Heavy Flavor at RHIC

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PHENIX Collaboration

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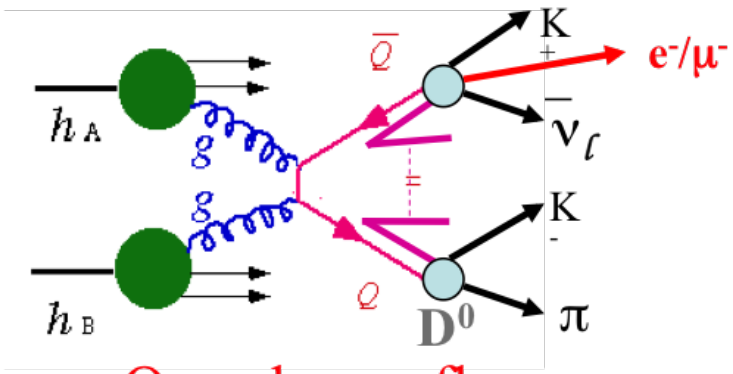
New RHIC results on heavy flavor

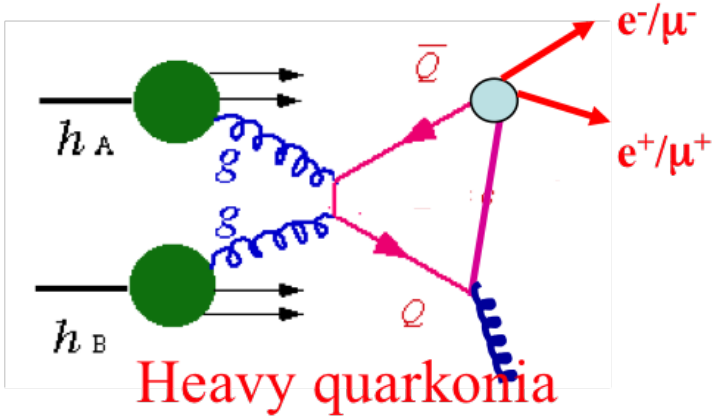
- Open Heavy Flavor
  - Heavy flavor decay electron spectra and anisotropy in 62.4 GeV collisions- *arXiv:1405.3301*.
  - Precise bottom cross section measurement via e^+e^- pairs - *arXiv:1405.4004*.
  - Heavy flavor $e-\mu$ correlations in p + p and d + Au collisions- *Phys. Rev. C 89, 034915 (2014)*.
  - System-size dependence of open-heavy-flavor production in nucleus-nucleus collisions at $\sqrt{s_{NN}}$ =200 GeV - *arXiv:1310.8286*.
  - Observation of D^0 meson nuclear modifications in Au + Au collisions at $\sqrt{s_{NN}}$ =200GeV- *arXiv:1404.6185*.
- Quarkonia
  - Nuclear matter effects on J/ψ production in asymmetric $Cu + Au$ collisions at $\sqrt{s_{NN}}$ =200GeV - *arXiv:1404.1873*.
  - Measurement of the Upsilon cross section in p + p and implications to the nuclear modification factor in Au + Au at $\sqrt{s_{NN}}$ = 200 GeV- *arXiv:1404.2246*.
  - Nuclear modification of ψ', χ_c and J/ψ production in d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV *-PRL 111 202301 (2013)*.
  - Suppression of Υ production in d + Au and Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV- *arXiv:1312.3675*.
  - J/ψ production at low p_T in Au + Au and $Cu + Cu$ collisions at $\sqrt{s_{NN}}$ =200 GeV at STAR- *arXiv:1310.3563*.

Why heavy quarks ....

- Natural probes to study the hot matter created in heavy-ion collisions:
  - large mass ($m_q >> \Lambda_{QCD}$)$\longrightarrow$ produced in the intial stages of HI collisions.
  - short formation time ($t_{charm} \sim 1/m_c \sim 0.1 fm/s << \tau_{QGP} \sim O(10 fm/c)$).
  - cannot be destroyed/created in the medium, traverse the full system evolution.
- Energy loss in the medium by
  - medium-induced gluon radiation.
  - collisions with medium constituents.
  - expected energy loss: $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$.
- Studied via semi-leptonic decay modes of B/D mesons or directly reconstucting B/D, or as bound quarkonia states.
- Au + Au, $Cu + Cu$, $U + U$ collisons to study medium effects.
- p + p as a baseline.
- d + Au to look into the intial state effects.



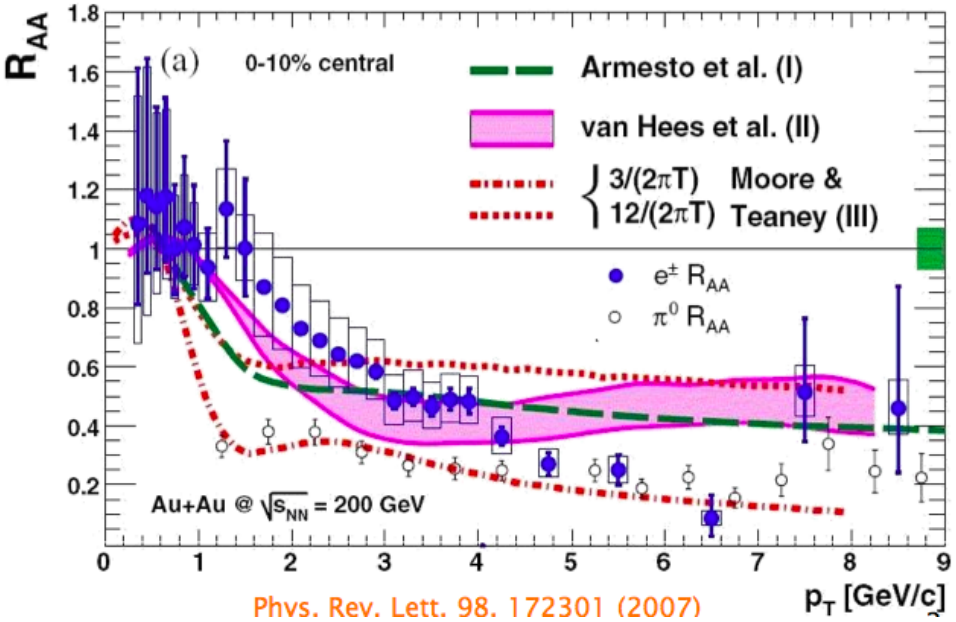
Open heavy flavor



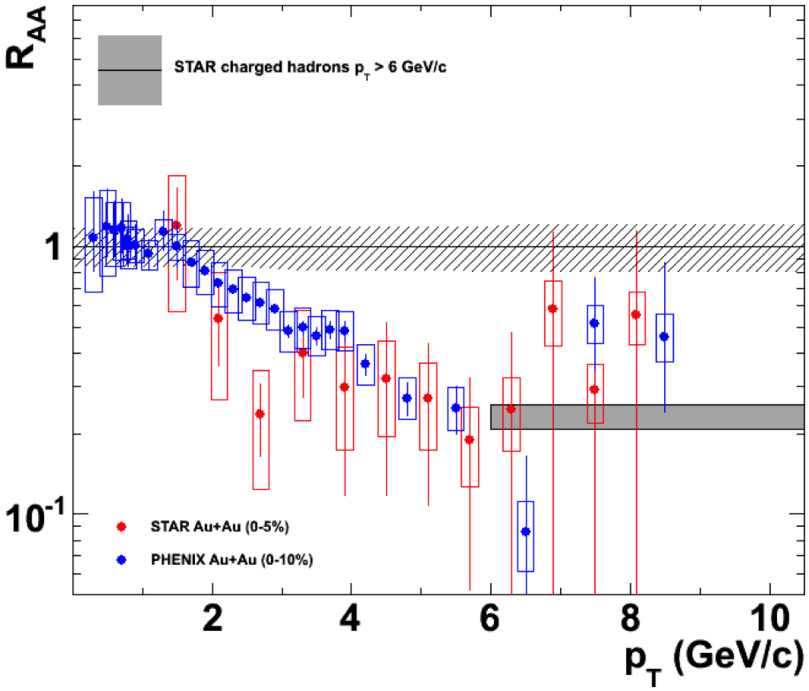
Heavy quarkonia

RHIC results on open heavy flavor electrons in Au + Au

PHENIX (2007)



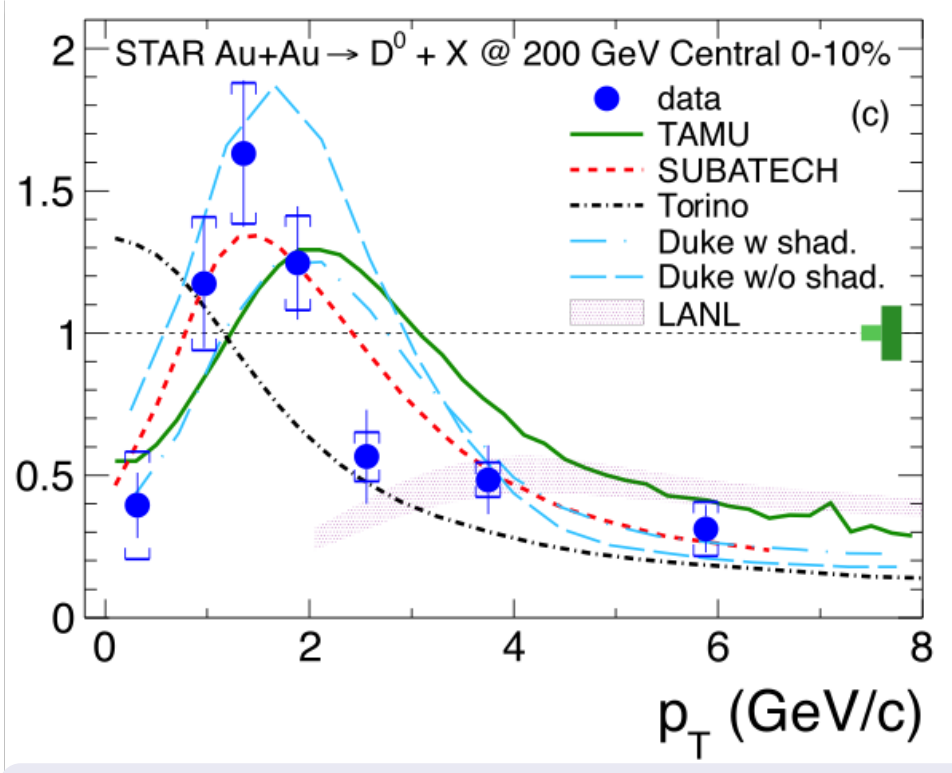
STAR (2011)



- One of the surprising results from RHIC was the large suppression of high p_T heavy flavor electrons.
- Energy loss models alone could not explain the data.
- One needs more differential measurements to understand these results.

D^0 R_{AA} *in* Au + Au *and* $U + U$

arXiv:1404.6185



$U + U$

- Suppression at high p_T, Enhancement at intermediate p_T.

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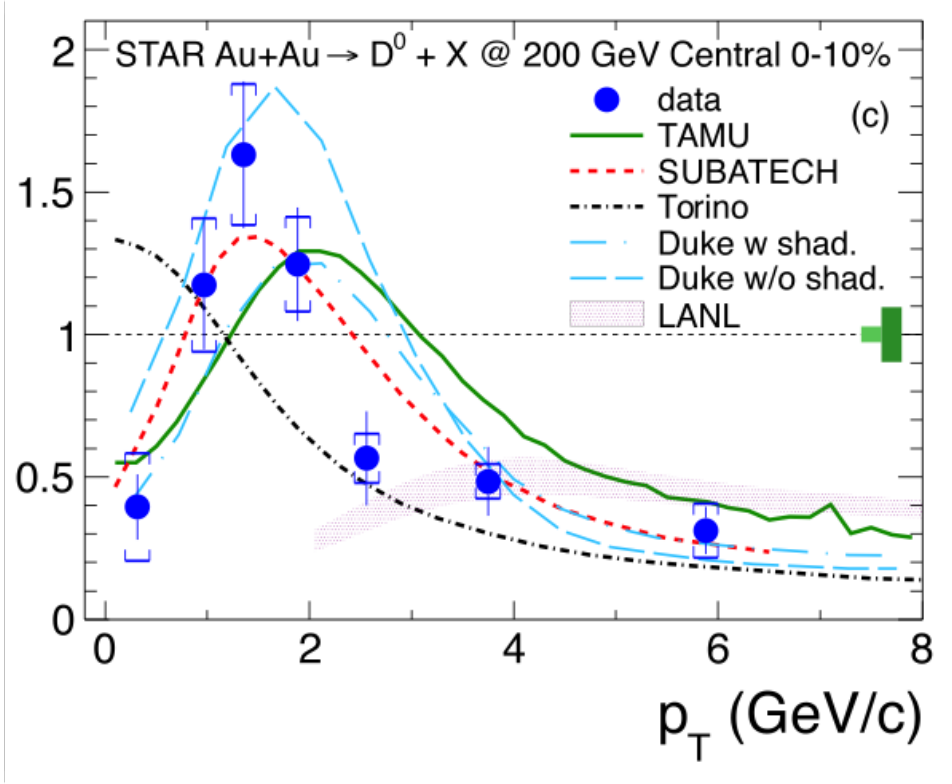
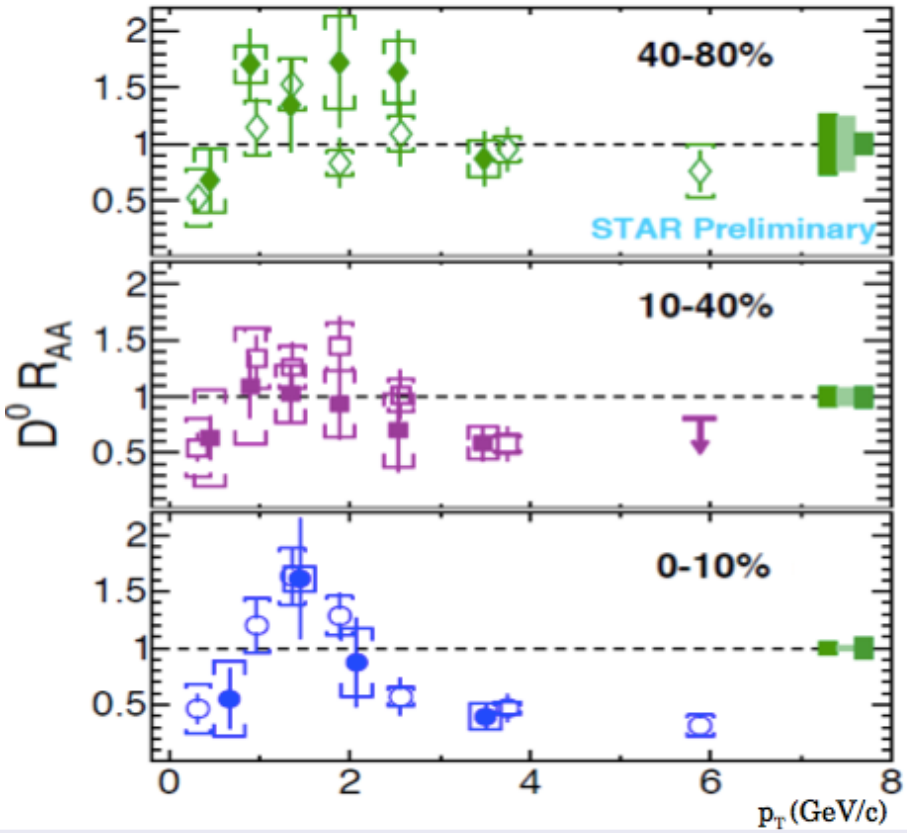


