Identified light hadron measurements from large to small systems from PHENIX

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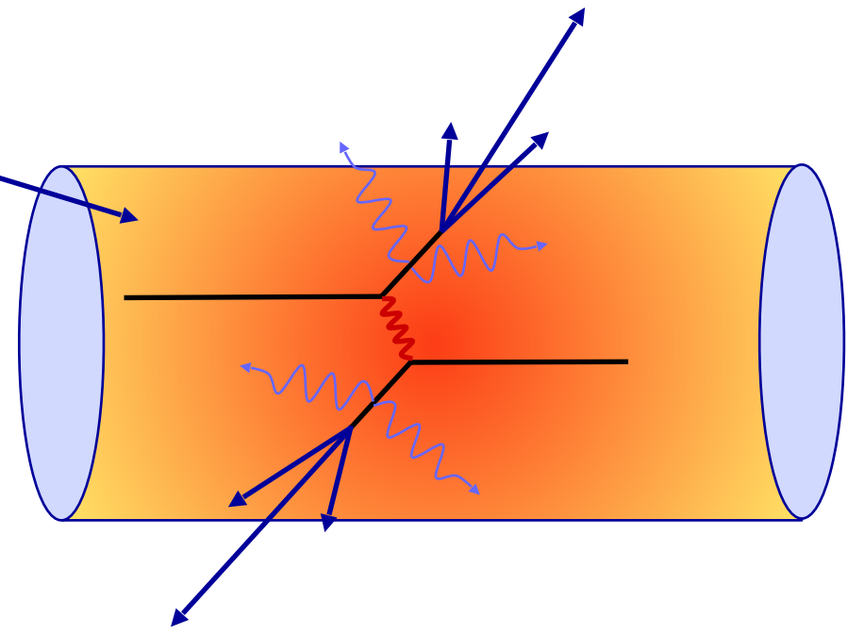
Meson production in nuclear collisions

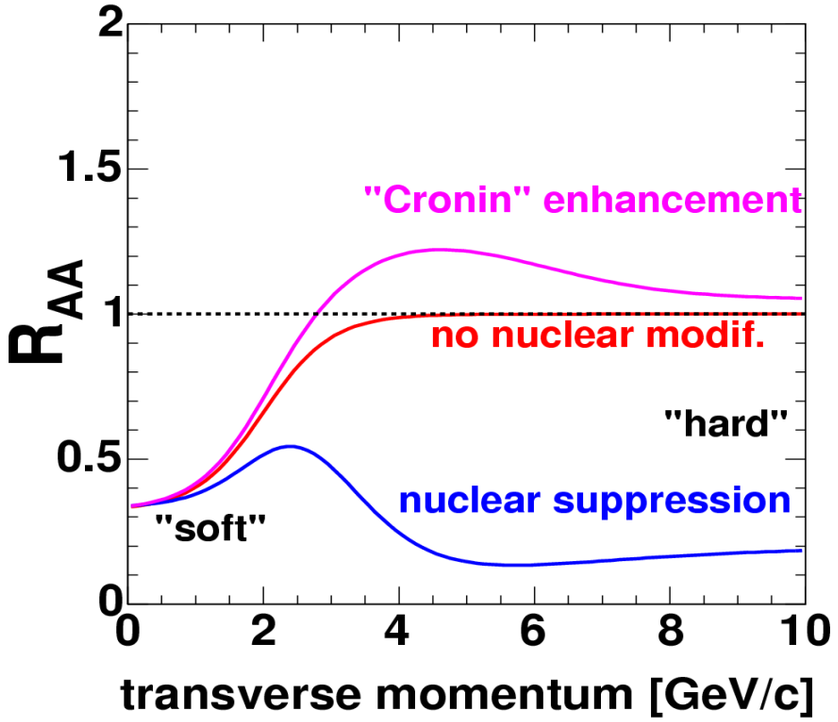
Hadron measurements provide both bulk observables and tomographic probes in nuclear collisions

Heavy-ion collisions produce ‘quasi-thermal’ QCD matter, Dominated by soft partons p ~ T ~ 100-300 MeV



Bulk observables
Soft hadrons from QGP

Hard Probes
Hard scatterings produce ‘quasi-free’ partons - probe the medium through energy loss

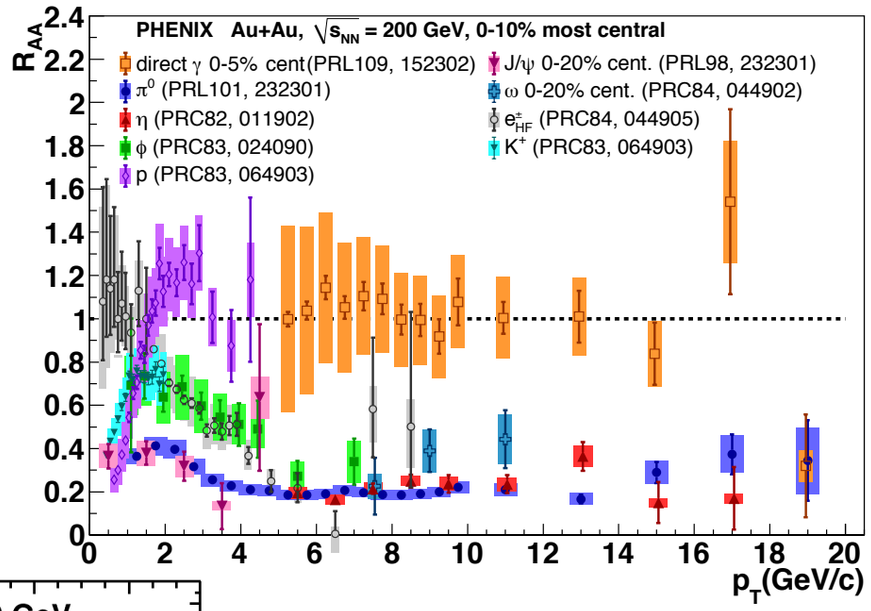


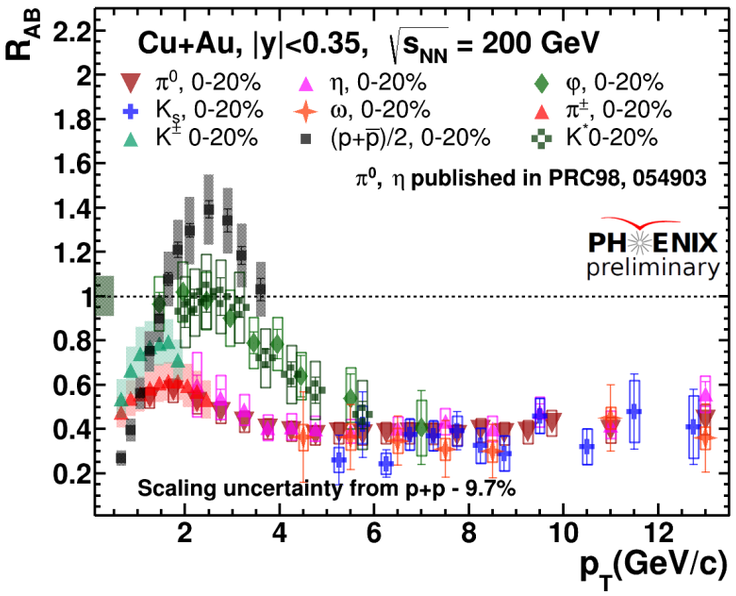
Nuclear modification factor:

$$R_{AA}(p_{\mathrm{T}}) = \frac{d^2N^{AA}/dp_{\mathrm{T}}d\eta}{\left\langle N_{binary}\right\rangle d^2N^{pp}/dp_{\mathrm{T}}d\eta}$$

N_{binary} (N_{coll}) varies by impact parameter ***b*** (centrality %)

Nuclear modification in A+A

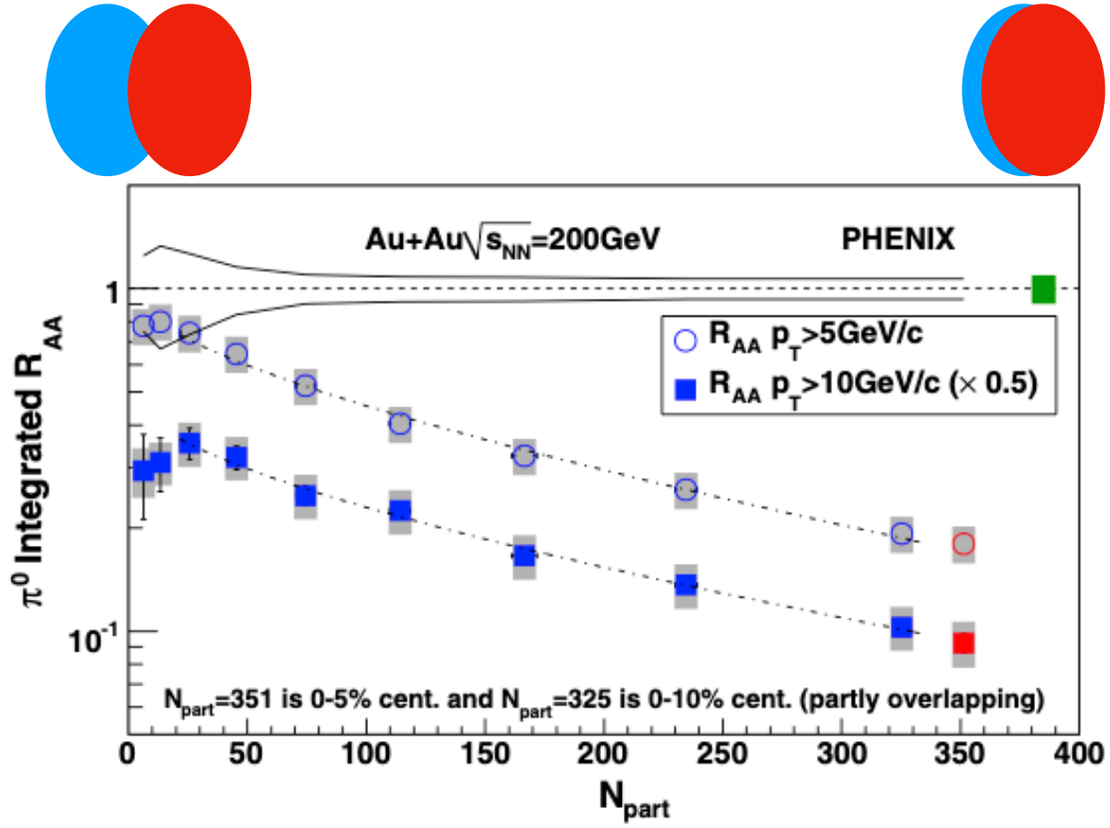




Nuclear modification factor:

- All hadron production is suppressed p_T > 5 GeV/c
  - π^0, η, ϕ, ω
- No suppression in direct photon

Convincing evidence for the final state partonic interaction

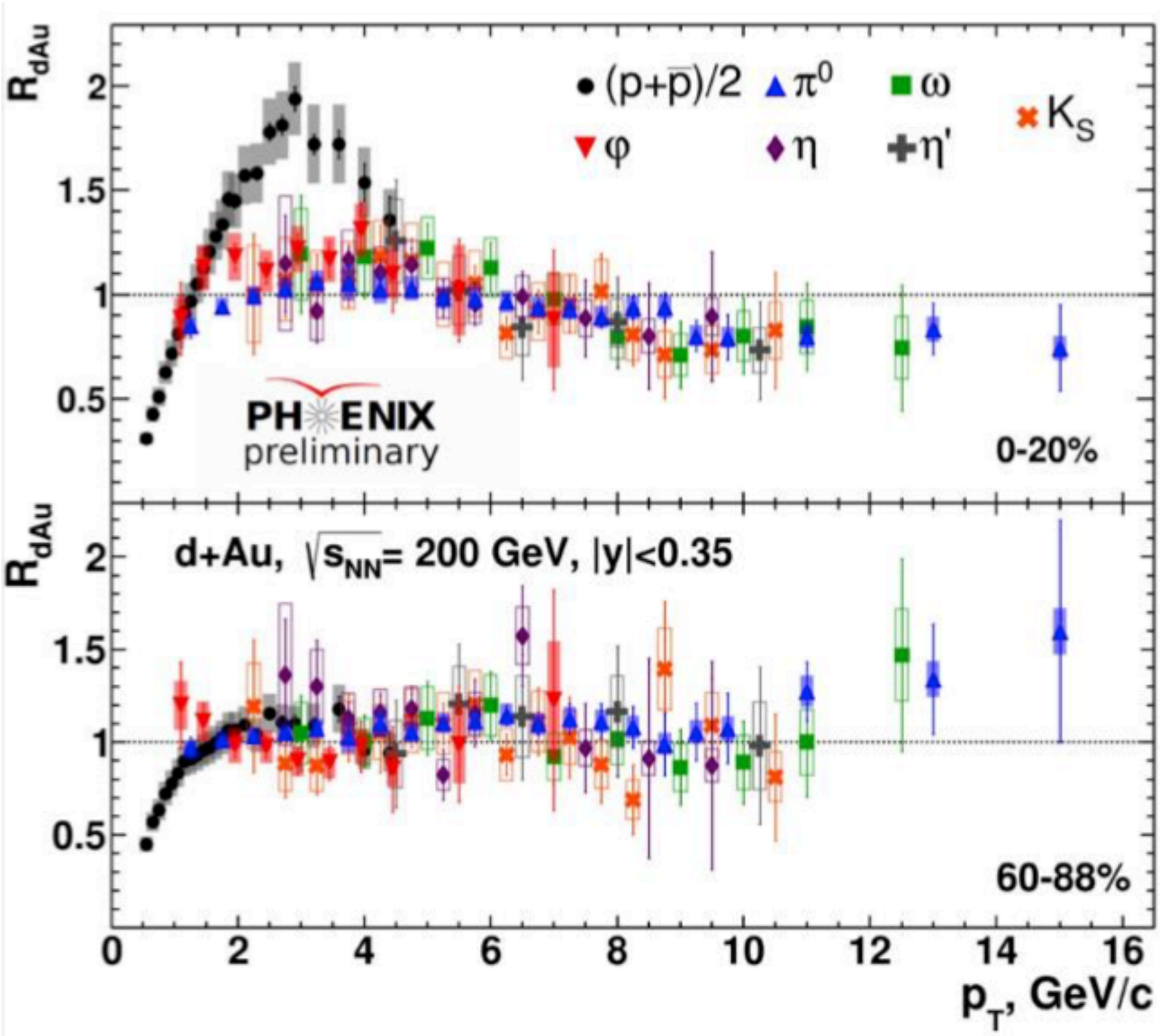


Centrality dependency of the R_{AA}:

- Monotonically increasing towards the peripheral collisions

Nuclear Modification in d+Au

PRC 90 054905 (2014)



All hadrons are consistent with unity within the experimental uncertainties

At low-p_T different behavior of hadrons in central or peripheral, at high-p_T we observe a common trend

Is there a room for partonic energy loss from QGP in these collisions?

