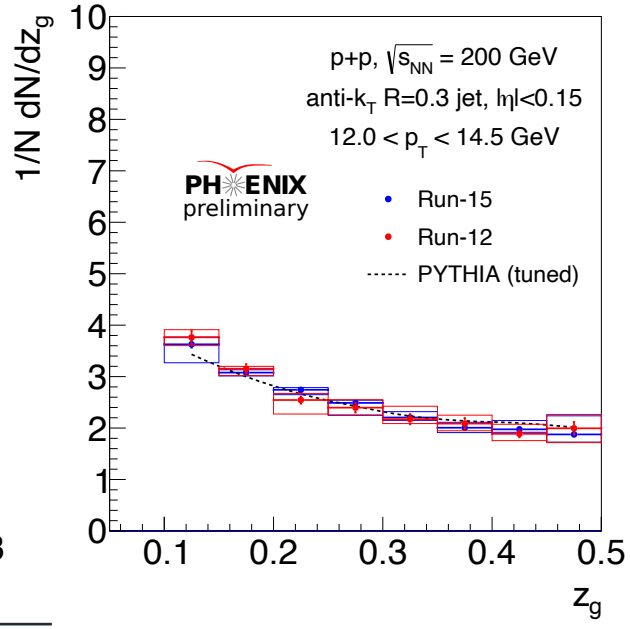
$j_T = |p_{jet} \times p_{track}|/|p_{jet}|$

Radial profile



$\Delta R = \sqrt{(\phi - \phi_{jet})^2 + (\eta - \eta_{jet})^2}$

Jet splitting function

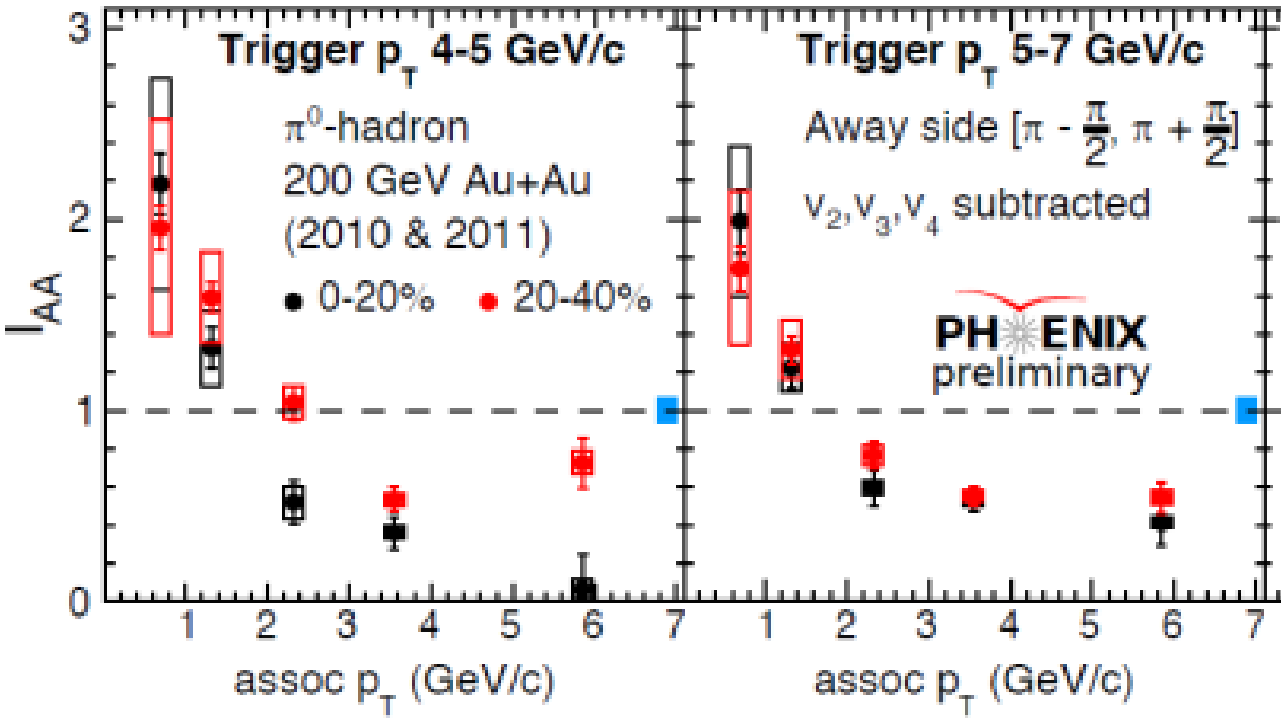


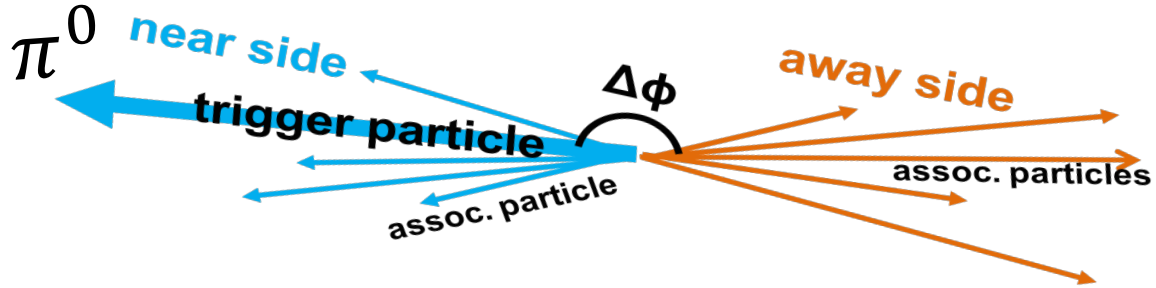
$z_g = \min(p_{T1}, p_{T2})/(p_{T1} + p_{T2})$

(Soft Drop, β=0, z_{cut} = 0.1)

- Unfolded substructure distributions for jets in p_T bin 12-14.5 GeV/c compared to tuned PYTHIA
- p+p measurements are an important baseline for p+A and A+A

Jet Modification in A+A





$$I_{AA} = \frac{Y^{AA}_{Away}}{Y^{pp}_{Away}}$$

- Suppression at high p_{Th}
- Enhancement at low p_{Th}
- Transition at similar p_{Th} for all trigger p_T

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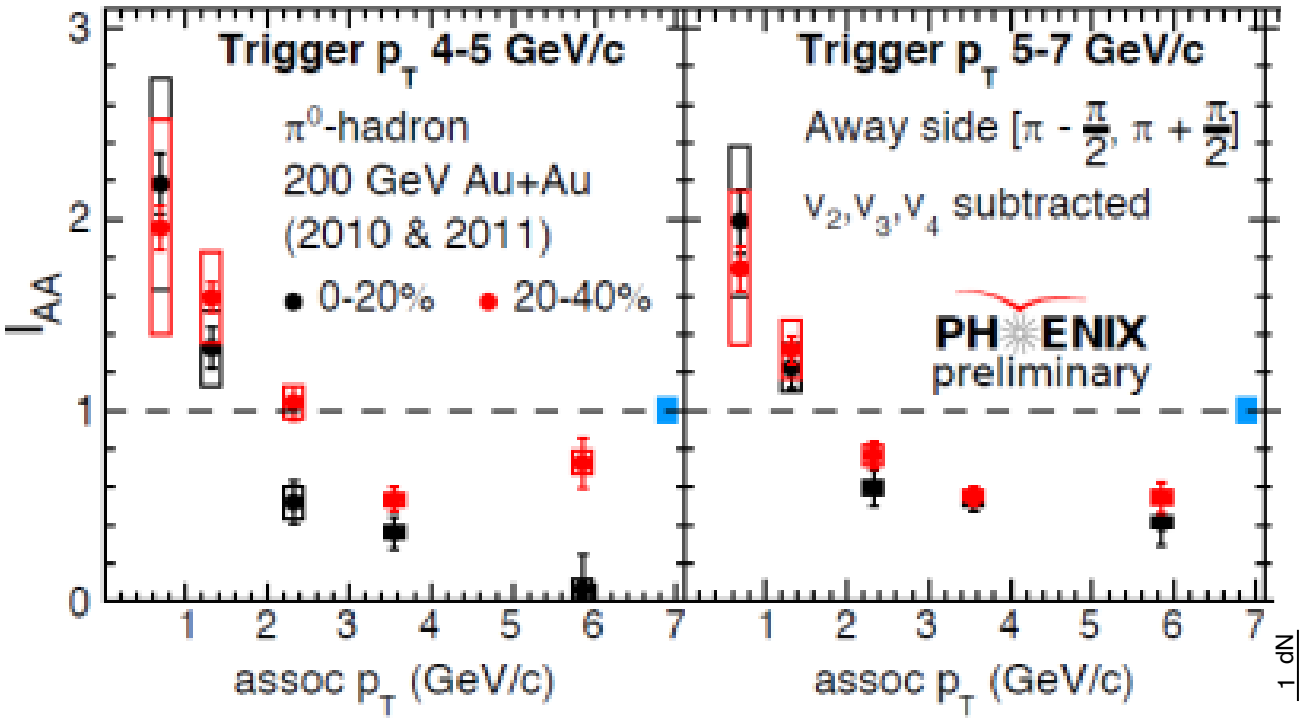

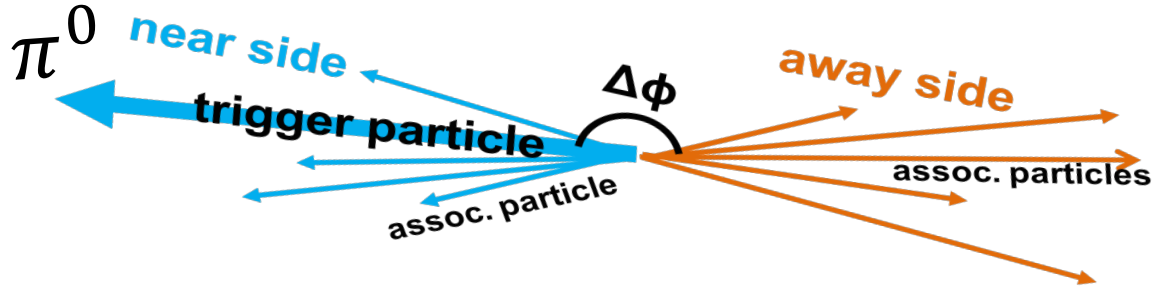

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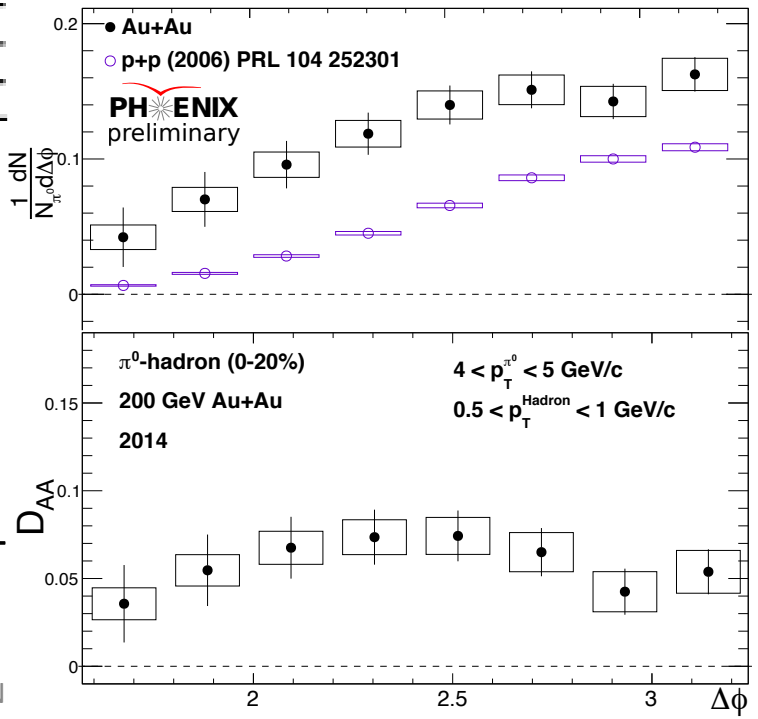
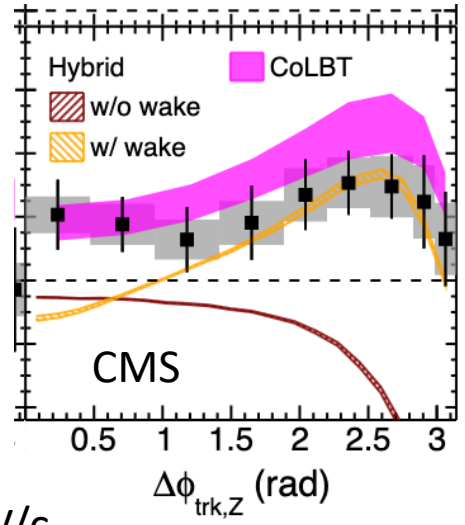


$$D_{AA} = YAA - Ypp$$

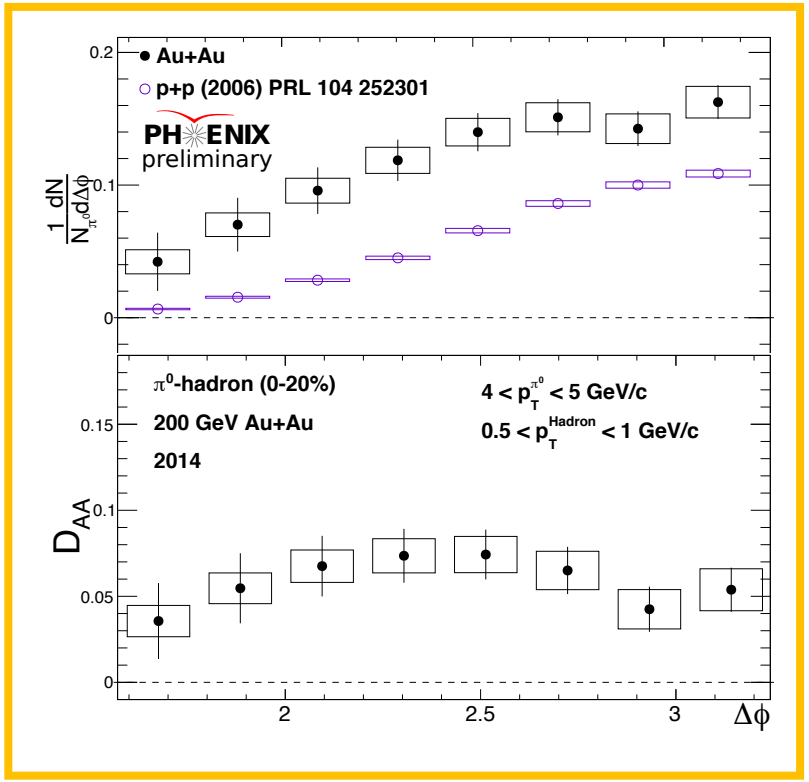
- Less sensitive to yields near zero than ratio
- Enhancement: $D_{AA} > 0$
- Suppression: $D_{AA} < 0$