$U + U$

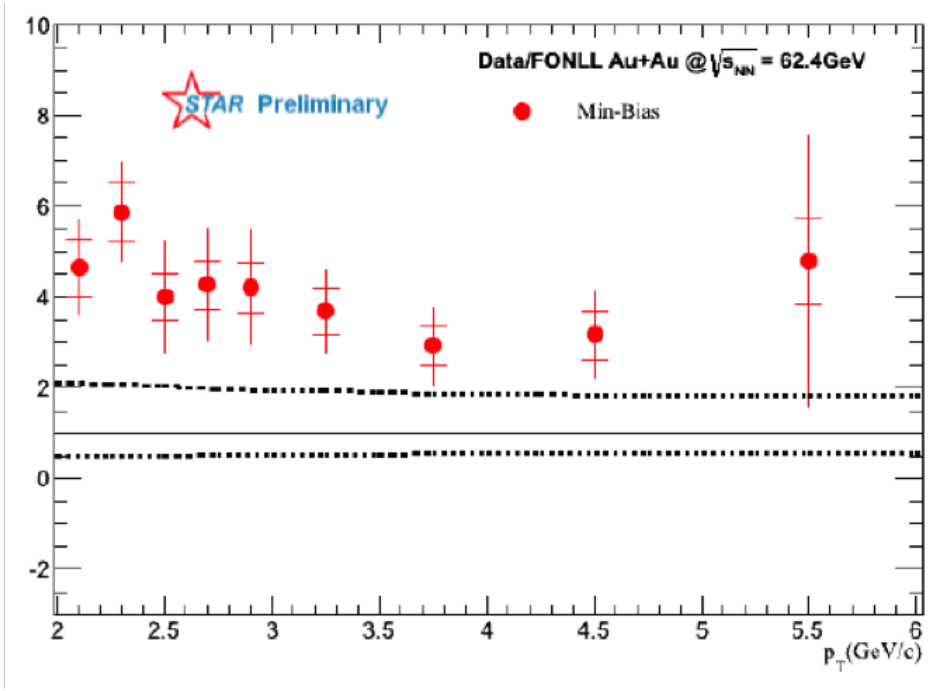


- Suppression at high p_T, Enhancement at intermediate p_T.

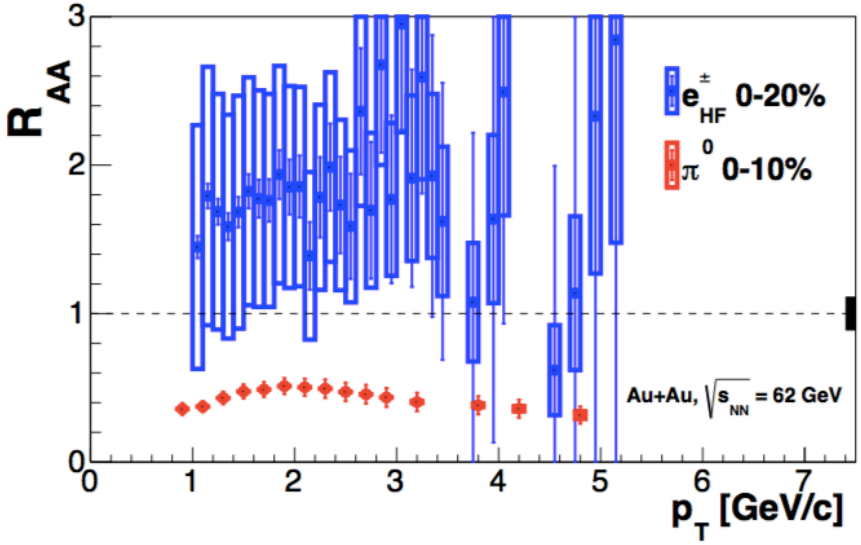
- Similar suppression seen for the high p_T charm in $U + U$ collisions. hadronization.
- Need data for the CNM effects.

Results from 62 GeV Au + Au

STAR

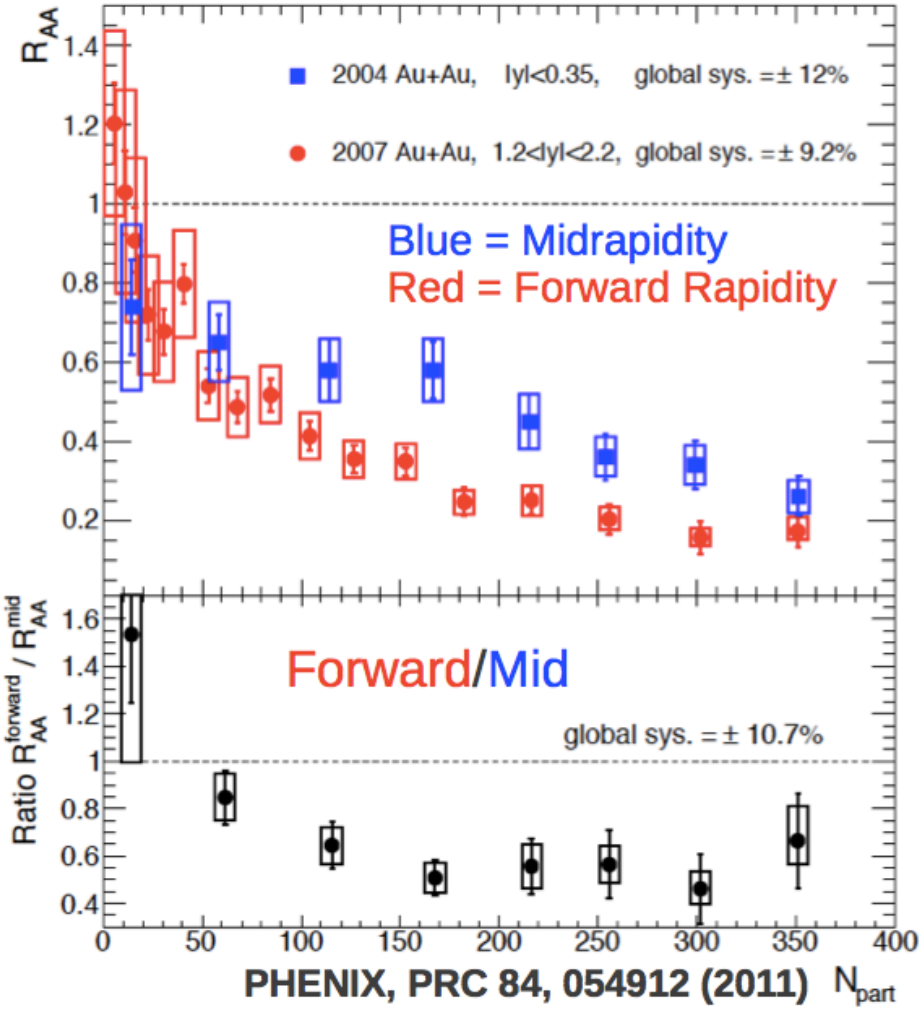


PHENIX arXiv:1405.3301



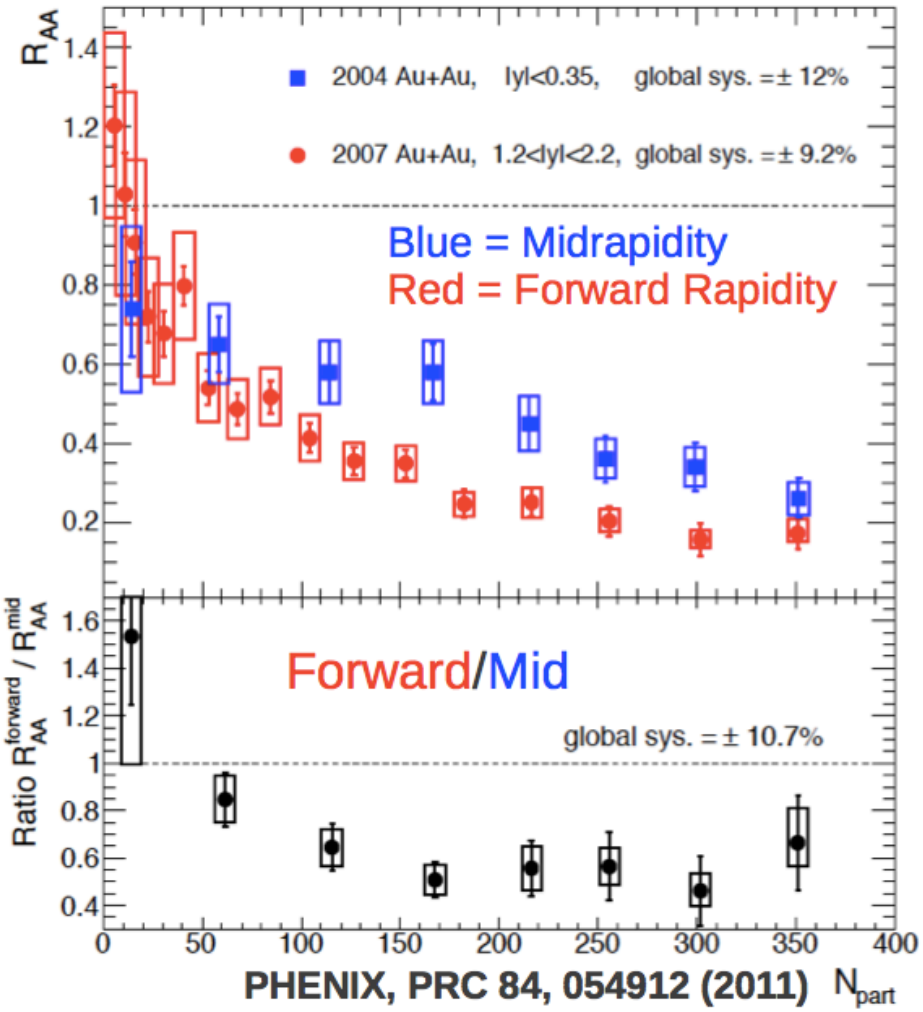
- Maybe not the same story in 62 GeV. p + p reference in PHENIX plot comes from ISR.
- Need p + p data at 62 GeV.

J/ψ *in* Au + Au— *mid vs forward rapidity*



PHENIX, PRC 84, 054912 (2011)

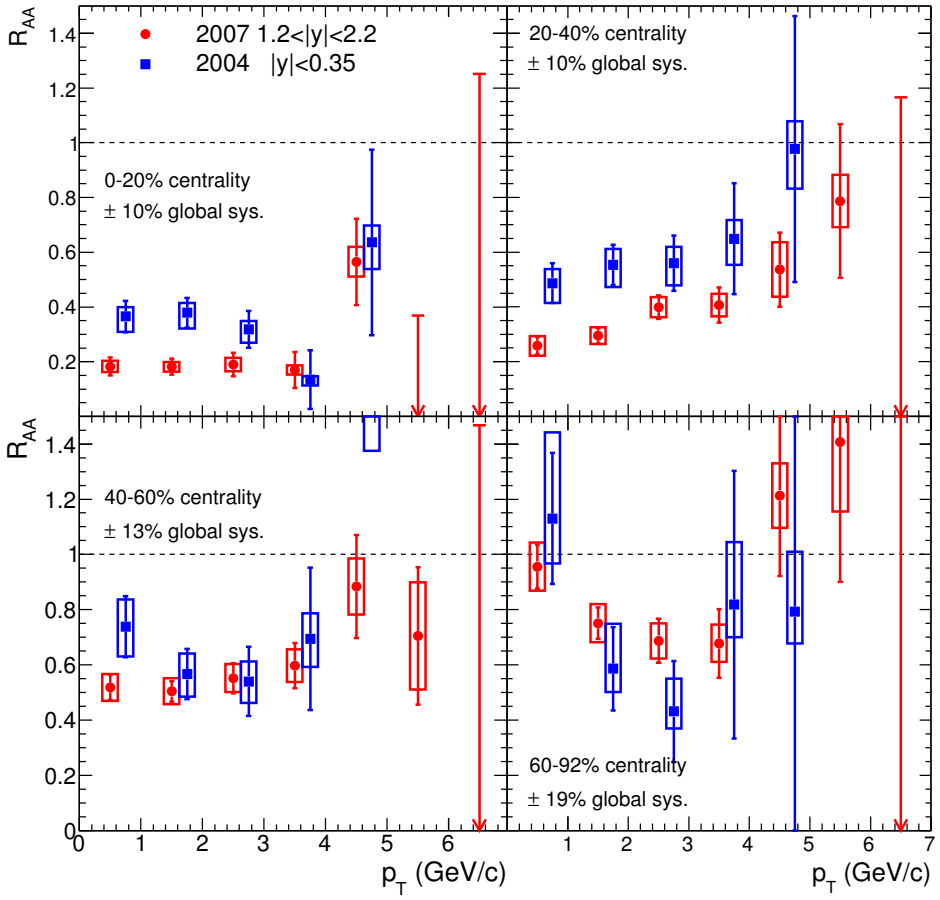
J/ψ *in* Au + Au— *mid vs forward rapidity*



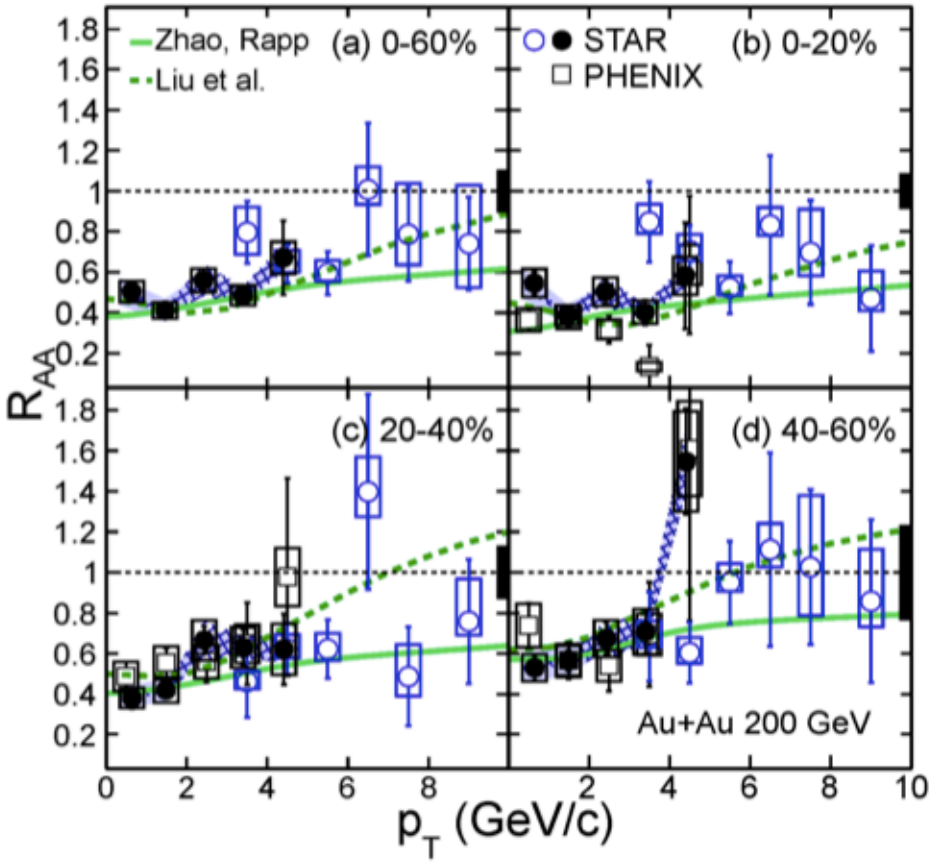
- Color screening model expectation, R_{AA}(mid)< R_{AA}(forward).
- Clearly data suggests something different.

