PHENIX Results on Nuclear Modification of Hadron Production in Small and Large Systems

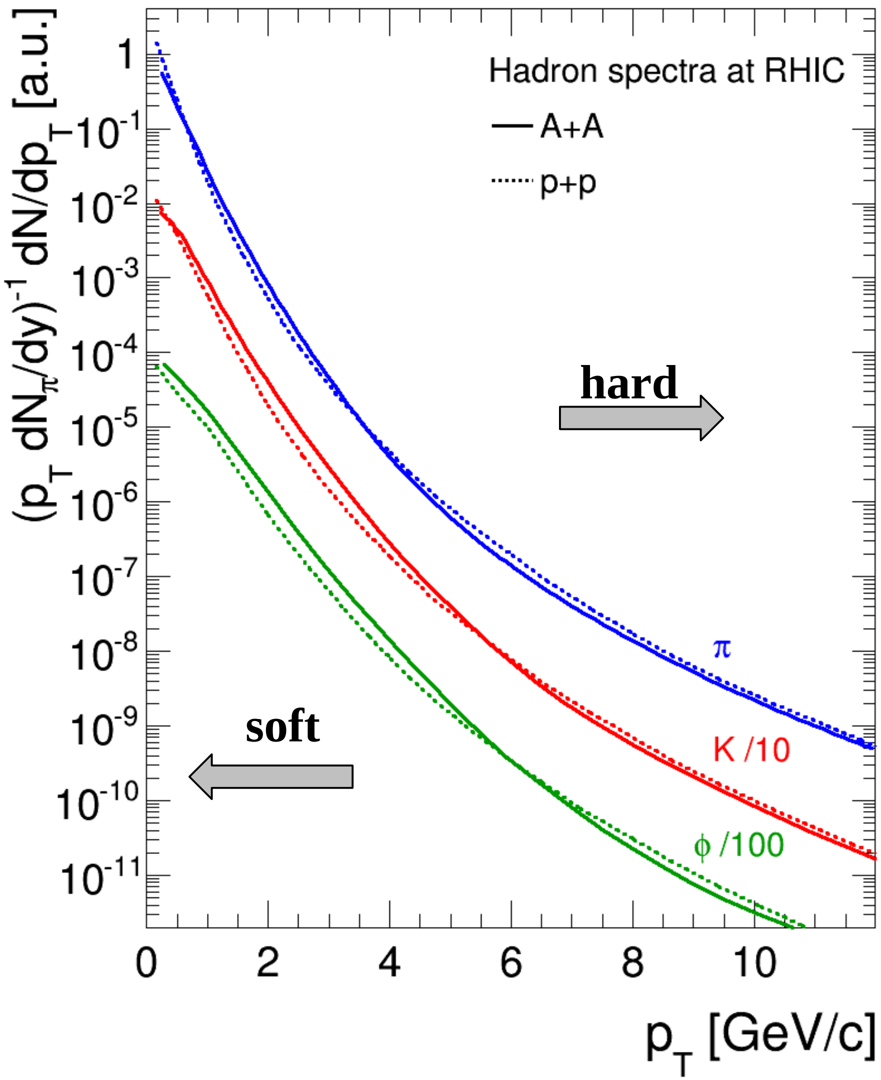
Axel Drees, Hard Probes 2020, June, Port Jefferson, NY

- **Introduction**
- **Heavy Ion Collisions Cu+Au and U+U**
- **Small systems p+Al, p+Au, d+Au, ^{3}He+Au**
- **Summary**

Stony Brook University

Nuclear Modification of Hadron Production

Schematic view of p_T spectra at RHIC



- **A+A collision compared to p+p**
- **High p_T region**
  - **Production dominated by jet fragmentation.**
  - **Jet quenching → suppression of hadron yields.**
- **Low p_T region**
  - **Soft particle production.**
  - **Collective expansion (radial flow) → enhancement of hadron yields.**
  - **Strangeness enhancement → change in particle composition**

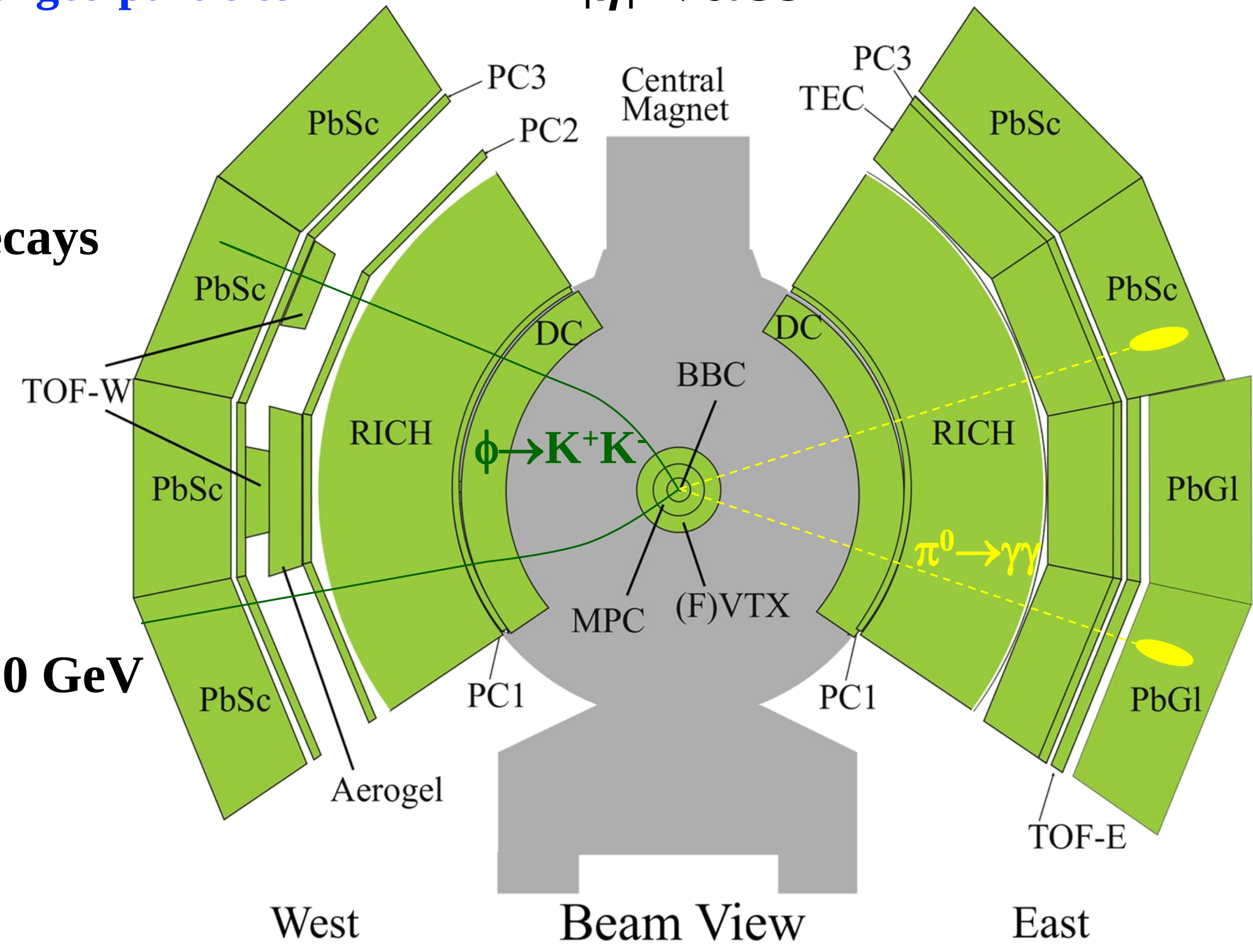
Rich information about dynamics of heavy ion collisions

Hadron Spectra with the PHENIX Detector

- **Key central arm detector systems**
  - **Drift Chambers → charged particles**
  - **EMCal → photons**
  - **TOF → $\pi^{\pm}, K^{\pm}, p, \bar{p}$**
- **Reconstruct Particle Decays**
  - $\pi^0, \eta \rightarrow \gamma\gamma$
  - $\phi \rightarrow K^+K^-$
  - $\omega \rightarrow \pi^0\gamma$
  - $K_s^0 \rightarrow \pi^0\pi^0$
  - $K^* \rightarrow \pi K$
- **Variety of systems at 200 GeV**
  - **p+p, Au+Au**
  - **Cu+Au, U+U**
  - **p+Au, d+Au, ^{3}He+Au**

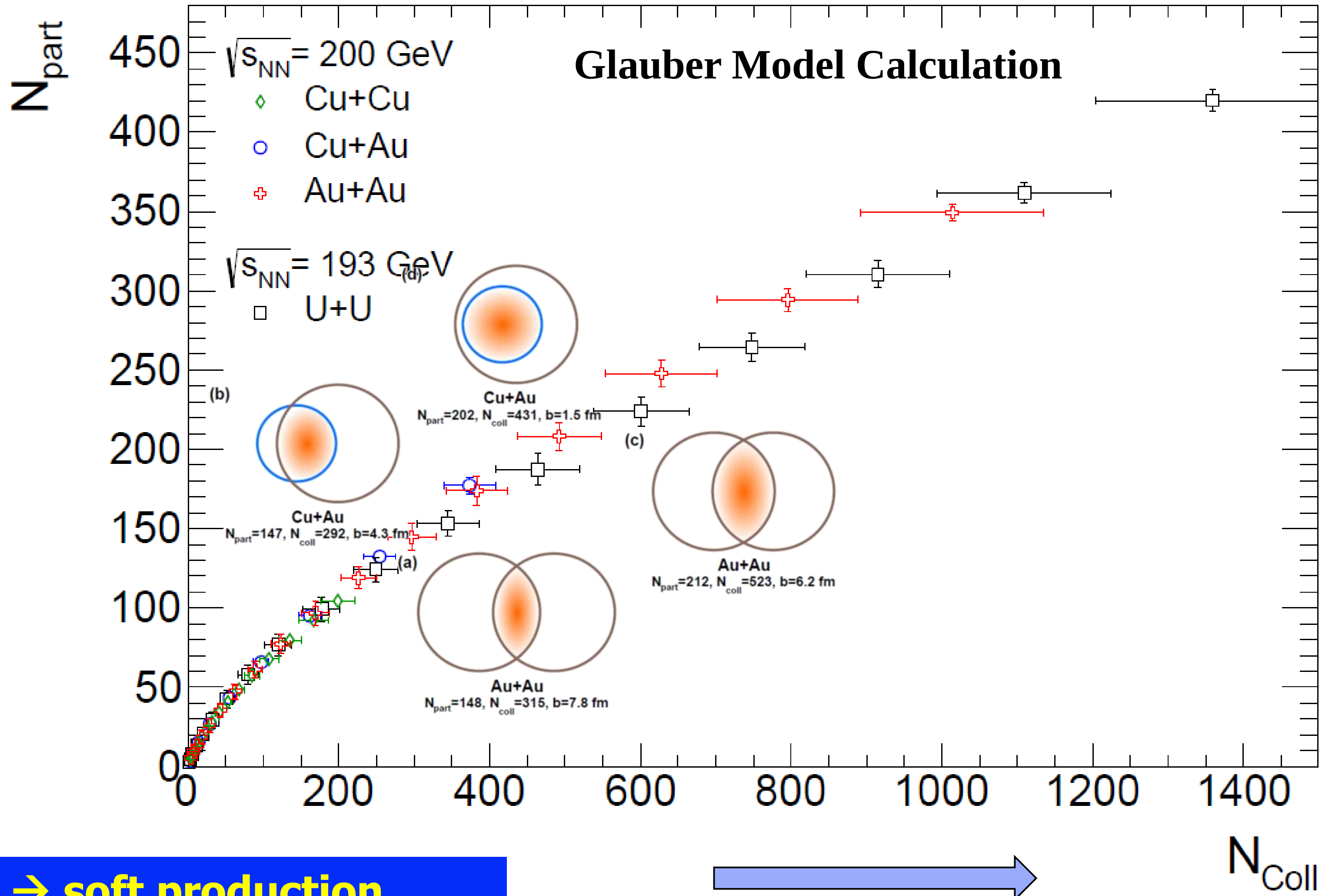
$2 \times \ \Delta\varphi = 90^o$

$|\eta| < 0.35$



Comparing Different Systems with N_{part} or N_{coll}

Soft particle production:
Reaction Volume × Energy Density
$N_{part} \sim V \times \varepsilon$