Medium Response

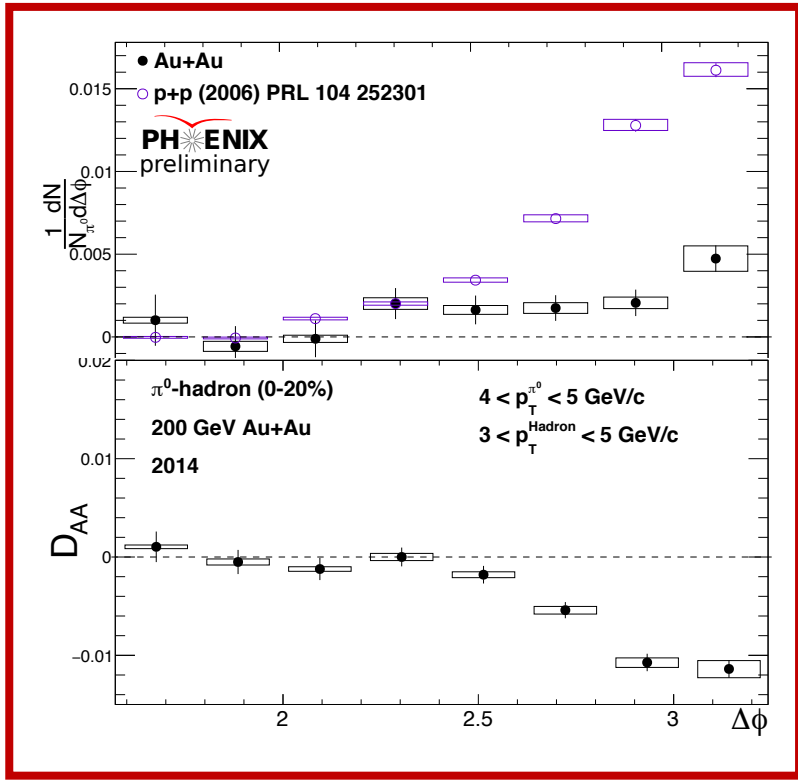
- Hybrid model shows different behavior with and without wake (medium response)
- What is the p_T dependence to this feature?
  - PHENIX π^0–h may imply wake is more relevant for low p_T hadrons



$0.5 < p_{T,h} < 1$ GeV/c



$3 < p_{T,h} < 5$ GeV/c



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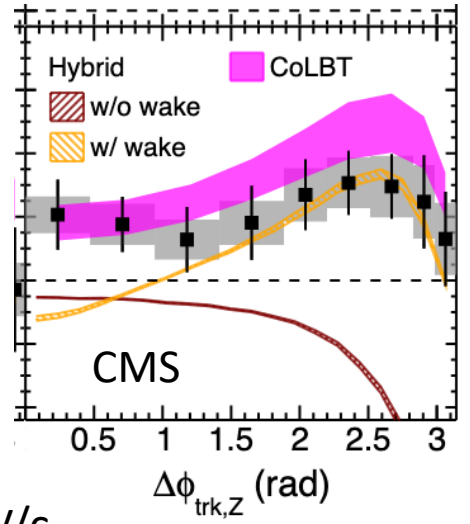

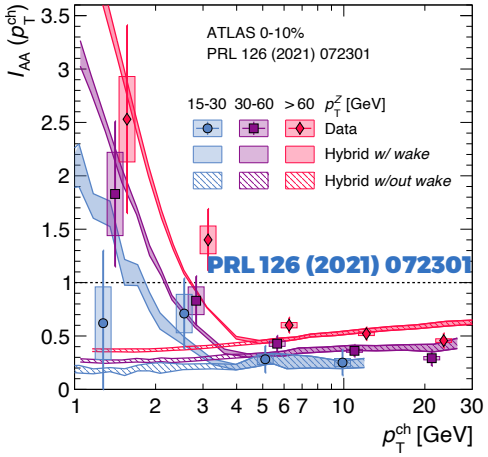

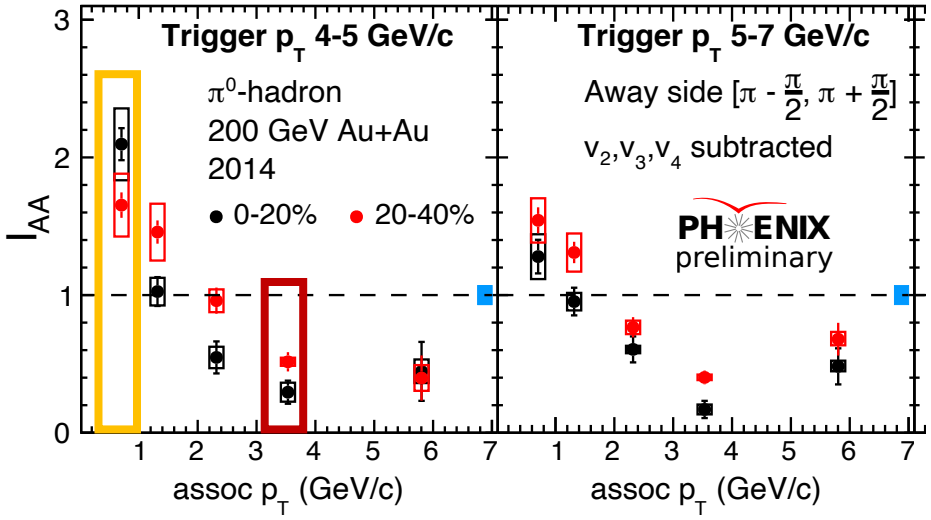

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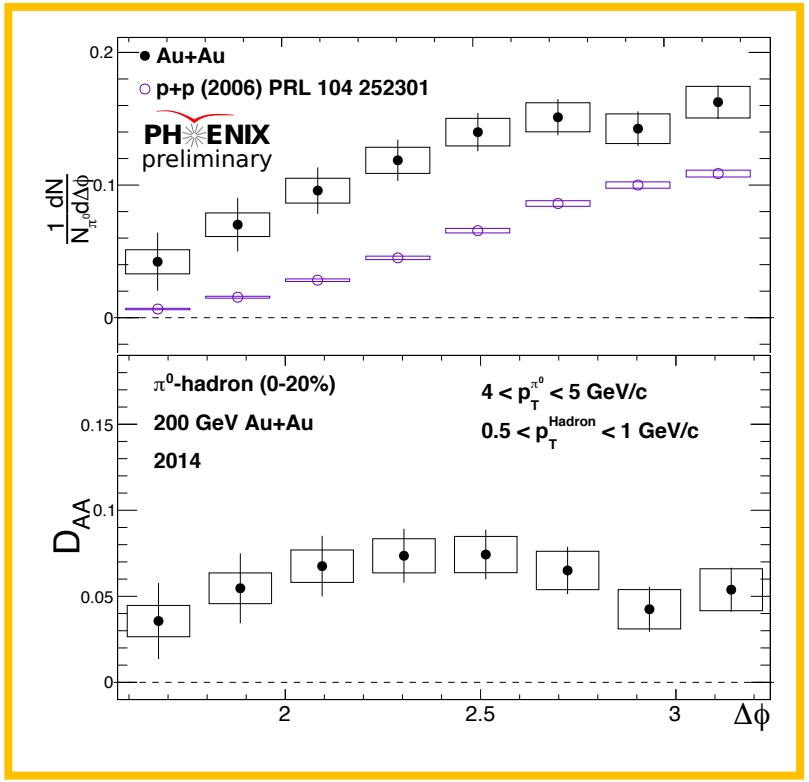

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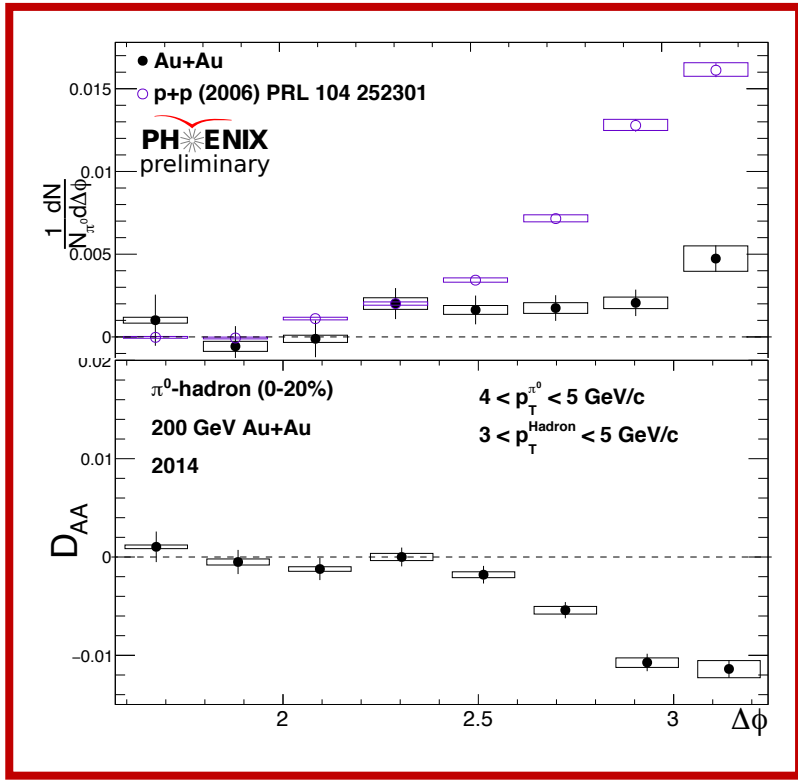
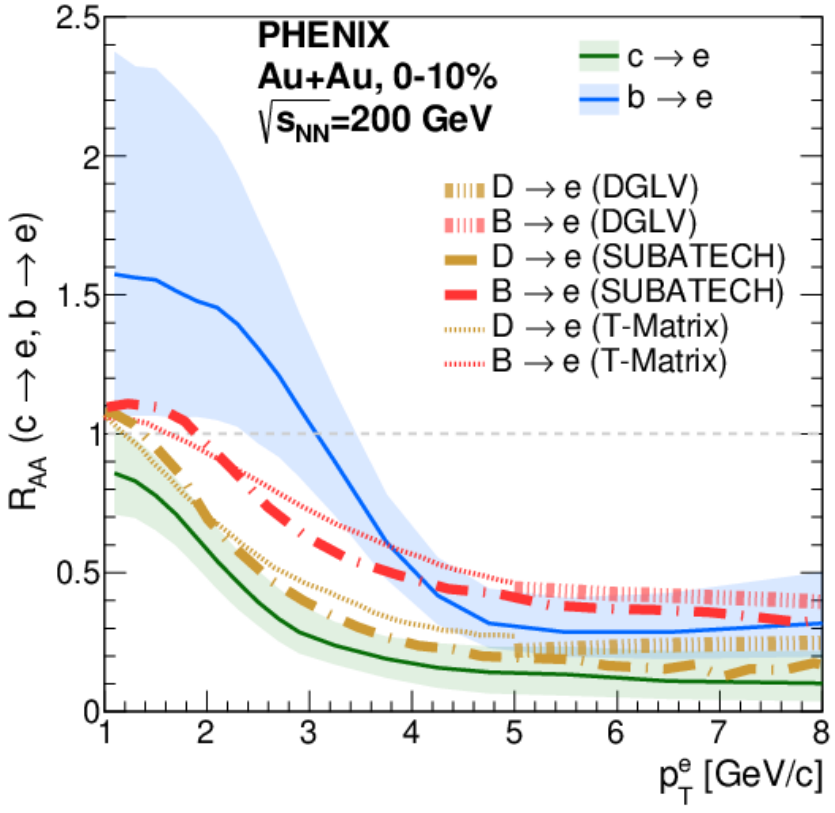
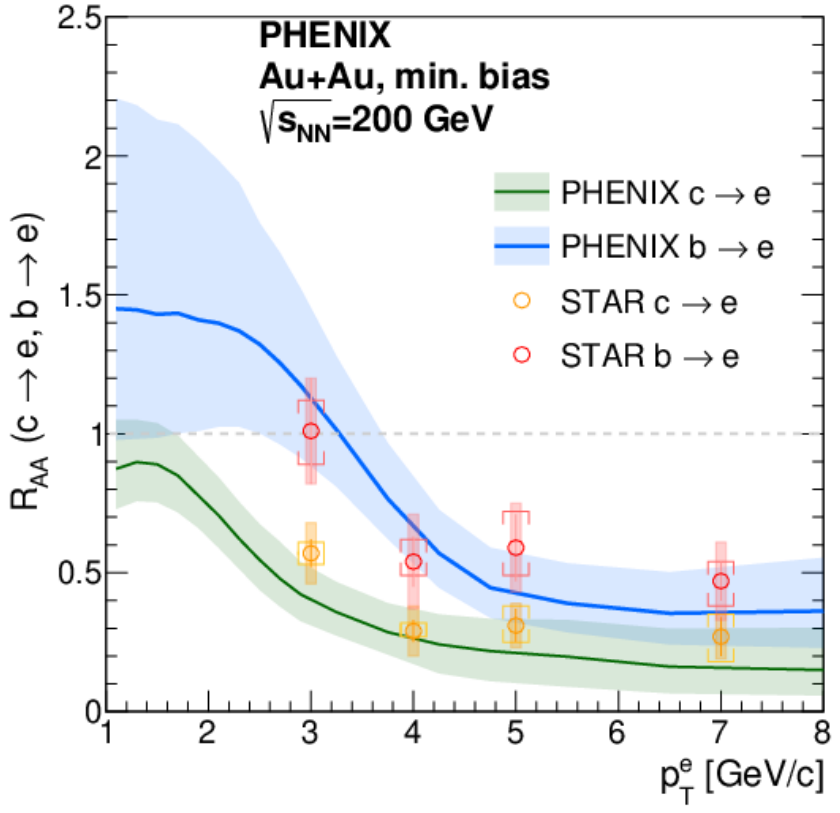