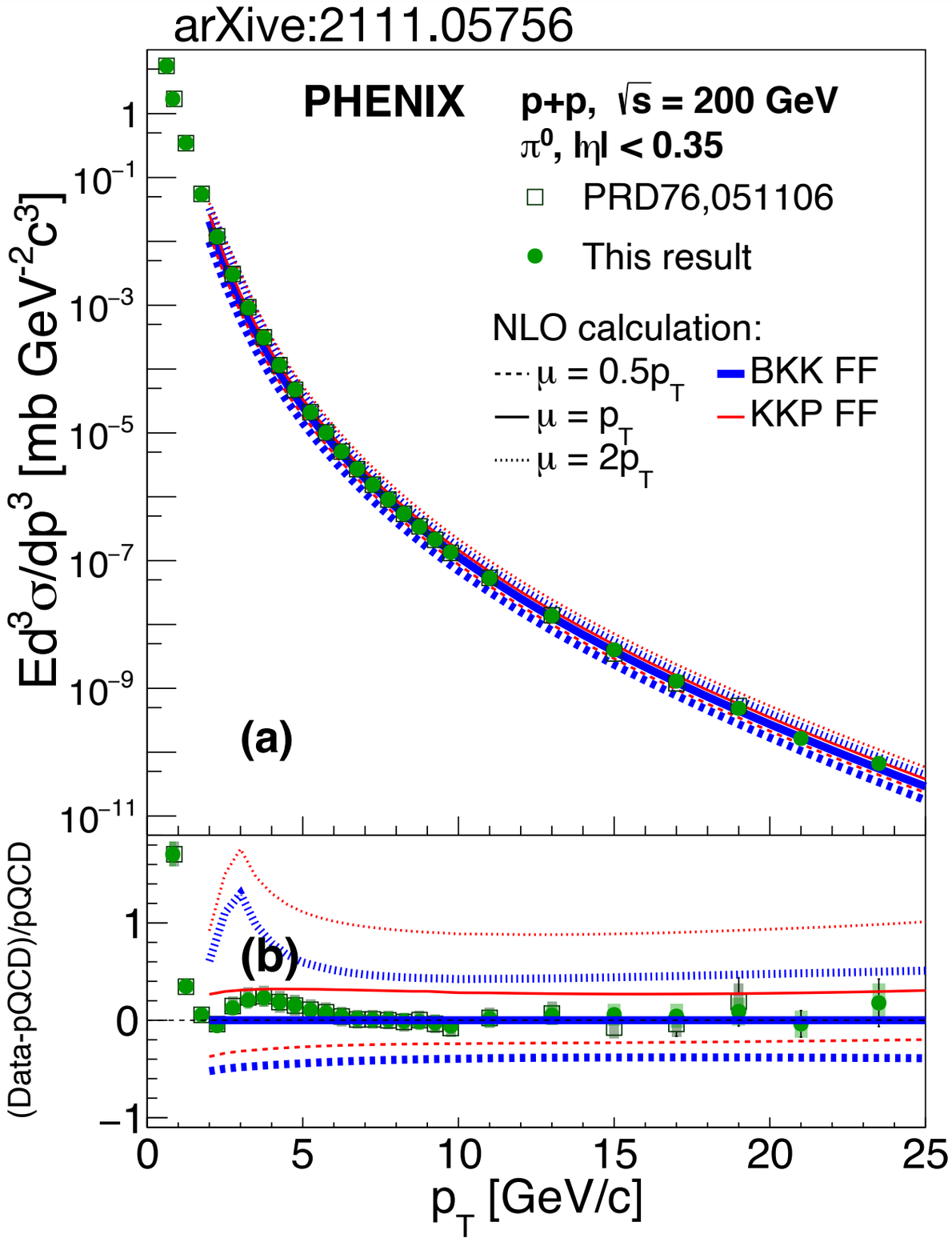
Are there other physics processes dominant:

- nPDF
- Cold nuclear energy loss
- Other initial state effects?

…

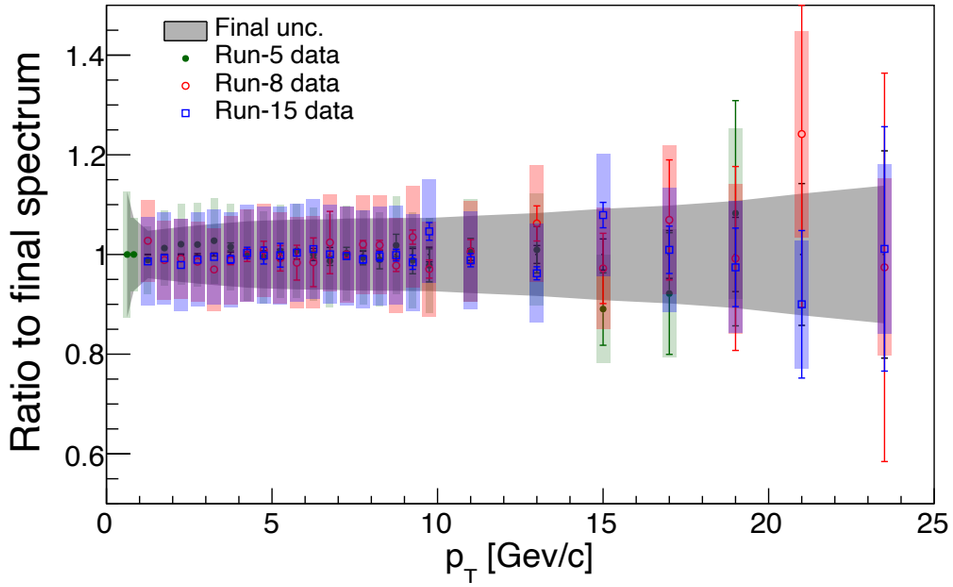
New results

New neutral pion yields in p+p



The final PHENIX neutral pion yield in p+p at 200 GeV:

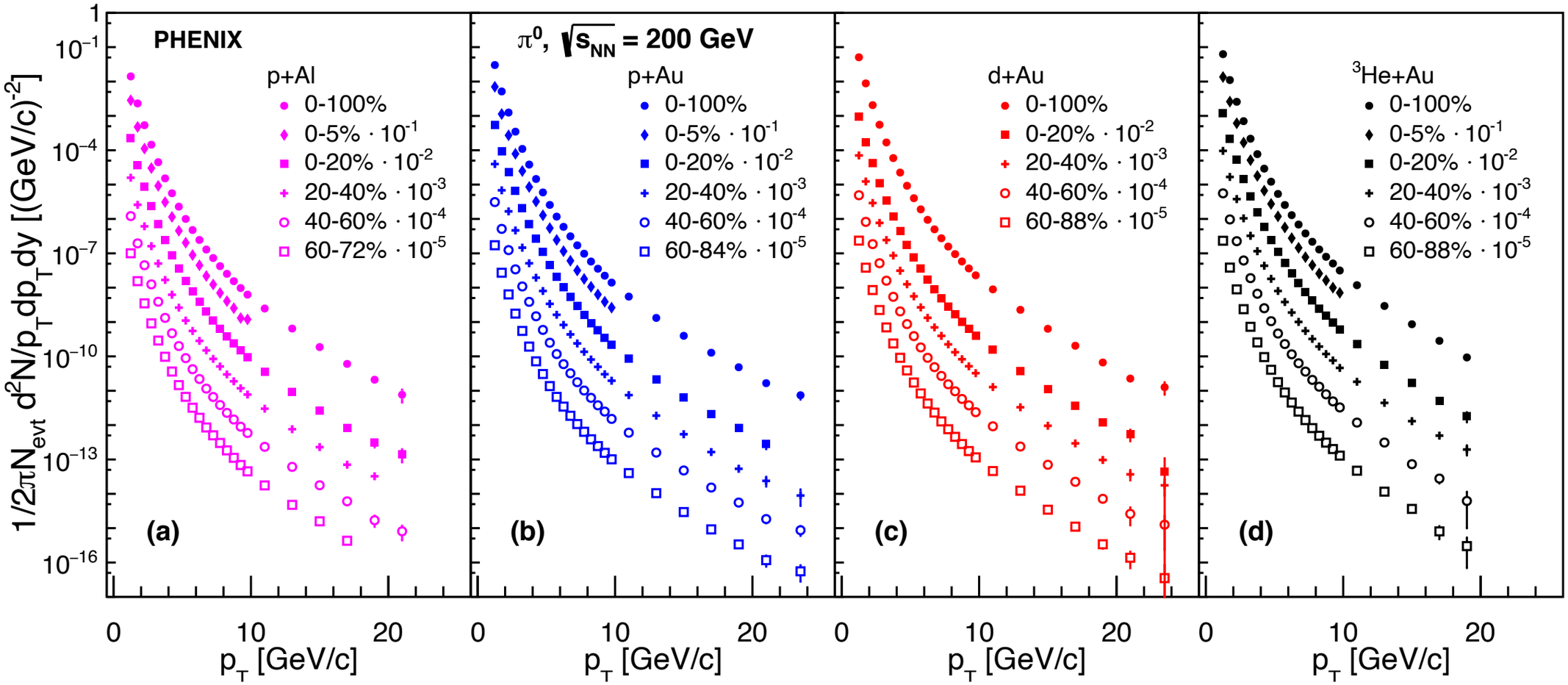
- We used three independent datasets, from 2005 (this was the last publication), 2008 and 2015
- Combined all the data using the Best Linear Unbiased Estimate (BLUE) method



The pQCD with the BKK FF is best describing the data above > 5 GeV/c

Systematic study of the collision systems

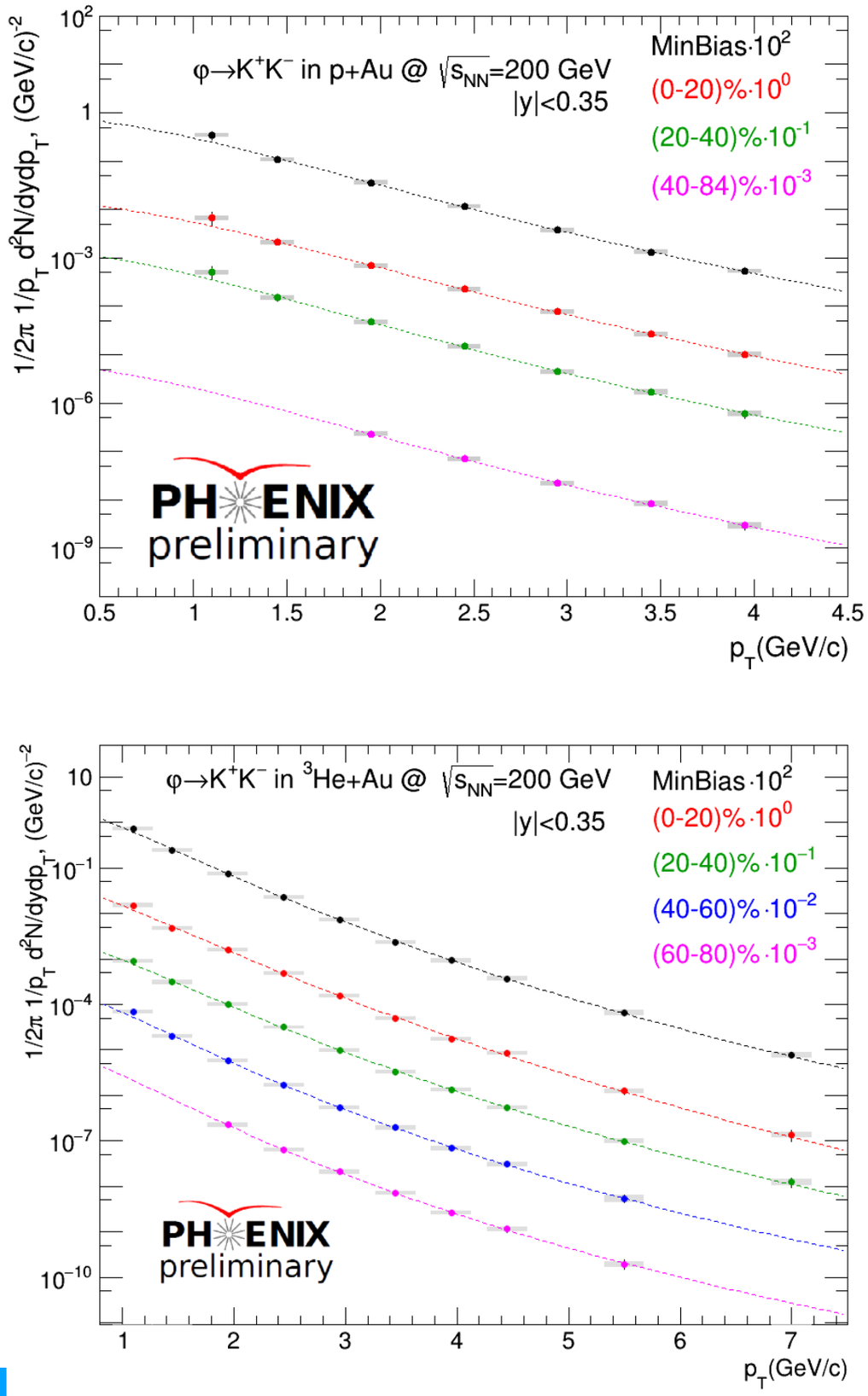
arXive:2111.05756

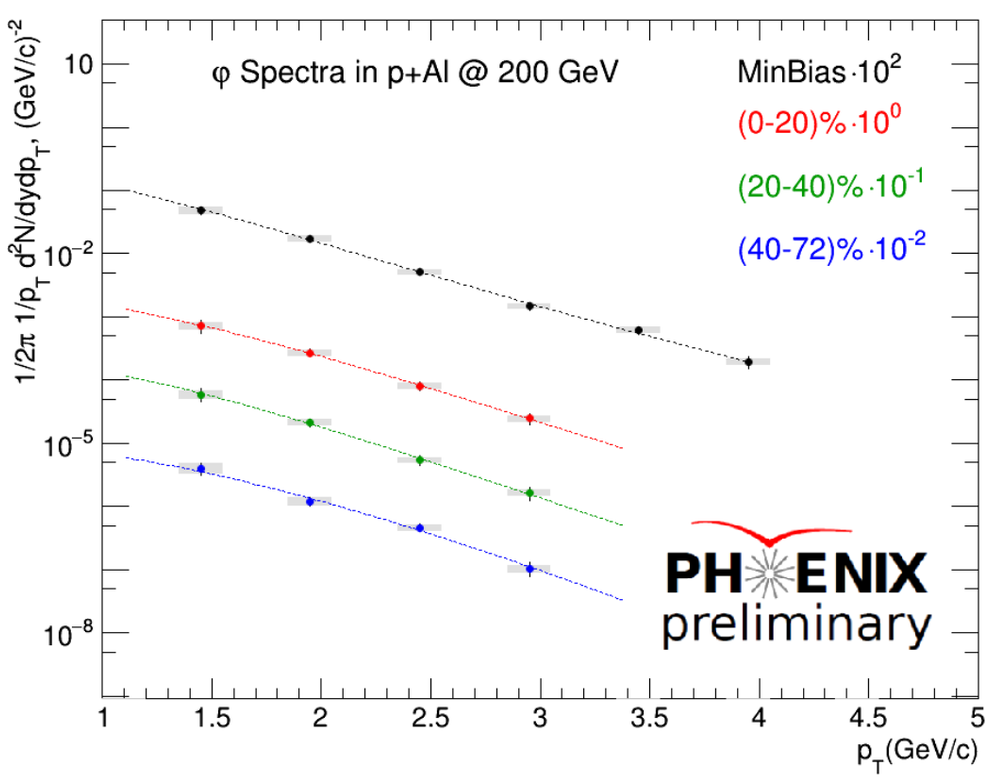


We collected enough data for the same centrality selections:

- We extended the analysis up to 25 GeV/c
- We utilized the high multiplicity event trigger (using the BBC south), and limit it to 0-5%:
  - p+Al, p+Au and He+Au
  - In 2008 we did not have a HM trigger in 2008 d+Au data. The 2016 d+Au data is not analyzed here

New measurements of ϕ mesons



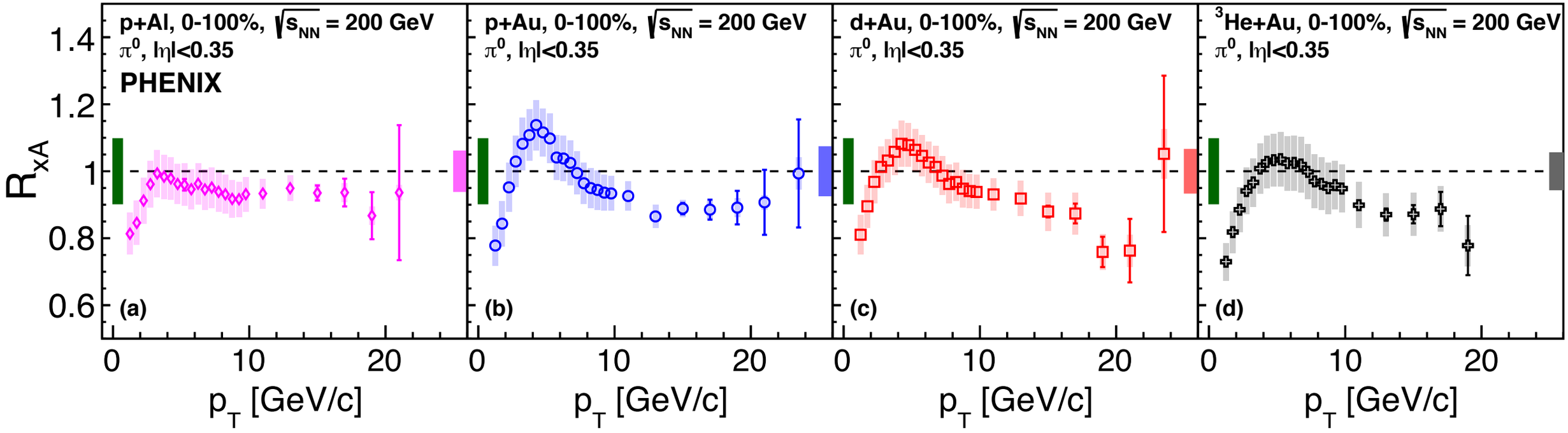


Systematic study of the ϕ meson production in small systems:

- New measurement from 3 different collision system
- Minimum bias and selected centrality classes
- Using K^+K^- decay channel
- *Soon to be published…*

R_{xA} in min. bias

arXive:2111.05756



Minimum bias collisions:

- High-p_T all are below unity, but consistent within the systematic uncertainties
  - We also extended the measurements up to p_T = 25 GeV/c
- All high-p_T points are in good agreement across different collision systems
- Cronin peak:
  - Most pronounced in p+Au collisions
  - Ordering between p > d > ^{3}He
  - p+Al collisions shows the smallest enhancement