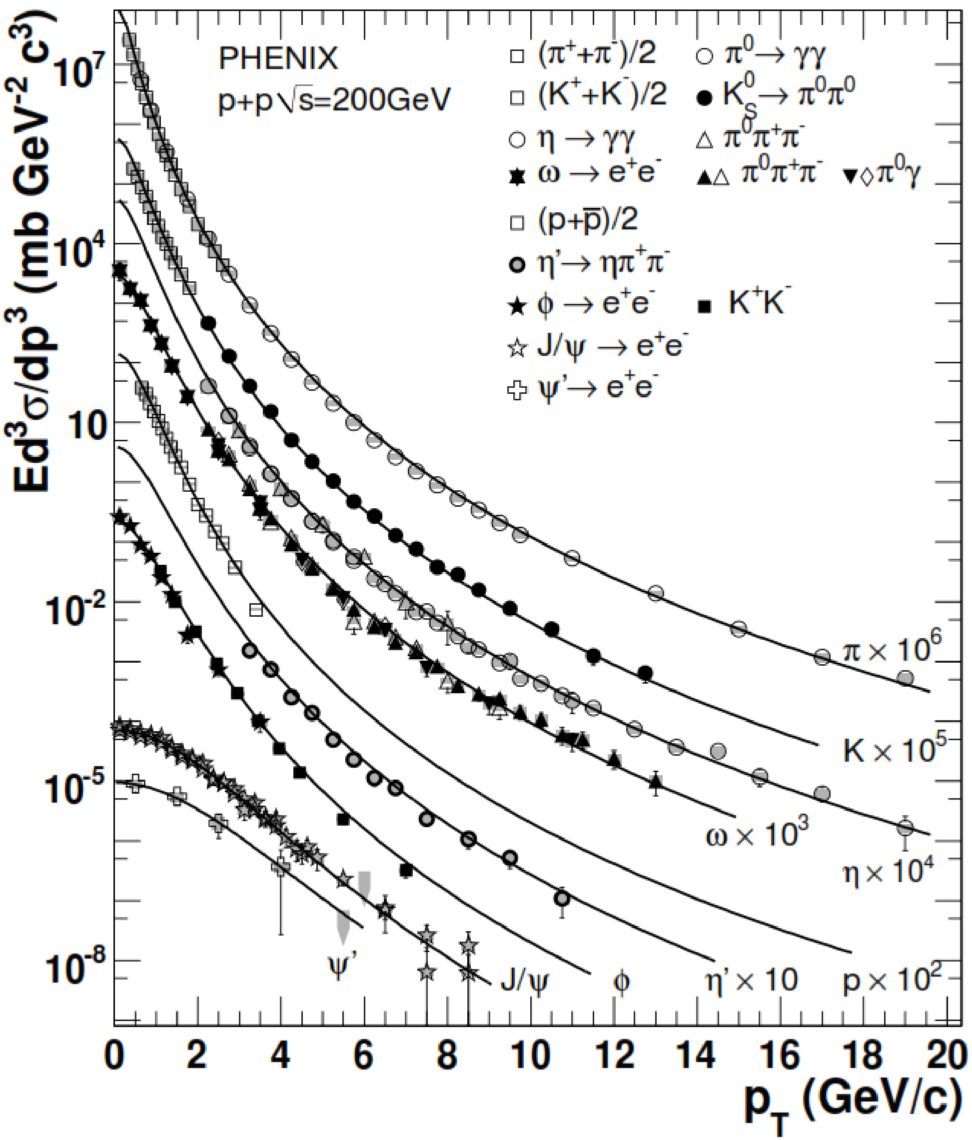


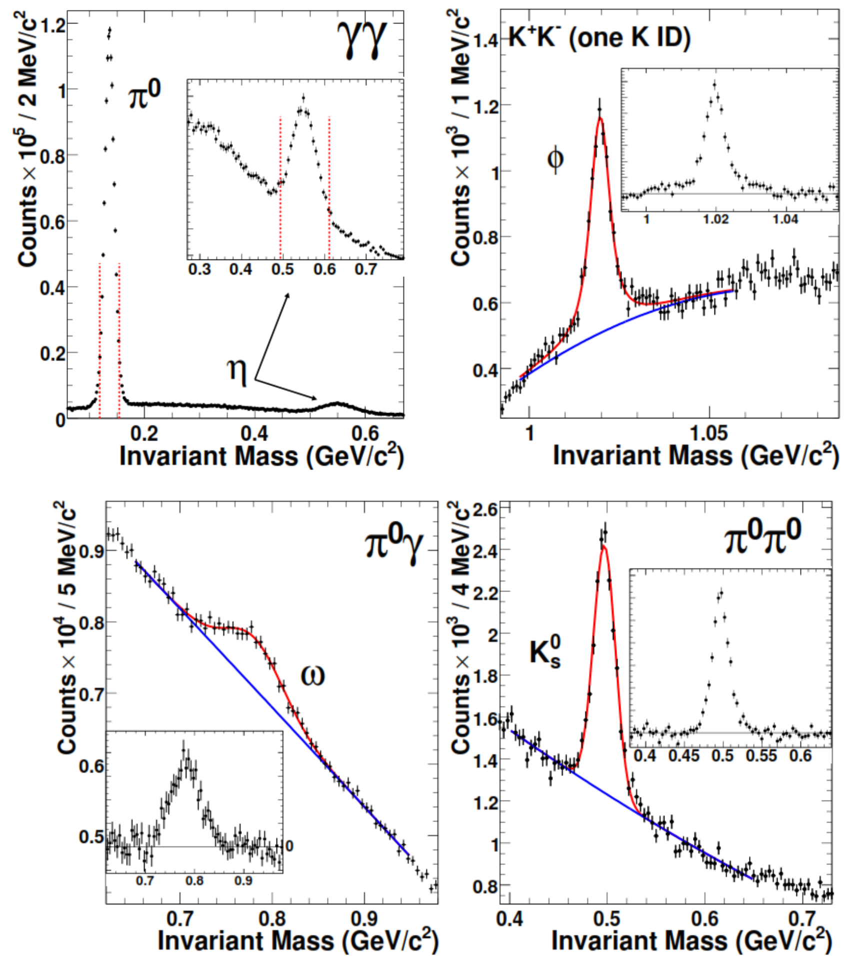
N_{part} → soft production
N_{coll} → hard production
Limited sensitivity to geometry