J/ψ R_{AA} as a function of p_T

PHENIX PRC 84, 054912 (2011)



STAR:arXiv:1310.3563



- R_{AA} (forward) $<$ R_{AA} (mid).
- Increases from low p_T to high p_T.

J/ψ R_{AA} as a function of p_T

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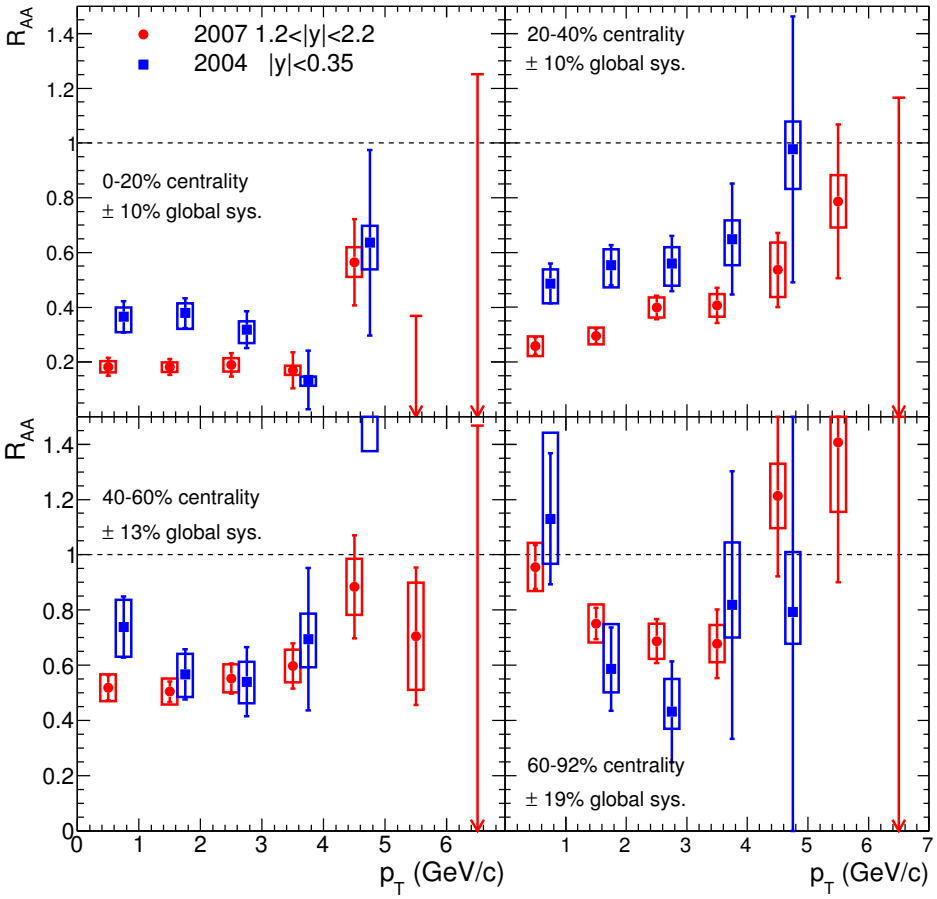

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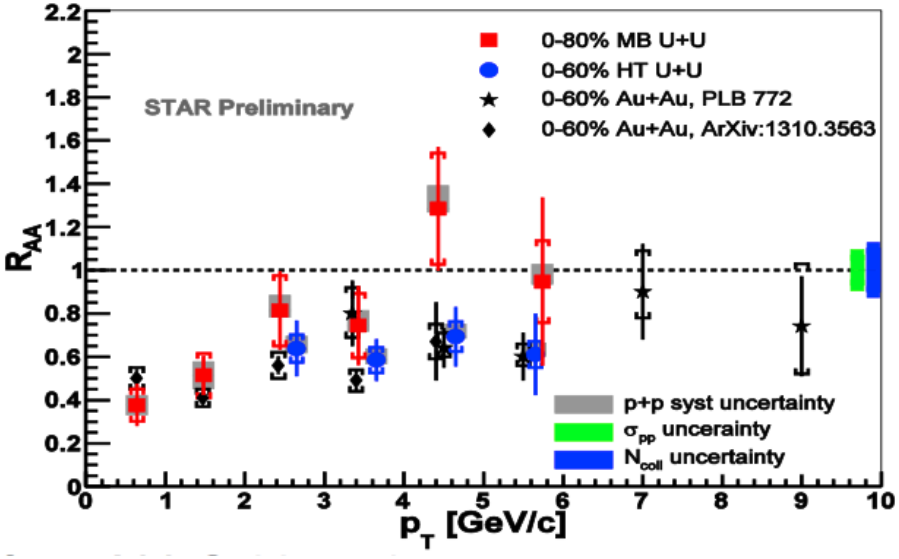
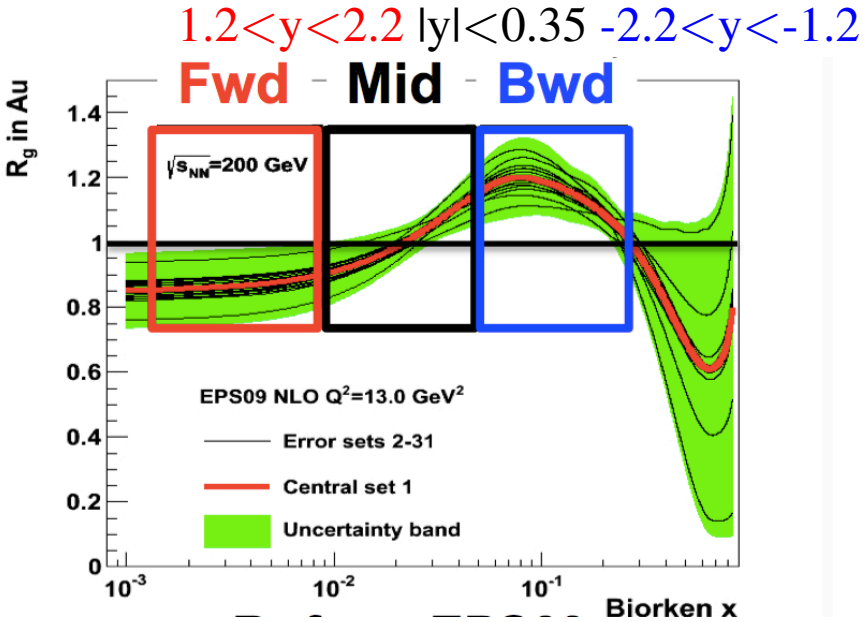


- R_{AA} (forward) $<$ R_{AA} (mid).
- Increases from low p_T to high p_T.
- Similar pattern for $U + U$ collisions.

Cold nuclear matter effects

Some of the CNM effects being studied are:

- Modification of nuclear PDF's
  - Shadowing, Antishadowing, Saturation etc



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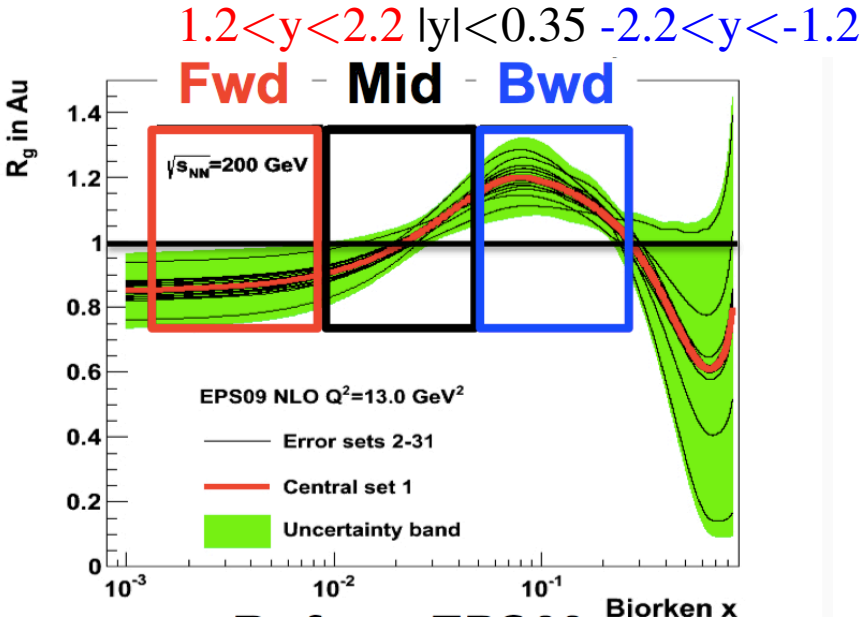
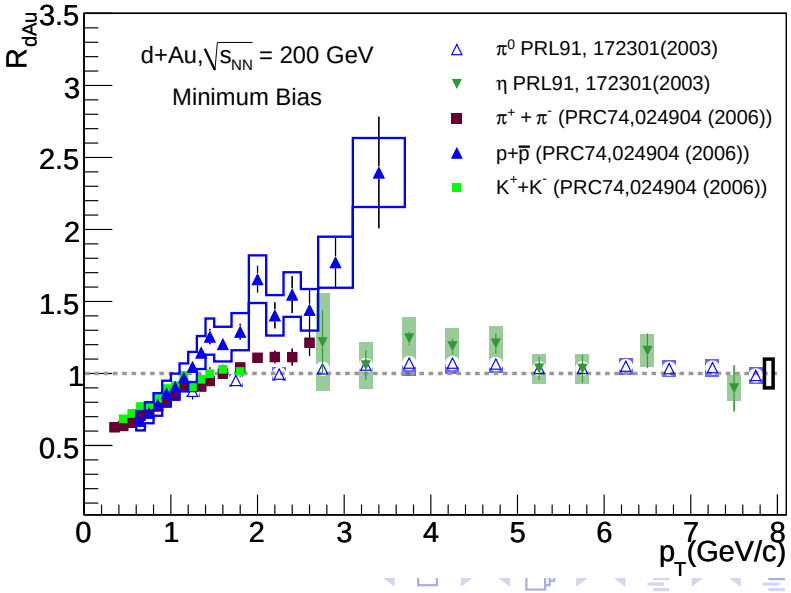
  - k_T kicks leading to p_T broadening (Cronin effect).





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- Modification of nuclear PDF's
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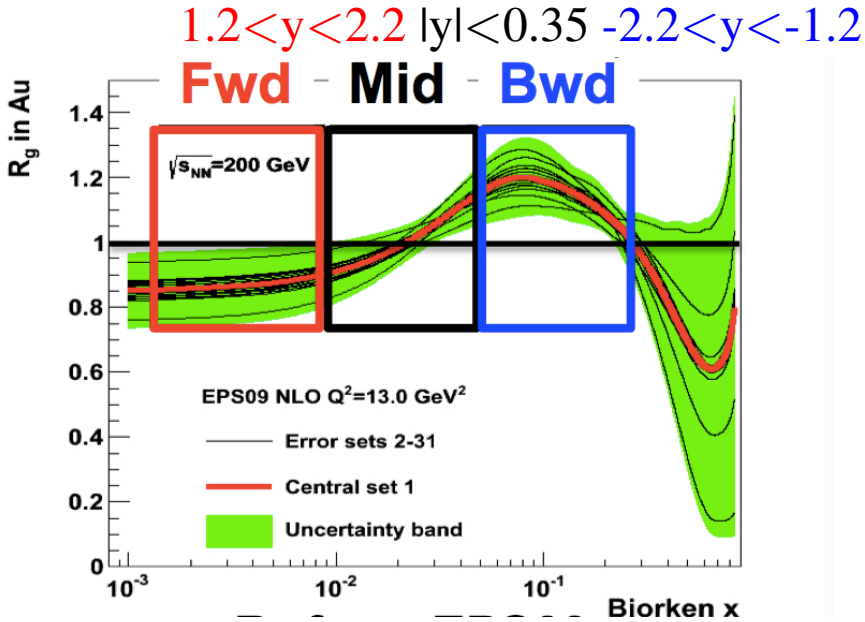
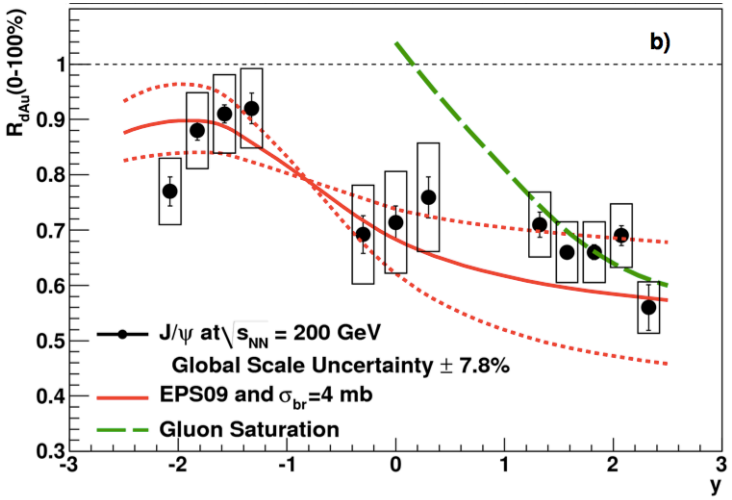
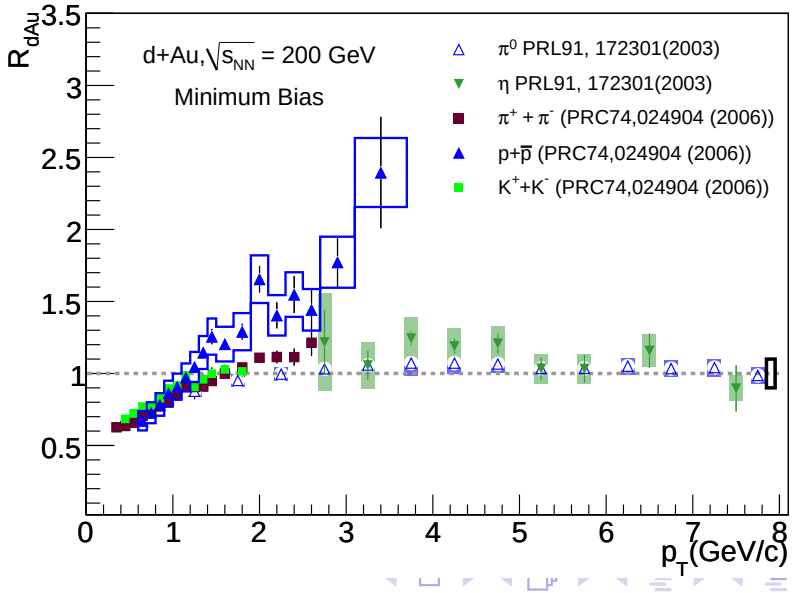
- Break-up effects
  - effects only the quarkonia states.