Comparison with nPDF

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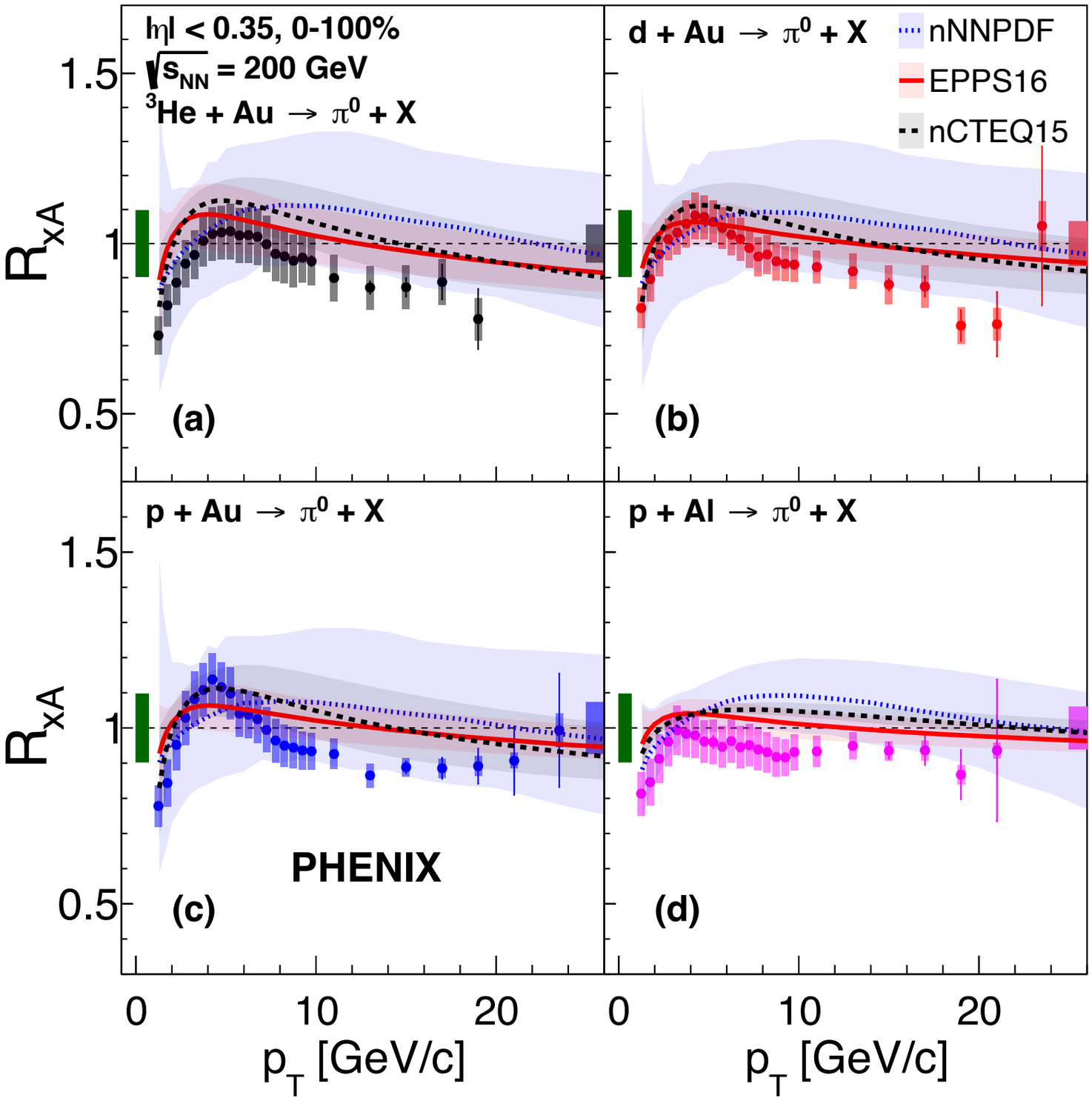
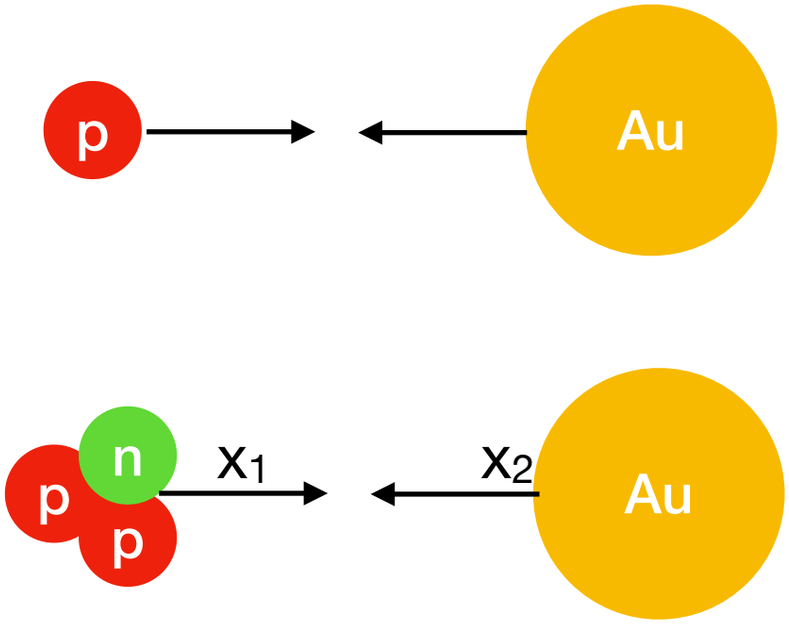


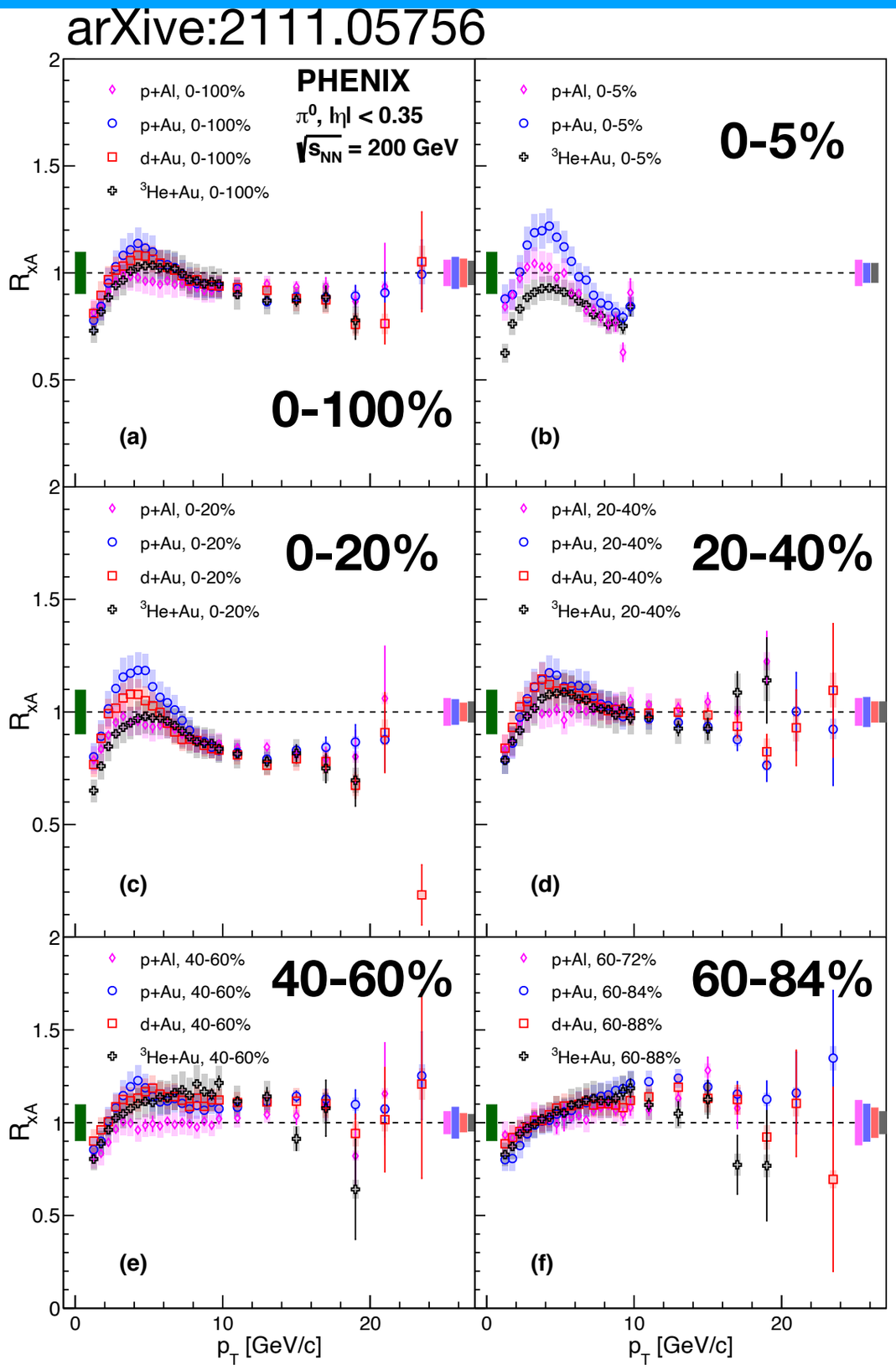
The shape of the nPDF is very similar to the data
There is a clear offset between the data and the model

From pure nPDF we would expect larger enhancement in the Cronin peak (anti-shadowing), larger suppression in high-p_T (shadowing)



Nuclear modification:
mid-p_T: p < d < ^{3}He
high-p_T: p > d > ^{3}He

Centrality selections



Clear centrality dependency is observed in the R_{xA}:

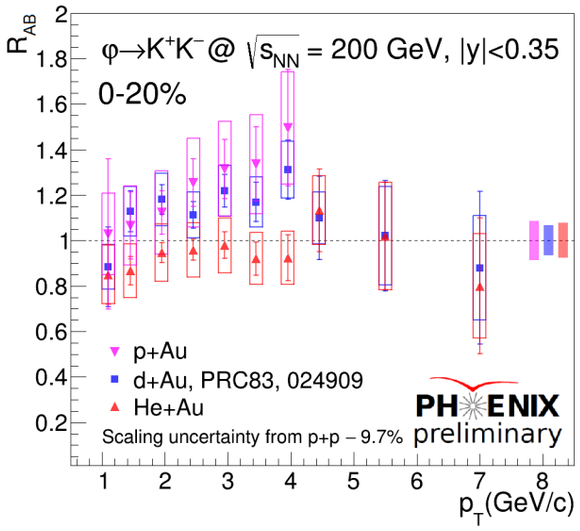
High-p_T:

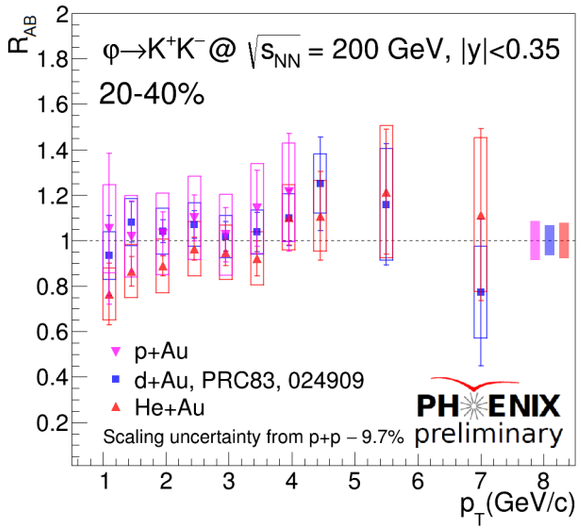
- Most central is below unity
- Most peripheral is above unity
- Very small p_T dependency
- All systems agree within uncertainties

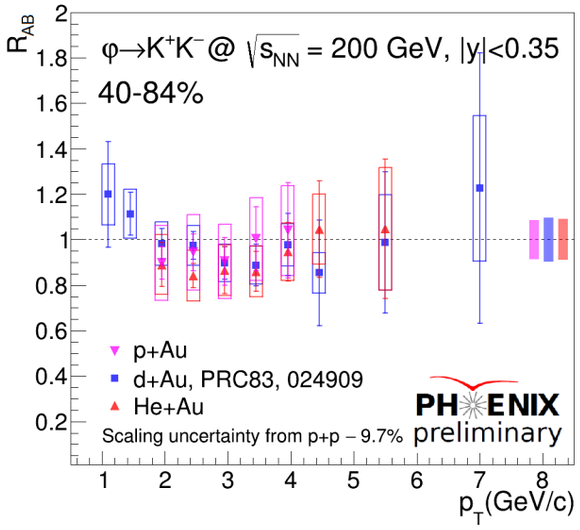
Mid-p_T:

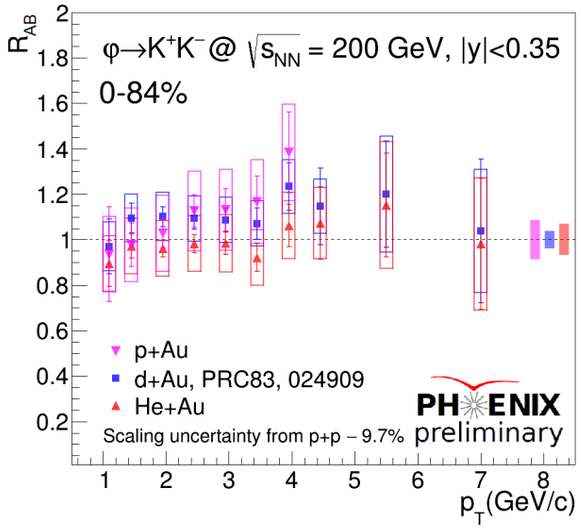
- More pronounced peak in central collisions
- No peak in peripheral collisions
- Clear system dependency. pAu shows the largest enhancement in most central collision

ϕ meson production



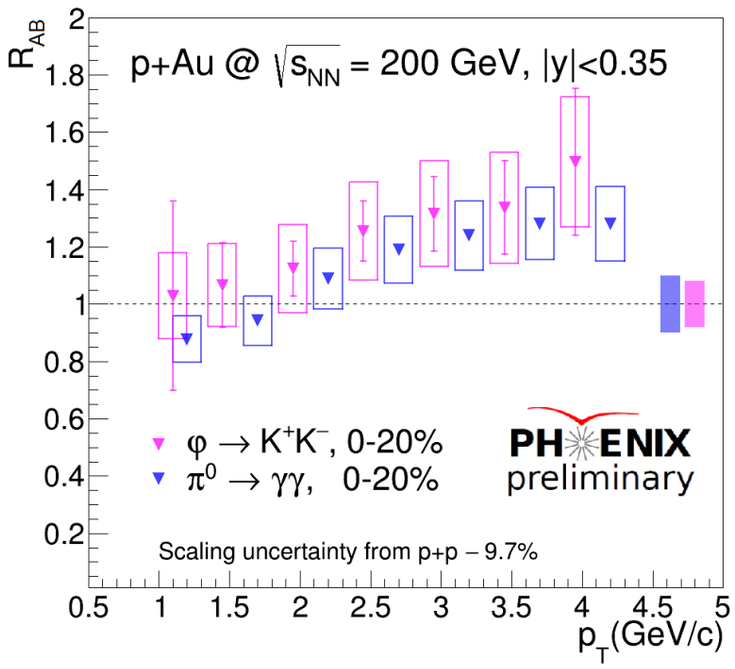






Systematic study of the ϕ-meson production:

- Similar behavior observed as in π^0
  - Larger uncertainties on the data
  - Hint of larger enhancement in 0-20% in p+Au, moderate enhancement He+Au
  - At larger p_T the data points are consistent in different collision systems