Quark Mass Dependent Energy Loss

arXiv:2203.17058

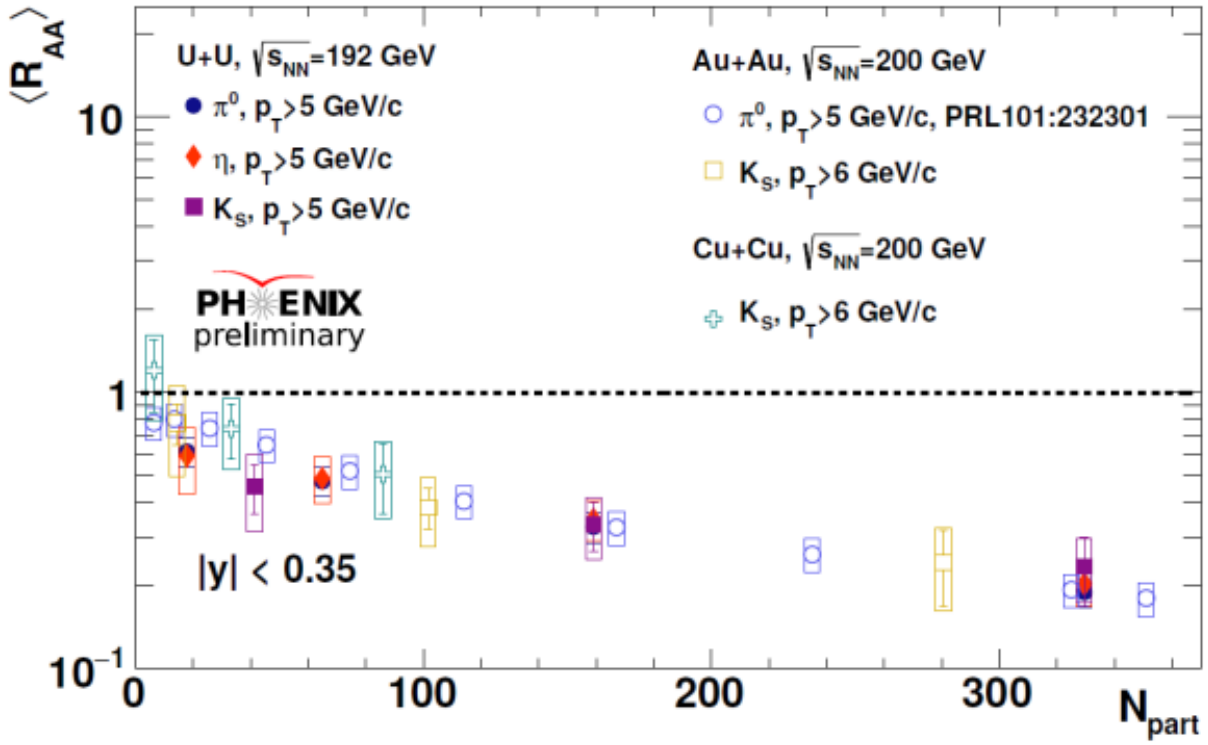




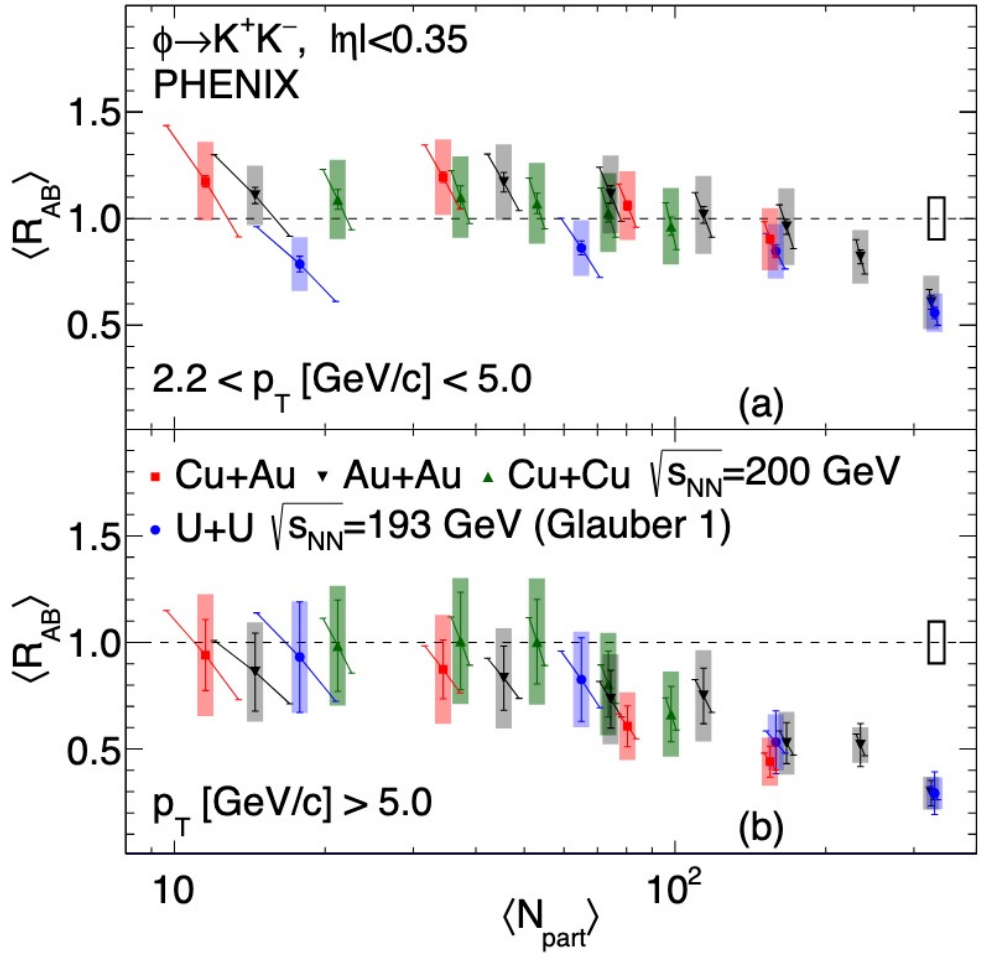
Beauty is less suppressed than charm

Various Collision Systems: R_{AA} at High p_T

- For p_T> 6 GeV/c same trend for all systems and particles as a function of N_{part}
- $<R_{AB}>$ for ϕ mesons consistent across Cu+Cu, Cu+Au, Au+Au and U+U

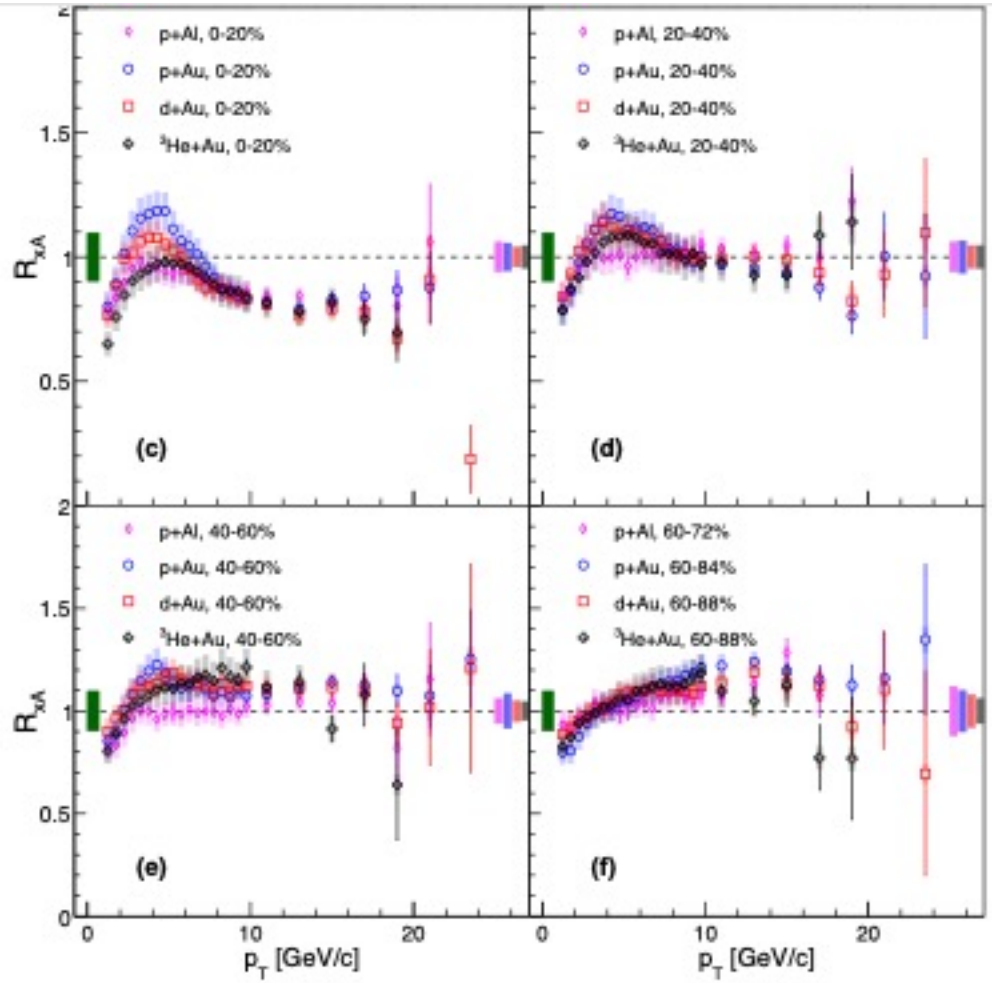


arXiv:2207.10745



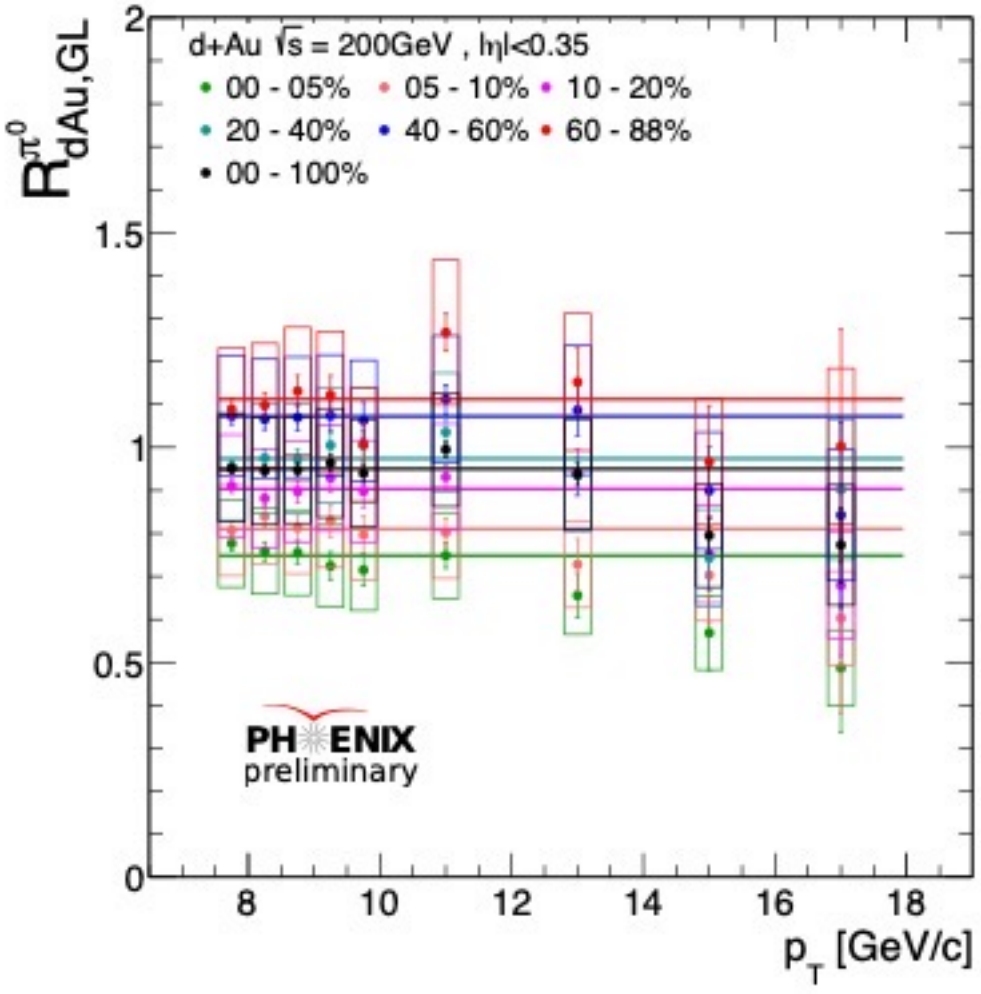
System Size Dependence…Small Systems

PRC 105, 064902 (2022)