Hard Scattering Probability
$N_{coll} \sim \sigma_{hard}$

Reference Spectra from p+p Collisions

PHENIX: Phys. Rev. D83 (2011) 052004

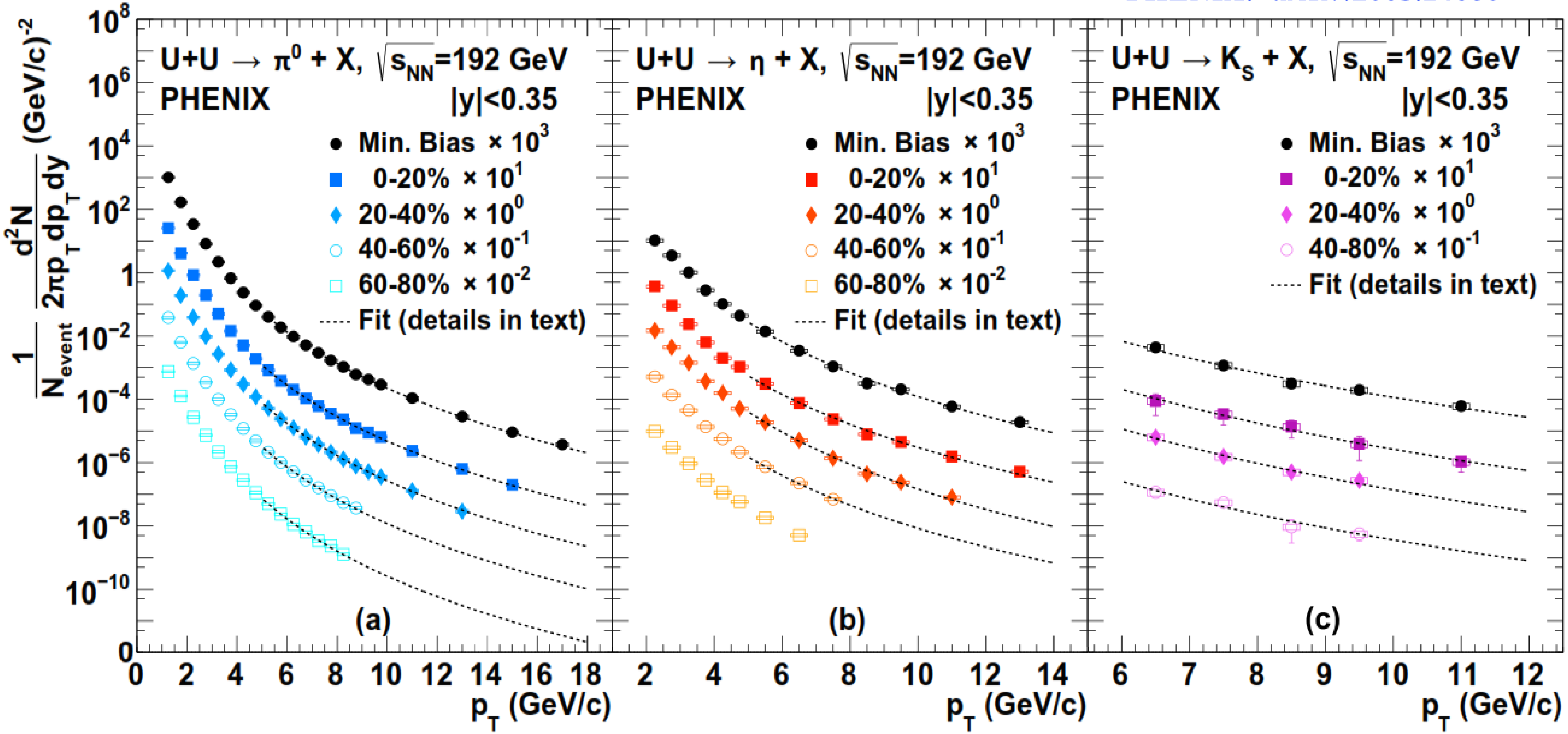




Spectra for many hadrons over broad p_T range

Meson Production in U+U at 192 GeV

PHENIX: arXiv:2005.14686

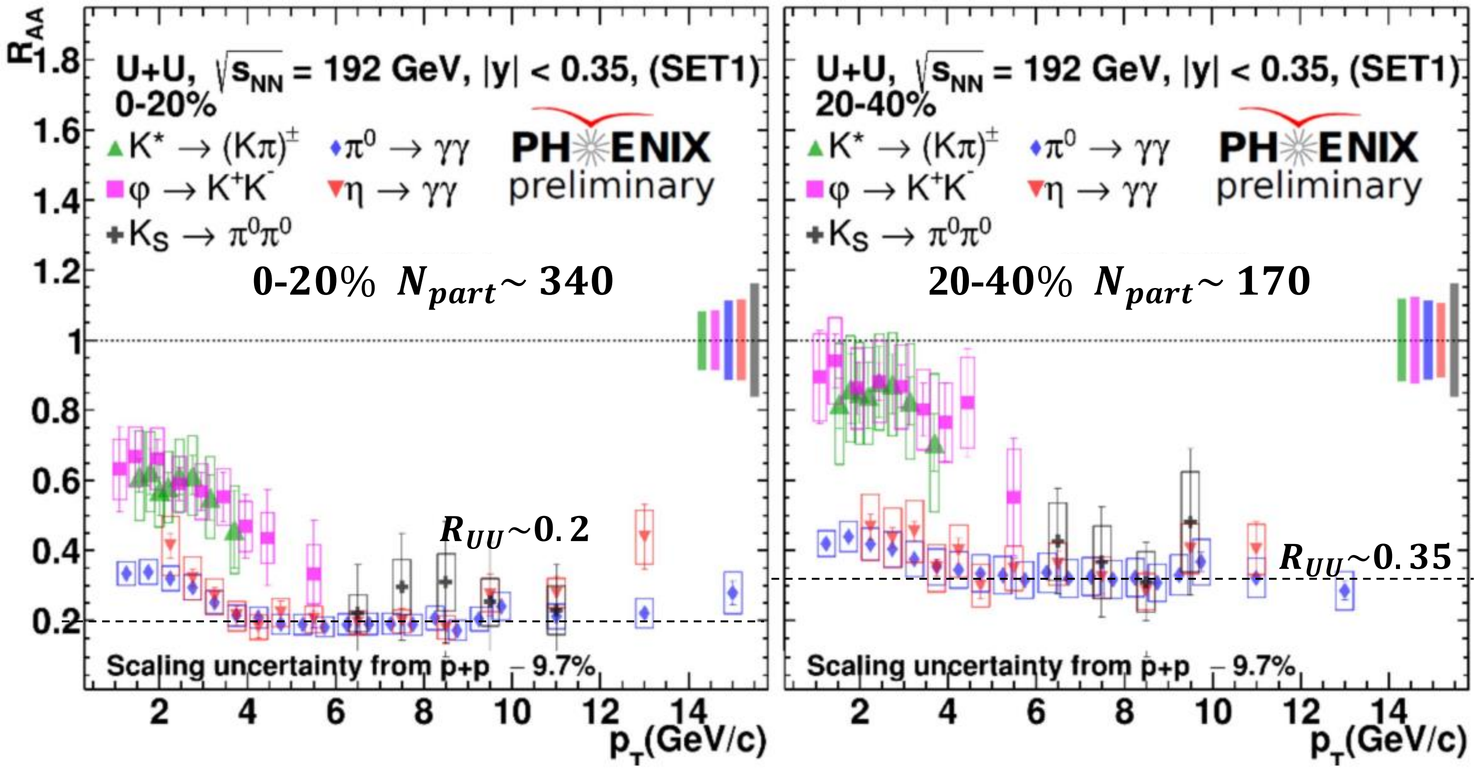


Compare to p+p and different centrality selections using nuclear modification factor:

$$R_{AB}(p_T, N_{part}) = \frac{\left(\frac{d^2N}{dp_t}\right)_{AB}}{N_{coll}\left(\frac{d^2N}{dp_t}\right)_{pp}}$$

Meson R_{AA} for Central U+U Collisions

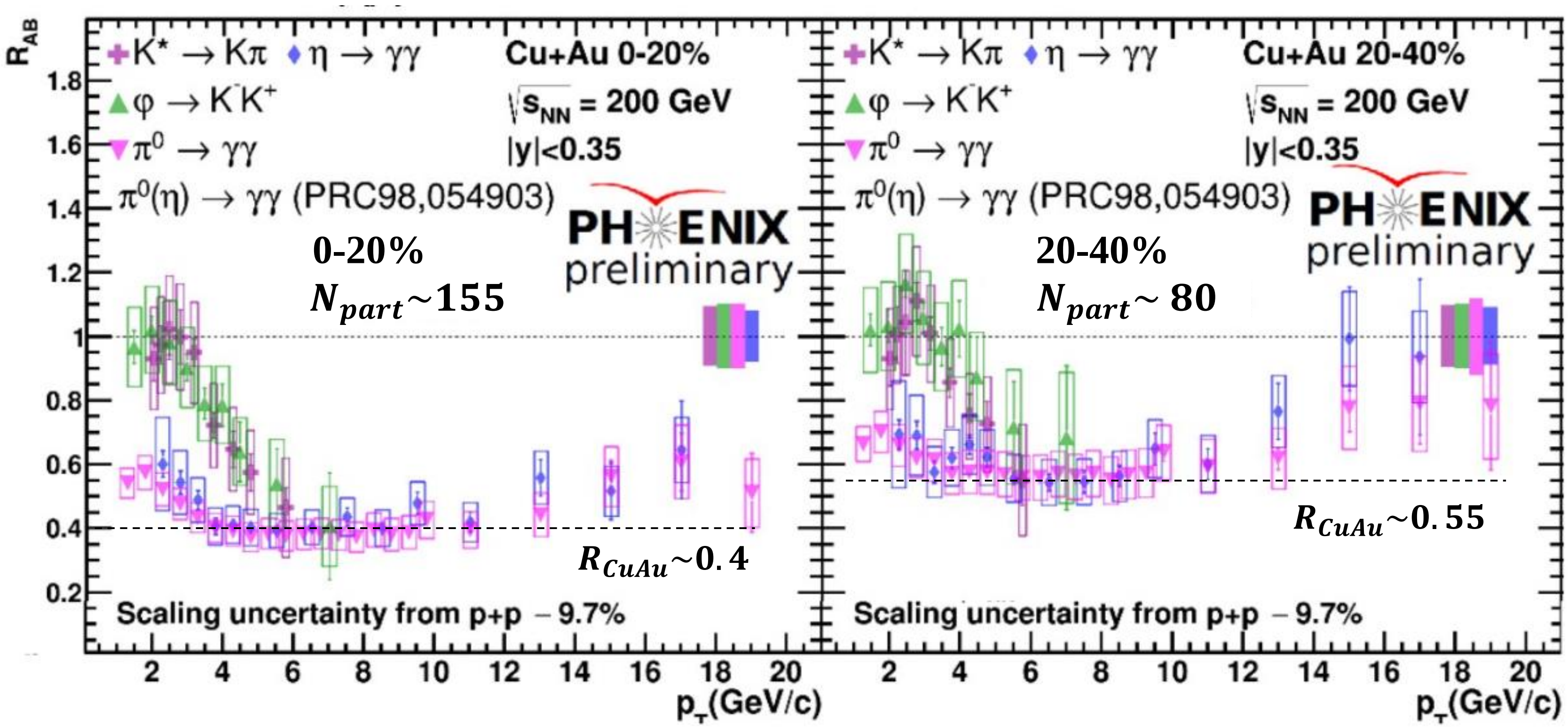
PHENIX: arXiv:2005.14686



- $R_{AA}(p_T,N_{part})$ qualitatively consistent between U+U and Au+Au
  - Common suppression for mesons (π, K, η, K*, ϕ) at high p_T
  - Nearly constant R_{AA} value that is lowest for central collisions
  - Less suppression at low p_T
  - K^*,ϕ less suppressed than π^0,η
  - K^*,ϕ reach common suppression at higher p_T

Meson R_{AB} for Central Cu+Au Collisions

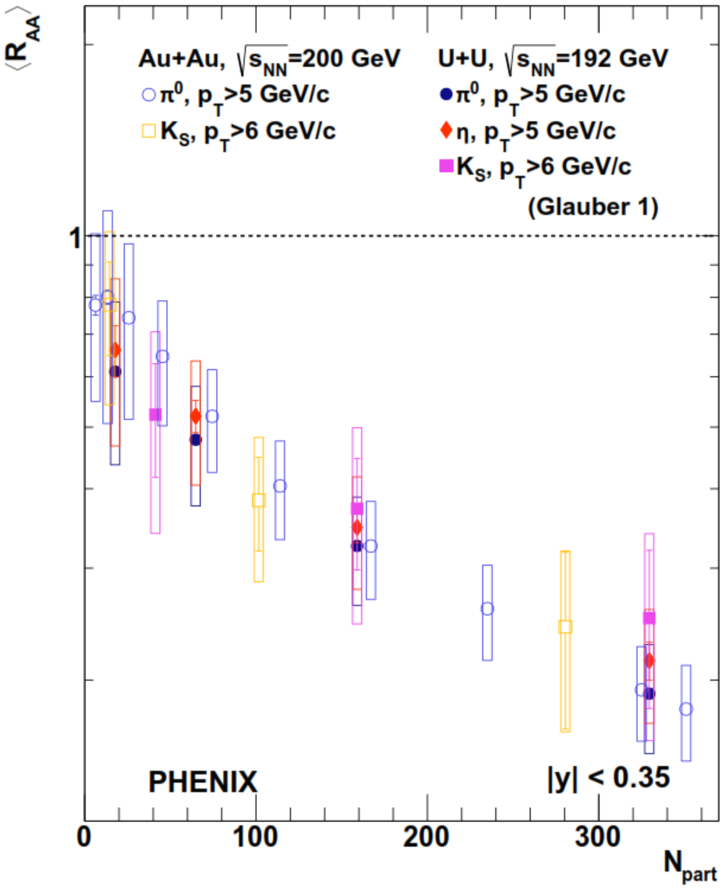
PHENIX: Phys. Rev. C98 (2018) 054903

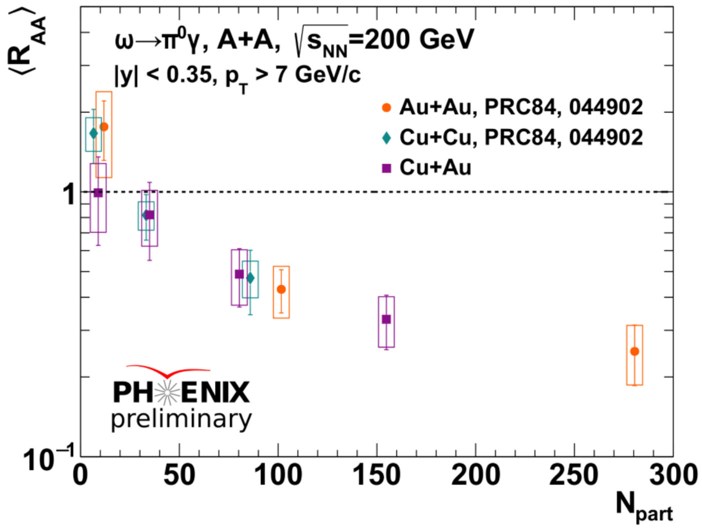


- $R_{AA}(p_T,N_{part})$ qualitatively consistent between U+U, Au+Au, Cu+Au
  - Similar centrality dependent suppression for π, η, K*, ϕ
  - Mass/flavor dependence at low pt
  - Increase of R_{AA} for p_T>10 GeV/c

Meson Modification at High p_T

PHENIX: arXiv:2005.14686





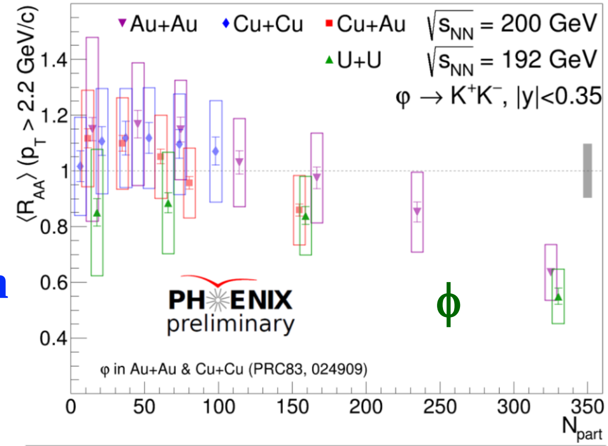
- **Universal centrality dependence of high p_T meson suppression**
  - **π, K_s, η, ω, (K^*, ϕ) same suppression**
  - **At same N_{part} Cu+Cu, Cu+Au, Au+Au and U+U show same suppression**