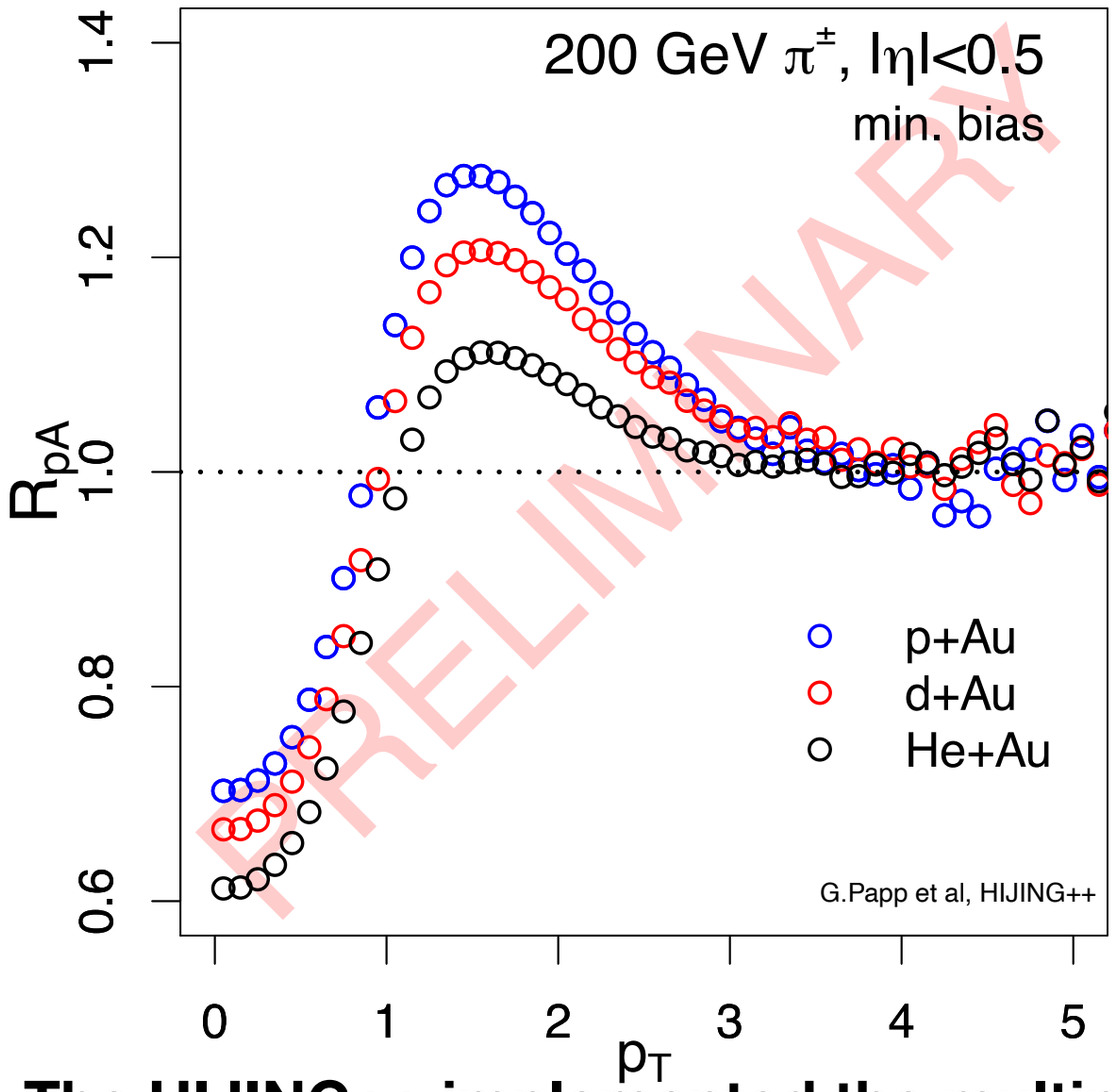


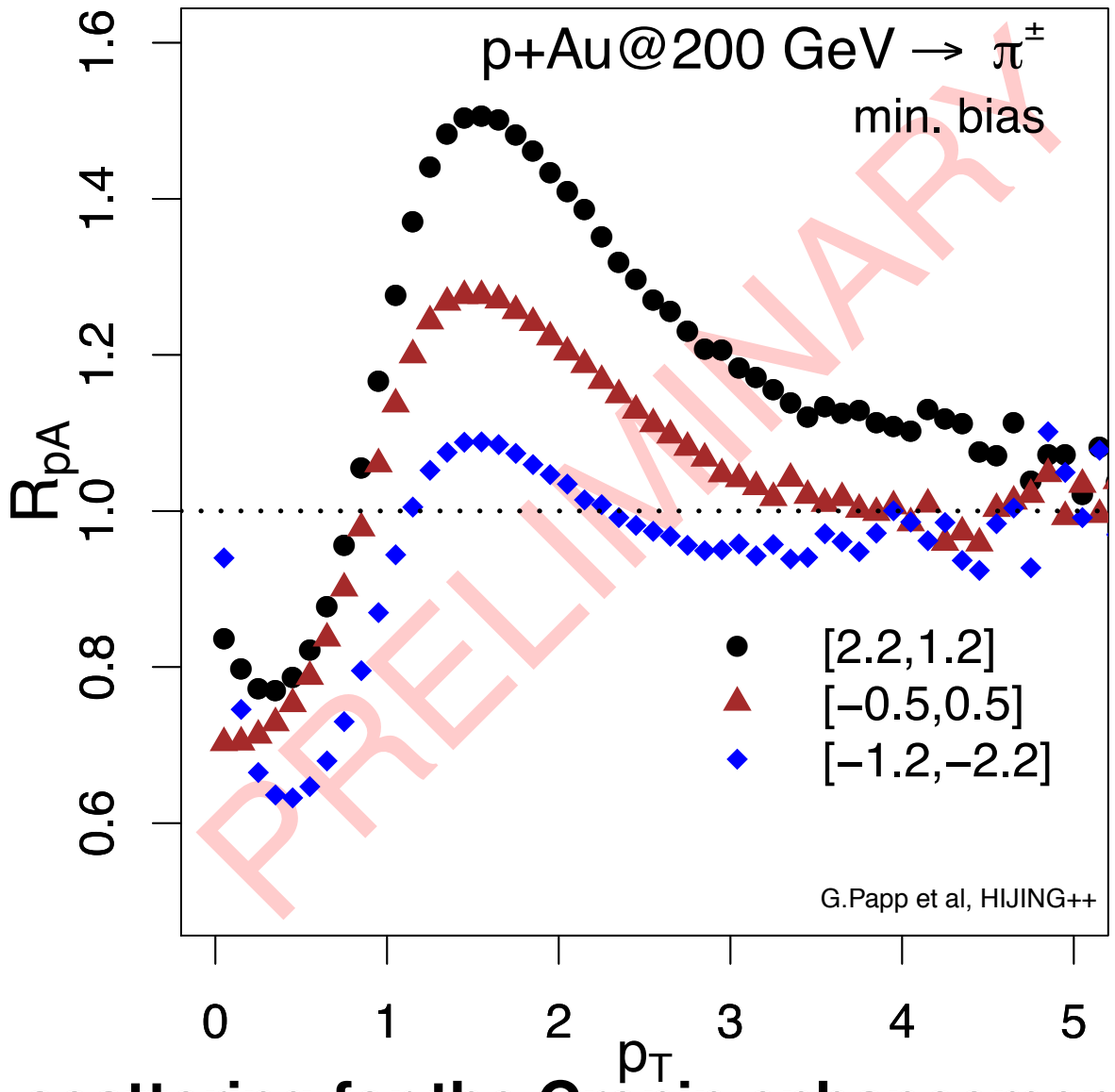
Comparison with the neutral pion shows very similar magnitude of enhancement:

- Very consistent in all centralities, all collision systems with the neutral pion measurements

Low p_T

HIJING++ with multiple scatterings



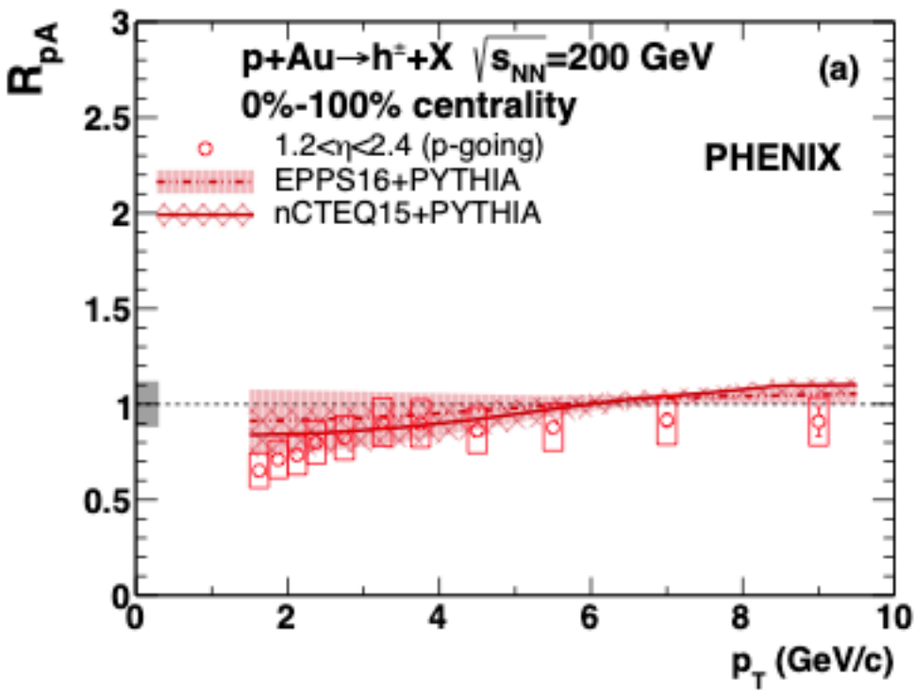


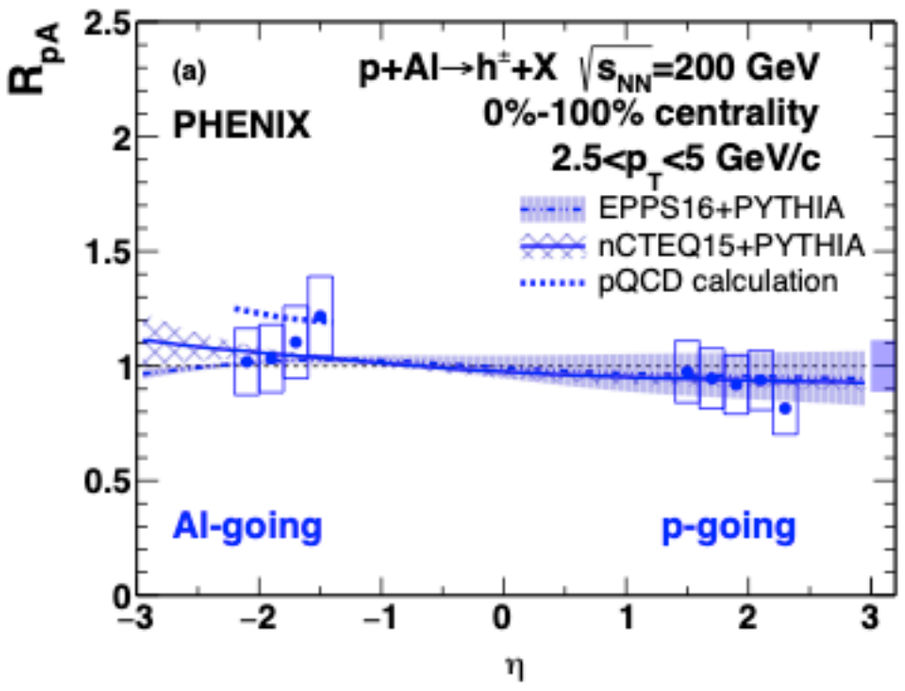
The HIJING++ implemented the multiple scattering for the Cronin enhancements:

- The ordering of the three systems are well described by the model:
  - The magnitude and the position (2 GeV/c instead of 5 GeV/c) is not yet described
- Forward/Backward prediction:
  - Proton going side will suffer more multiple scatterings
  - Au going side will have less enhancement

Forward and backward

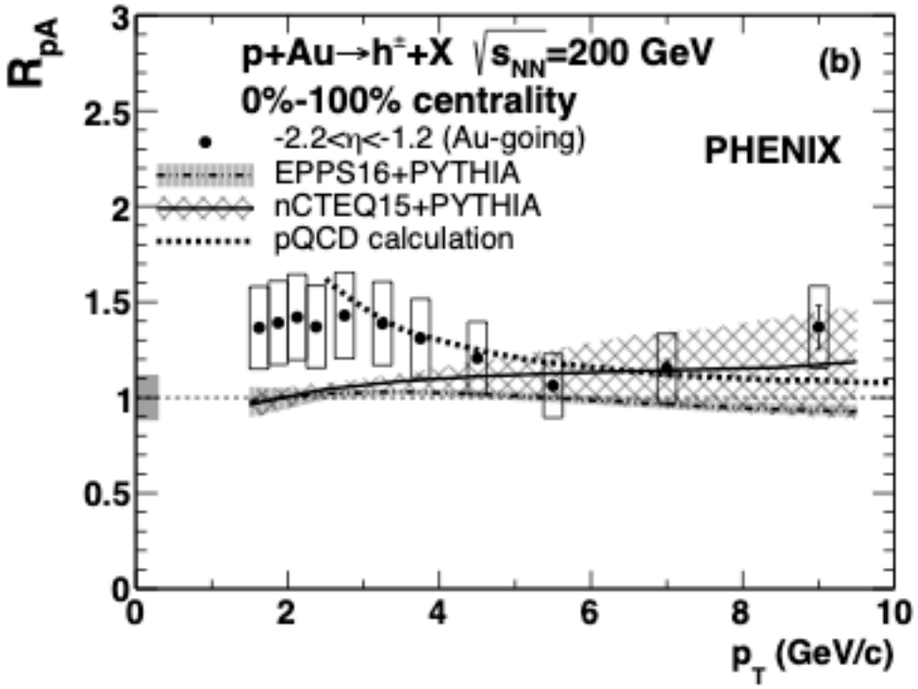
Phys.Rev.C 101 (2020) 3, 034910

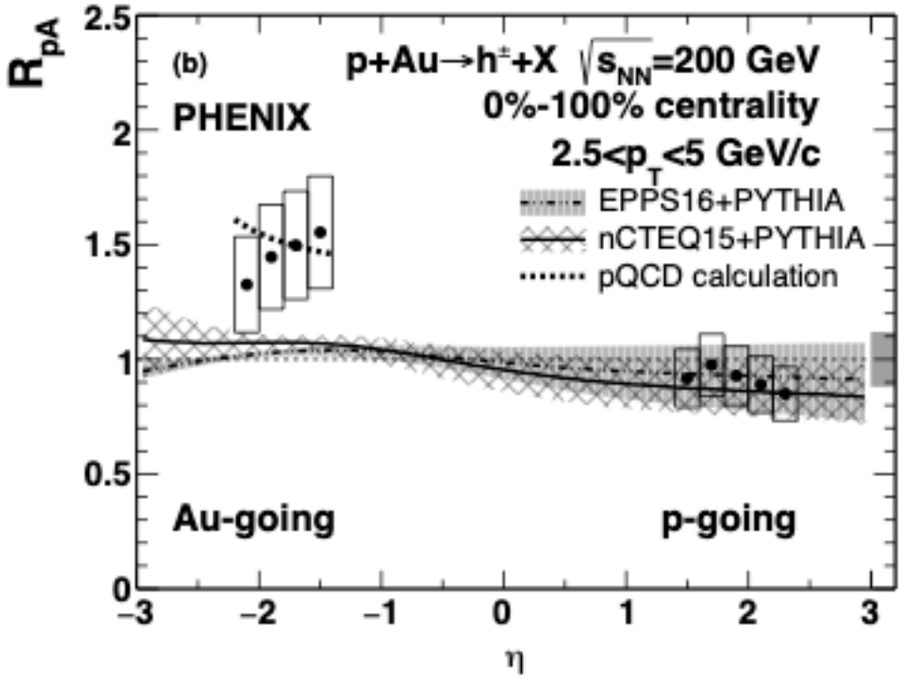




Data shows the opposite behavior

The forward going side is also better described by nPDF, completely missed in the backward going side