- High p_T R_{xA} similar across all collision systems
- Suppression in central collisions
- Enhancement in peripheral collisions
  - Difficult to explain…

System Size Dependence…Small Systems



- Previously observed centrality dependence of R_{dA}
  - 0-5% < 1 < 60-88%
- High p_T direct photons should not be modified

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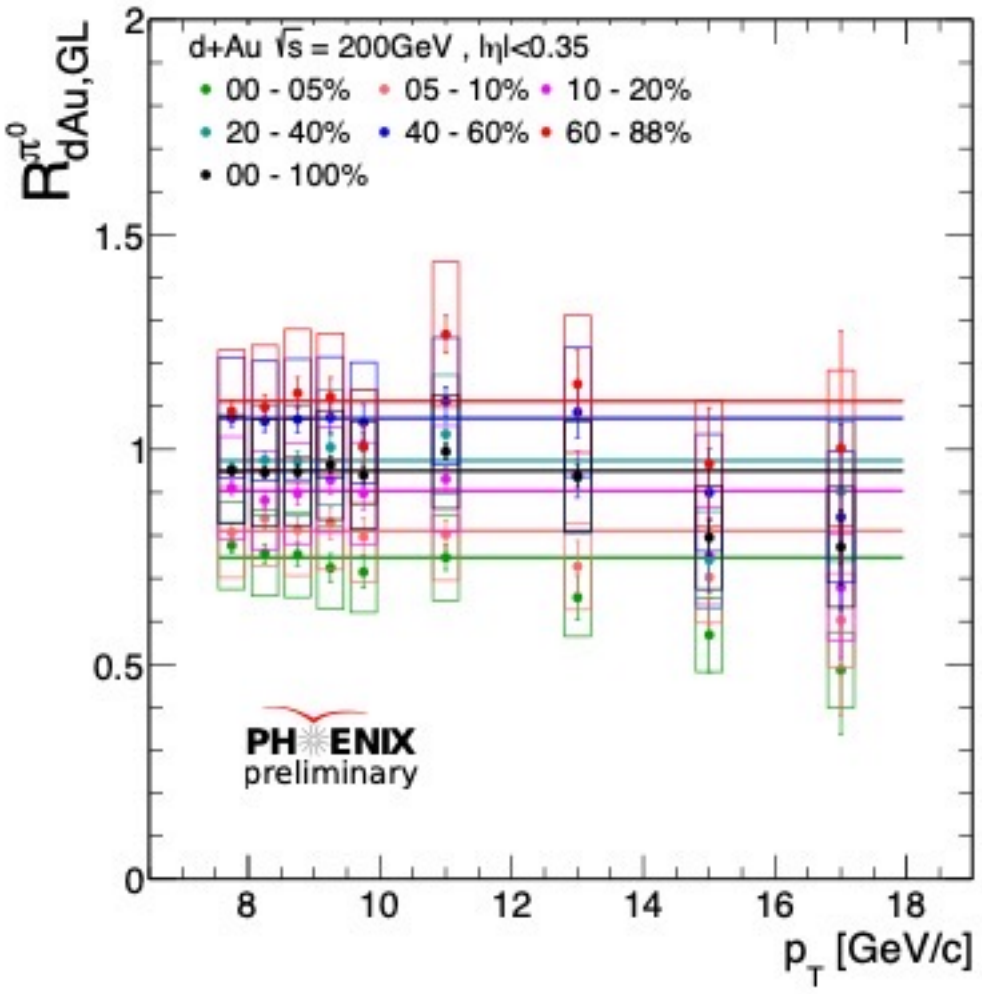
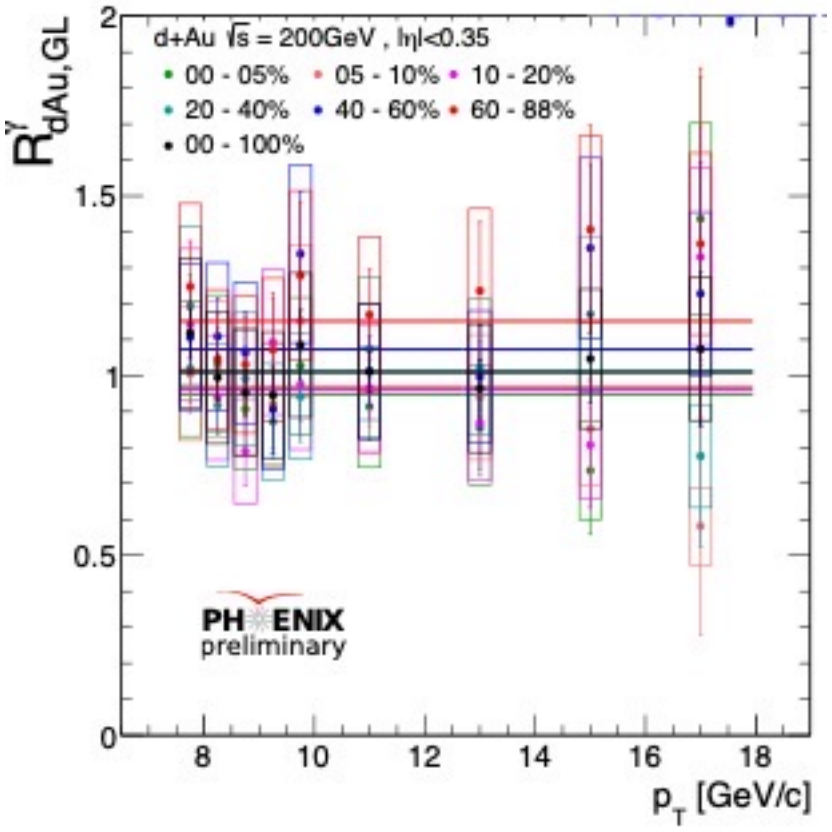
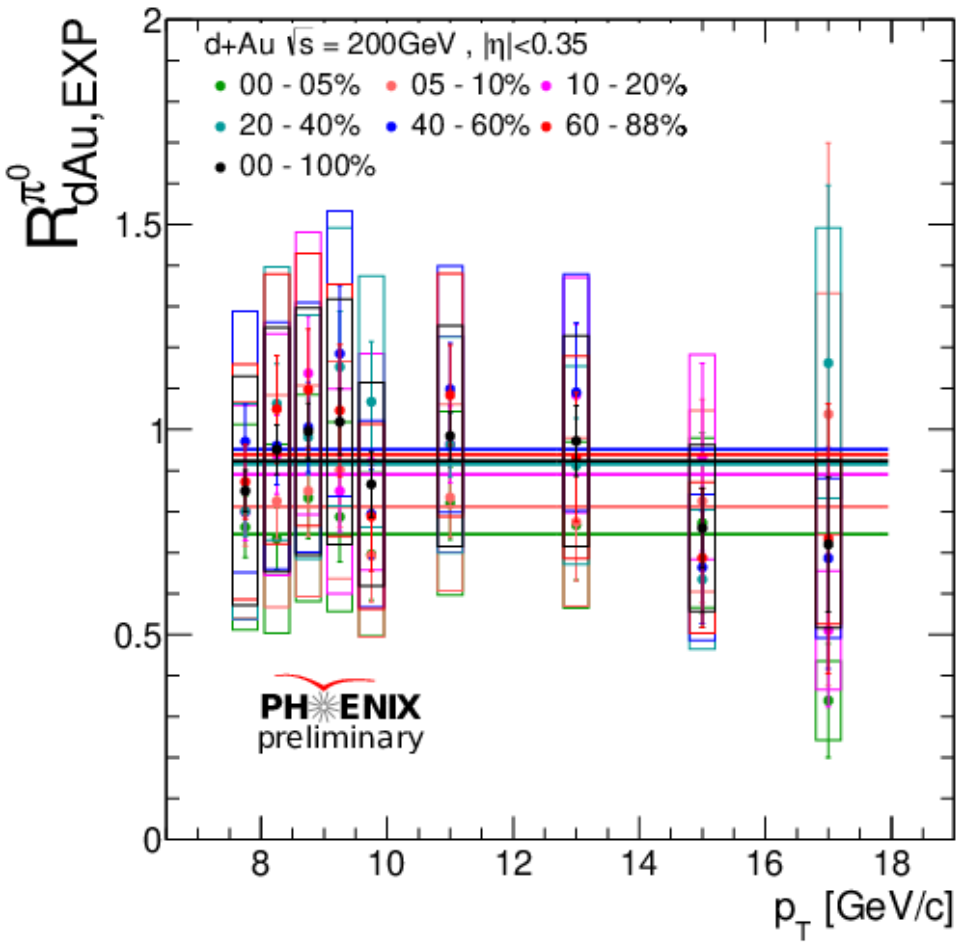
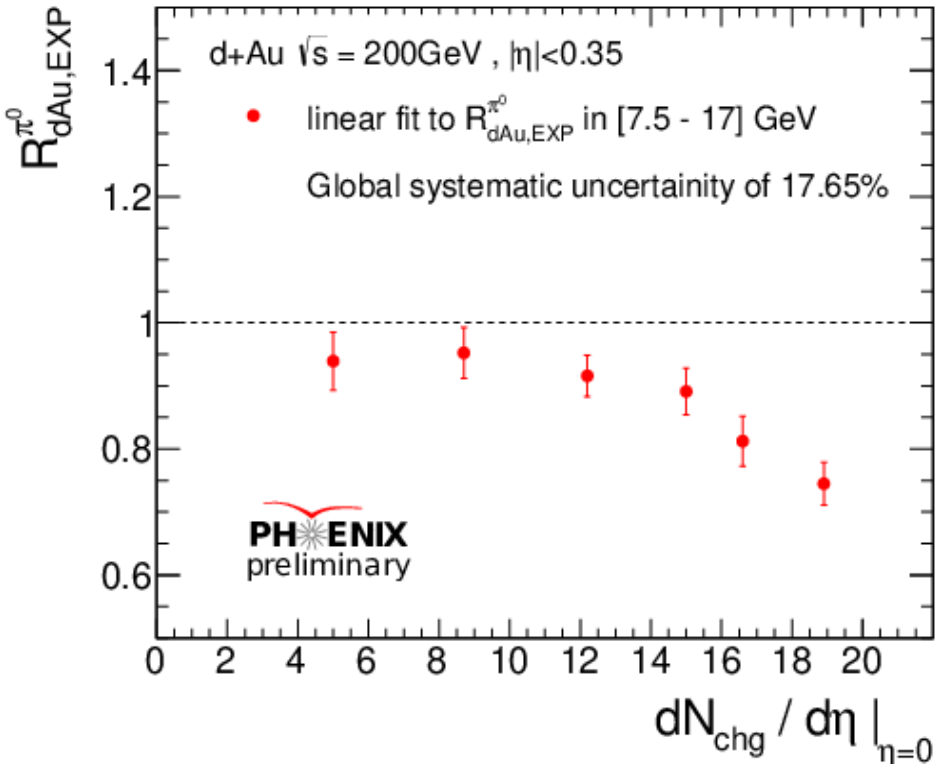


- Previously observed centrality dependence of R_{dA}
  - 0-5% < 1 < 60-88%
- High p_T direct photons should not be modified
- But similar trend is observed!
- Can use photon R_{dAu} to correct for bias in N_{coll} determination



Direct Photons as a calibration tool

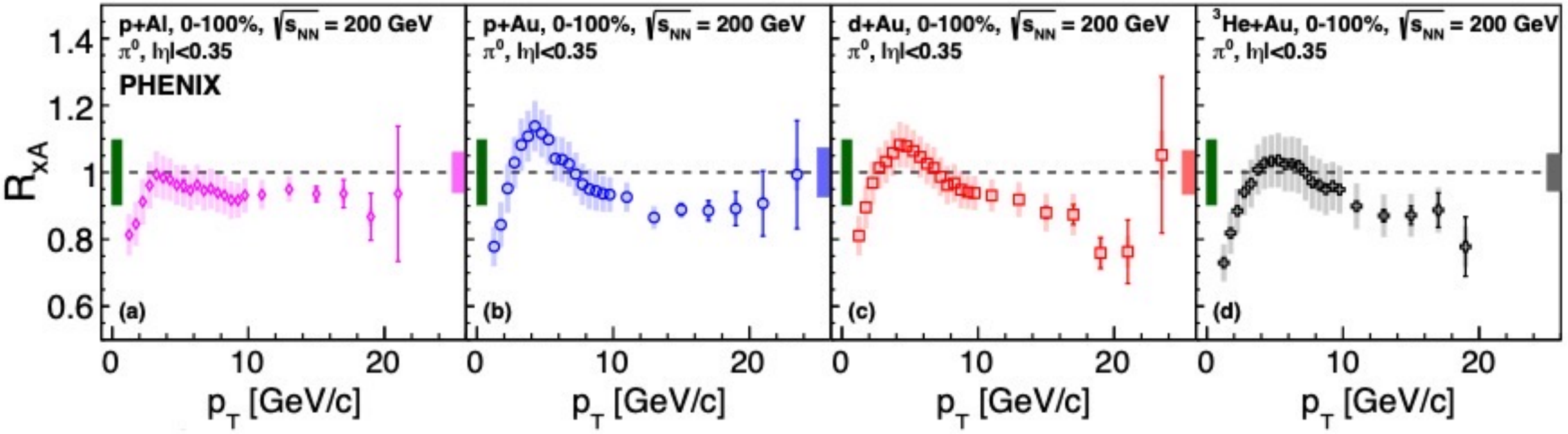




- Removes apparent enhancement in peripheral collisions
- Small suppression in central collisions remains
  - EMC effect? QGP?