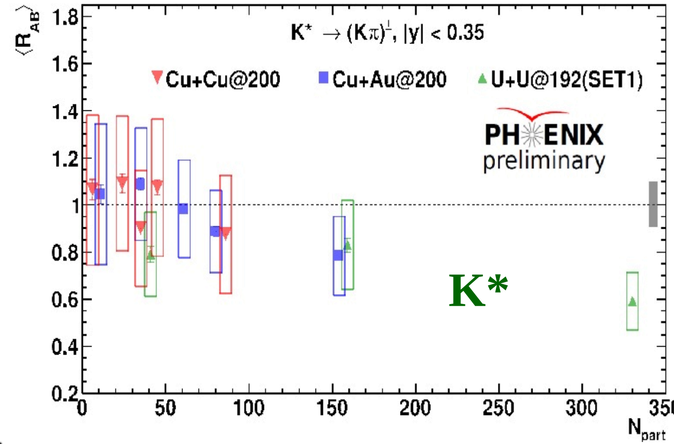
Universal high p_T suppression with N_{part} for light and strange quark mesons

Jet fragmentation not modified or modified equally

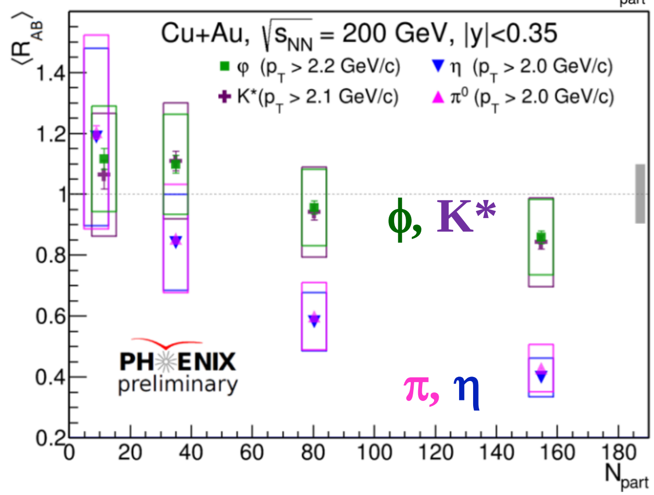
Meson Modification at Low p_T

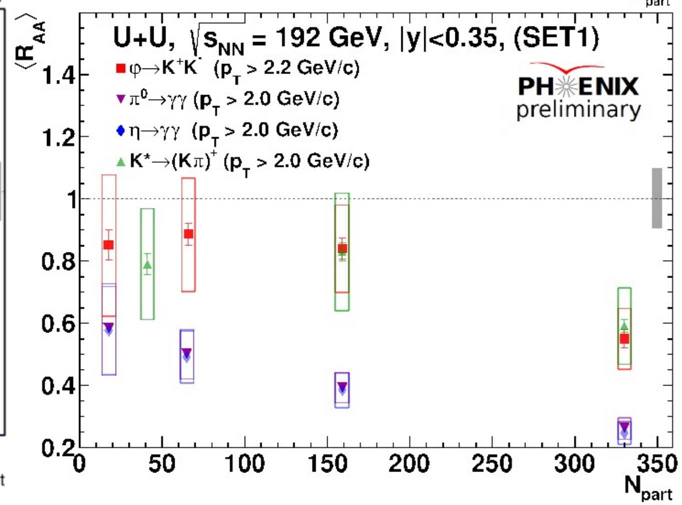
- **Collison System Dependence**
  - Cu+Cu to U+U
  - Common modification
  - with N_{part}





- **Mass dependence**
  - Cu+Au & U+U
  - K*, ϕ less modified than π, η

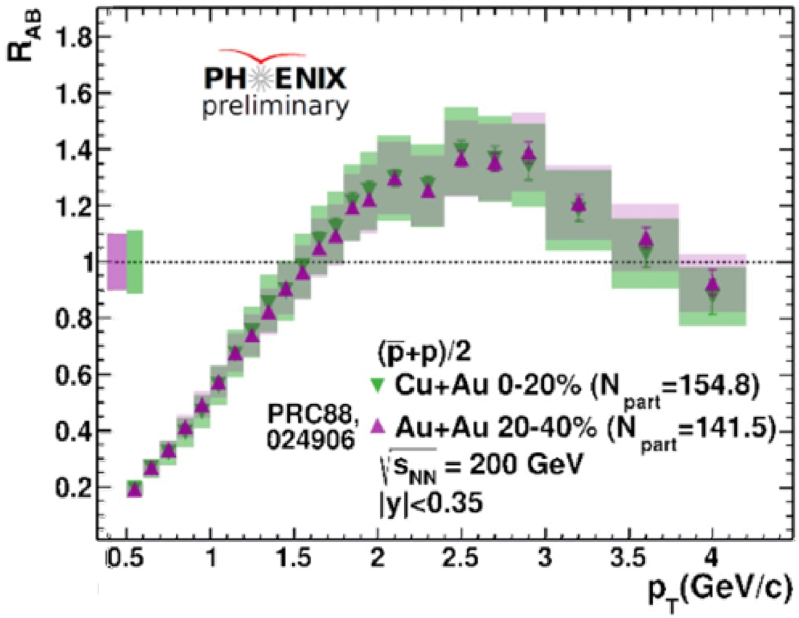


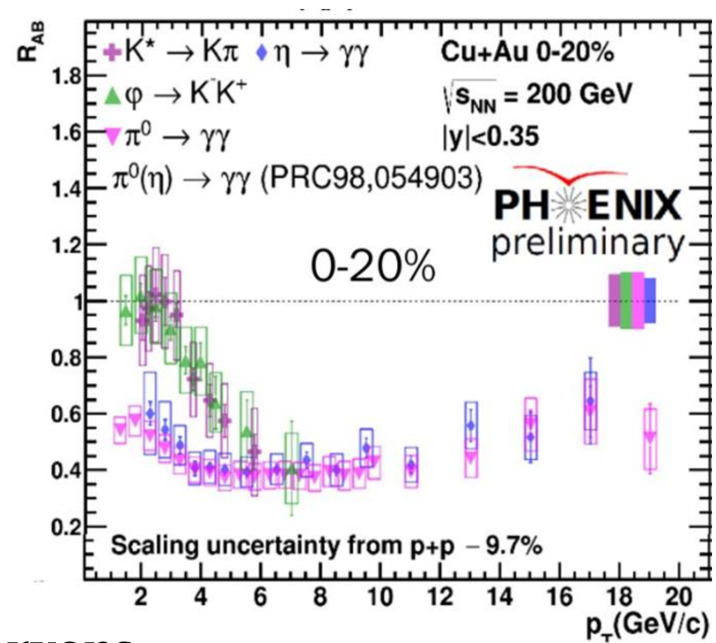


Low p_T R_{AA}: mass ordering and universal N_{part} dependence

Fireball dynamics and hadroniztion similar
Meson modification mass driven
Consistent with radial flow of hadrons

Low p_T R_{AA} Baryons vs Mesons





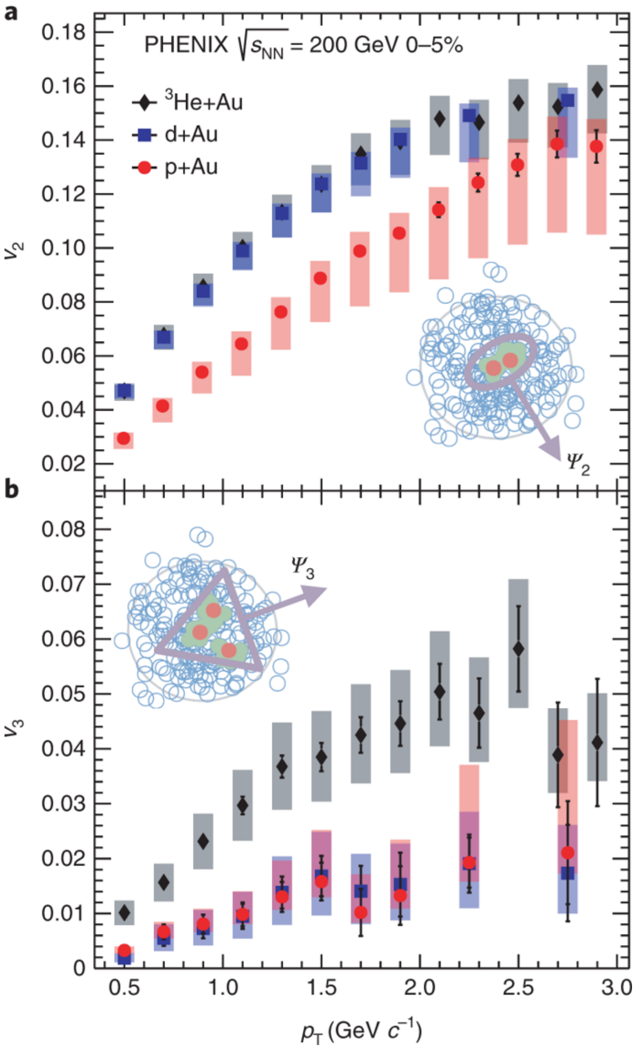
- **Common features of mesons and baryons**
  - **Universal trend with N_{part} independent of collision system**
  - **Peak in R_{AA} around 2 -3 GeV/c**
- **Differences between mesons and baryons**
  - **At same mass baryons ($p/\bar{p}$) are enhanced compare to mesons (K*, ϕ)**