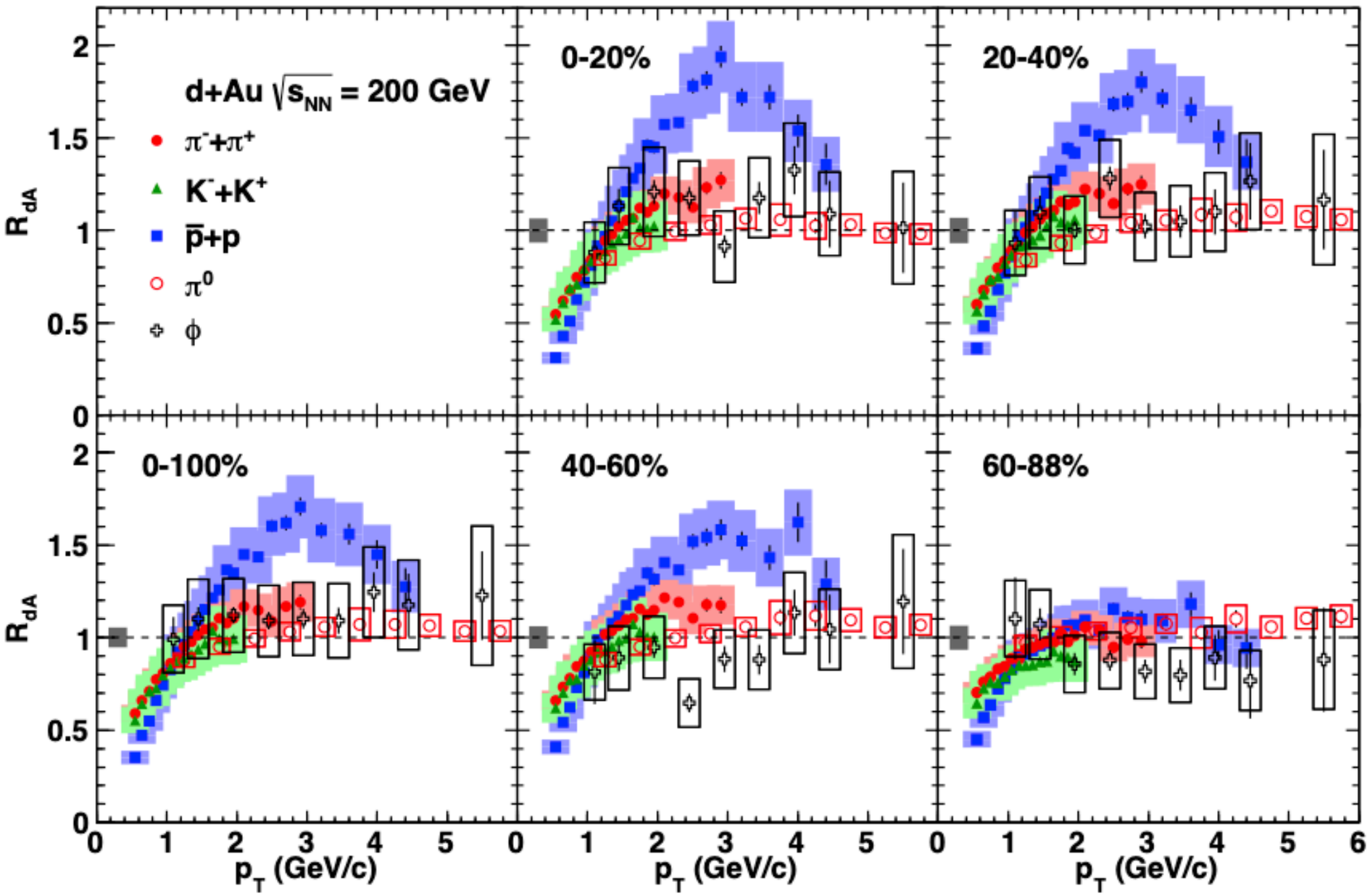




Multiple scattering is not probable behind the enhancement

Reminder of identified R_{dAu}

Phys.Rev.C 88 (2013) 2, 024906



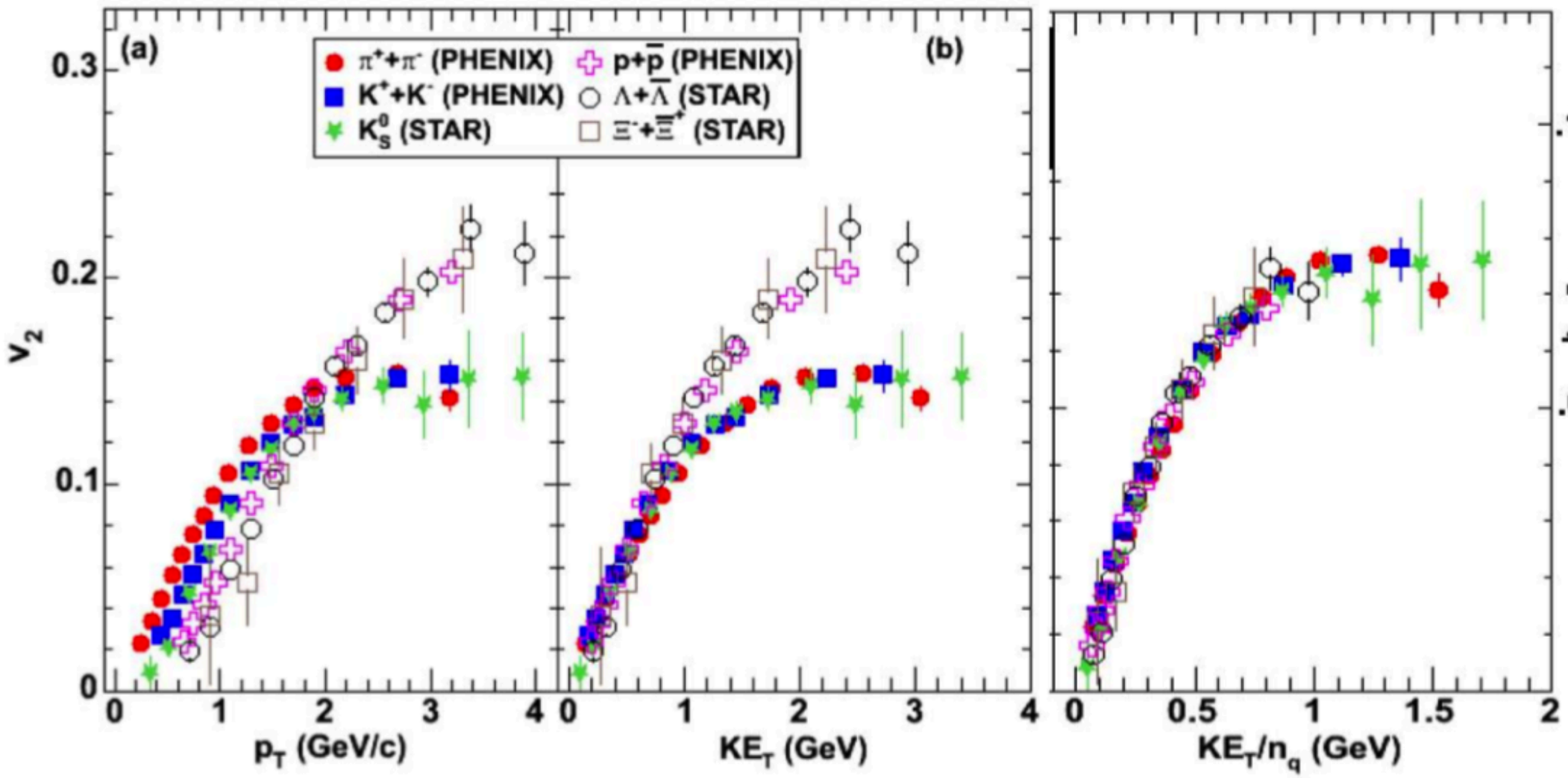
Initial idea was that the Cronin peak comes from the multiple scatterings

Then the pion should be larger than proton, instead of the other way around

Multiple scattering doesn't describe the identified R_{dAu}

Where did we see such ordering also

Phys.Rev.Lett. 98 (2007) 162301



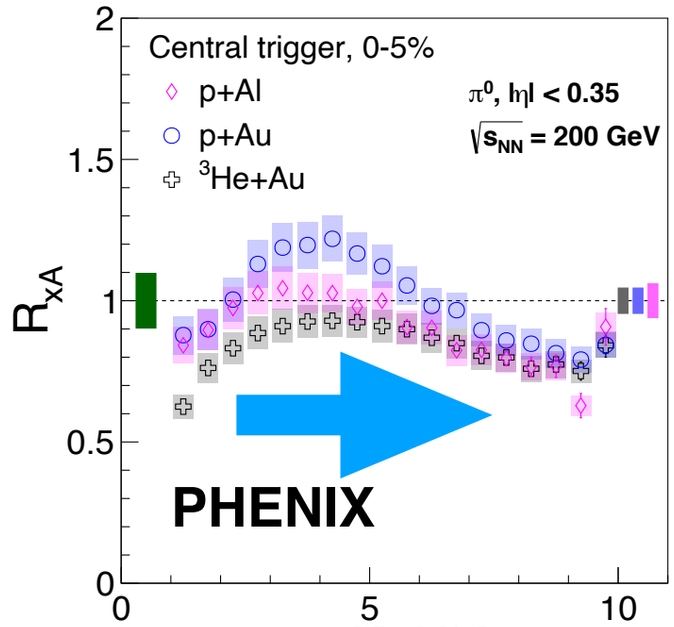
This is a very well know results:

- The quark content scaling of the identified particle flow
- The elliptic flow of the baryons is higher (at mid-p_T) than the mesons

Cronin peak - radial flow?

If the small systems see elliptic flow, there should be also radial flow:

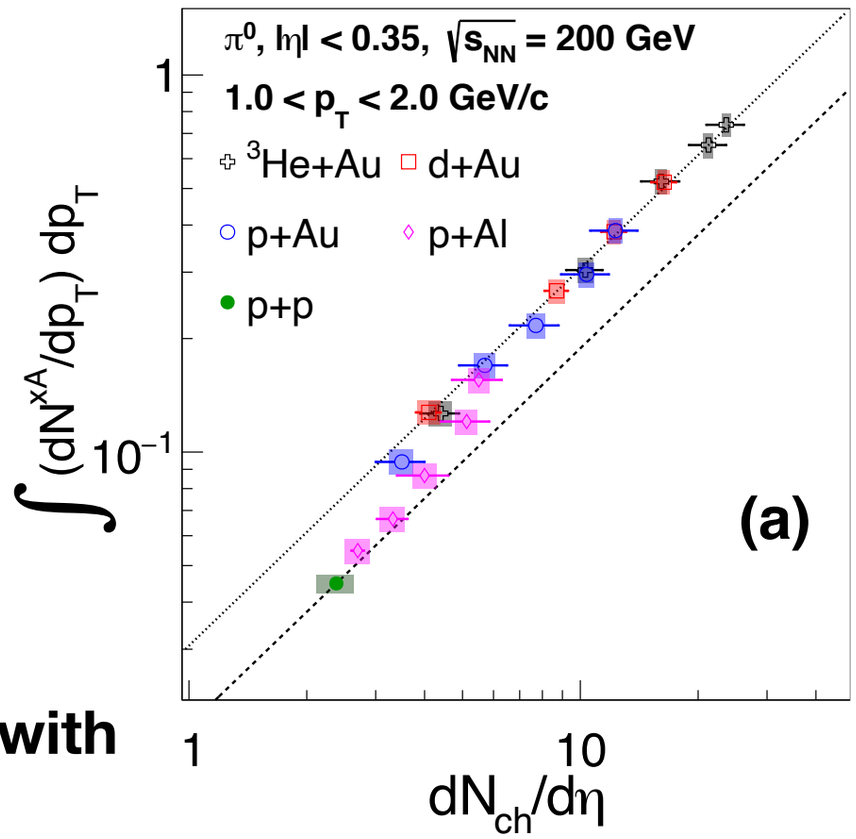
- Mostly prominent at lower p_T region
- If there is radial flow, the very low-p_T pions should be shifted to higher p_T values
- No direct measurement of radial flow is small systems as of now

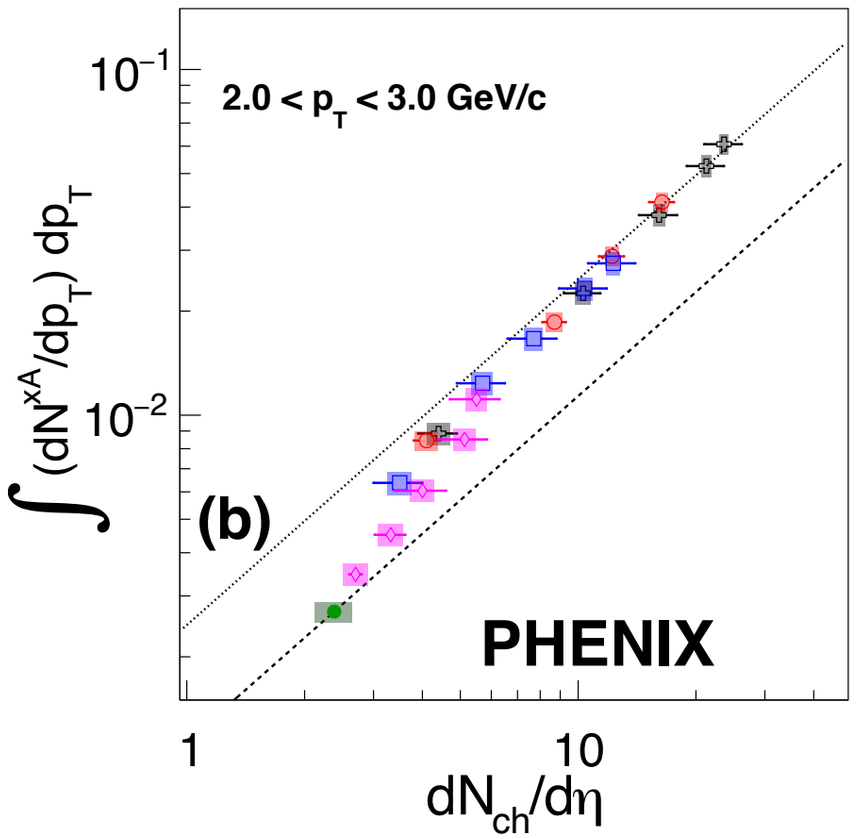


Integrated yield in very low-p_T region:

- Comparing the different systems (including p+p) as the function of the multiplicity
- There is a hint of a common transition around 10 multiplicity