System Size Dependence at Lower p_T

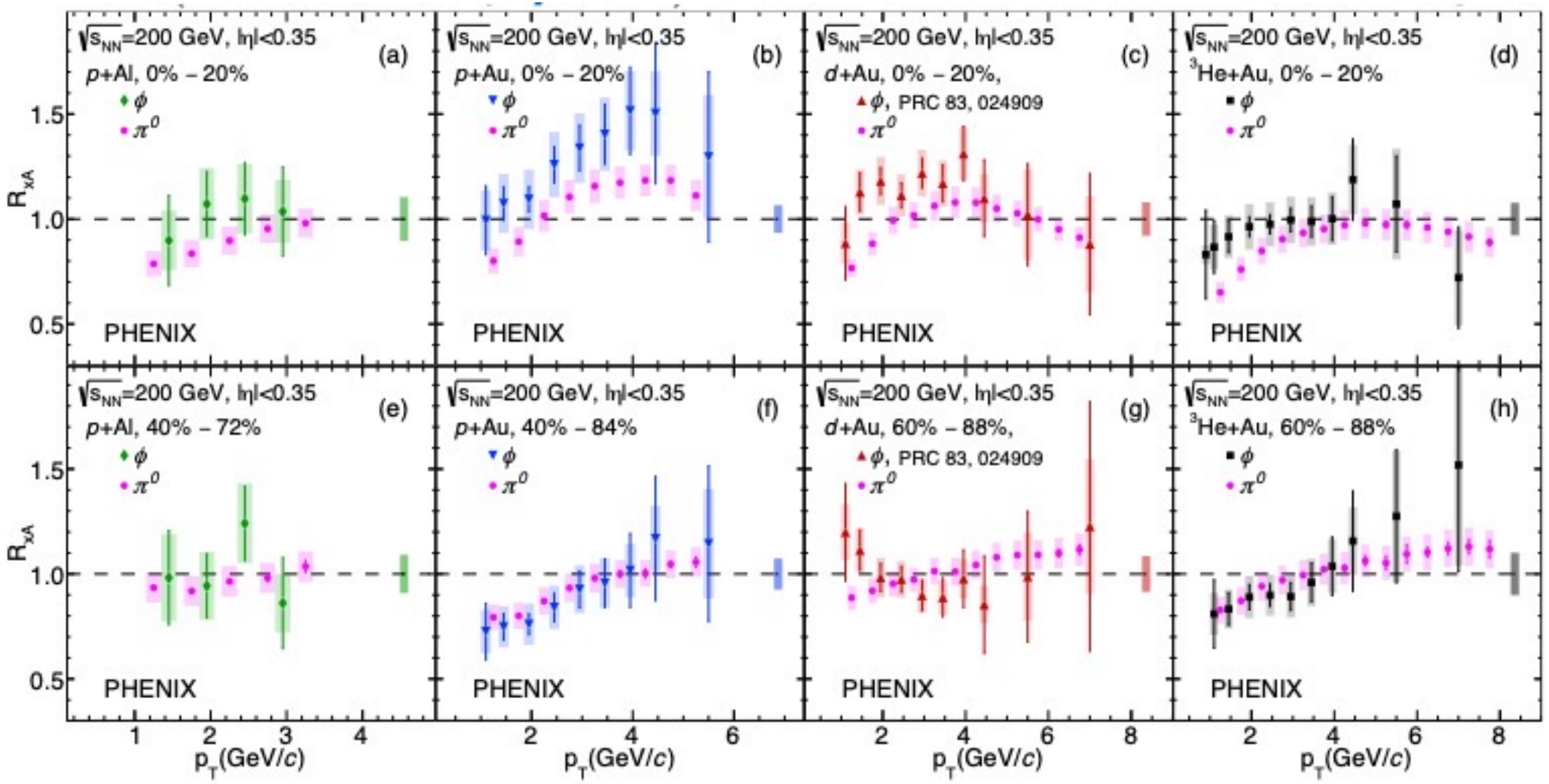
PRC 105, 064902 (2022)



- Varying the collision system (minimum bias shown)
- Cronin enhancement at intermediate p_T
  - Lighter target shows smaller enhancement (p+Al < p+Au)
  - Heavier projectile shows smaller enhancement (He+Au < d+Au < p+Au)

ϕ mesons in small systems

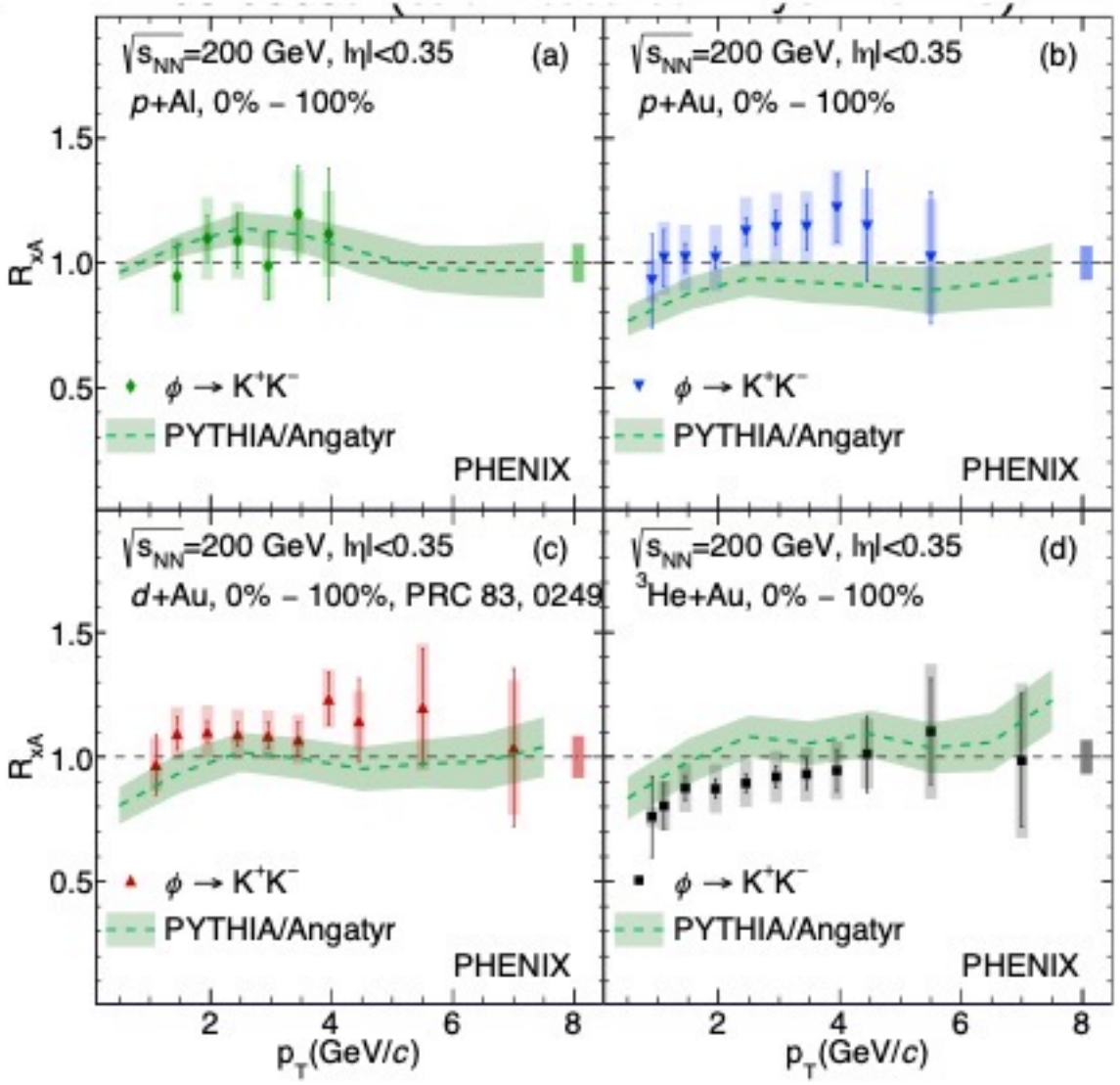
arXiv:2203.06087



- R_{xA} for ϕ similar to π^0
- Hints of slight ϕ enhancement relative to π^0

ϕ mesons in small systems

arXiv:2203.06087



- R_{AA} well-described by PYTHIA/Angantyr
  - Misses overall system size ordering

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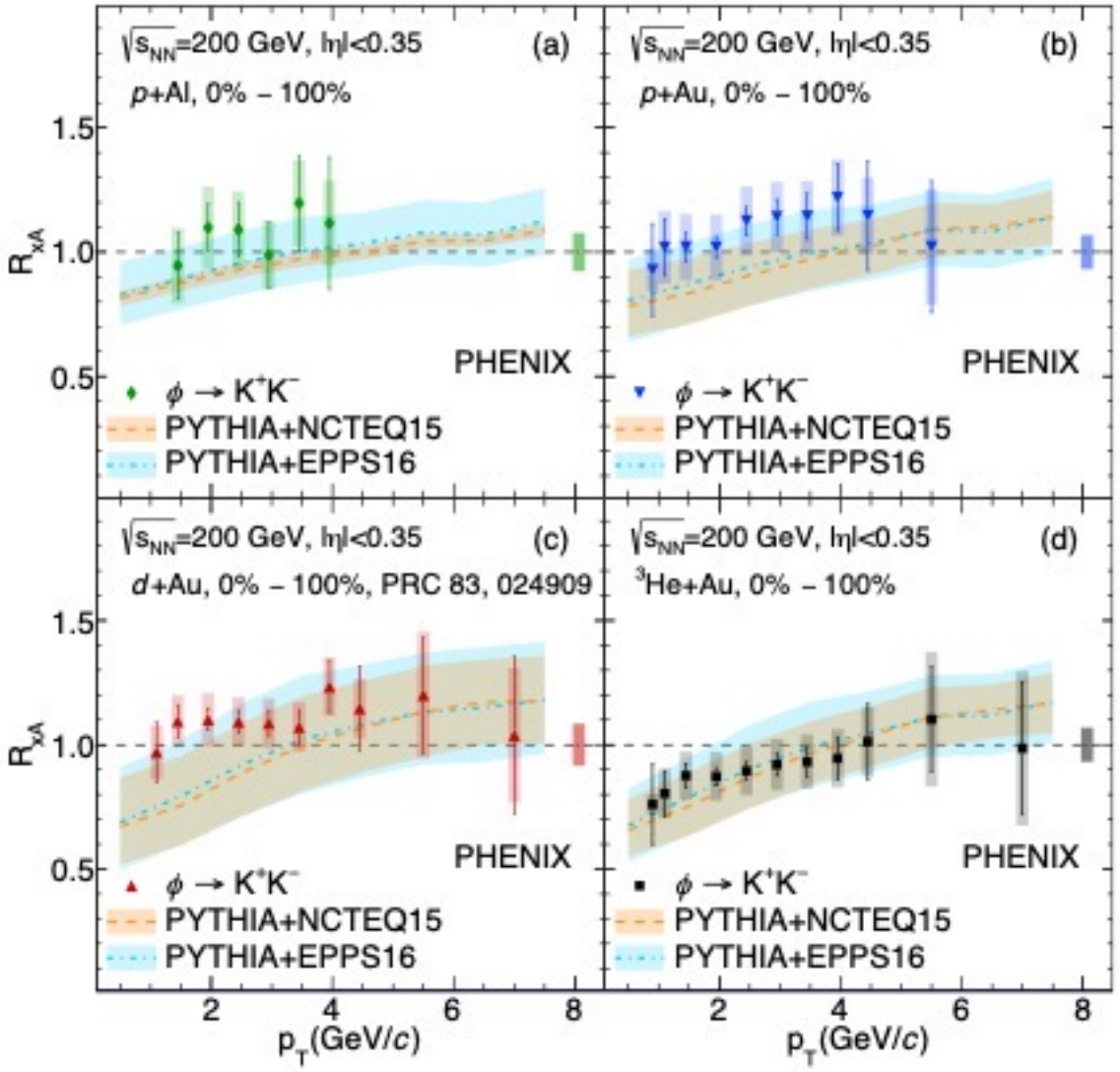
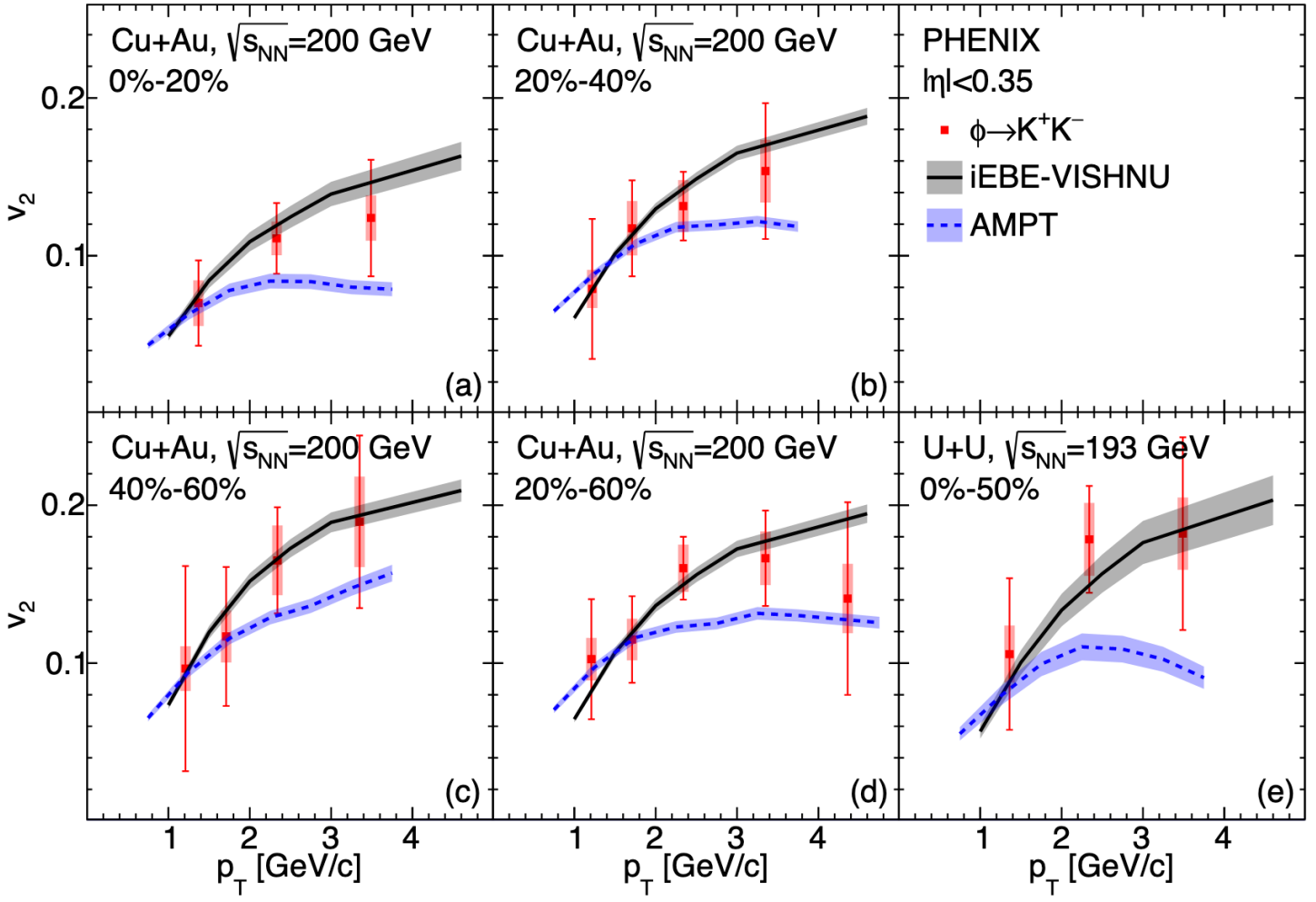