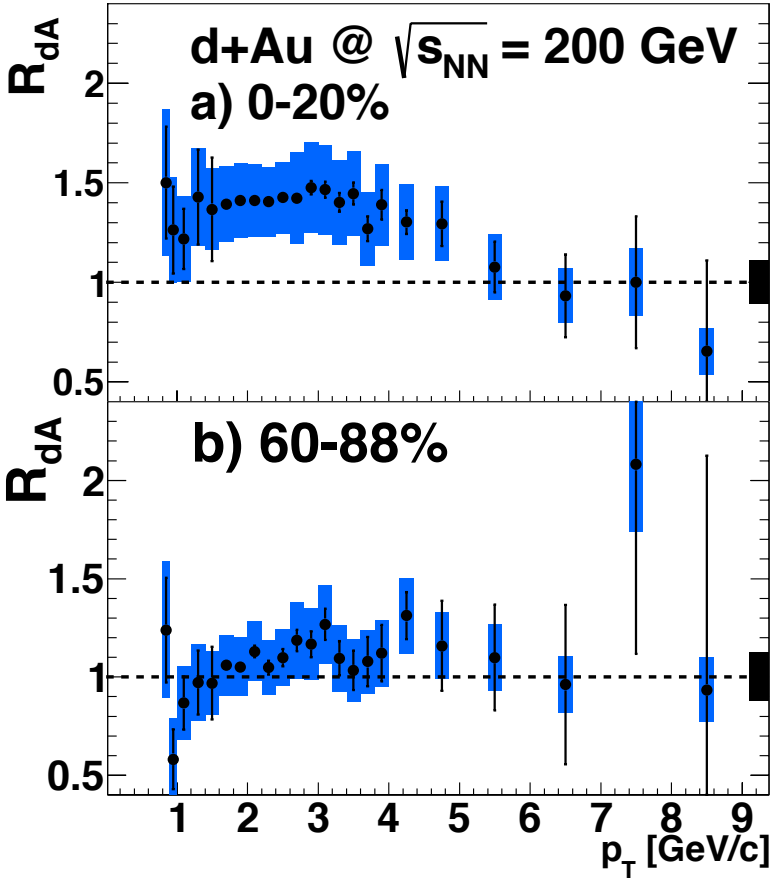






HF electrons in d + Au *at mid-rapidity*

PRL 109, 242301 (2012)



- Peripheral collisions consistent with the scaled p + p results.
- Enhancement at the intermediate p_T in most central collisions.
- Cronin Enhancement or something else ?

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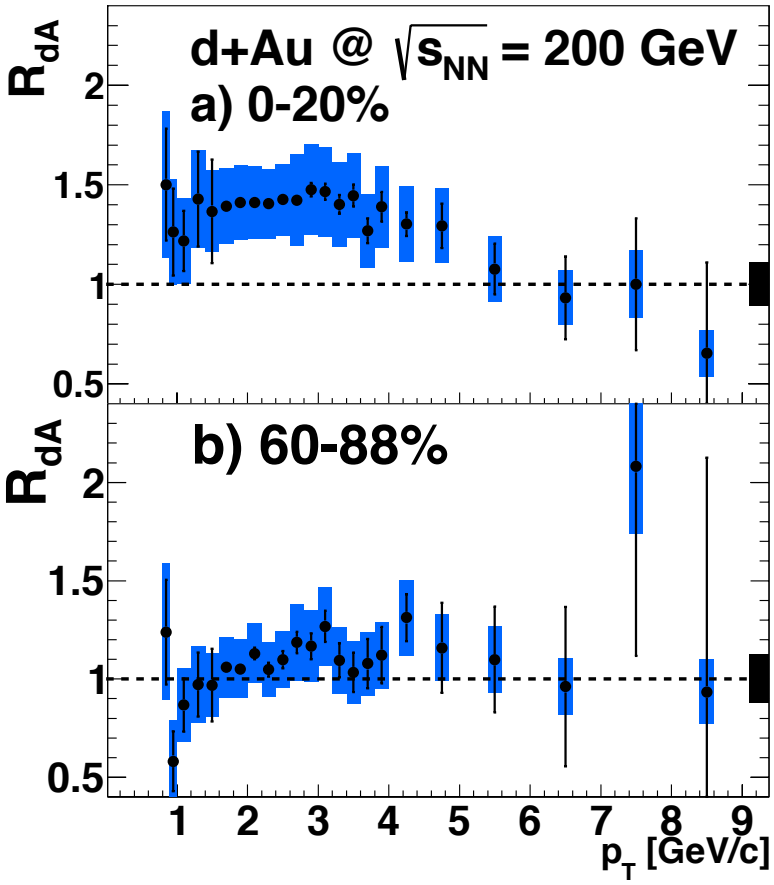
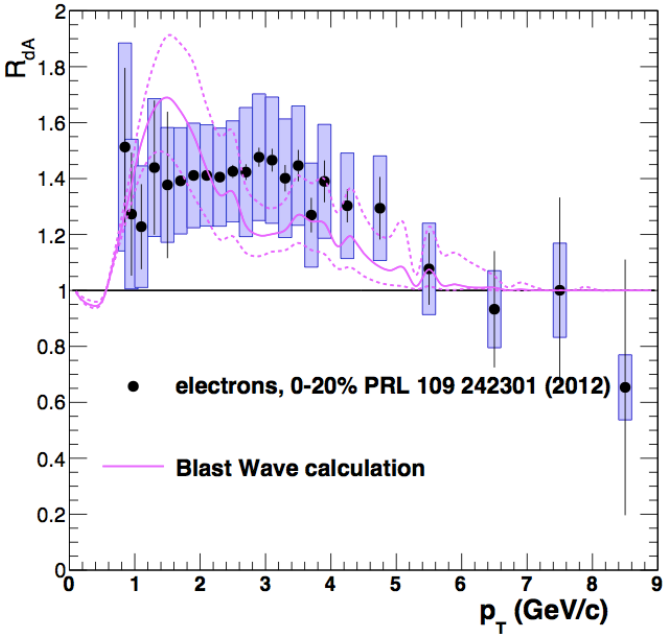
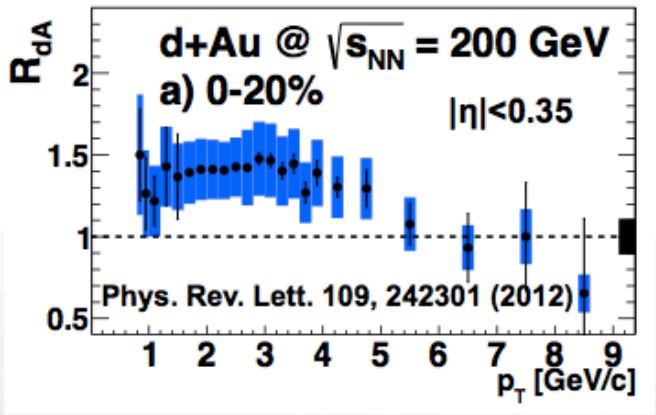
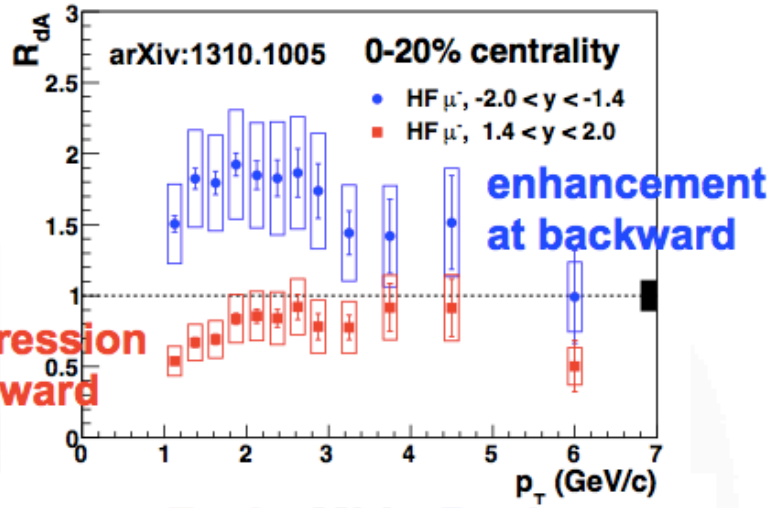


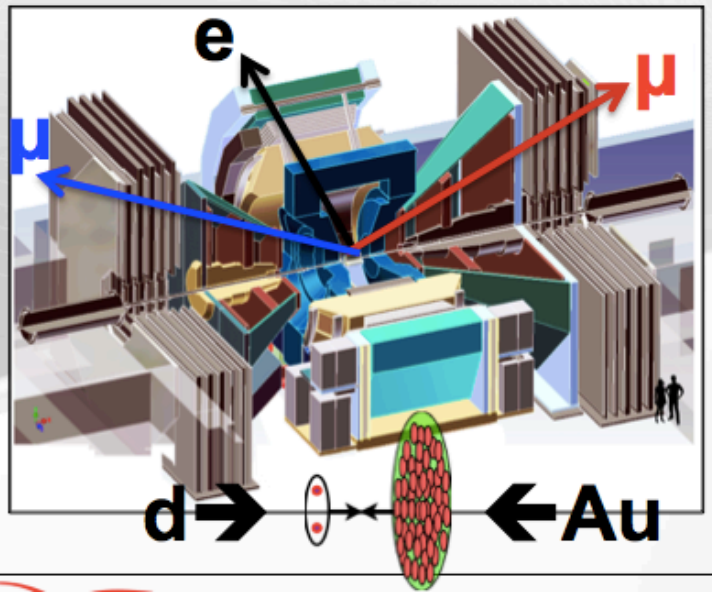
- Peripheral collisions consistent with the scaled p + p results.
- Enhancement at the intermediate p_T in most central collisions.
- Cronin Enhancement or something else ?
- Radial flow qualitatively describes the data !!

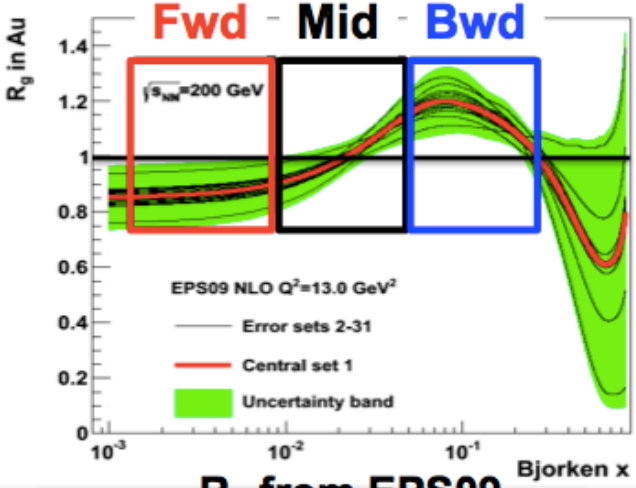


Rapidity expansion in d + Au



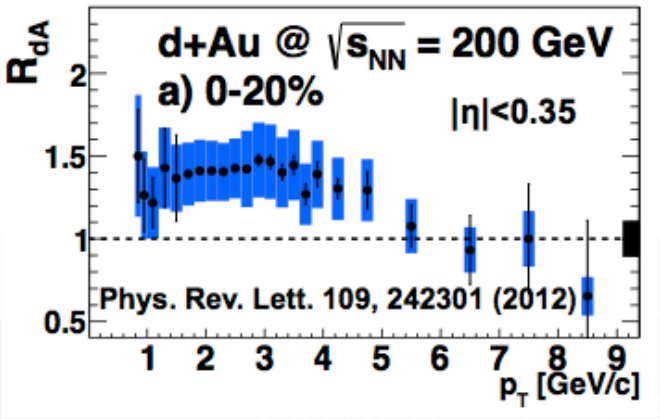


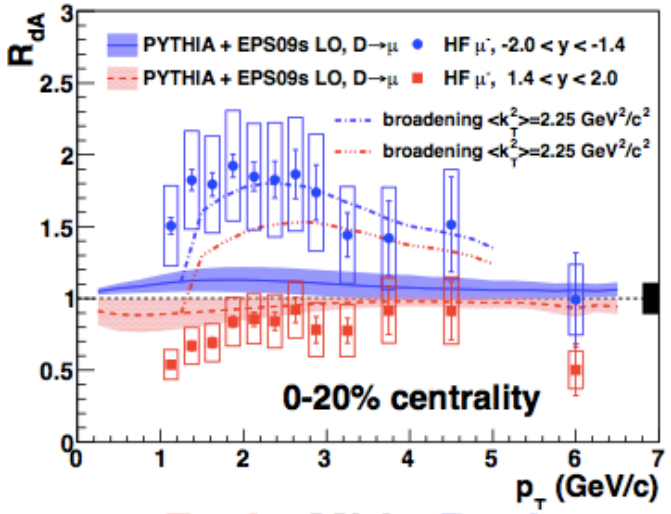




R_g from EPS09

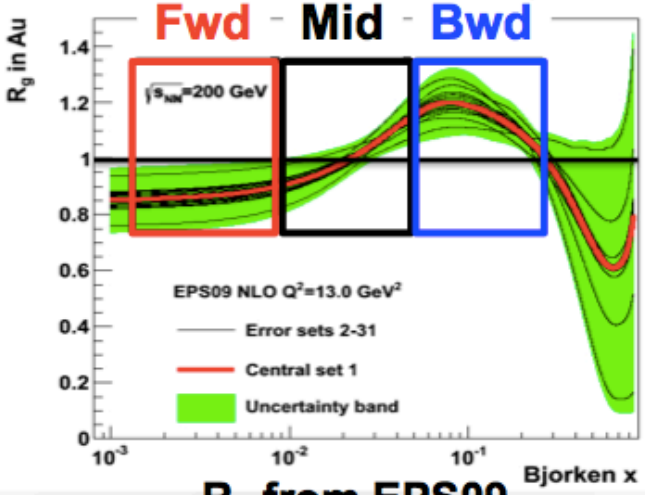
Rapidity expansion in d + Au





Fail to reproduce the data at both rapidity simultaneously w/ combinations of initial-state effects!