Qualitatively consistent with a radial flow picture

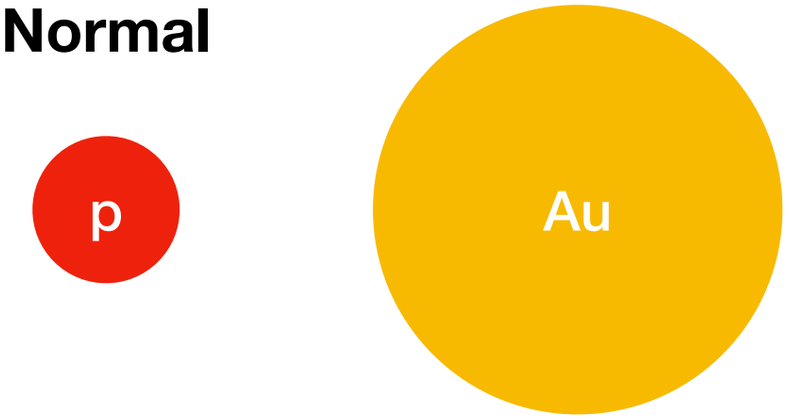




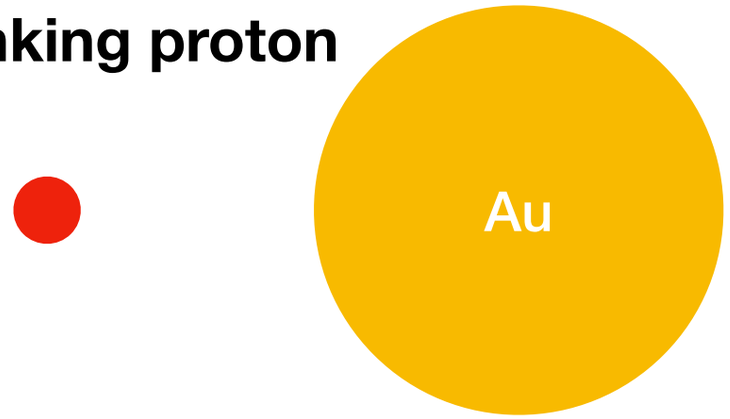
High p_T

Proton fluctuation model

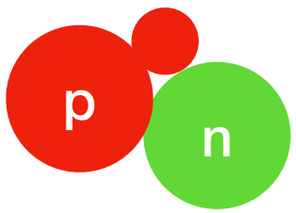
Normal



Shrinking proton

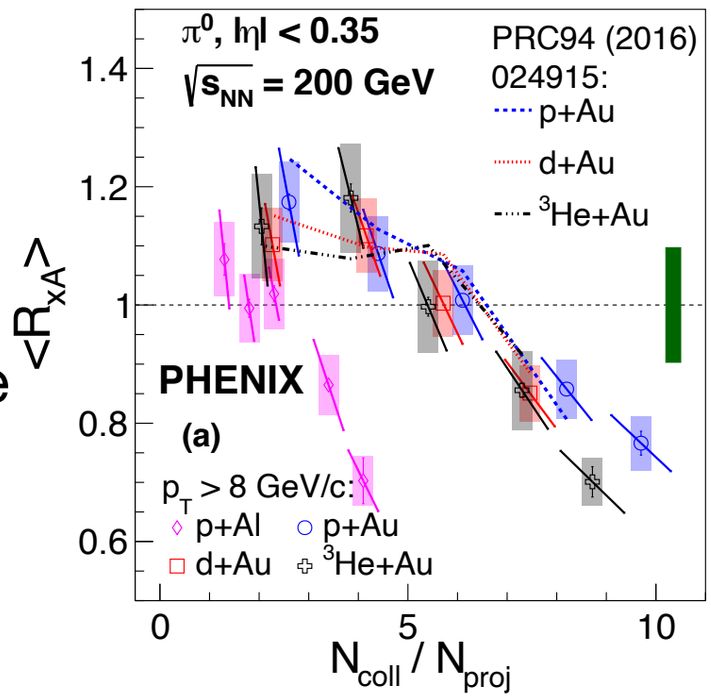


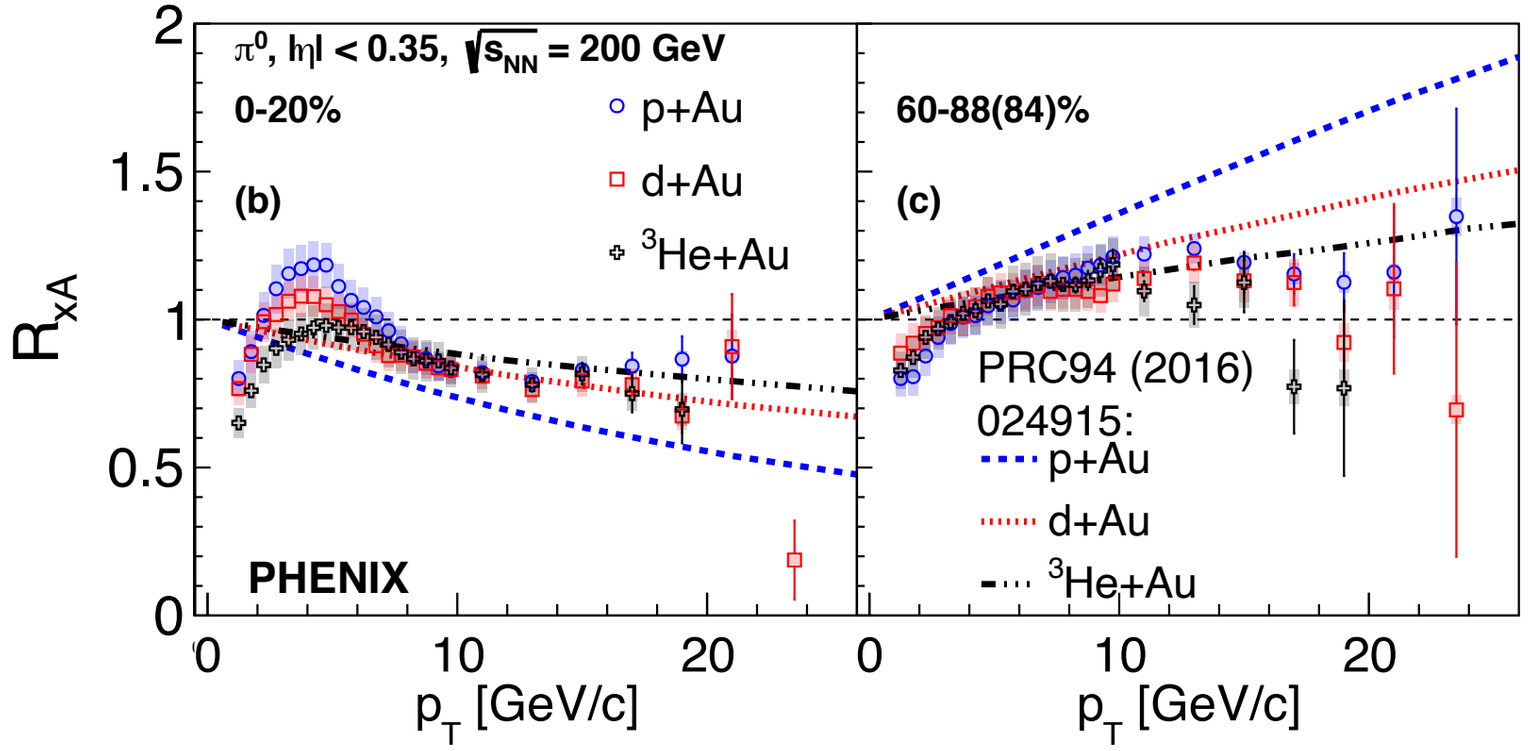
Shrinking proton in ^{3}He



The idea is that at large-x parton production the nucleons are "shrinking":

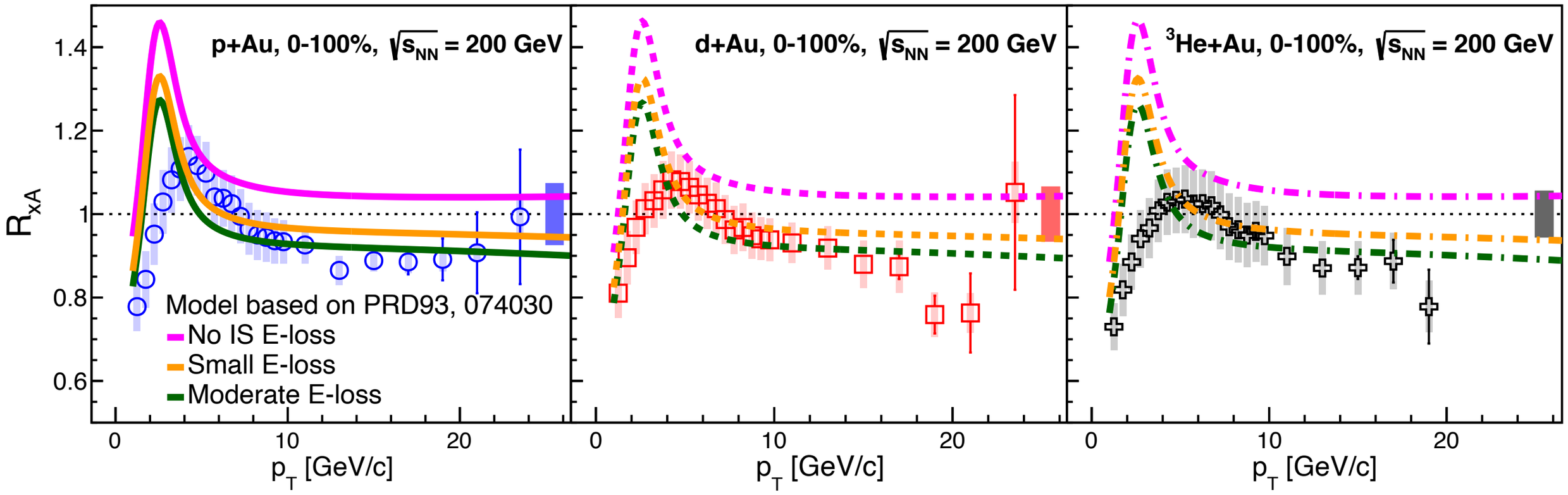
- The integrated R_{xA} shows similar behavior for the three larger systems
- The p_T dependence is not described by the model





Cold-nuclear energy loss

Based on *Phys.Rev.D* 93 (2016), 074030



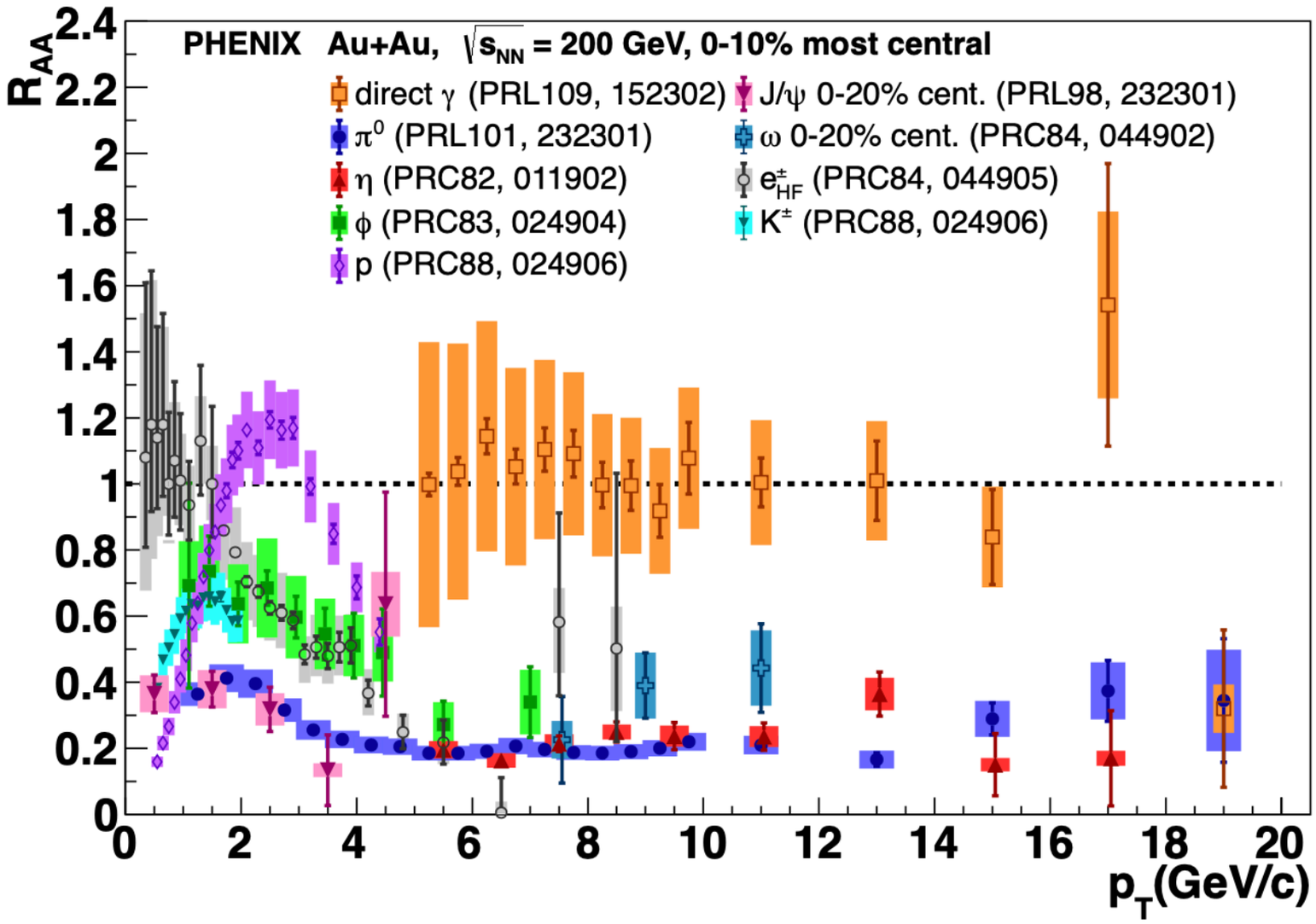
Comparison with Vitev's cold-nuclear energy loss:

- Data is consistent with moderate energy loss:
  - While the no initial state energy loss is above unity.
  - In case the NO IS E-loss == 1, there is still room for small E-loss

Cronin peak:

- No system dependency <-> data shows system dependency
- Maximum ~3 GeV/c <-> data peaks p_T ~ 5 GeV/c

Direct photons to solve the centrality



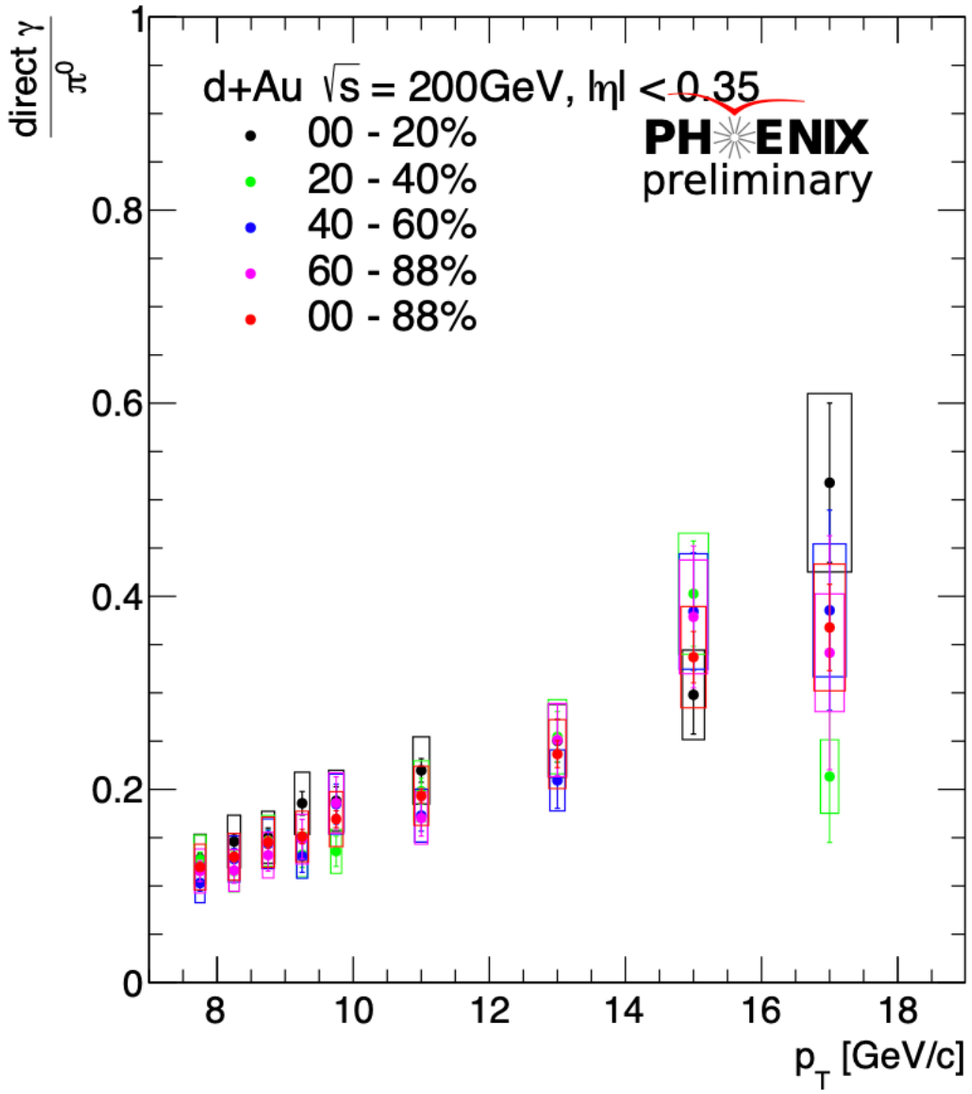
PHENIX R_{AA} measurement in heavy ion collisions

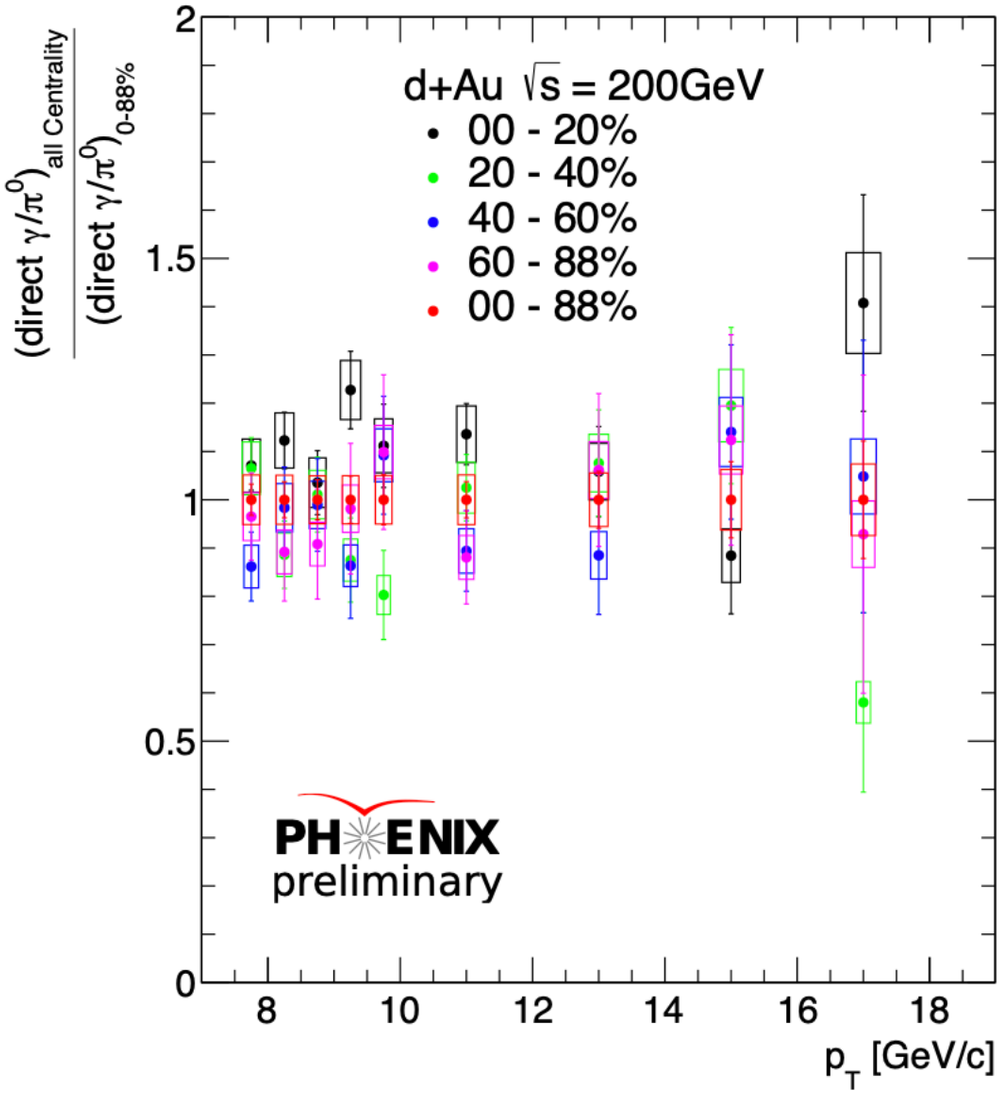
All the hadrons are suppressed in the most central collisions, the direct photons are consistent with unity

We can also measure the direct photons in small systems:

1. $R_{xA}^{\pi 0} > R_{xA}^{\gamma}$ - there is an enhancement of hadrons in small systems
2. $R_{xA}^{\pi 0} = R_{xA}^{\gamma}$ - every effect is coming from initial state, centrality has to be redefined
3. $R_{xA}^{\pi 0} < R_{xA}^{\gamma}$ - suppression in final state? Energy loss?