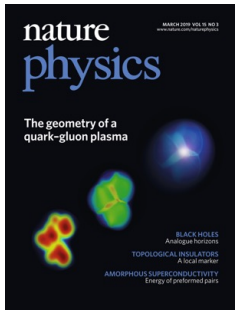
- R_{AA} well-described by PYTHIA/Angantyr
  - Misses overall system size ordering
- R_{AA} also well-described by PYTHIA with nPDFs
  - Misses overall system size ordering

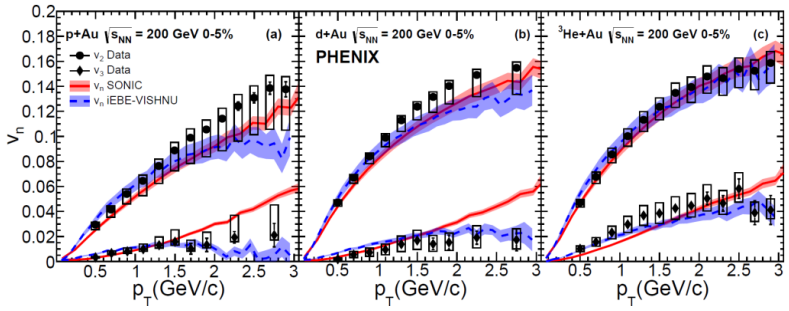
ϕ meson v_2 in Cu+Au and U+U

- ϕ v_2 scales with 2nd order eccentricity and characteristic nuclear overlap length
- Agrees with same hydrodynamic model shown for the small systems

arXiv:2207.10745





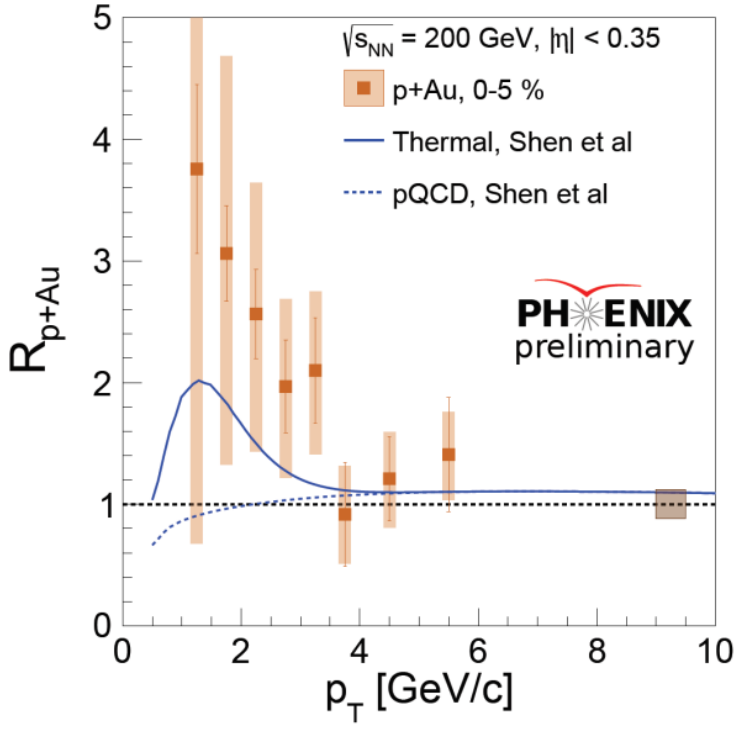


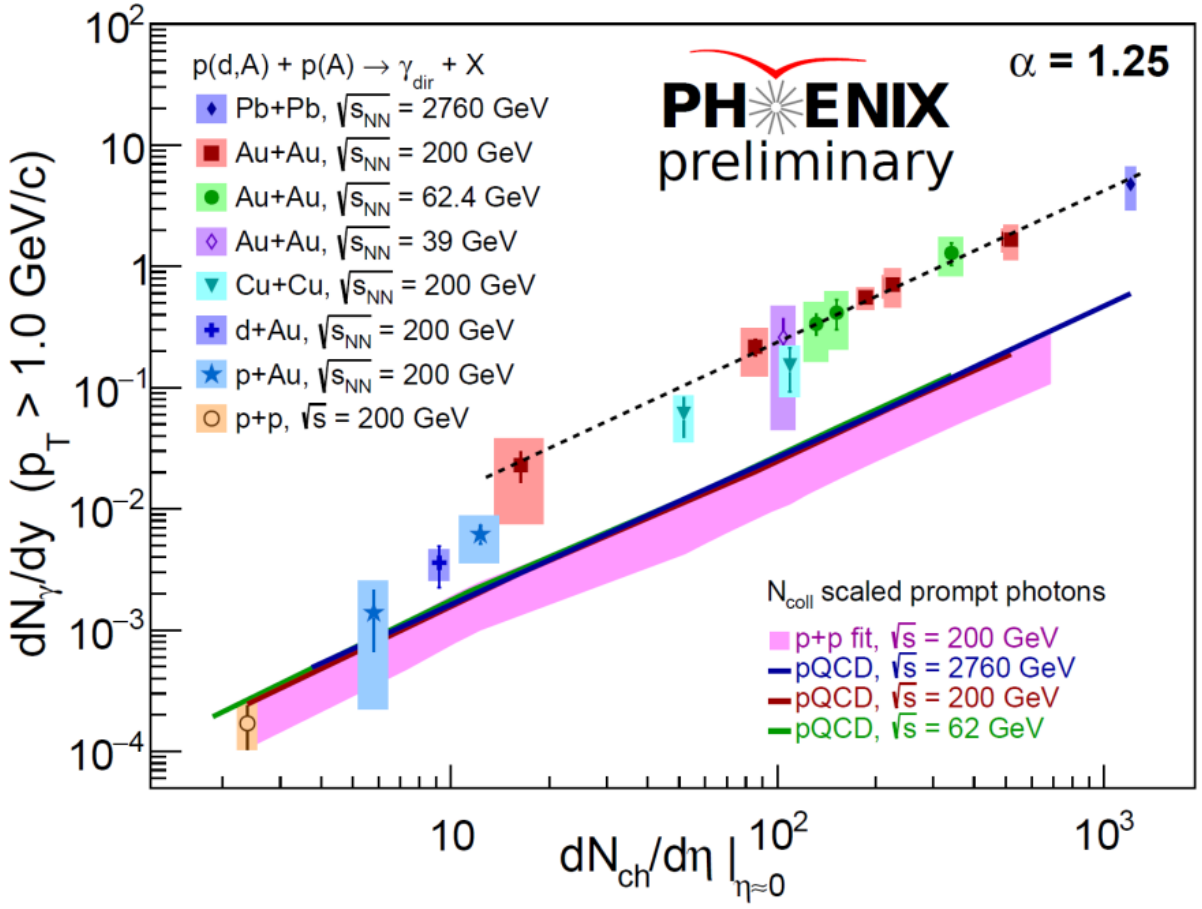
Nature Physics **15**, pages214–220 (2019)

PRC 105, 024901 (2022)

Thermal photons in small systems

- Enhancement of low p_T photons in central p+Au
- Consistent with expected thermal photon production (PRC 95 014906 (2017))





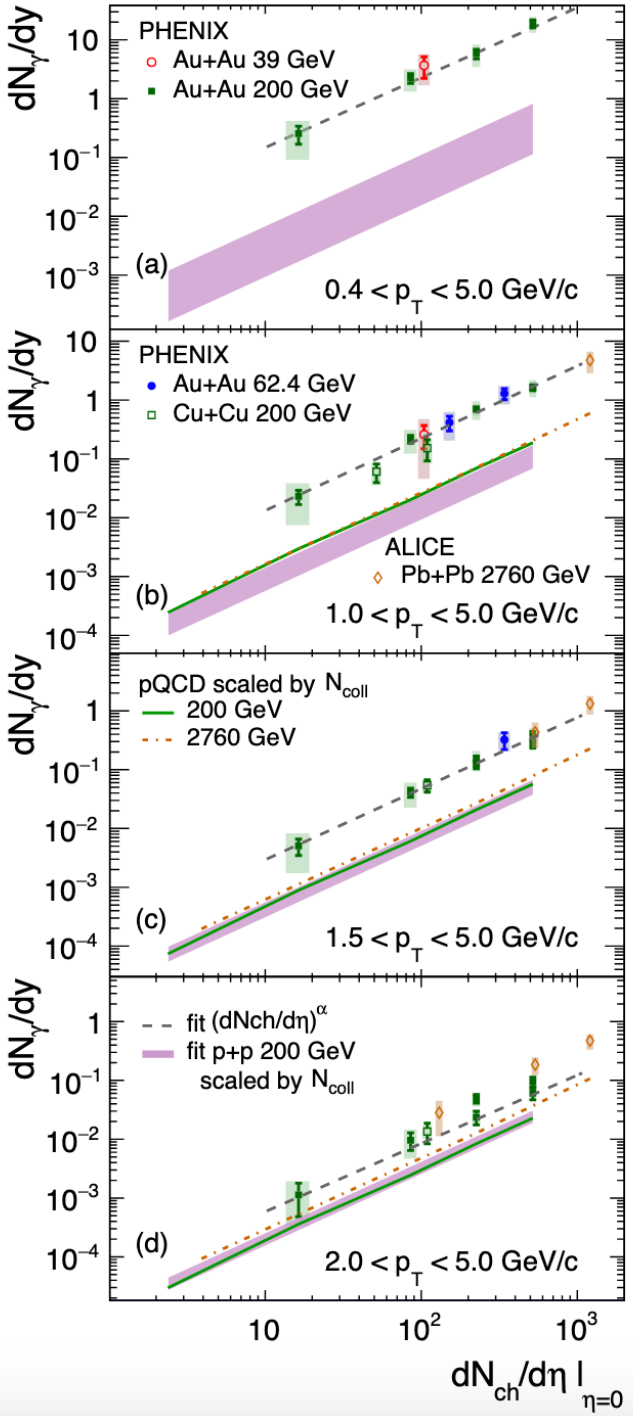
Smooth trend between small and large systems

Thermal Photons in Au+Au

- Recently published 39 and 62.4 GeV Au+Au data (arXiv:2203.12354)
- Studies α in more detail

$$\int_{p_{T,\min}}^{5\ \mathrm{GeV}/c} \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\,dp_T = A_{ch}\left(\frac{dN_{\mathrm{ch}}}{d\eta}\right)^{\alpha}$$

- $\alpha = 1.21 \pm 0.04$ (stat) consistent for all p_{Tmin}
- Consistent but slightly less than the previously used $\alpha = 1.25$ from $N_{coll} \propto (dN_{ch}/d\eta)^{\alpha}$
- Also insensitive to collision energy and centrality
- May suggest that direct-photon radiation at low p_T originates from thermal processes while system transitions from the QGP phase to a hadron gas



Data and Analysis Preservation (DAP)

- To ensure reproducibility of published results:
  - Standardized analysis notes
  - All analysis code, macros, relevant files stored in HPSS
  - Upload published data to HEPData
- Ideal Goal: re-analysis possible “forever” by “everyone”
  - Docker/REAna
  - Github and Zenodo
  - CERN OpenData for the general public
  - RIVET
- Find out more at on the Analysis tab on the phenix website: https://www.phenix.bnl.gov/

Conclusions

- PHENIX has measured jet cross section and substructure distributions in 200 GeV p+p collisions
- PHENIX high p_T particle correlations measurements reveal jet energy loss and medium response effects in 200 GeV Au+Au collisions.