- **modification of nPDF**
- **initial k_T broadening**

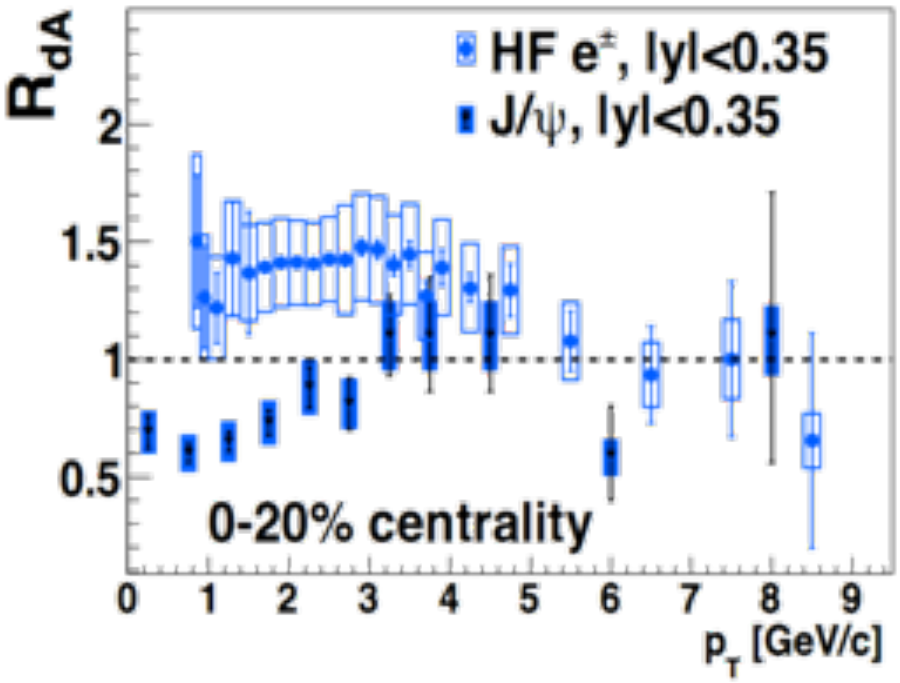


R_g from EPS09

Open vs closed charm in d + Au

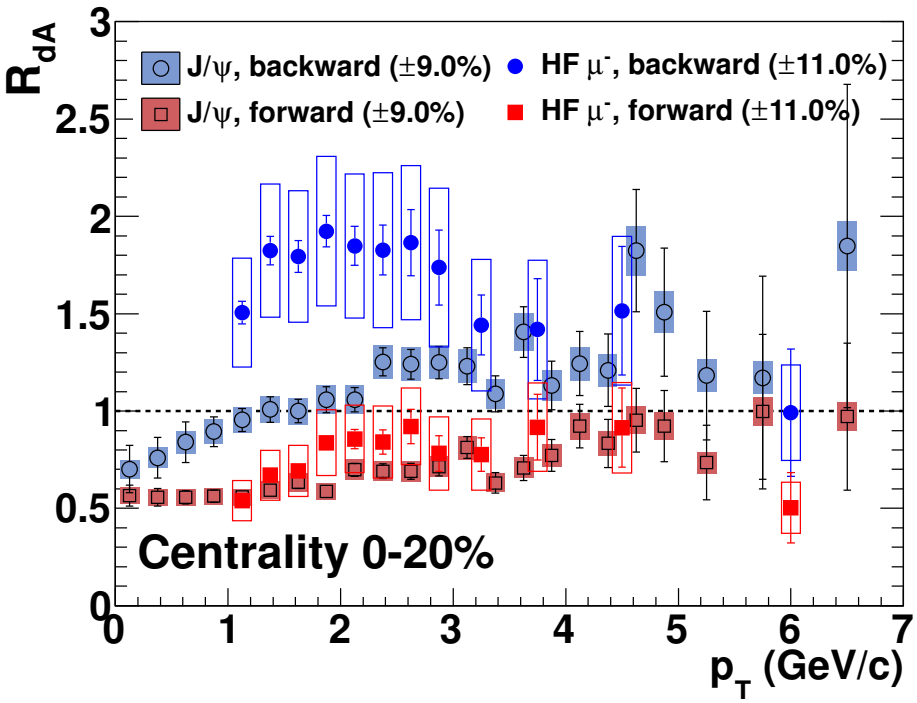
Both are sensitive to the same intial state effects, with J/ψ being subject to nuclear break-up effects

|y|<0.35



- Different behavior at mid- and backward rapidity: *enhanced* open HF versus *suppressed* J/ψ.

Forward/Backward



- Similar behavior in forward direction, small final state effects.

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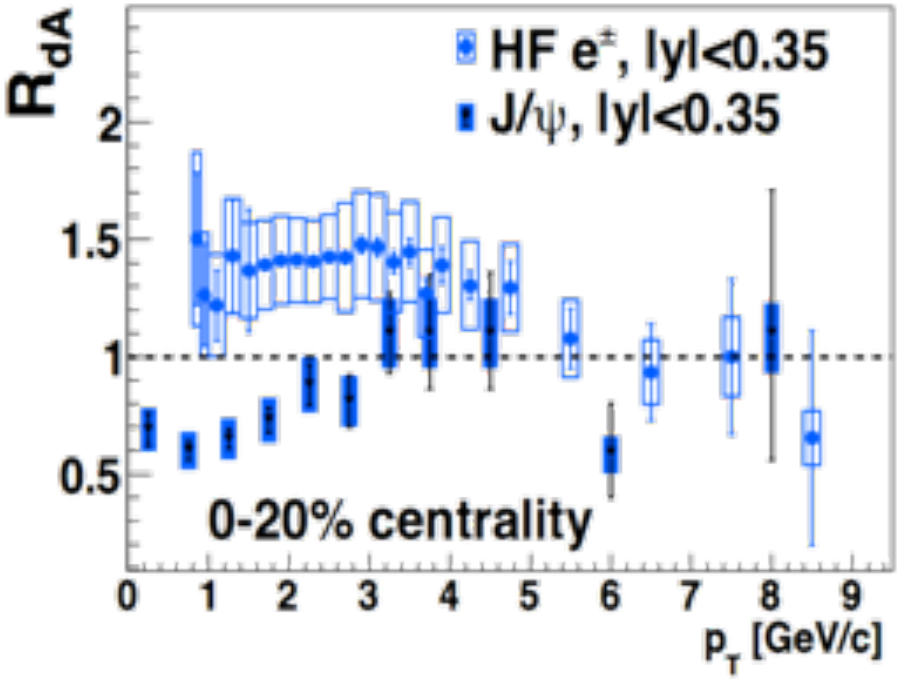

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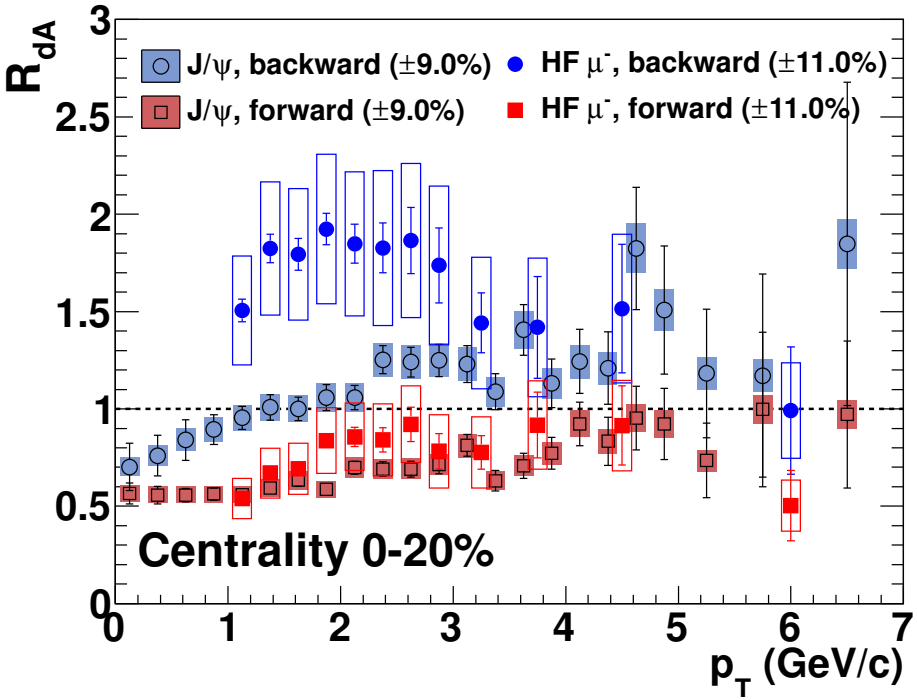
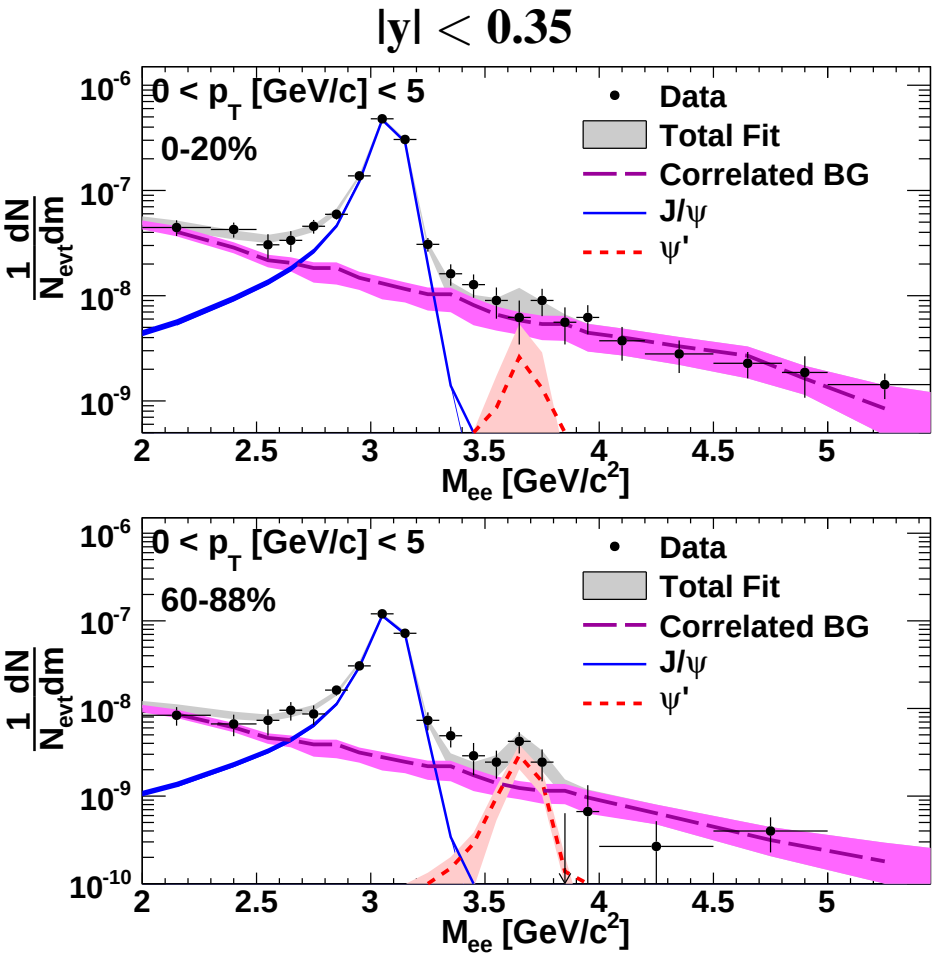
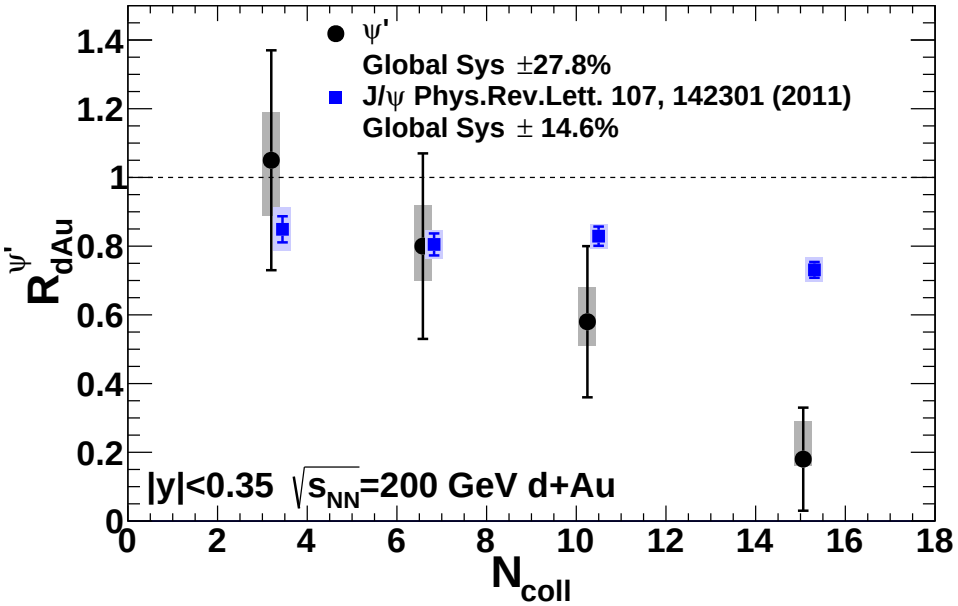


- Different behavior at mid- and backward rapidity: *enhanced* open HF versus *suppressed* J/ψ.
- Similar behavior in forward direction, small final state effects.

- **Significant final state effects at low p_T mid- and backward rapidities.**
- **J/ψ shows a significant break-up in the nuclear matter.**

ψ' *in* d + Au *collisions at mid-rapidity*

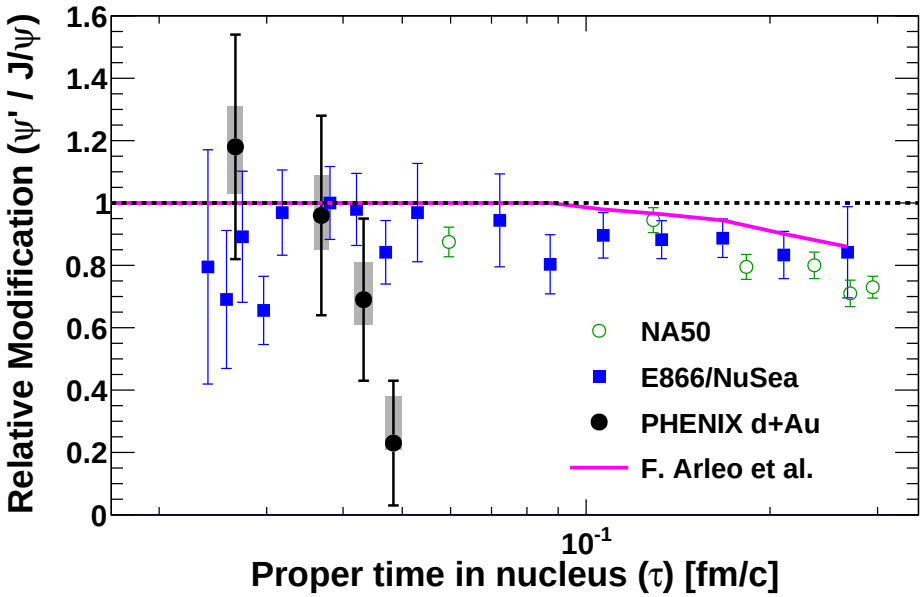




- $R^{\psi'}_{dAu} = \frac{[\psi'/(J/\psi)]^{dAu}}{[\psi'/(J/\psi)]^{pp}} \times R^{J/\psi}_{dAu}$
- ψ' binding energy is $12\times$ smaller than J/ψ.
- Data confirms that ψ' is more sensistive to the final state effects.
- Suppression increases with the increasing N_{coll}.