The first preliminary on direct photons





This double ratio represents the first look in the direct photon results:

- There is no strong centrality dependency observed
- No p_T dependent difference
- The analysis is still in progress

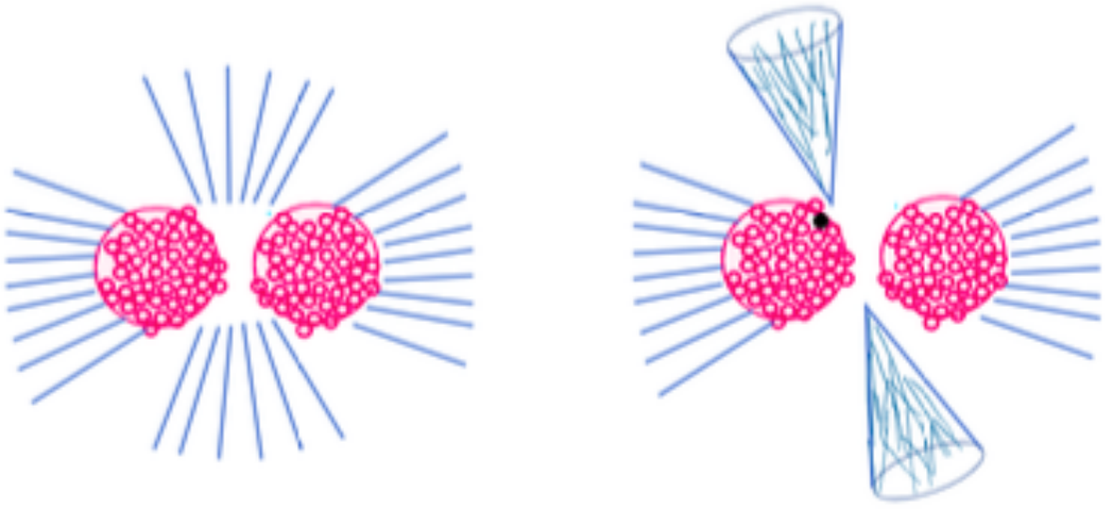
Zhandong Sun Fri 11:30

Summary

New results of the systematic study of neutral pions, ϕ mesons in highly asymmetric collisions:

- New measurements from p+Al, p+Au, d+Au and ^{3}He+Au at 200 GeV
  - Very good agreement between the ϕ and π^0 mesons
- Low-p_T:
  - Clear indication of system size dependency in central collisions:
    - p+Au > d+Au > ^{3}He+Au
  - Peripheral collisions all in good agreement
  - Radial flow as a good possibility to explain the Cronin peak
- High-p_T:
  - Different systems in good agreement
  - The nuclear modification is about ~0.85 consistently in all systems in minimum bias
  - Large centrality dependency, central '*suppressed*', peripheral '*enhanced*'
  - Shrinking proton picture is mostly excluded
    - Not the dominant physics process behind the data
  - Room for small to moderate cold nuclear energy loss
  - Direct photon analysis is ongoing and it will be used to calibrate the data:
    - The photons could resolve the bias in centrality selection

Centrality bias

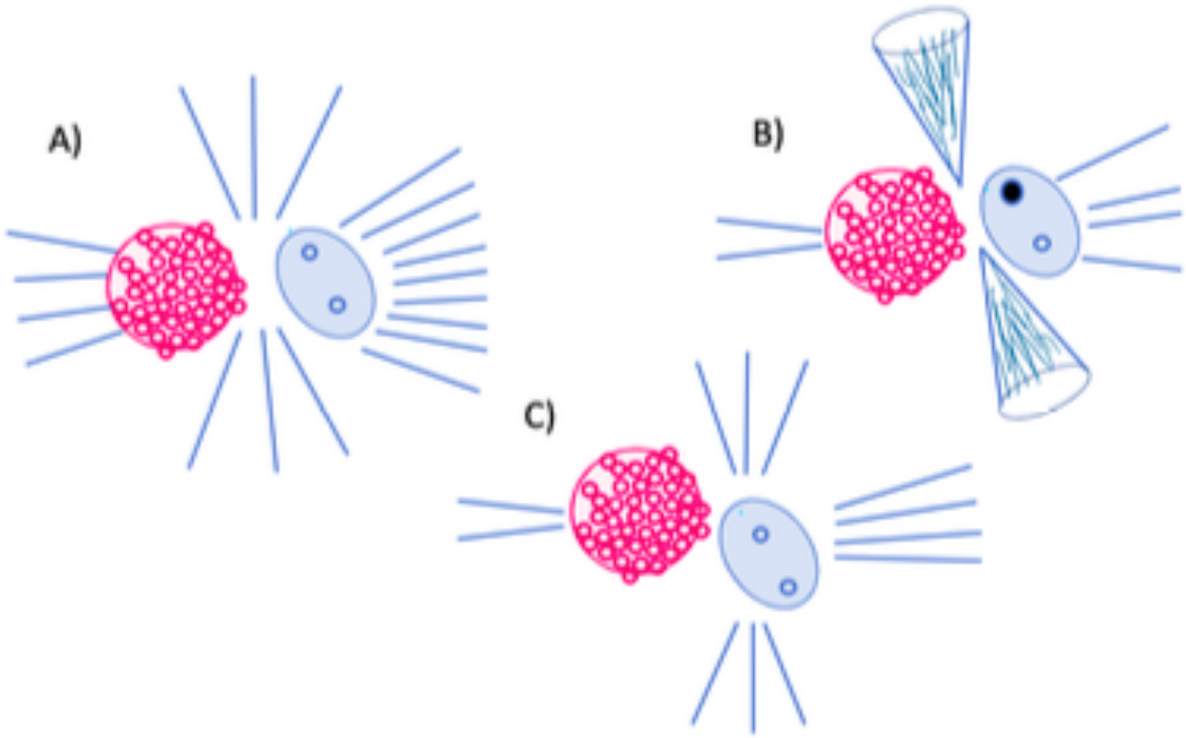


In Au+Au collisions a presence of the hard scattering does not fundamentally change the underlying event multiplicity

Centrality dependency is very closely correlated to the colliding nuclei - maybe except the very peripheral collisions

In d+Au collisions a presence of the hard scattering CAN fundamentally change the underlying event multiplicity

The jet depleted the available energy in the collision system, producing less forward particle multiplicity —> shifting events towards more peripheral centrality



Investigating the QGP evolution

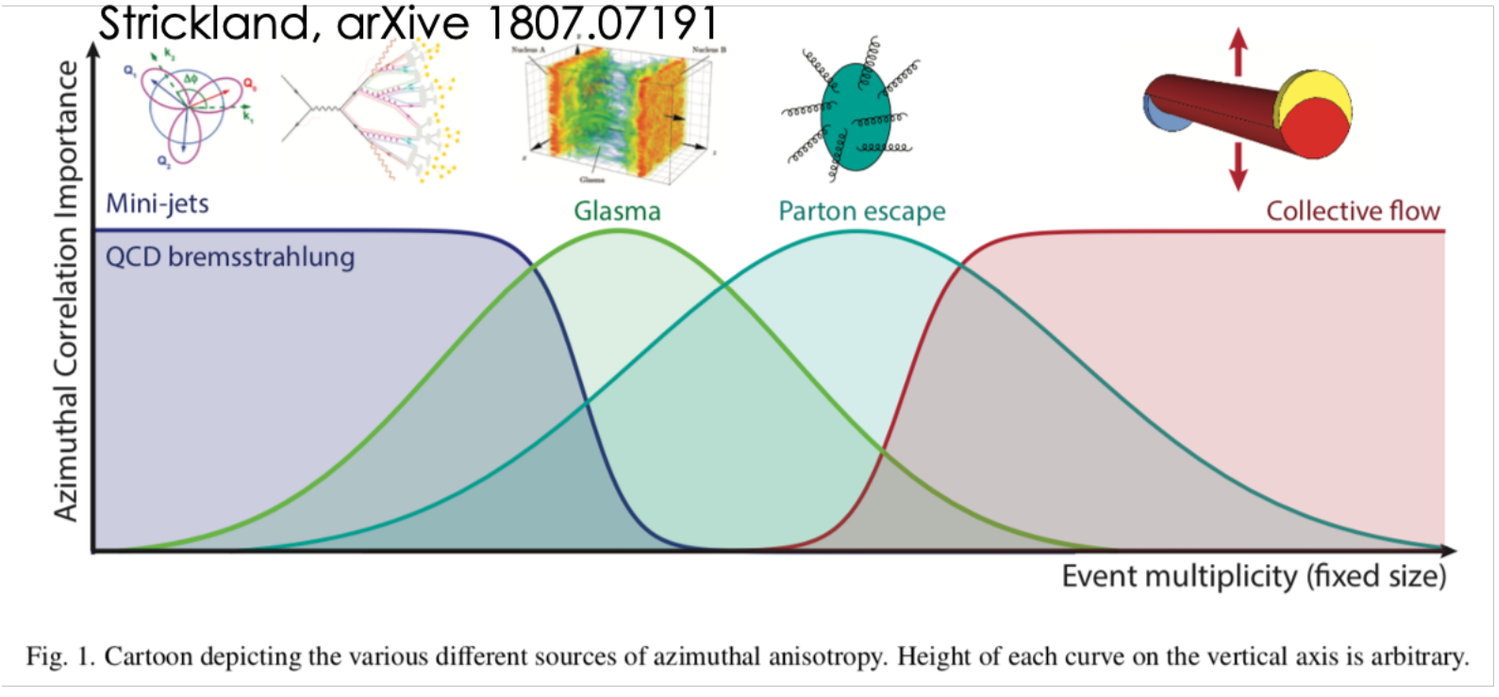
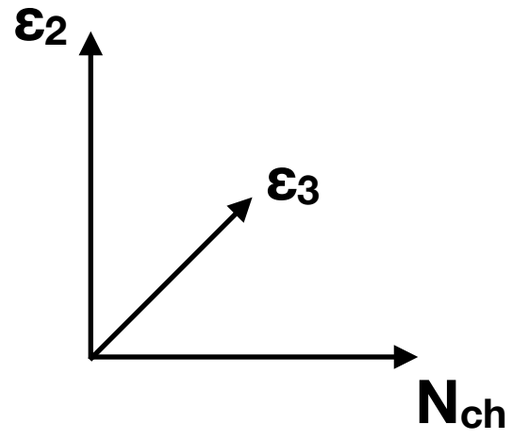


Fig. 1. Cartoon depicting the various different sources of azimuthal anisotropy. Height of each curve on the vertical axis is arbitrary.

Varying the size, geometry, volume of the collision system



Measure system size via event multiplicity (dN/dη):

- dN/dη is an experimental observable
- at fixed √s: dN/dη ~ N_{part} ~ volume
- varying √s: dN/dη ~ energy density **X** volume

Discovery of a scaling behavior:

- Found a general slope of the binary collision dependency on the number of charged particle multiplicity
- Connecting the *bulk particle* production with the *hard scattering* processes

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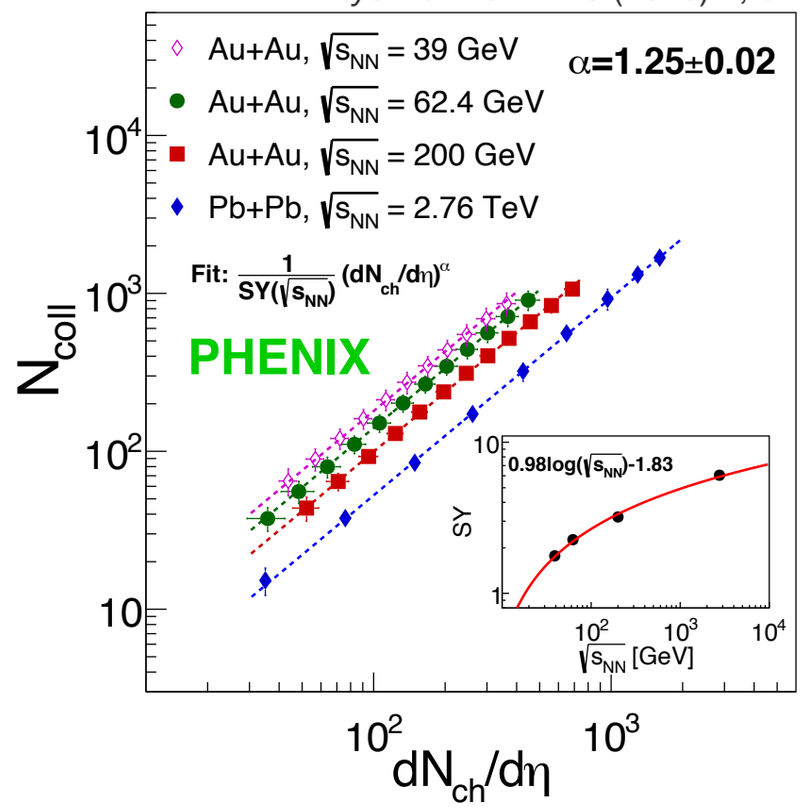
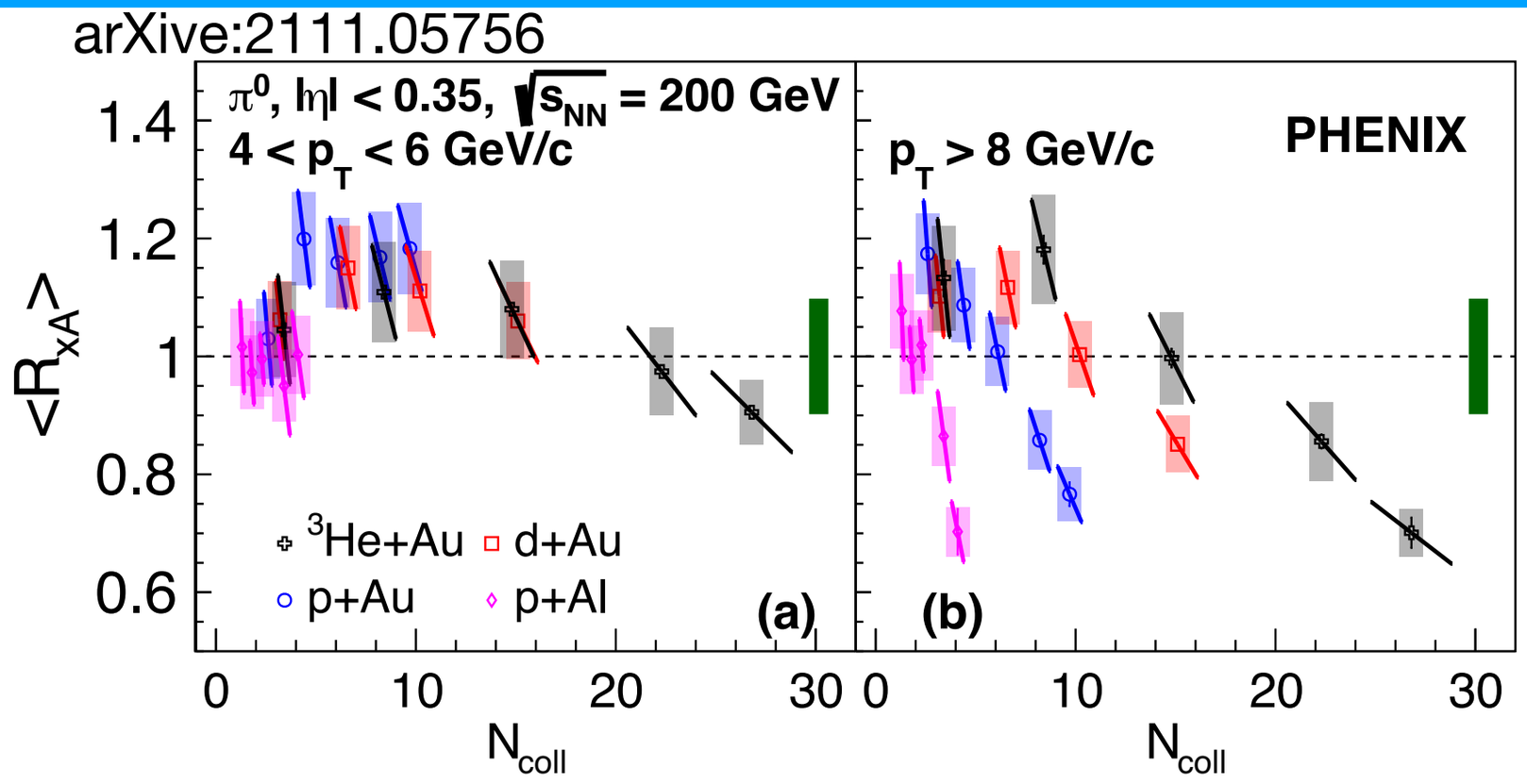