Low p_T R_{AA} peak at 2-3 GeV/c for mesons and baryons

Mass not only factor in modification
Possibly consistent with partonic flow

Hadron Modification in Small Systems

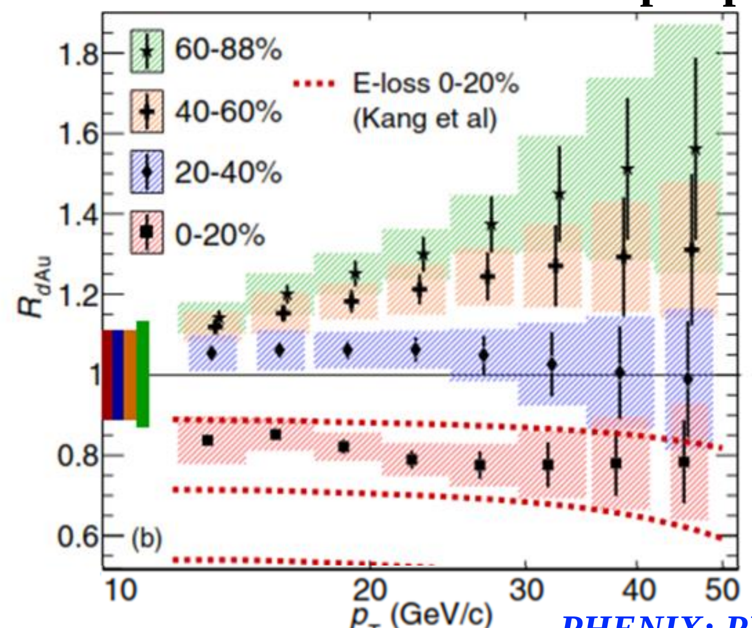
PHENIX: Nature Physics 15 (2019) 214



Anisotropy v_2,v_3 consistent with hydrodynamic expansion

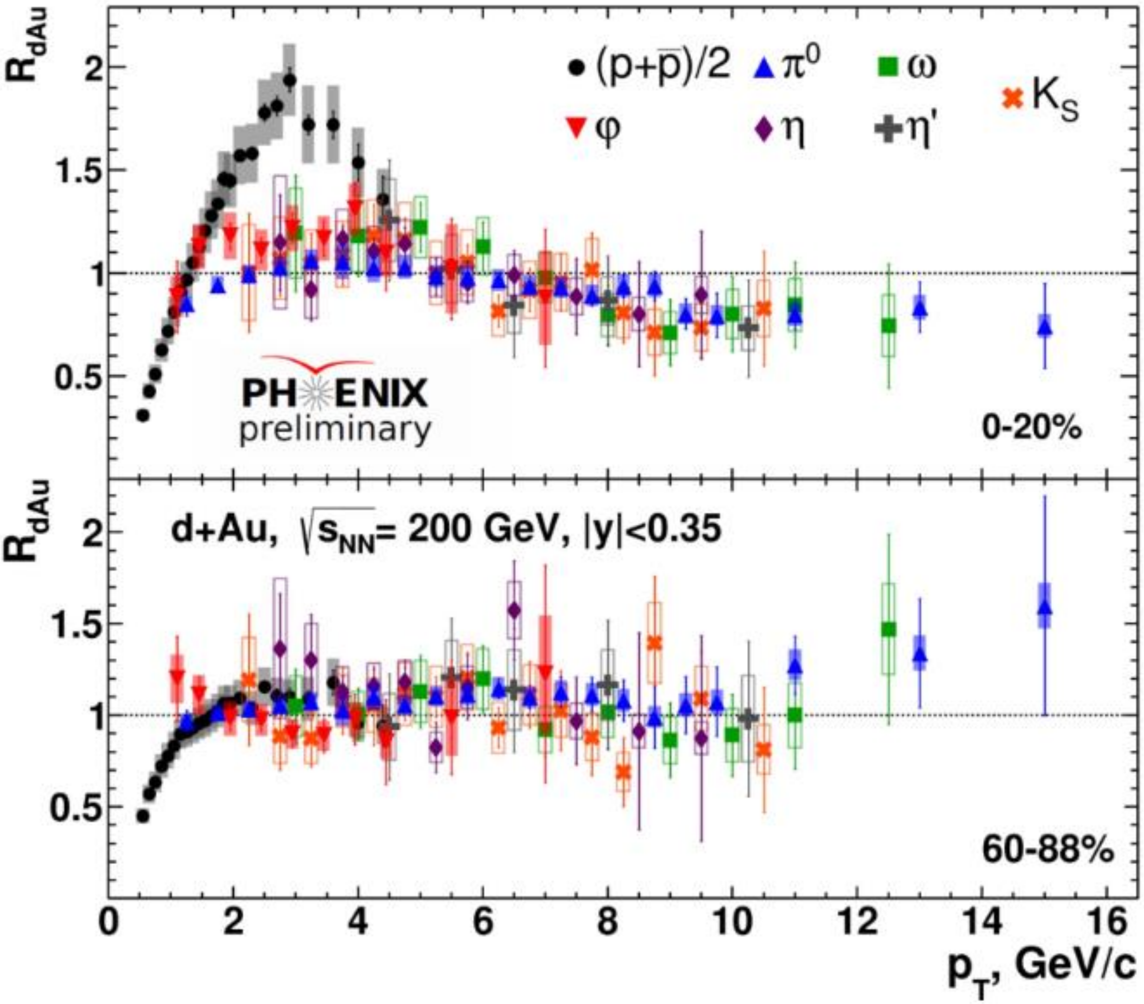
- **Small systems p+Au, d+Au, ^{3}He+Au**
  - **Benchmark for Cold Nuclear Matter effects**
- **Search for Hot Matter Effects**
  - **If v_2 , v_3 is evidence for hydronamic behavior there needs to be also radial flow!**
  - **Is jet modification in d+Au related to energy loss, or driven by proton size fluctuation etc. ?**

Jets suppressed in central, but enhanced in peripheral collisions.



PHENIX: PRL 116 (2016) 122301

Hardon Modification in d+Au Collisions



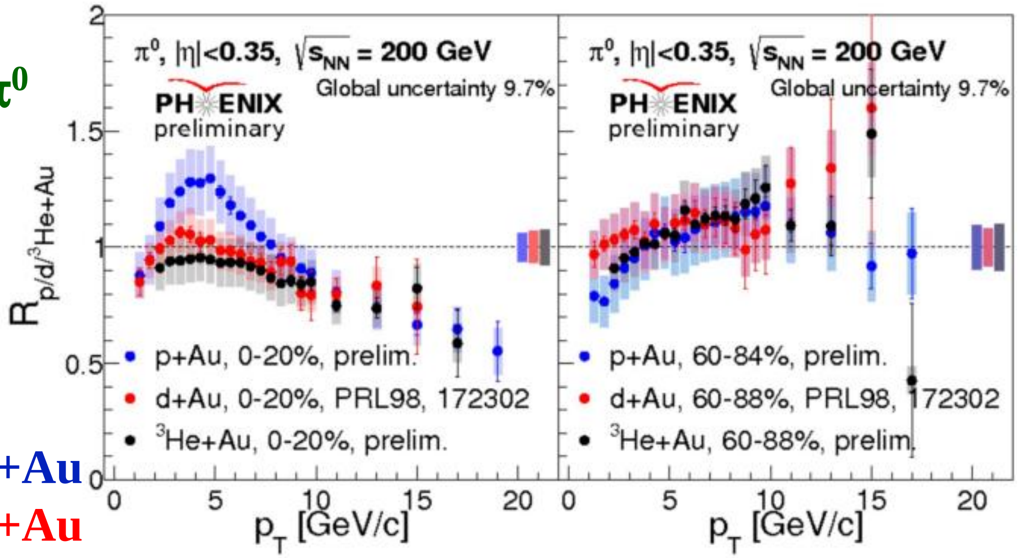
- **Mesons:**
  - **Similar shape over full p_T range for fixed centrality**
  - **For 0-20%**
    - **Cronin peak ~ 4 GeV/c**
    - **Suppression at high p_T**
  - **For 60-80%**
    - **Consistent with unity > 2 GeV/c**
- **Protons**
  - **For 0-20%**
    - **Cronin peak at ~ 3 GeV/c**
    - **Comparable to fix target exp.**
  - **For 60-80%**
    - **Consistent with mesons**

Hadron systematics different from heavy ion collisions

Meson Modification in Small Systems

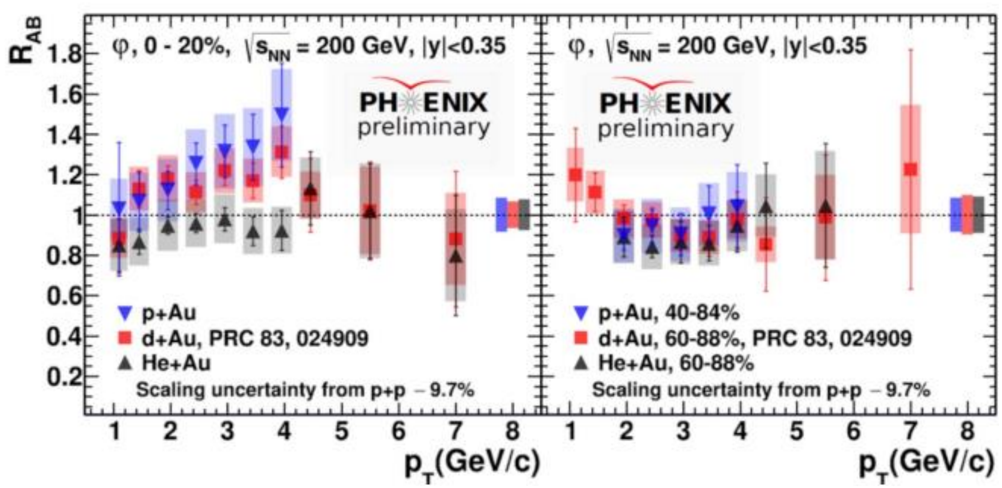
central peripheral

π^0



p+Au
d+Au
^{3}He+Au

ϕ



- **High p_T > 8 GeV/c**
  - $R_{pAu} \sim R_{dAu} \sim R_{HeAu}$
  - π^0 suppressed in 0-20%
  - π^0 enhanced in 60-80%
- **Low p_T < 6 GeV/c**
  - π^0 and ϕ similar R_{AB}
  - For 0-20%

    Cronin peak at ~4 GeV/c

    $R_{pAu} > R_{dAu} > R_{HeAu}$

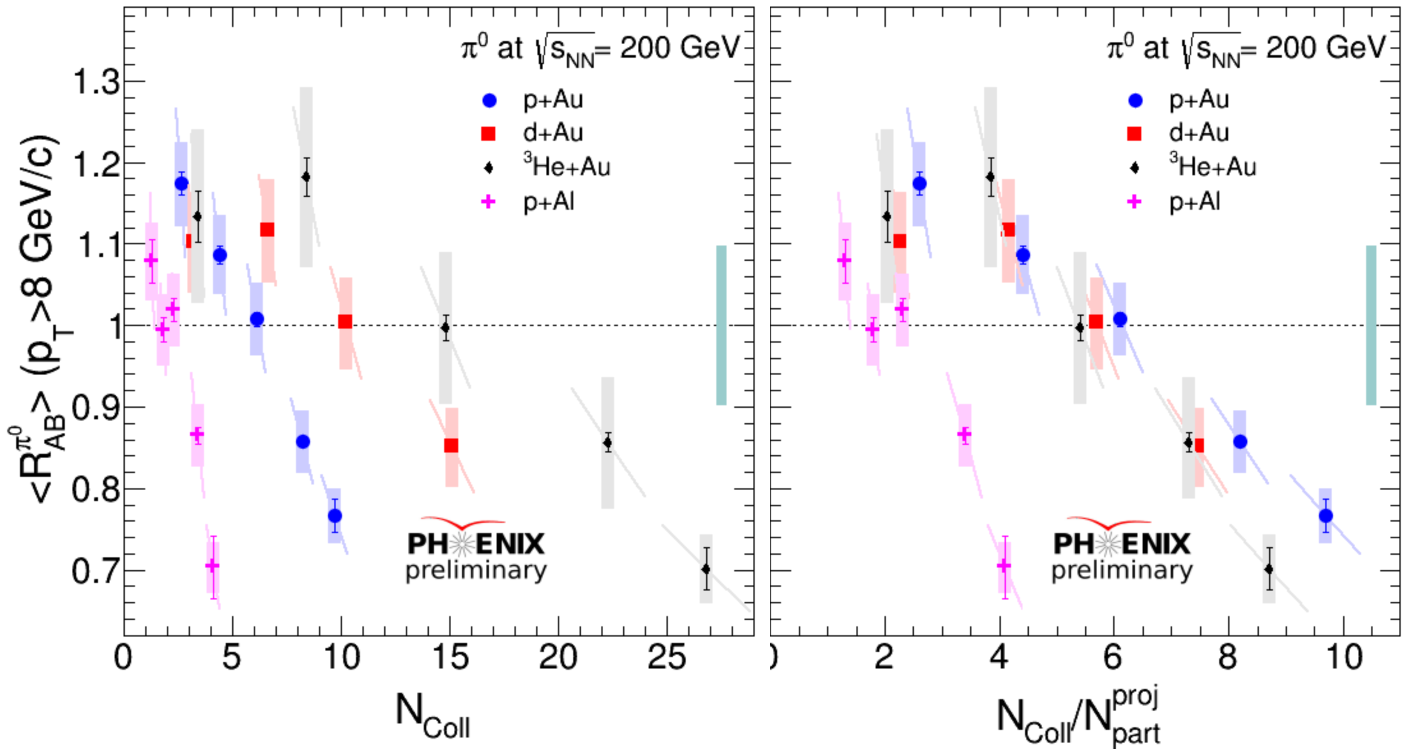
    Ordering with system size
  - For 60-80%

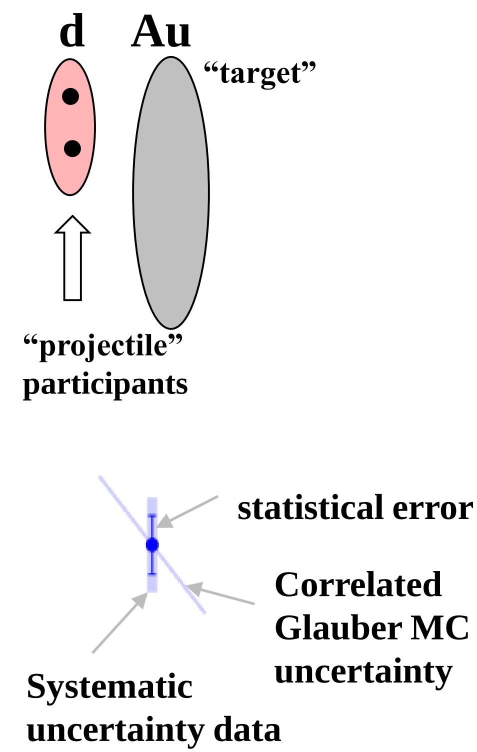
    $R_{pAu} \sim R_{dAu} \sim R_{HeAu}$