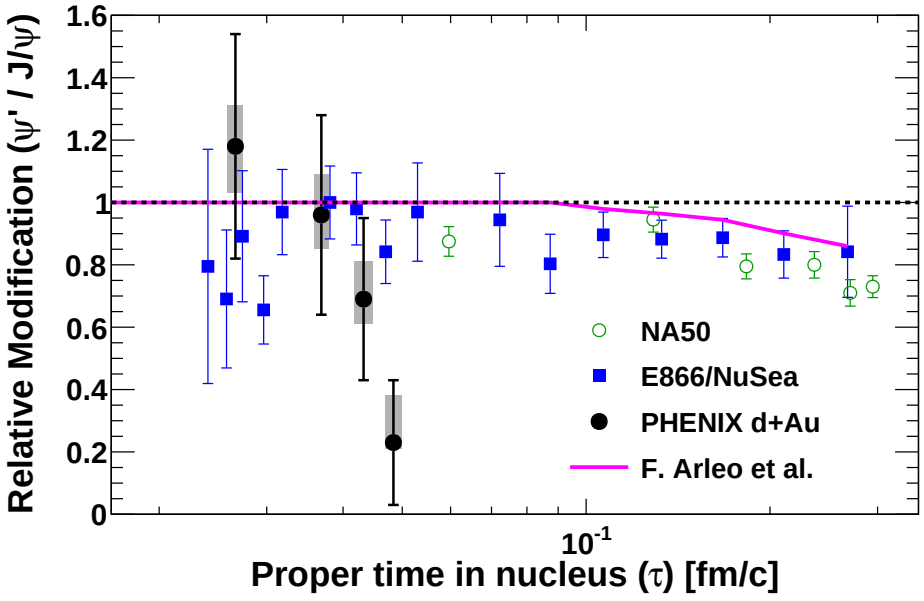
Excellent tool to study charmonium absorption

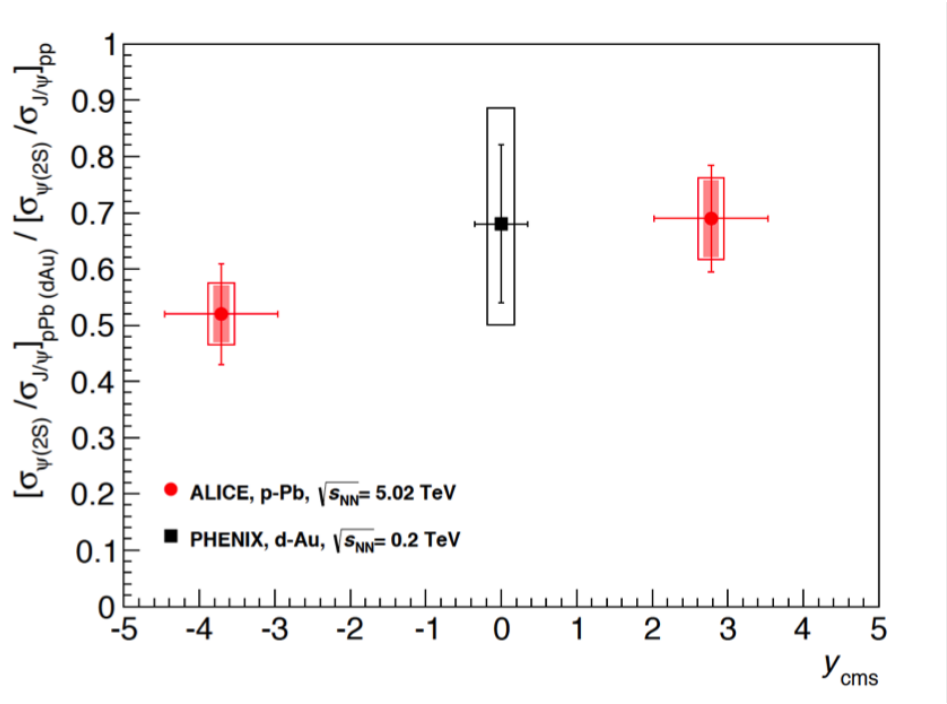
ψ' *in* d + Au *collisions at mid-rapidity*



- $c\bar{c}$ formation time $\sim$ 0.15fm; nuclear crossing time $\sim$ 0.05 fm at RHIC at mid-rapidity.
- Bound $c\bar{c}$ may cross the nucleus as a pre-resonant state $\Longrightarrow$ J/ψ and ψ' should have the same suppression.
- Data shows different results.

ψ' *in* d + Au *collisions at mid-rapidity*





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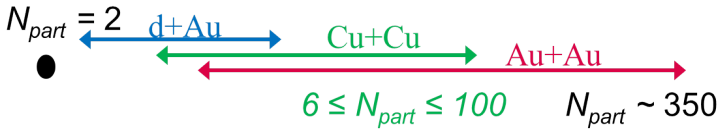
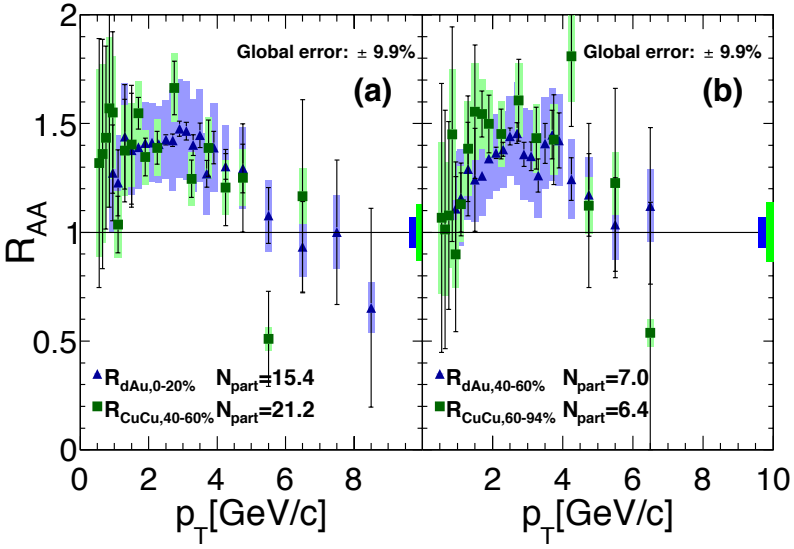
- Bound $c\bar{c}$ may cross the nucleus as a pre-resonant state $\Longrightarrow$ J/ψ and ψ' should have the same suppression.
- Data shows different results.

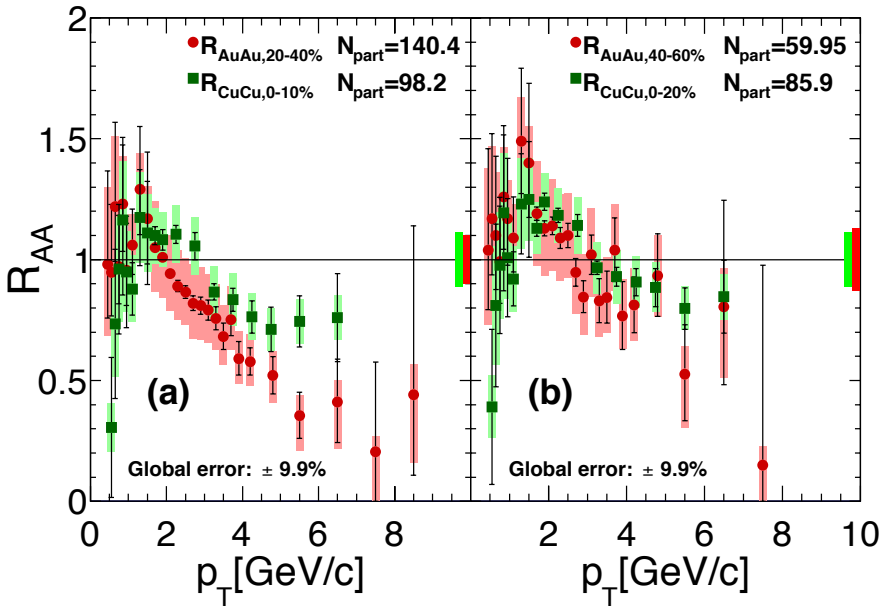
- Similar results seen at LHC.
- co-movers ?

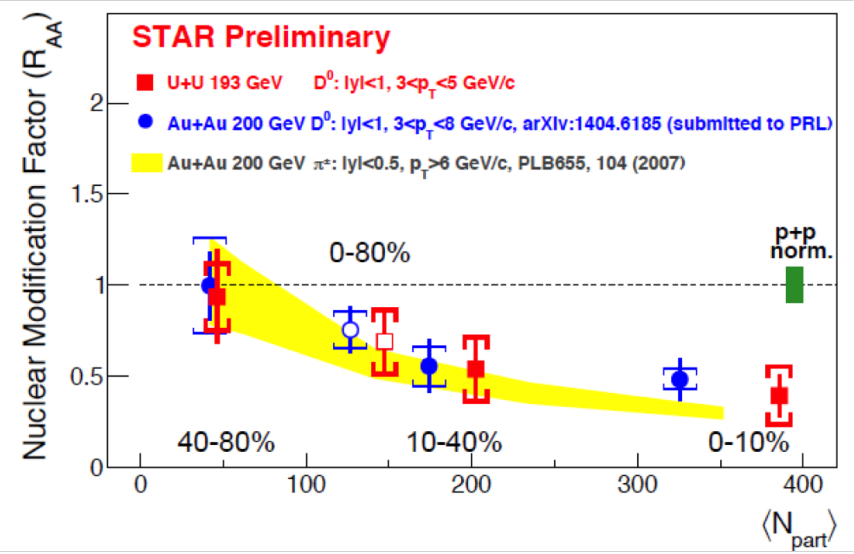
Intermediate Cu + Cu collisons: bridging d + Au *to* Au + Au

Comparison among different systems with similar values of N_{part}



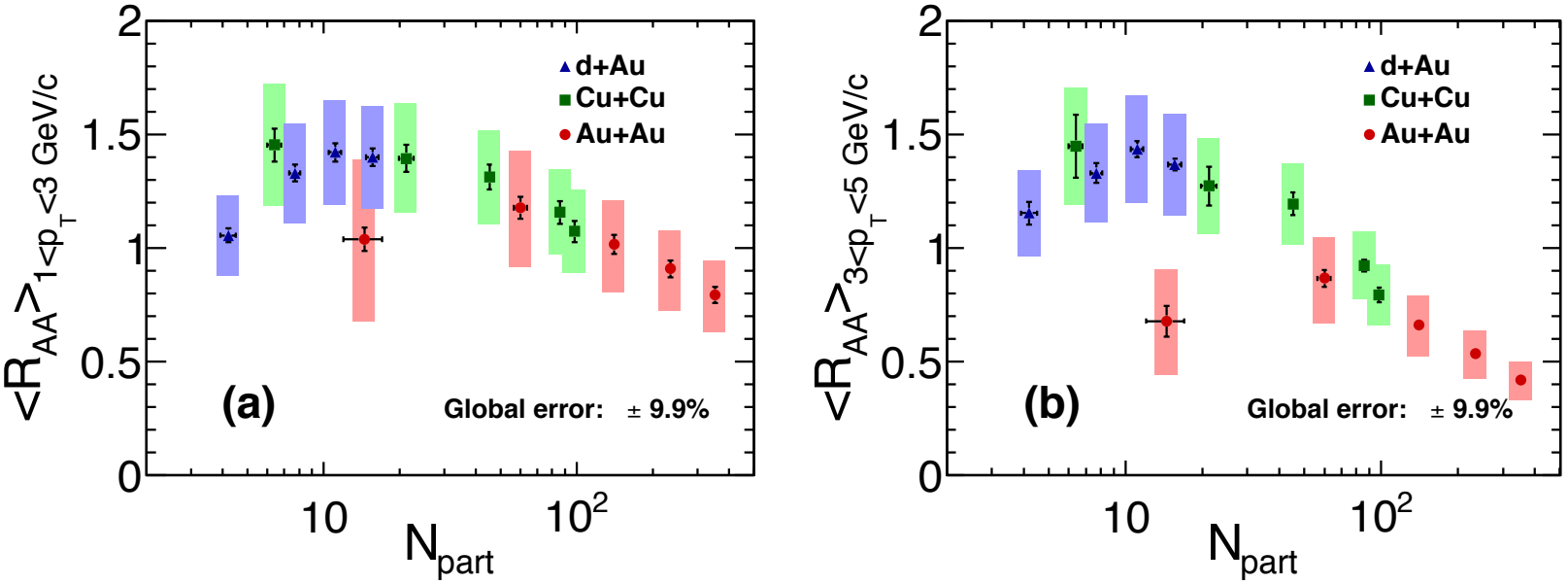






- Similar enhancement and suppression are seen for the different systems at similar N_{part}.