Integrated R_{xA}

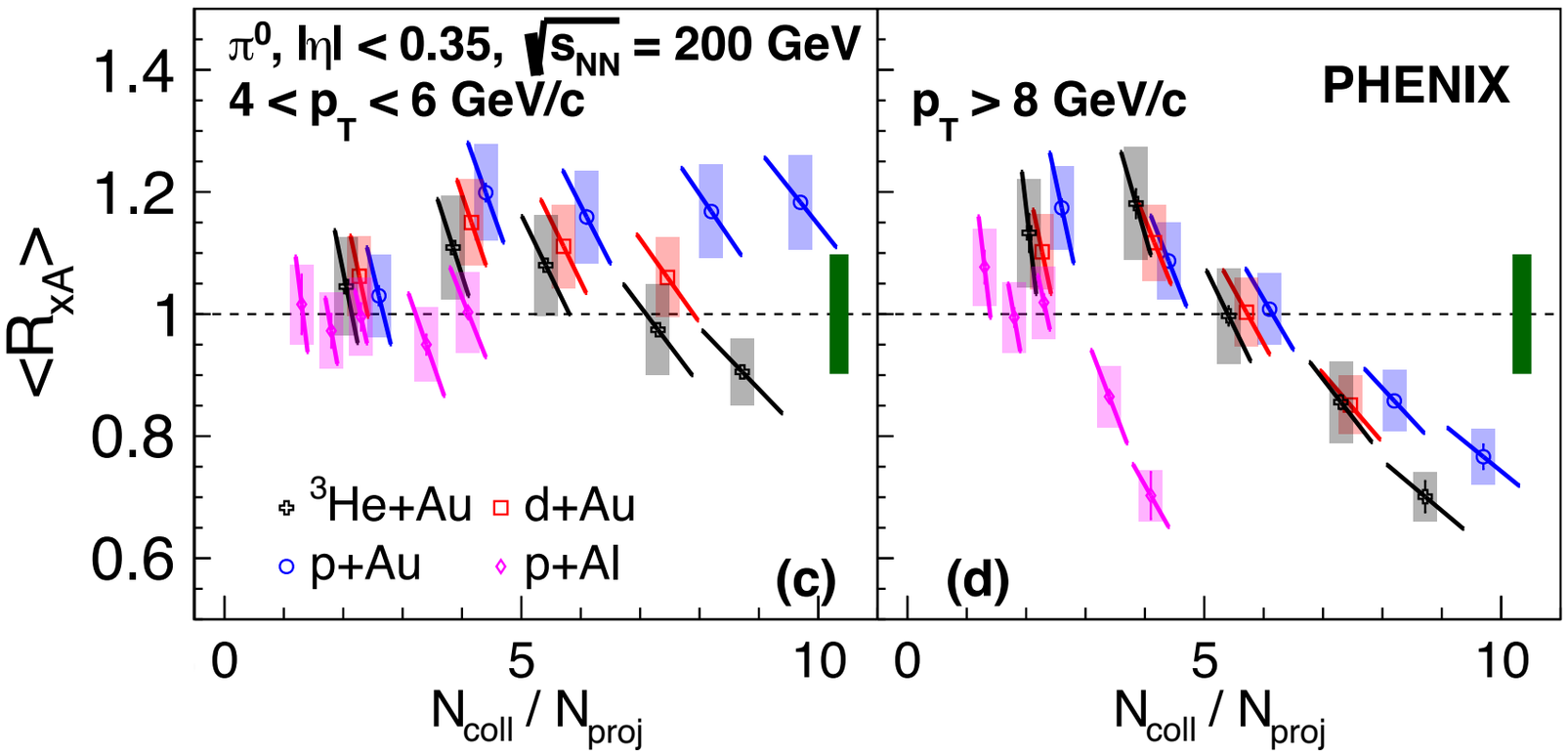


Integrating the R_{xA} as a function of N_{Coll}:

- Cronin peak shows more uniform behavior across the different systems

Integrating the R_{xA} as a function of N_{Coll}/N_{proj}:

- At high-p_T it shows more uniform behavior in Au target
- Al target is similar shape, but different x-magnitude



Can we find evidence for energy loss?

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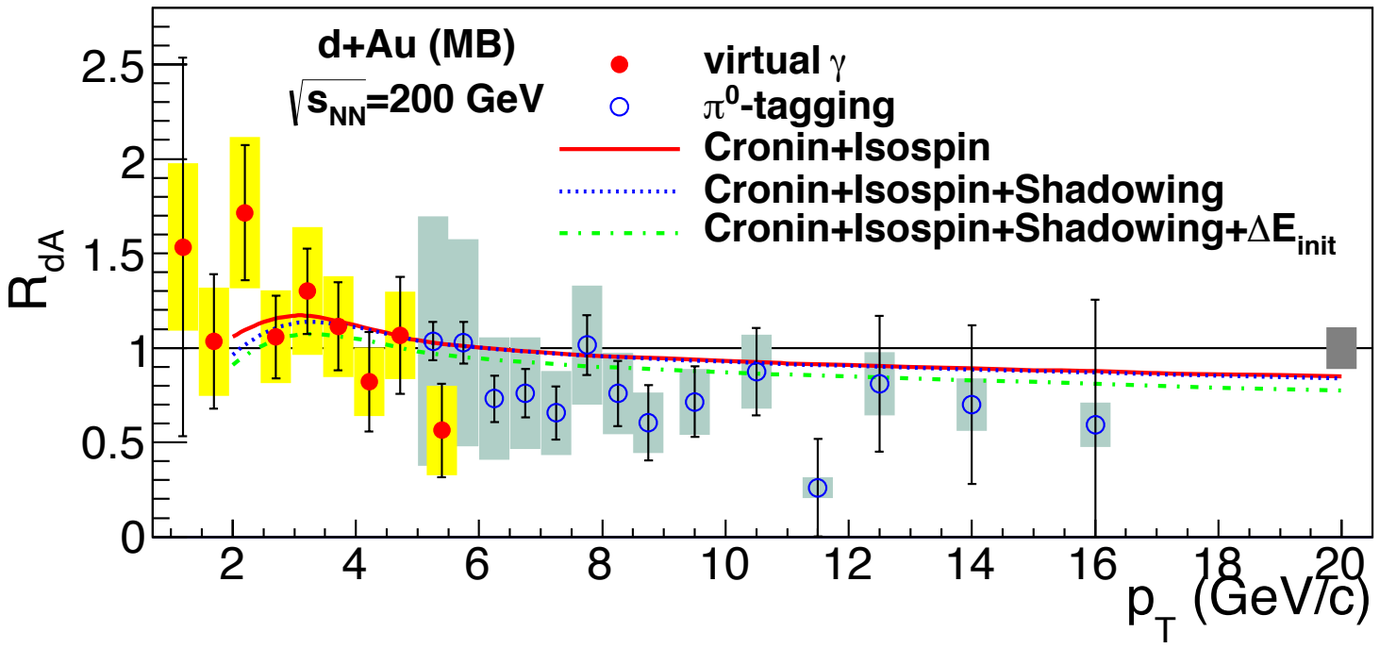
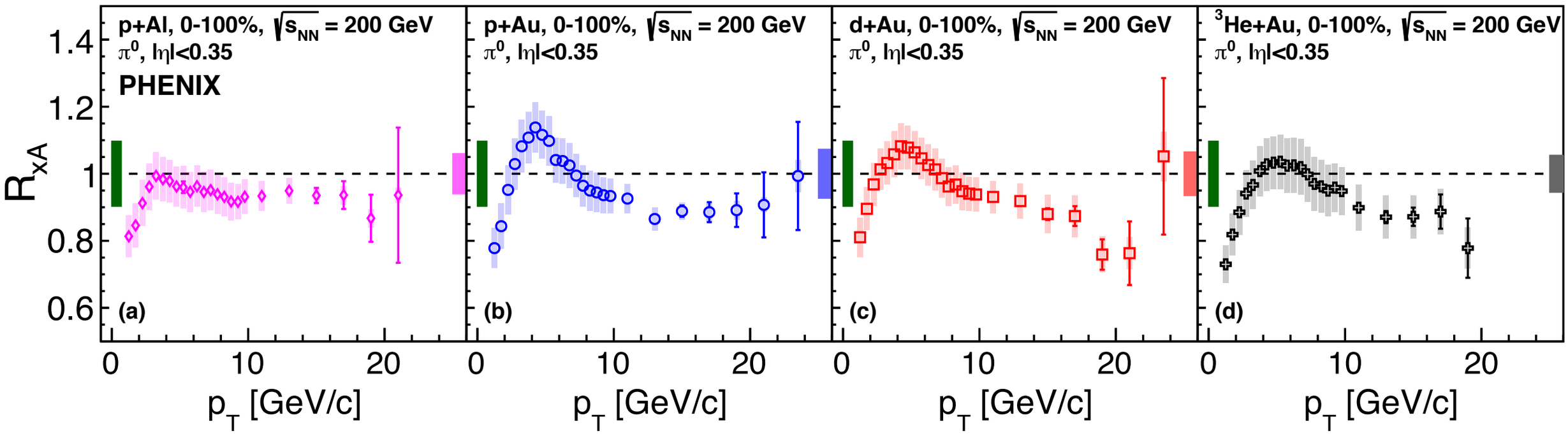
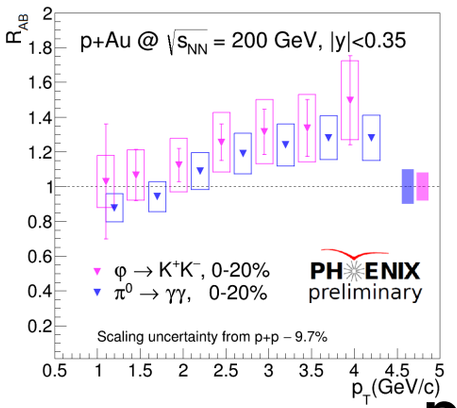


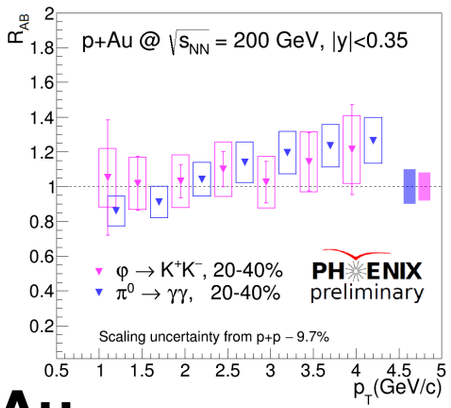
The measurement of the d+Au direct photons:

- The R_{AA} shows no modification
  - Systematically lower R_{AA} for $p_T > 6$ GeV, around ~0.85

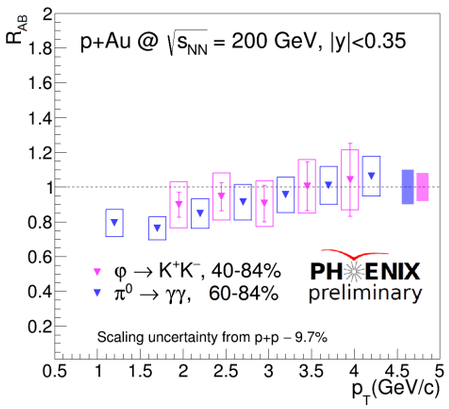


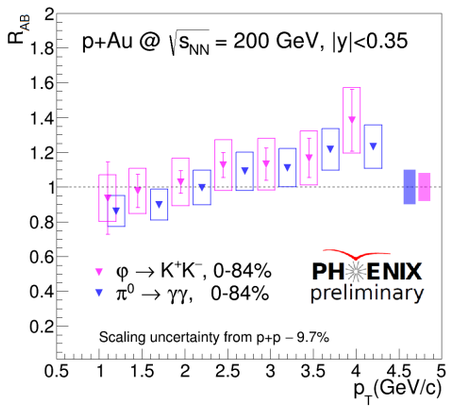
ϕ/π⁰ meson in small systems

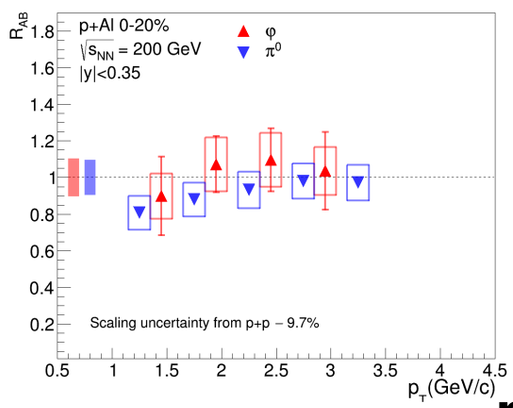


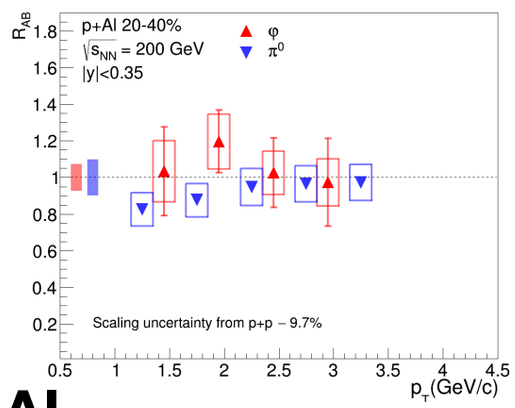


p+Au

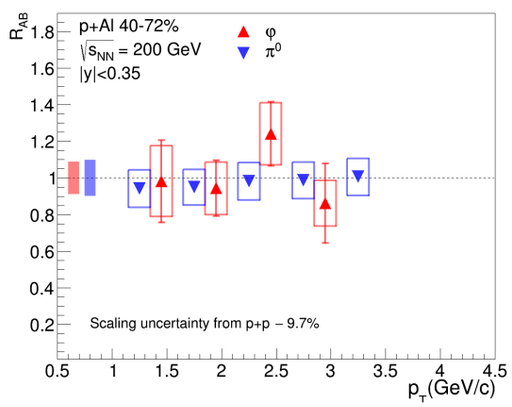


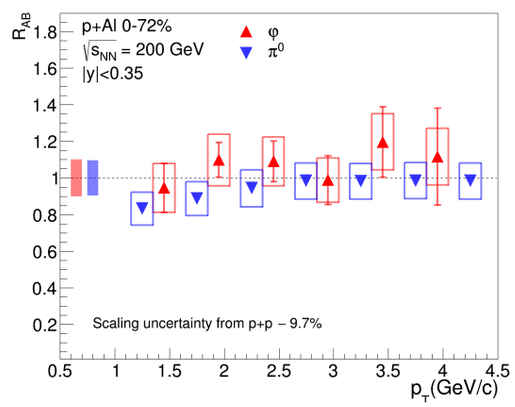


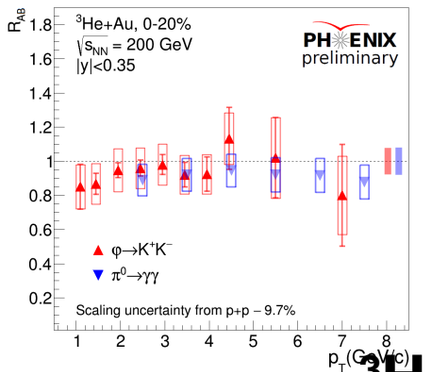


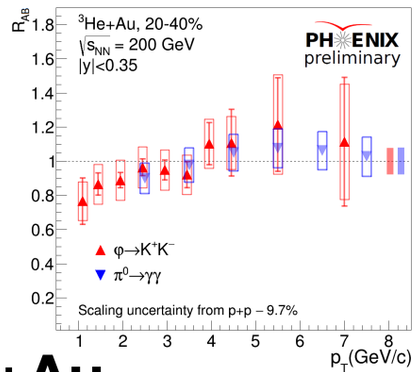


p+Al









^{3}He+Au