    Consistent with unity

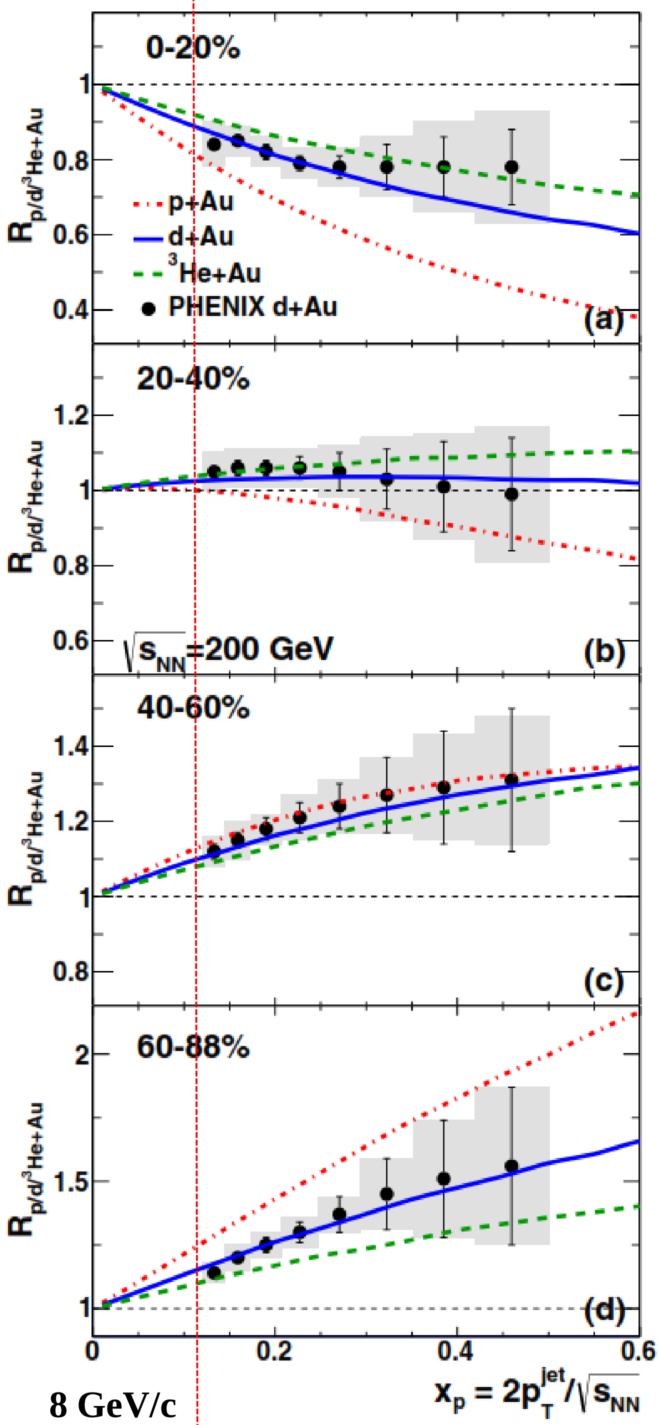
Meson systematics different from heavy ion collisions

High p_T π^0 Modification





- **Model independent conclusions for the mechanism for high p_T nuclear modification in small systems:**
  - **mostly independent interaction of each projectile**
  - **not driven thickness of matter traversed by projectile**



PHYSICAL REVIEW C **94**, 024915 (2016)

Consequences of high-x proton size fluctuations in small collision systems at $\sqrt{s_{NN}} = 200$ GeV

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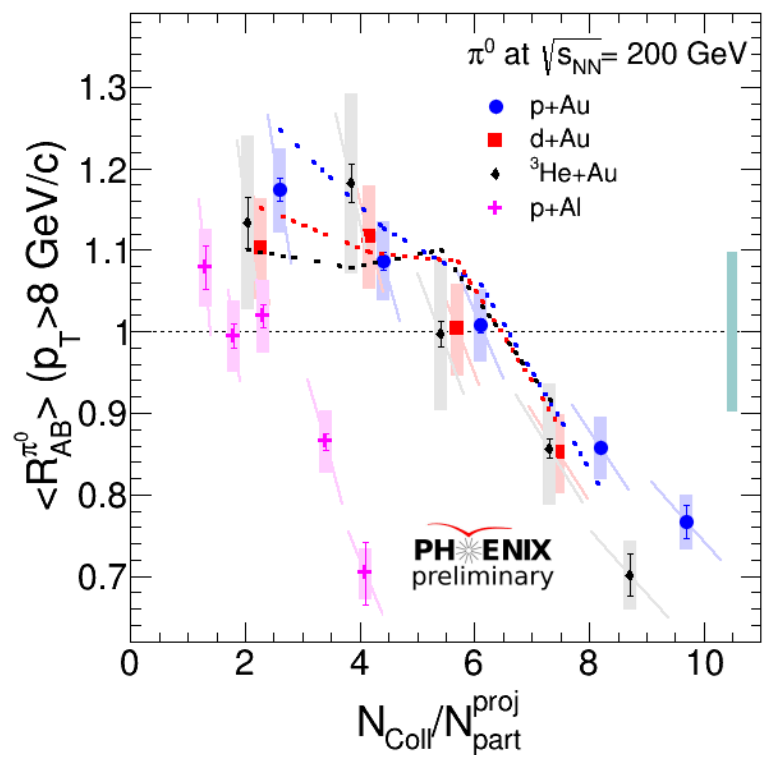
- $p_T(\pi^0) = 0.7\, p_T^{jet} = 0.7 \times 100\, GeV \times x_p$
- $\langle R_{AB} \rangle \approx R_{AB}(p_T)$
- N_{Coll}/N_{prat}^{proj} **from PHENIX Glauber**



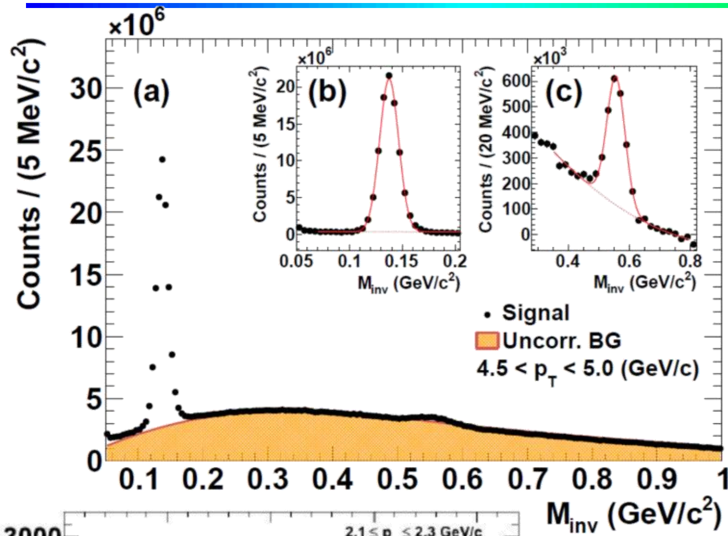
Centrality dependence of π^0 suppression consistent fluctuating proton size

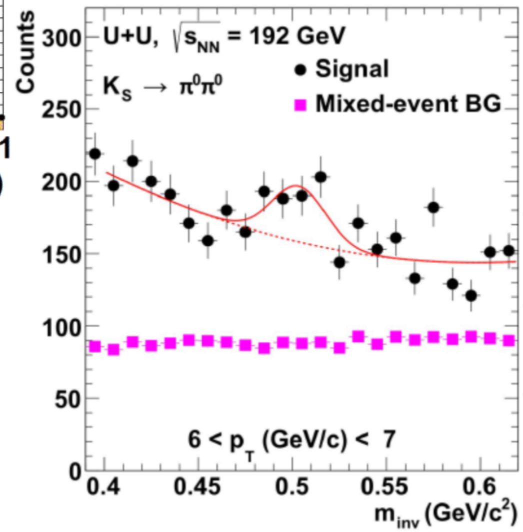
Summary

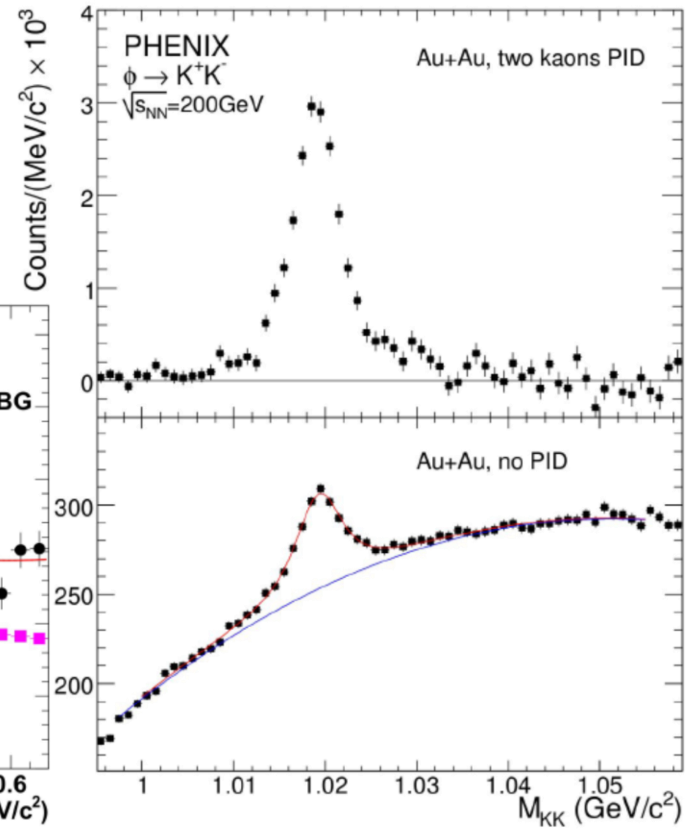
- **PHENIX R_{AA} for hadrons in Cu+Cu, Cu+Au, U+U, Au+Au at 200 GeV**
  - **Universal high p_T suppression with N_{part} for all measured hadrons**
    Jet fragmentation not modified or modified equally for mesons
  - **Low p_T meson R_{AA} exhibit mass ordering (small at low mass) and common N_{part} dependence**
    Similar fireball dynamics and hadroniztion
    Mass driven modification consistent with radial flow of hadrons
  - **Low p_T R_{AA} for proton larger than for similar mass mesons (ϕ, K*)**
    Mass not only factor in modification, possibly indicating partonic flow
- **Hadron modification in small systems: p+Al, p+Au, d+Au, ^{3}He+Au**
  - **Peripheral collisions: hadron R_{AB} consistent with unity for p_T > 2 GeV/c**
    No evidence of nuclear modification
  - **Central collisions:**
    Cronin peak ~ 4 GeV/c, system ordering $R_{pAu} > R_{dAu} > R_{HeAu}$, larger for baryons
    Connection to radial flow? No evident …
    Suppression for p_T >8 GeV, independent for each projectile, not driven by target thickness
    Connection to energy loss? Not easy to see ..