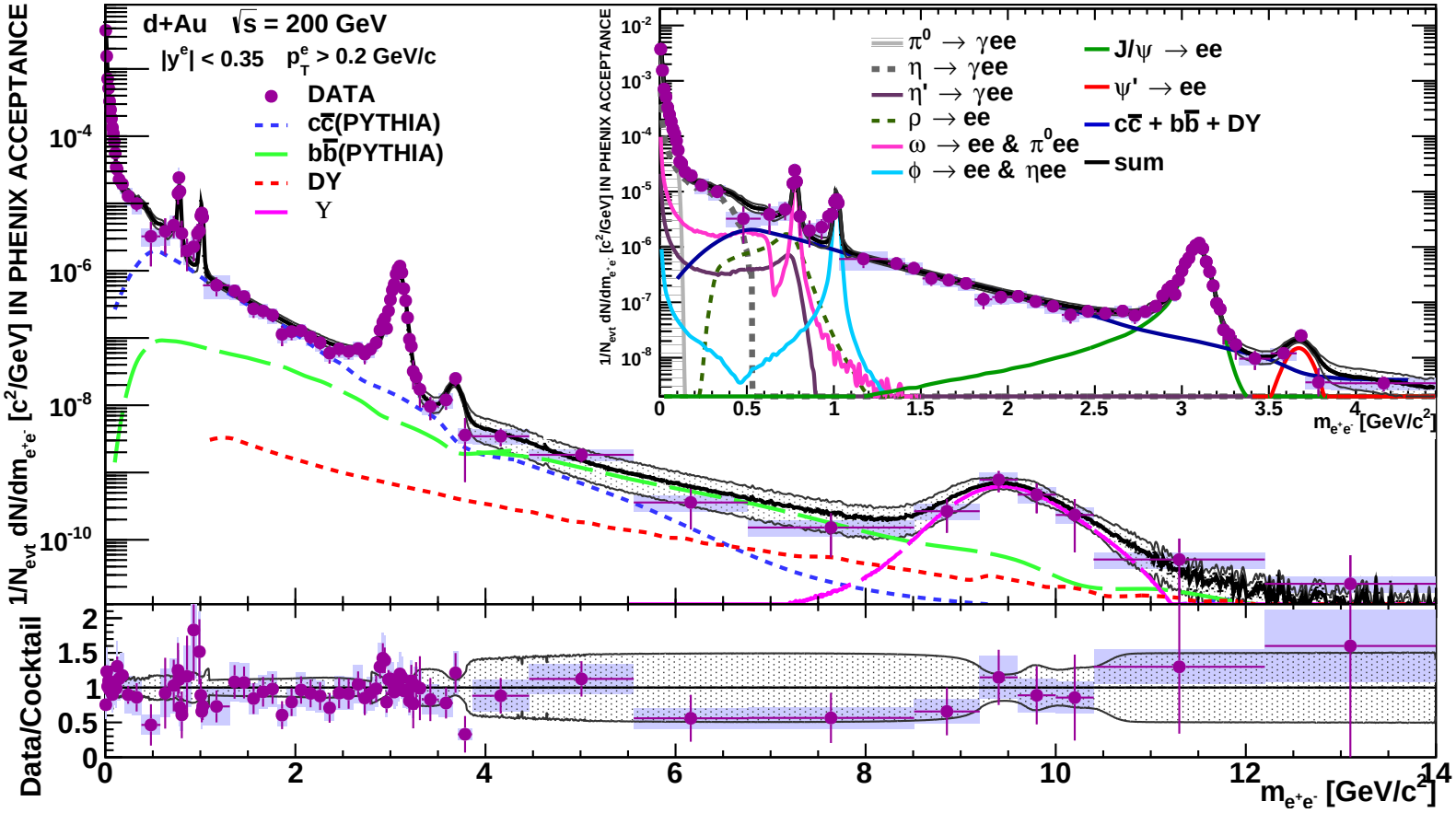
System size dependence



- A *trend* is seen from d + Au to *peripheral Cu + Cu* collisions where *enhancement* is dominating.
- To *central Cu + Cu* and Au + Au collisons where *suppression* effects take over

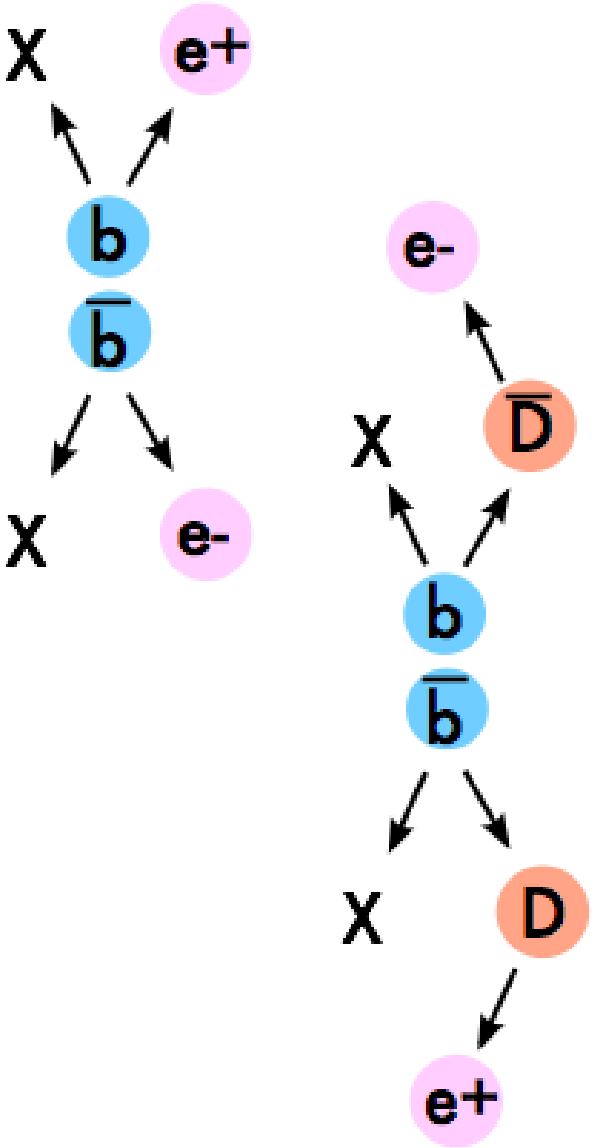
Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

arXiv:1405.4004

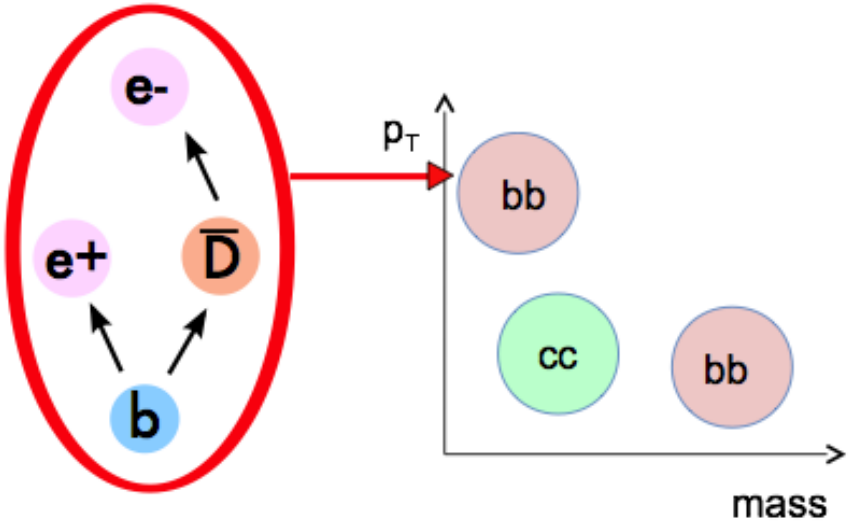


- High quality d + Au data covering large mass range $0 - 14\ GeV/c^2$.
- Can probe heavy production as well as modification through cold nuclear matter effects.

Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

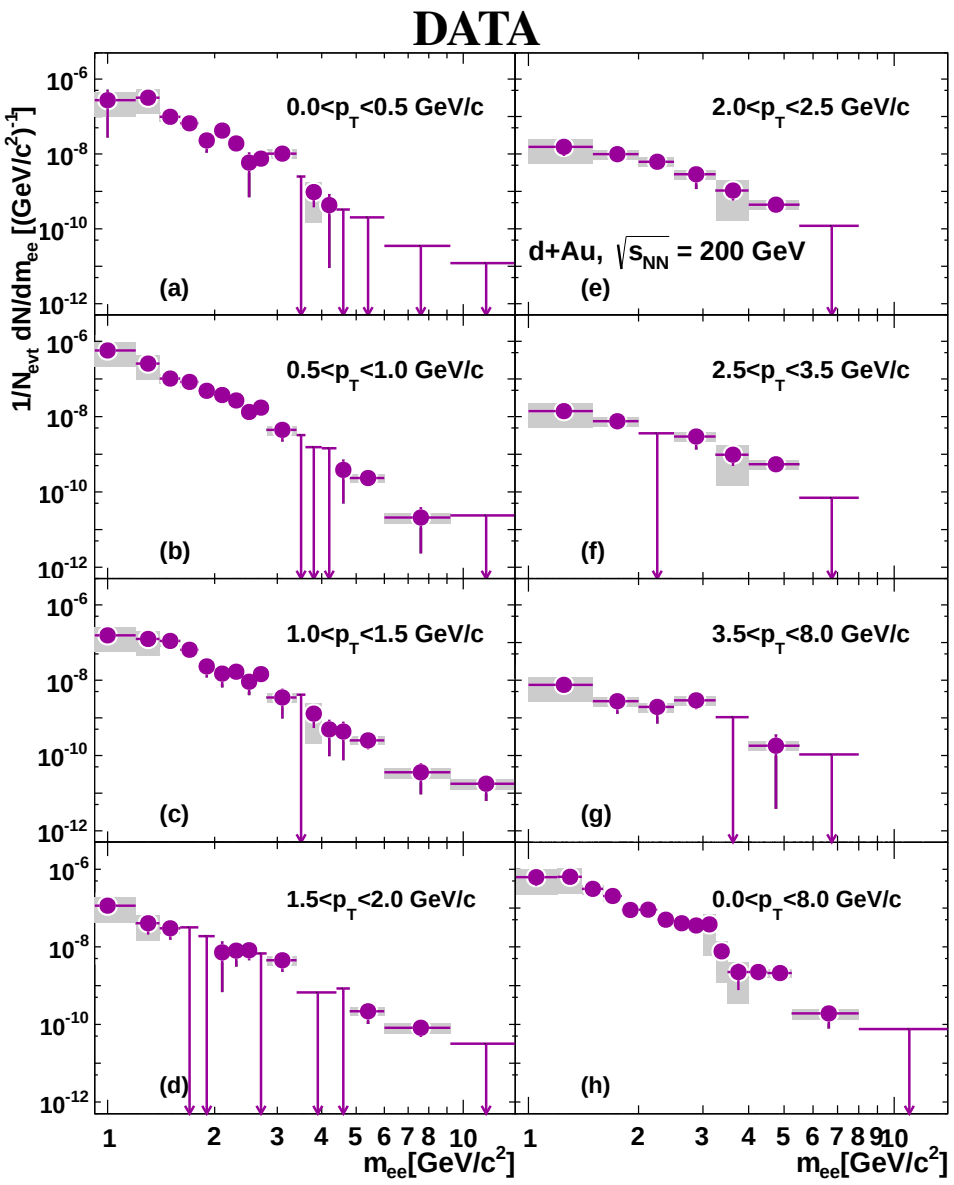


- Multiple ways to produce e^+e^- pairs.
- All contribute similar total pairs.
- But they populate different regions aof mass, p_T space.



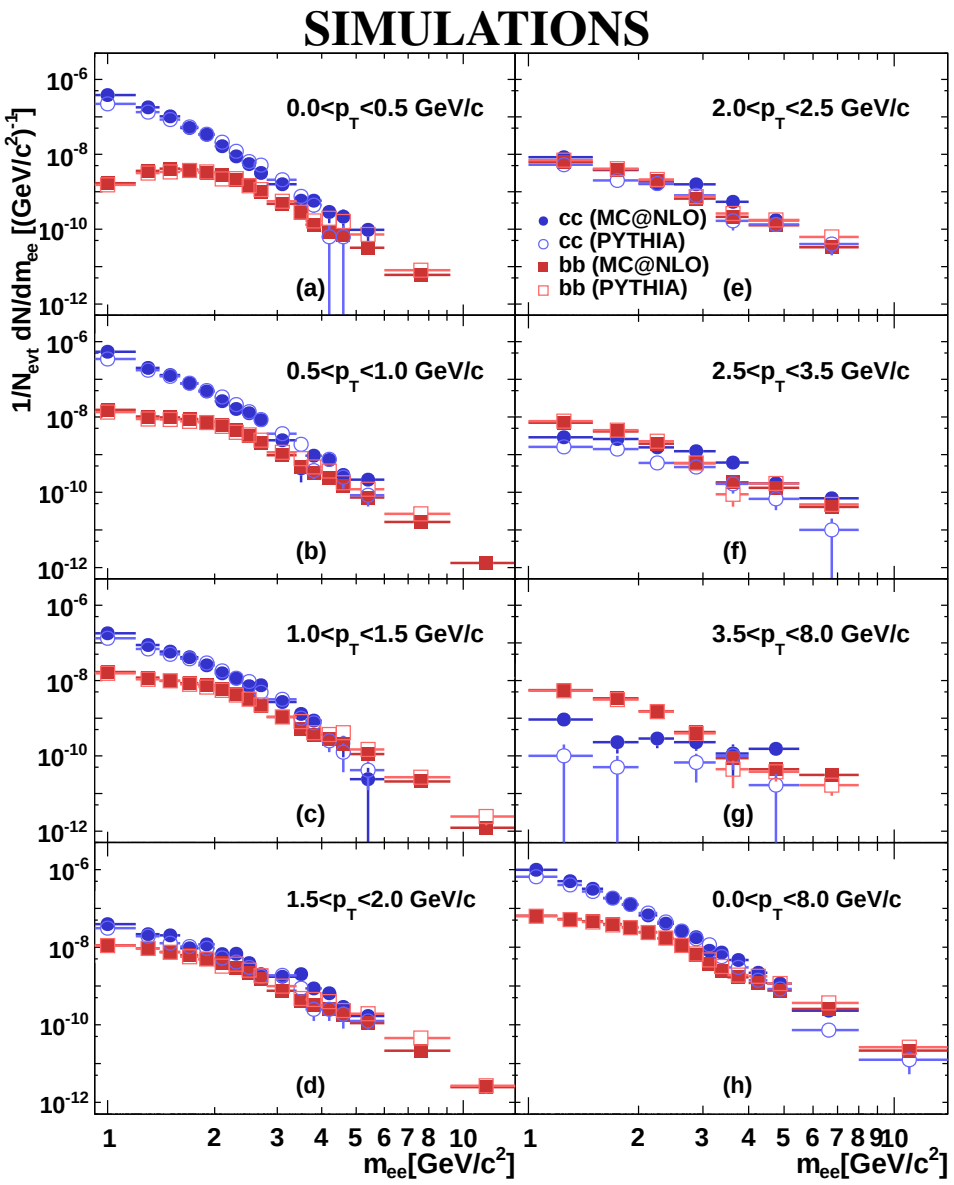
Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

- Subtract out the yield of the pseudoscalar and vector mesons, and the Drell-Yan. The left-over yield is from the heavy flavor decays.