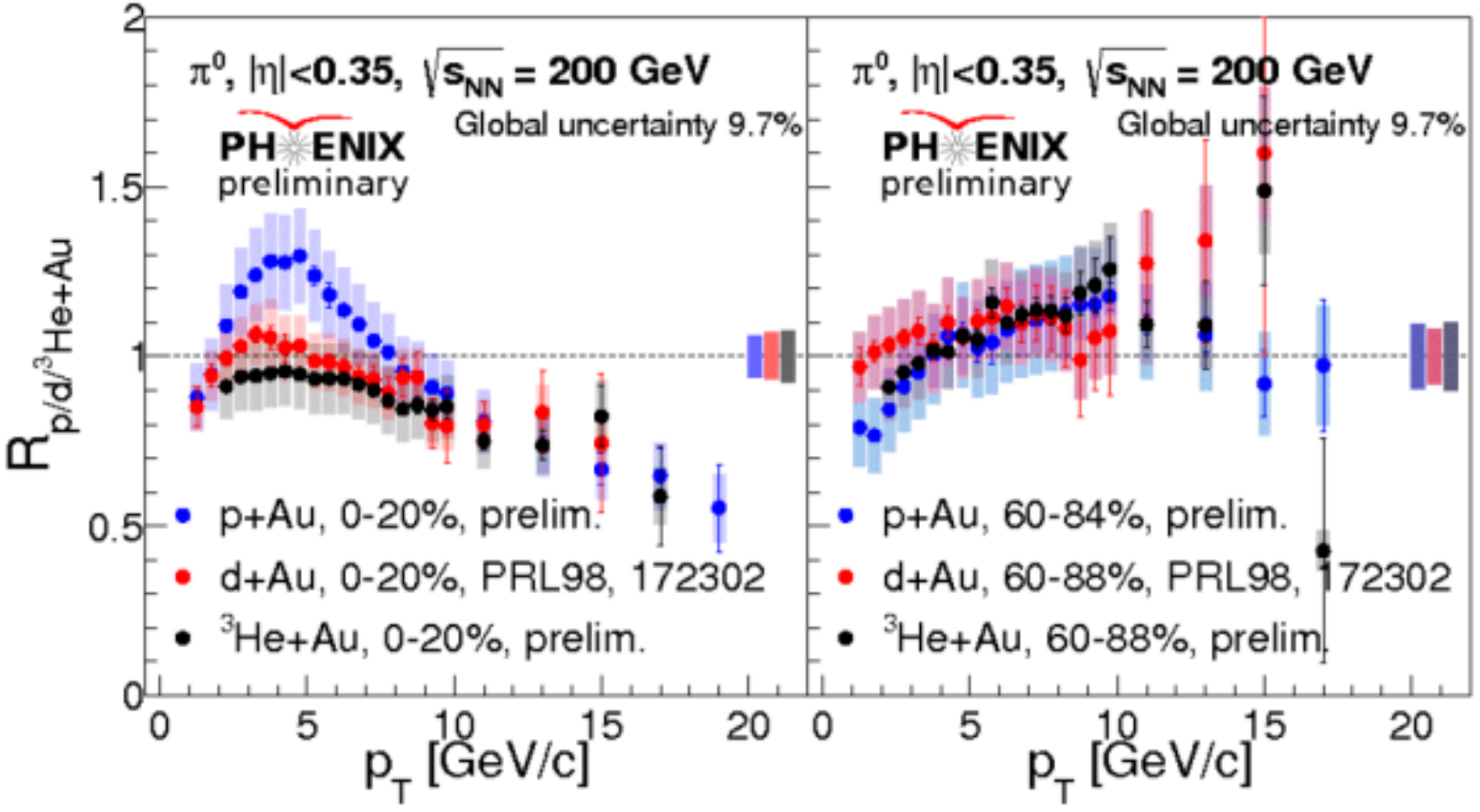
- The PHENIX collaboration continues to measure many unique and important results…
  - Spanning hard probes and bulk measurements
  - Spanning a variety of collision systems and energies
  - Including spin related results (excluded from this presentation for time)
  - Several new publications and PhD theses
  - DAP will ensure this can continue far into the future

…and many more results to come soon…

PHENIX

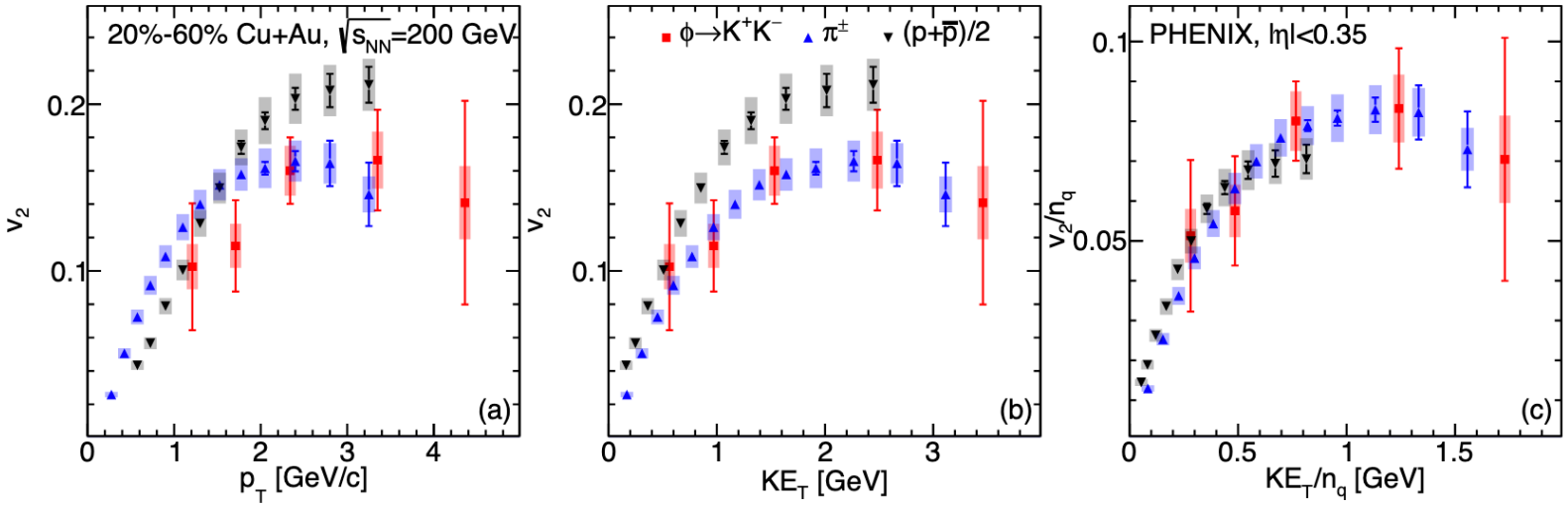
Backup Slides

R_{AB} Collision dependences

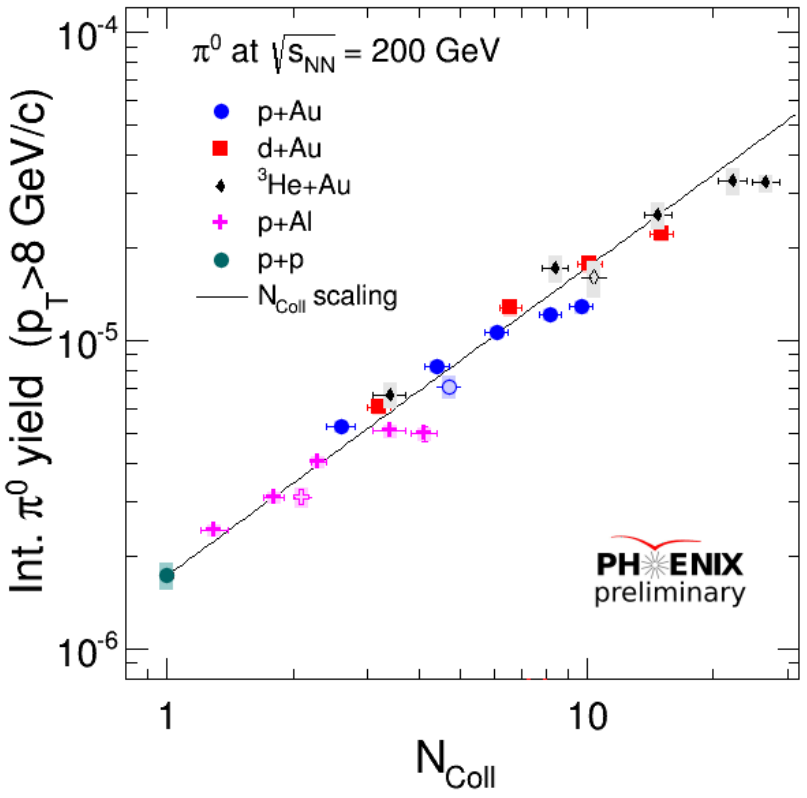


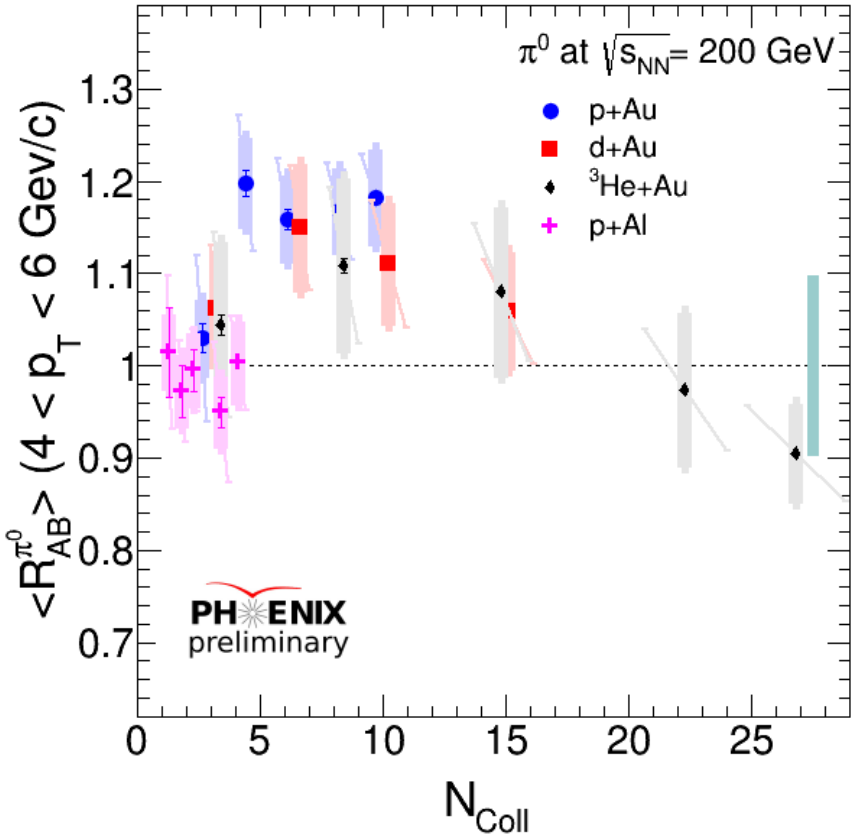
- Cronin enhancement at low p_T
  - Projectile dependence
- Suppression seen at high p_T
  - Same for all collision systems
- Peripheral consistent with 1 but also consistent with >1