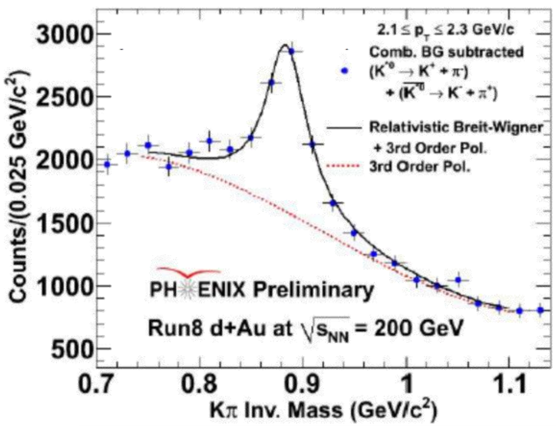
Backup Slides

Meson Extraction From Heavy Ion Collisions





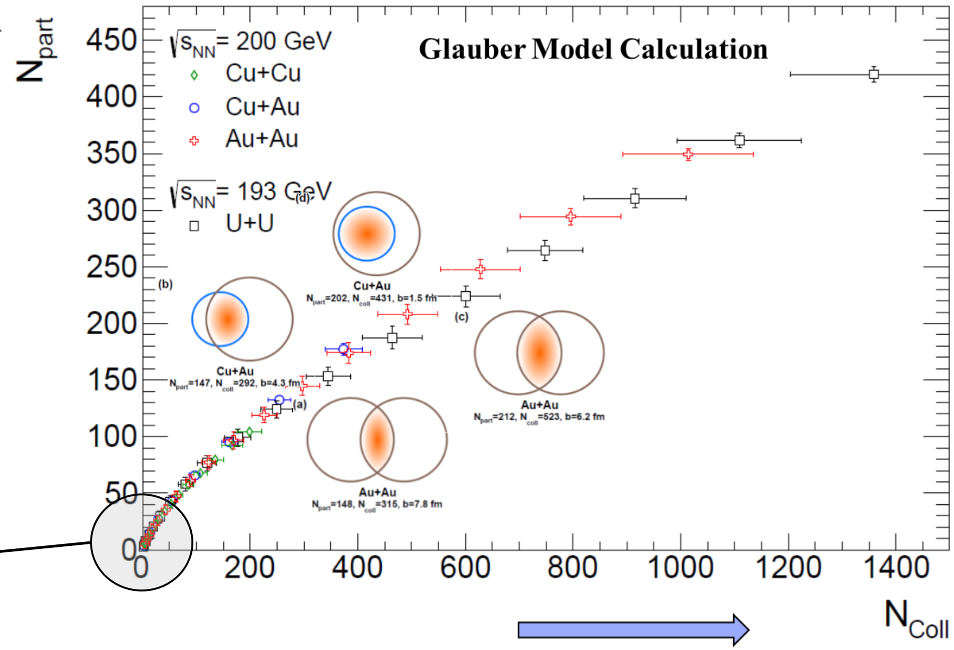




	π^0	η	K_s^0	ω	K^*	$p(\overline{p})$	ϕ
Mass [MeV/c²]	135	548	498	782	892	938	1019
Quark content	$u\bar{u}\|\|d\bar{d}$	$\frac{1}{6}(u\bar{u}+d\bar{d}-2s\bar{s})$	$\frac{1}{\sqrt{2}}(d\bar{s}+s\bar{d})$	$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$	$d\bar{s}$	$uud(\bar{u}\bar{u}\bar{d})$	$s\bar{s}$
Lifetime [fm/c]	2.5 10^7	1.6 10^5	2.7 10^{13}	23	4.16	stable	46

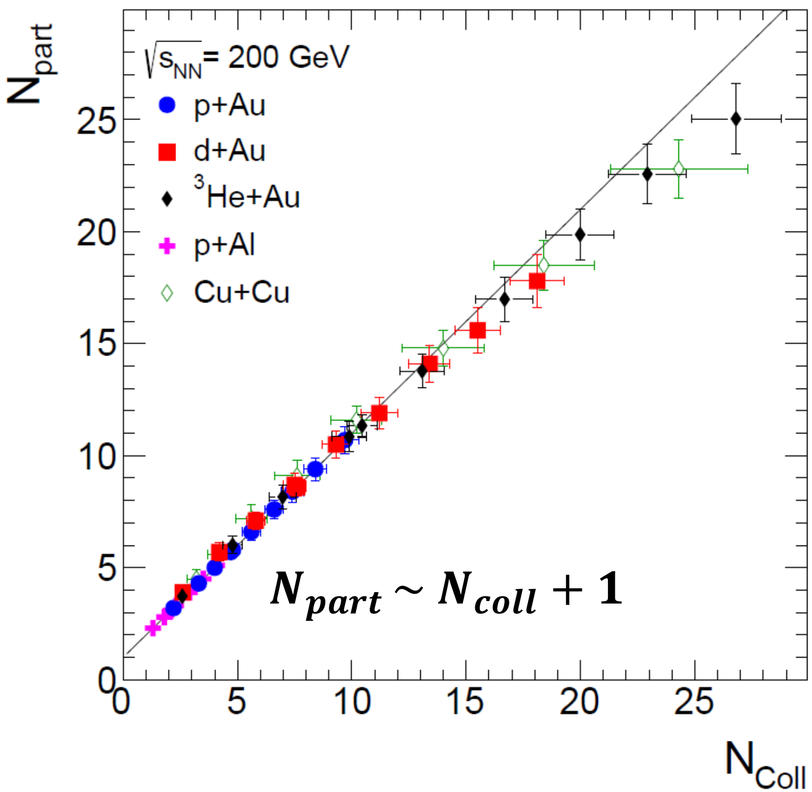
Comparing Different Small Systems

Soft particle production:
Reaction Volume
$N_{part} \sim V$



Hard Scattering Probability

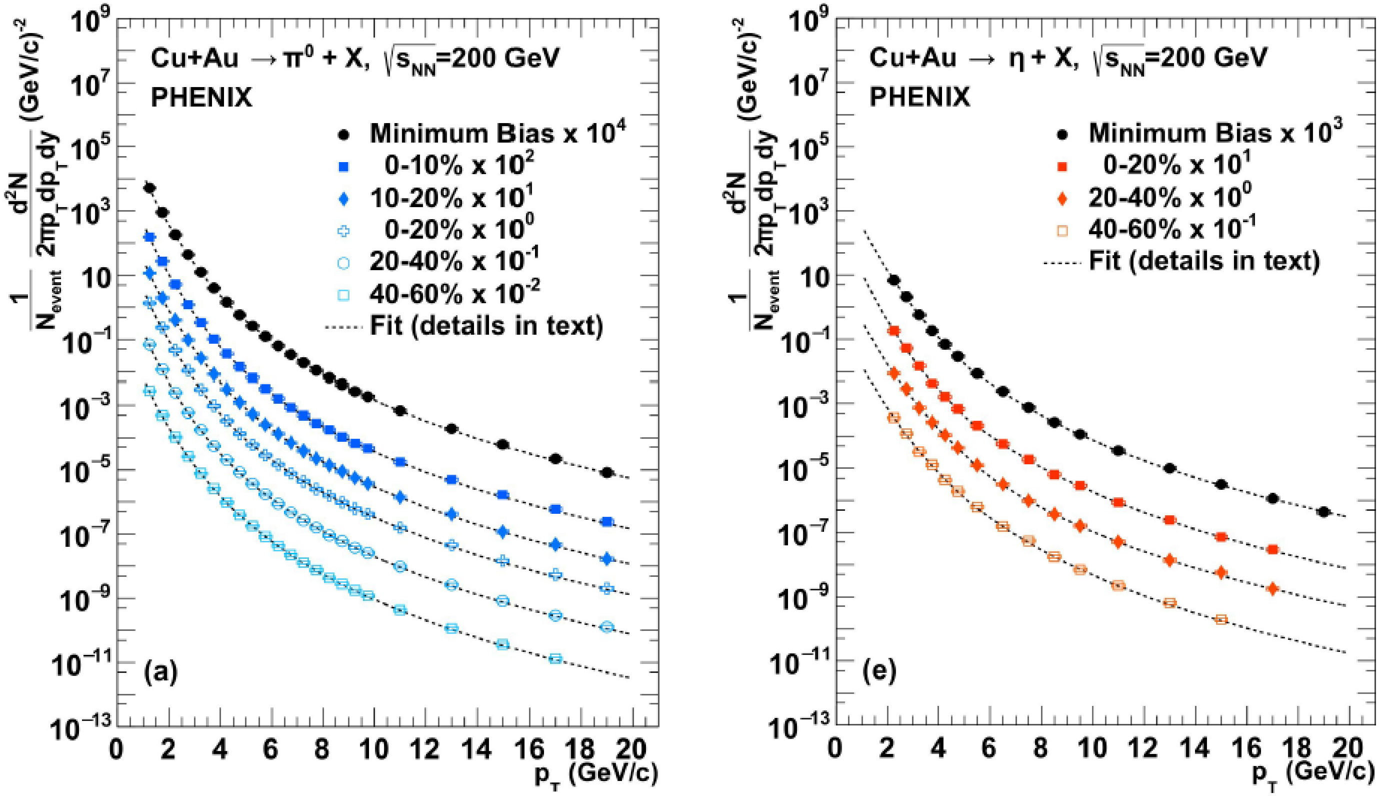
$N_{coll} \sim \sigma_{hard}$



N_{part} and N_{coll} dependence expected to be similar

Meson Production in Cu+Au at 200 GeV

PHENIX: Phys. Rev. C98 (2018) 054903



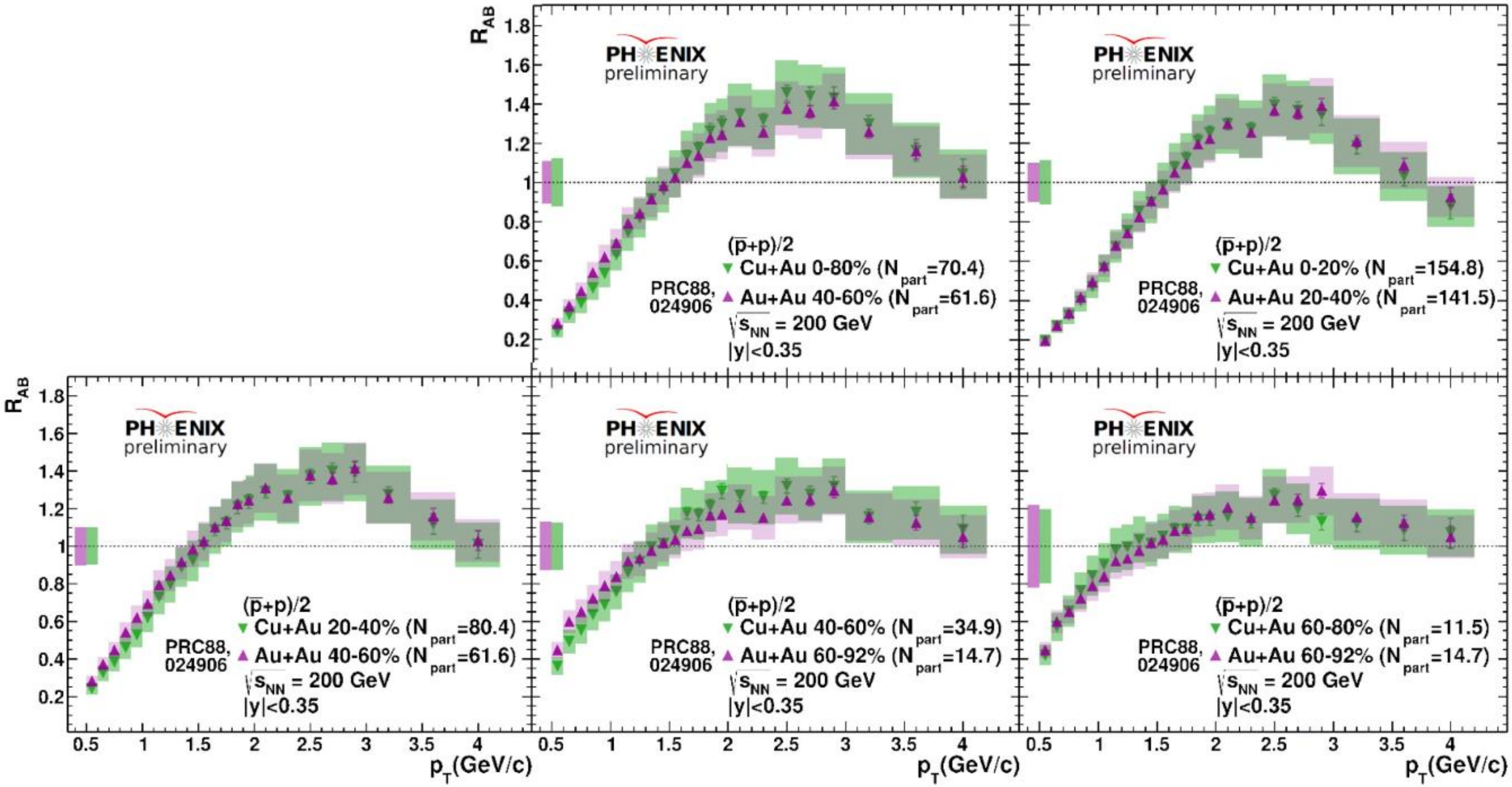
π^0 invariant yield

η invariant yield

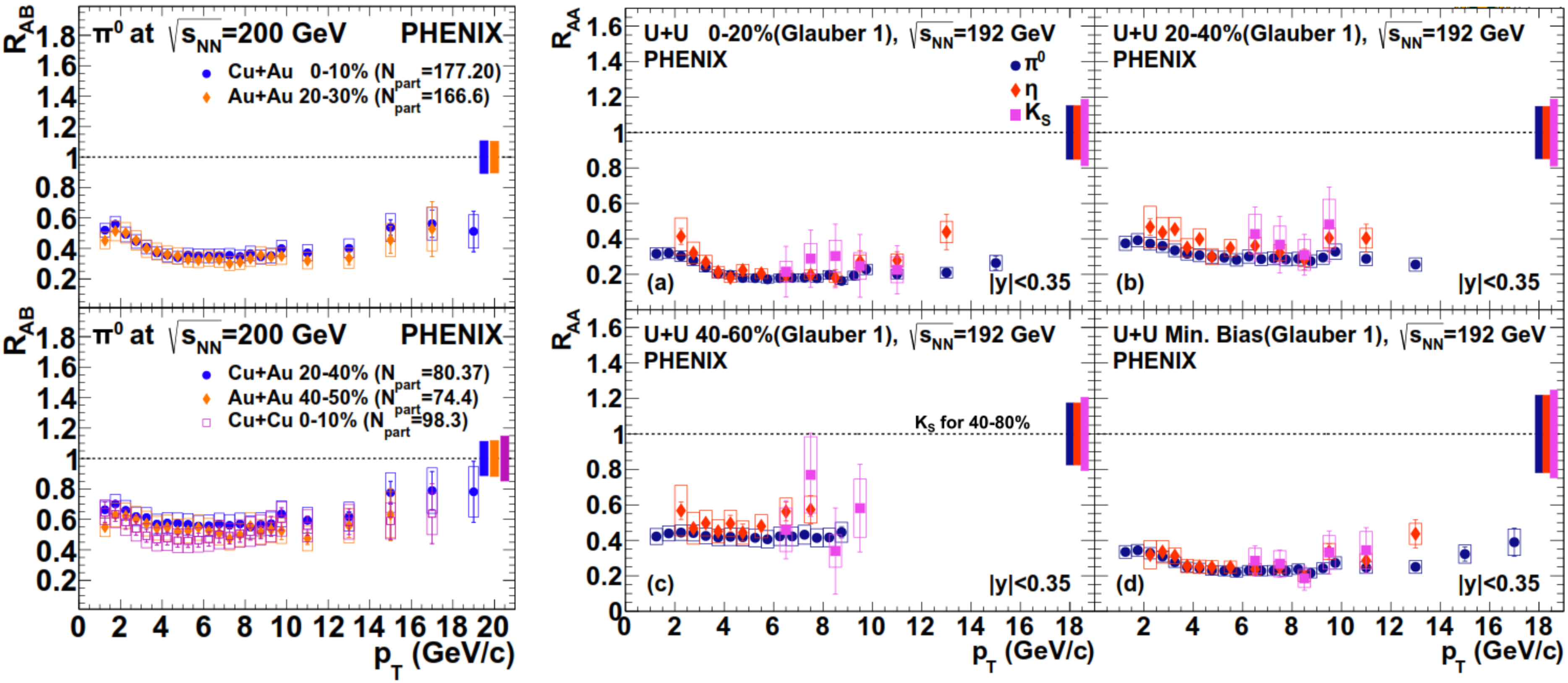
Compare to p+p and different centrality selections using nuclear modification factor:

$$R_{AB}(p_T, N_{part}) = \frac{\left(\frac{d^2N}{dp_t}\right)_{AB}}{N_{coll}\left(\frac{d^2N}{dp_t}\right)_{pp}}$$

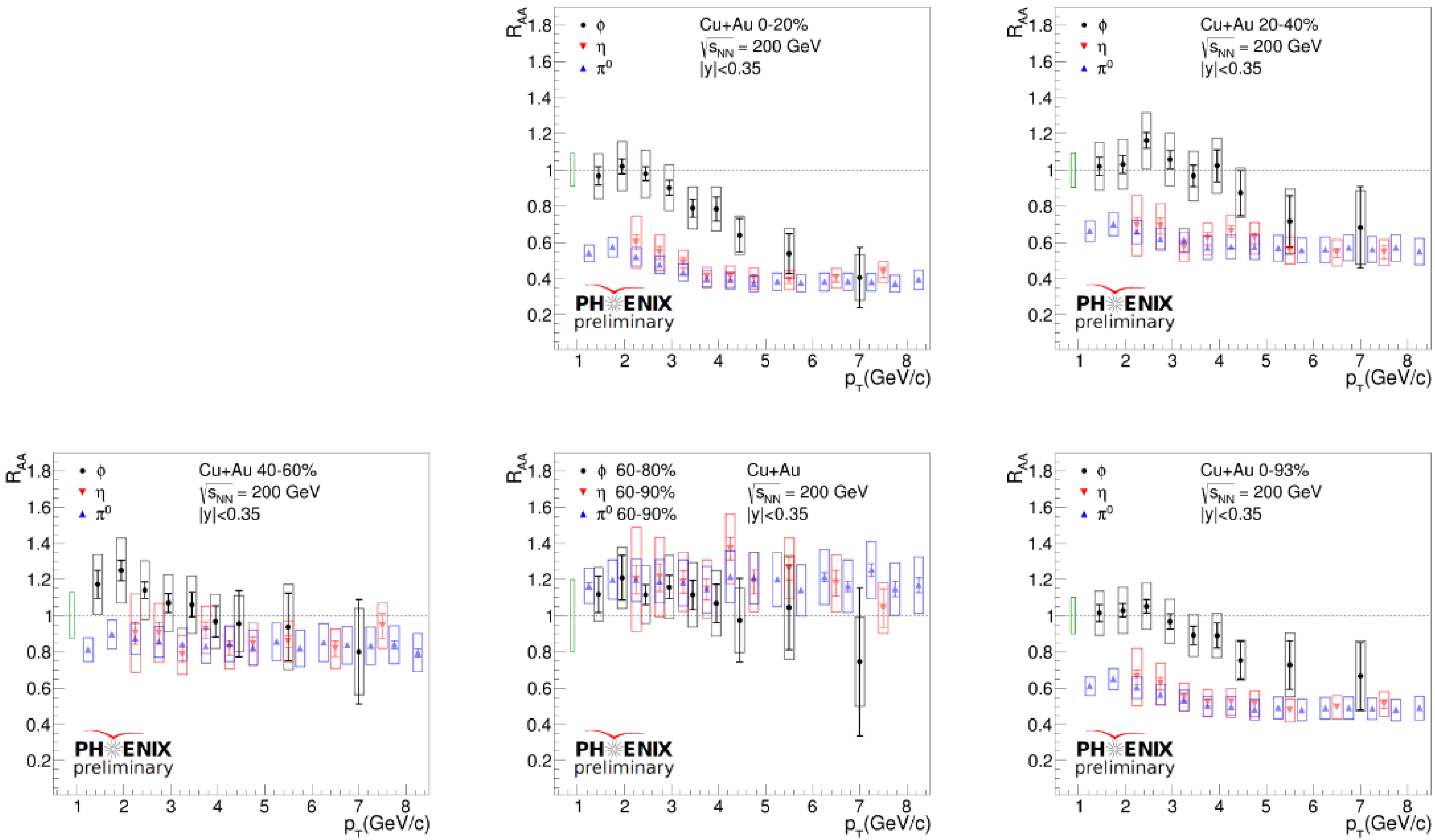
Full Centrality Dependence of Proton R_{AA}



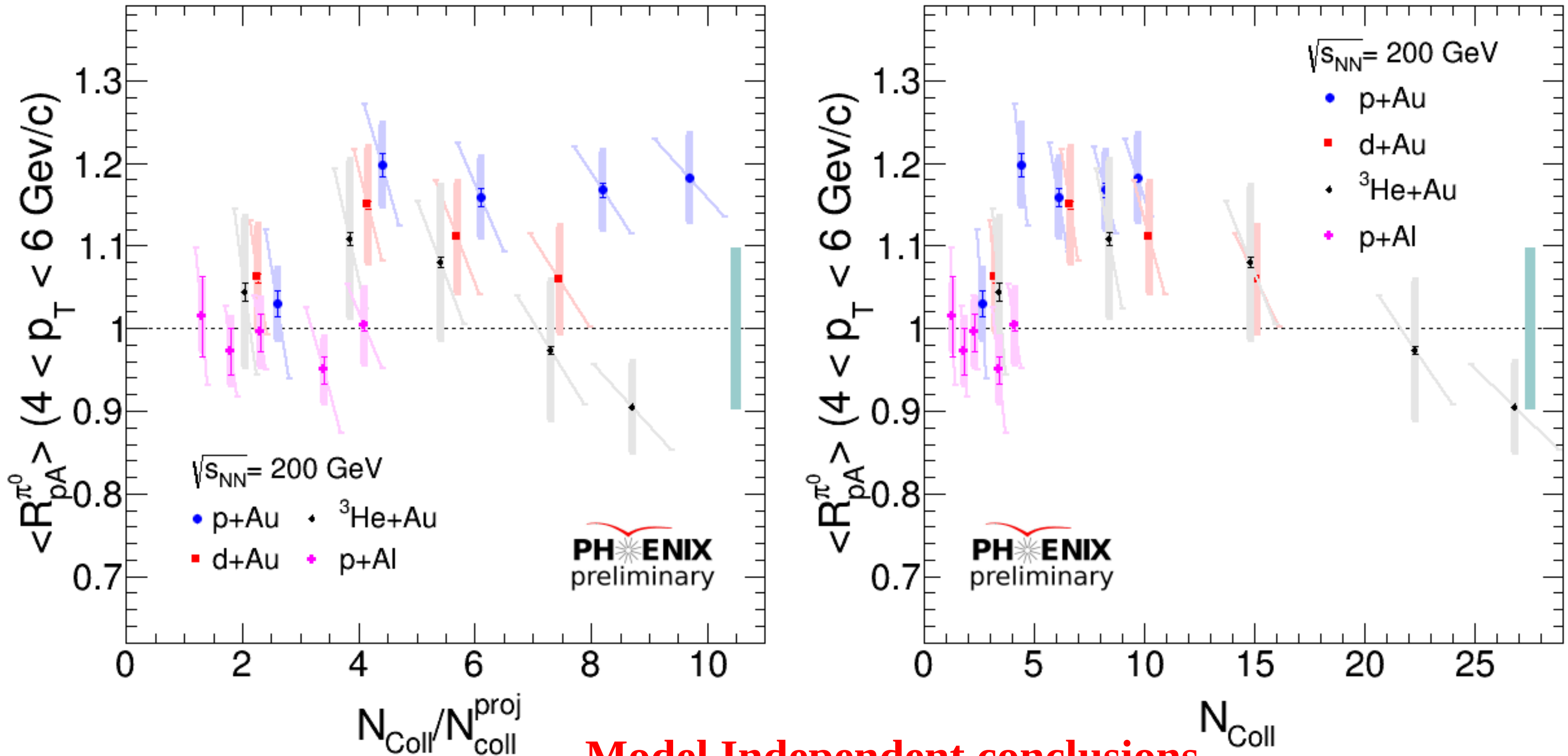
N_{part} Dependence of Hadron R_{AA}



N_{part} Dependence of Hadron R_{AA}



Small System Low p_T <R_{AA}>



Model Independent conclusions
The mechanism of nuclear modification:

(i) Different mechanism at high/low p_T
(ii) Driven by thickness of traversed material at low p_T
(iii) Transition between 5-7 GeV/c