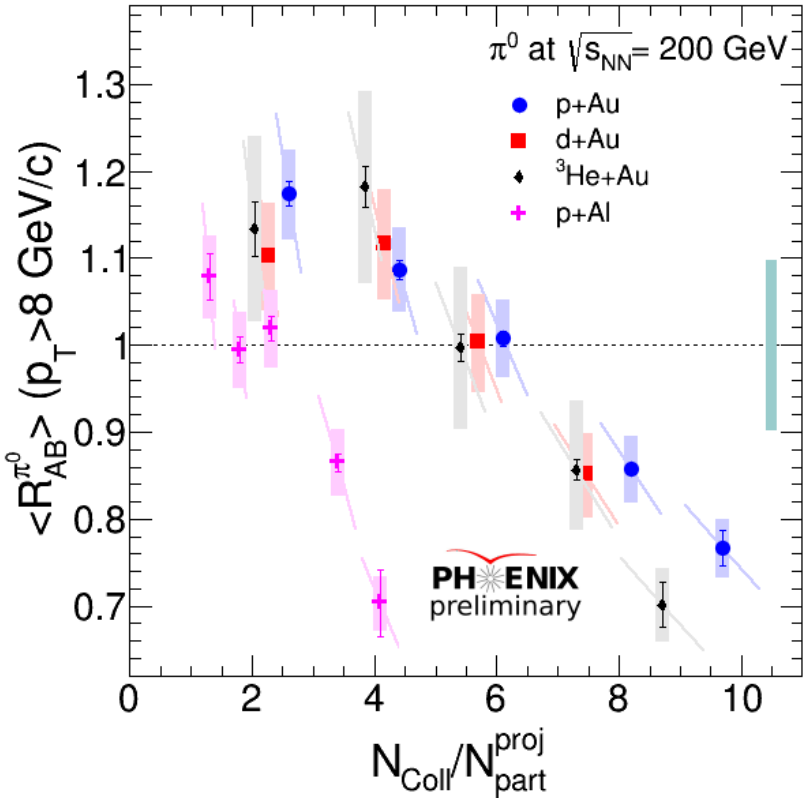
Phi v2 in Cu+Au



Momentum Dependence of Modification

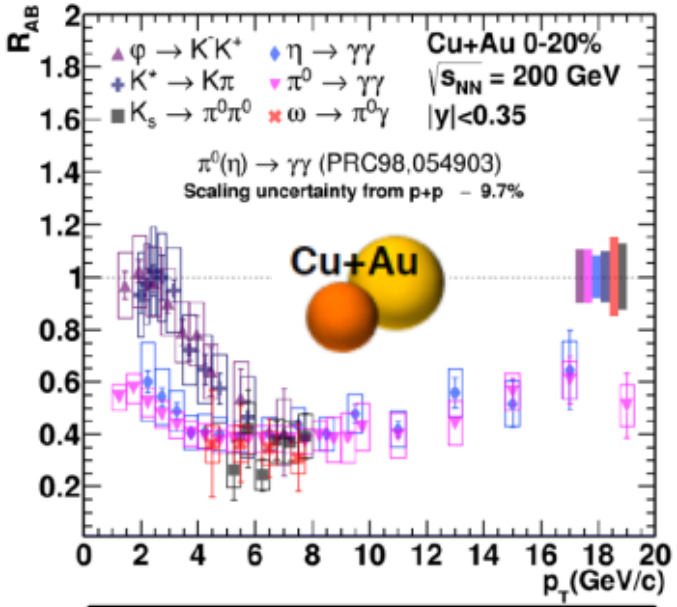


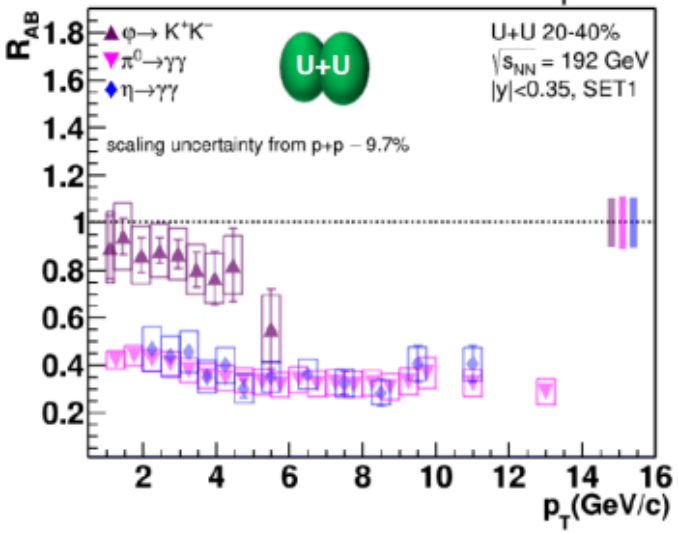




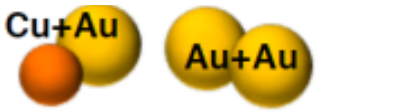
- High p_T suppression independent of nuclei being traversed
- Cronin region follows N_{coll} scaling

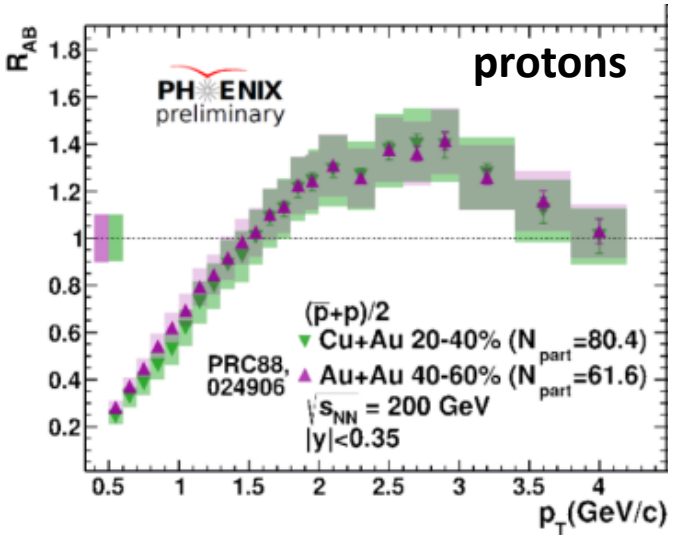
R_{AA} in Large collision systems

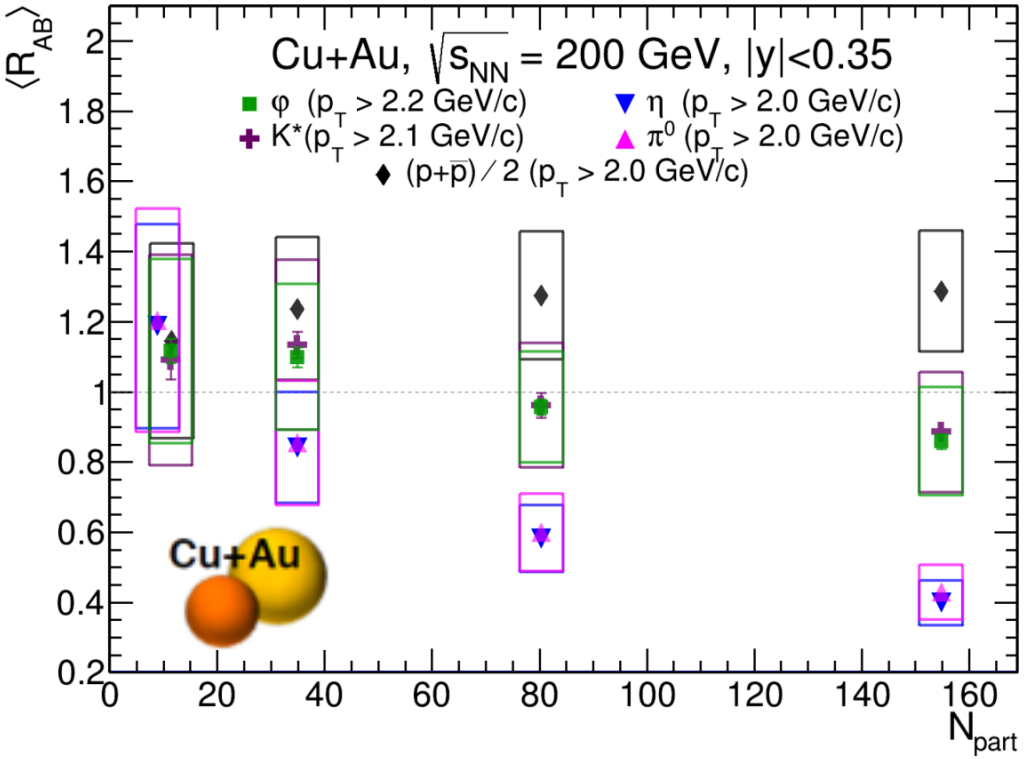




- At low p_T
  - ϕ is less suppressed then lighter mesons in Cu+Au and U+U
  - K* is also less suppressed in Cu+Au
  - Protons are enhanced



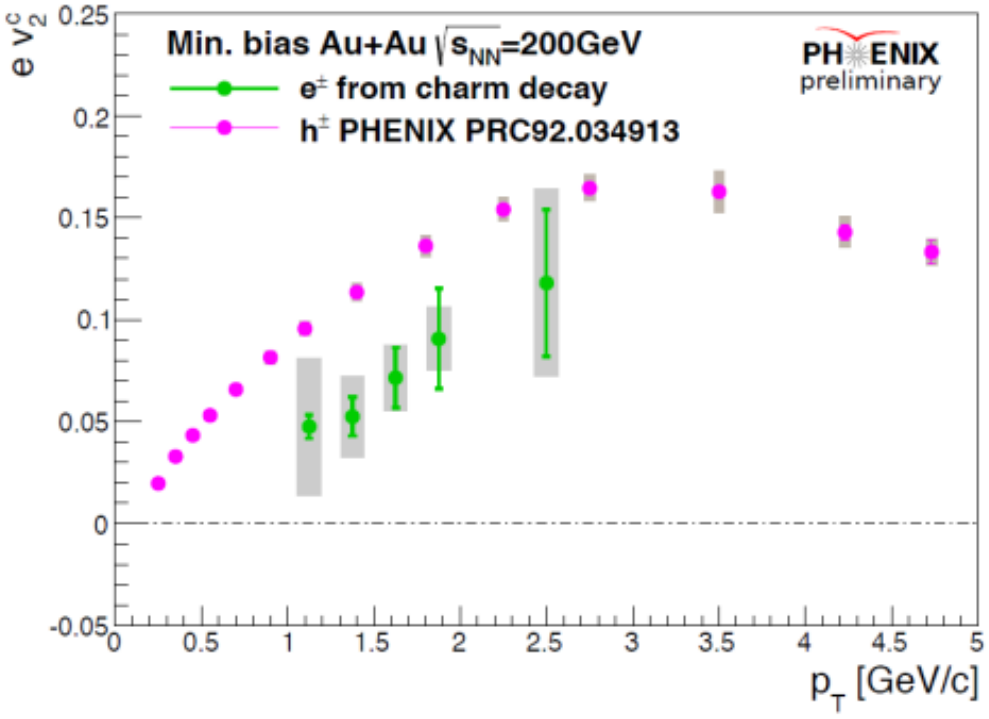




- Interplay of radial flow, strangeness + recombination different from small systems

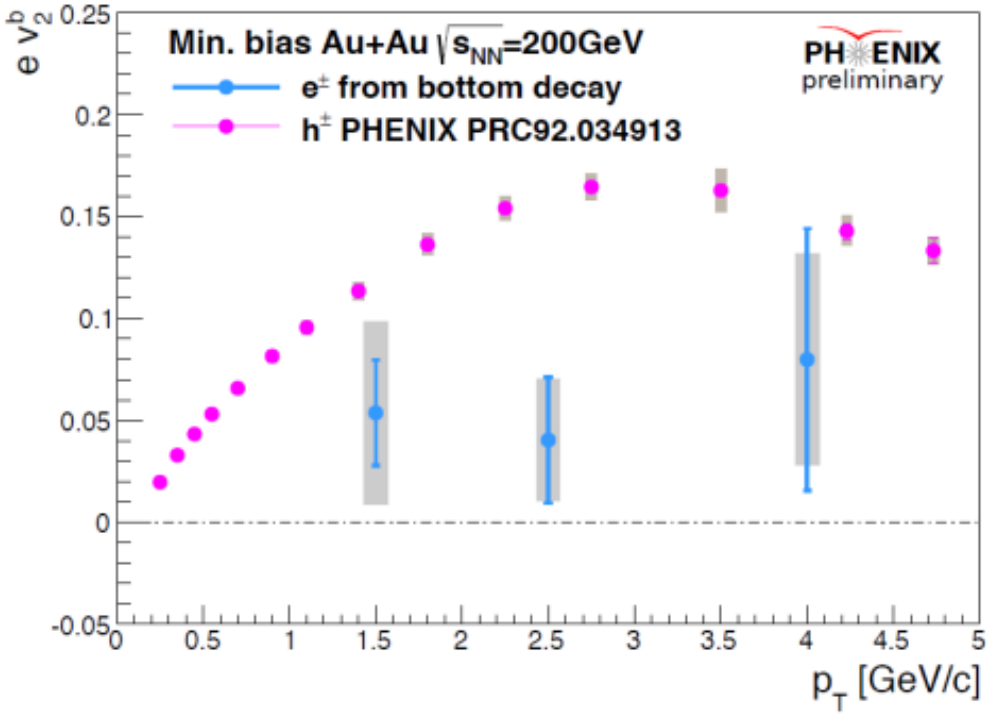
Pathlength Dependent Energy Loss: Heavy Flavor v_2

Charm



v_2 (c→e) > 0 (~3.5σ)

Bottom



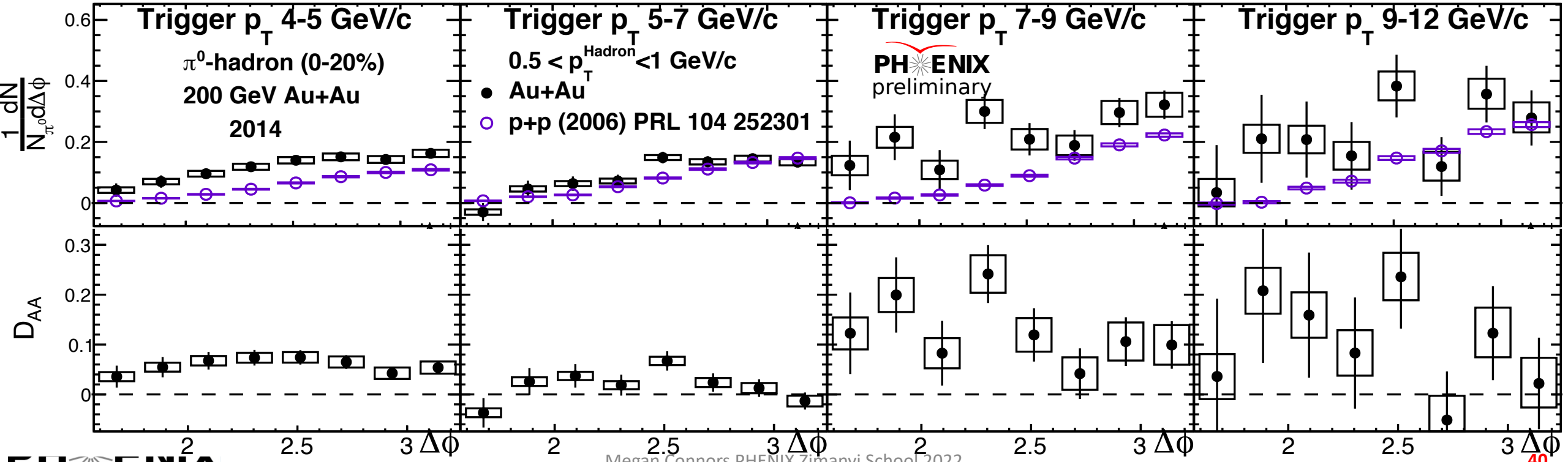
v_2 (b→e) > 0 (~1.1σ)

v_2 (c→e) appears larger than v_2(b→e)

$D_{AA}(\Delta\varphi)$ for fixed Associated Hadron p_T

$$D_{AA} = YAA - Ypp$$

- Measure the difference in the yields instead of the ratio
- Less sensitive to yields near zero



$D_{AA}(\Delta\varphi)$ for fixed Trigger p_T

$$D_{AA} = YAA - Ypp$$

- What is the dependence on hadron p_T?
- Trigger p_T: 4-5 GeV/c