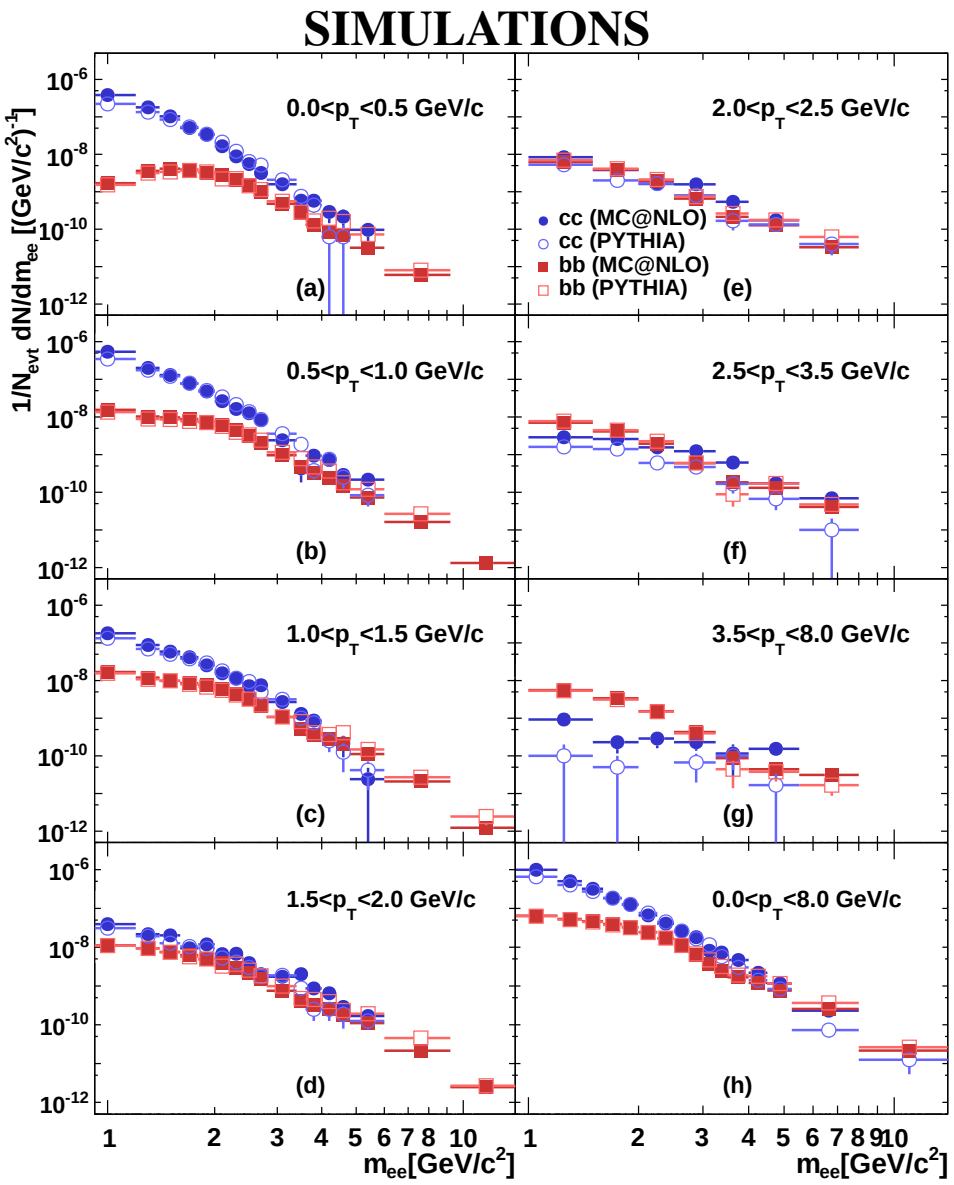
Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

- Subtract out the yield of the pseudoscalar and vector mesons, and the Drell-Yan. The left-over yield is from the heavy flavor decays.
- Fit in mass and p_T space with MC@NLO and PYTHIA

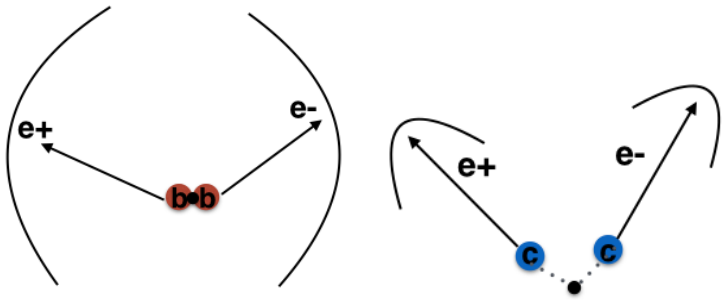


Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

- Subtract out the yield of the pseudoscalar and vector mesons, and the Drell-Yan. The left-over yield is from the heavy flavor decays.
- Fit in mass and p_T space with MC@NLO and PYTHIA
- Following general trend is observed:
- Charm dominates at **low mass** and **low** p_T
- Bottom dominates at:
  - **low mass** and **high** p_T
  - **high mass** and **high** p_T

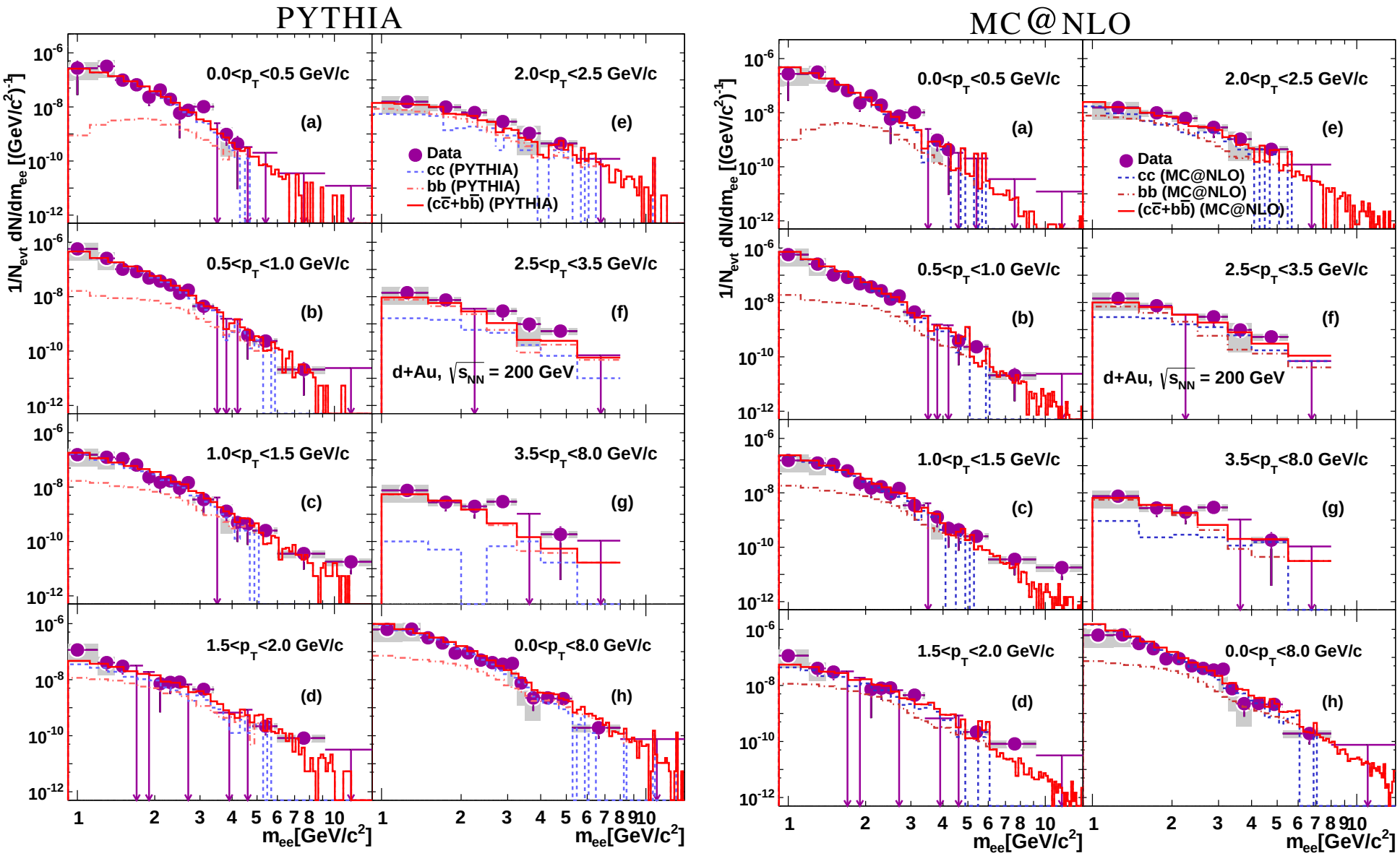


Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in $\mathrm{d} + \mathrm{Au}$

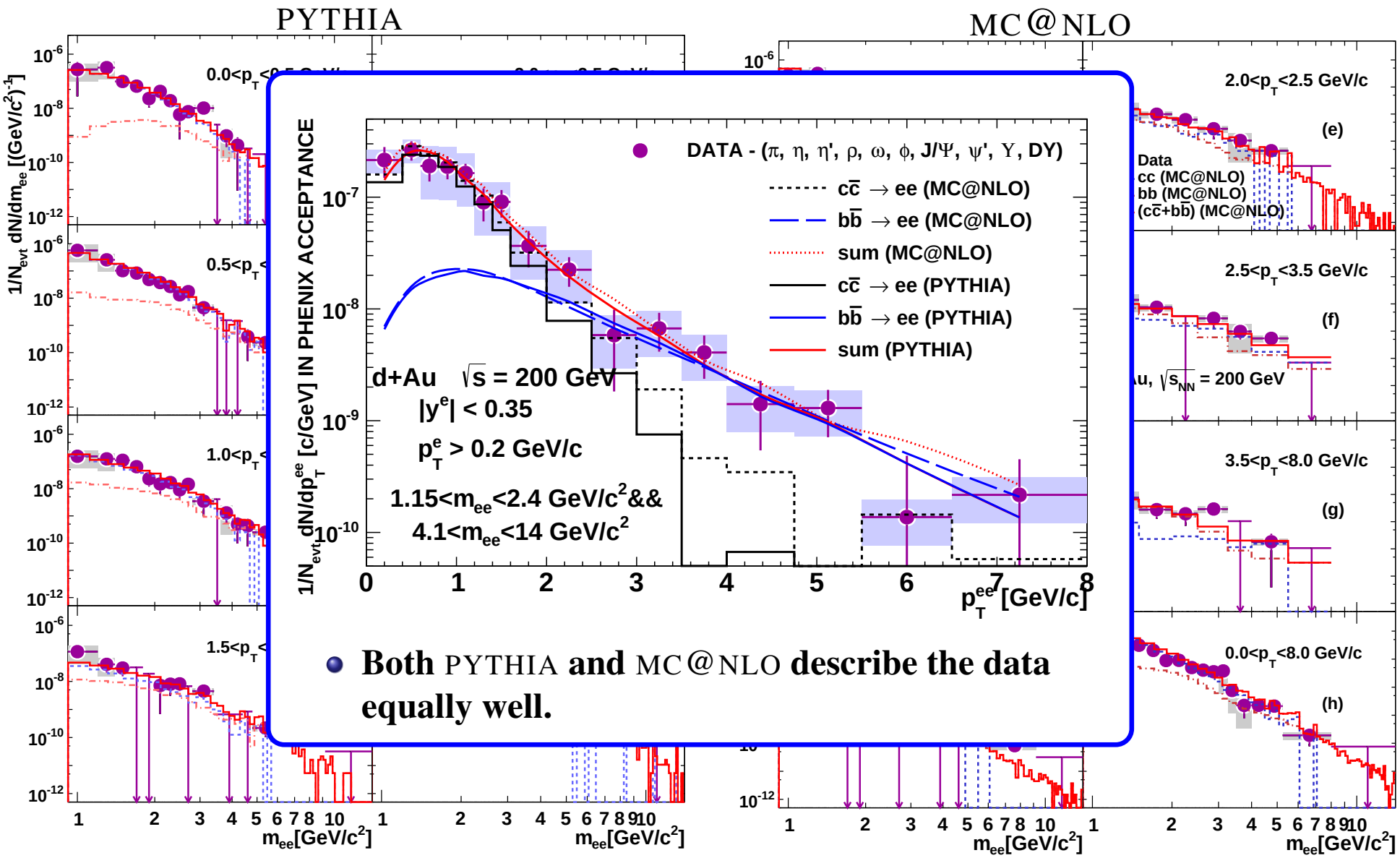


- For $m_q >> p$, the e^+e^- decay randomizes the opening angle.
- Otherwise the opening angle between electrons depends upon the opening angle beweem $q - \bar{q}$ pair.
- Thus expect more model dependence for extracted charm quark cross-section than for the bottom.

Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au

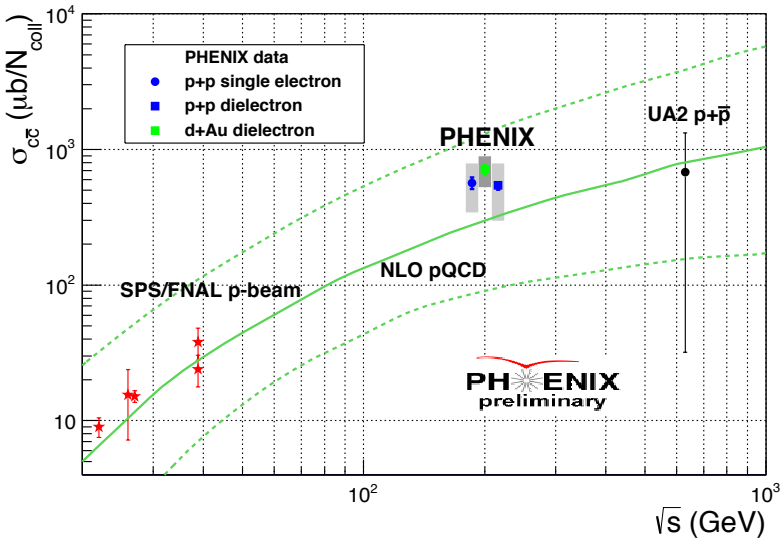


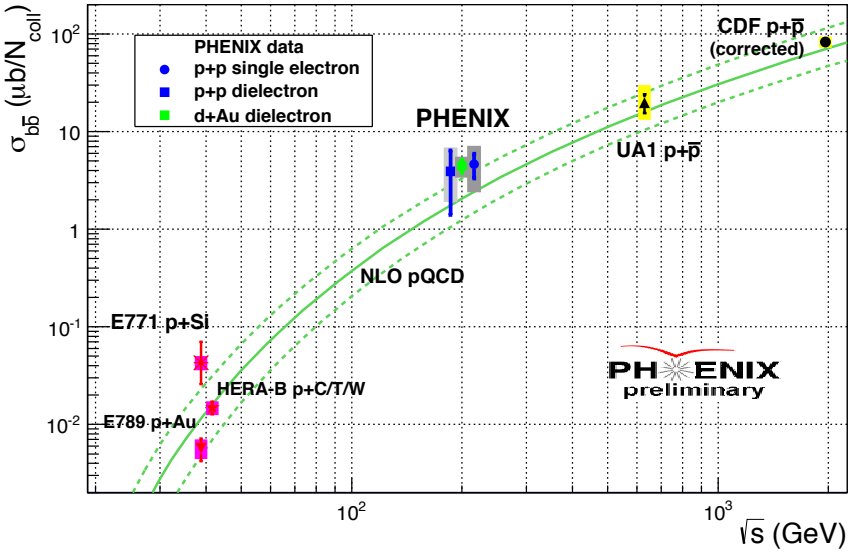
Separating $c\bar{c}$ and $b\bar{b}$ via dielectron correlations in d + Au



- **Both PYTHIA and MC@NLO describe the data equally well.**

Extracted $c\bar{c}$ and $b\bar{b}$ cross-sections





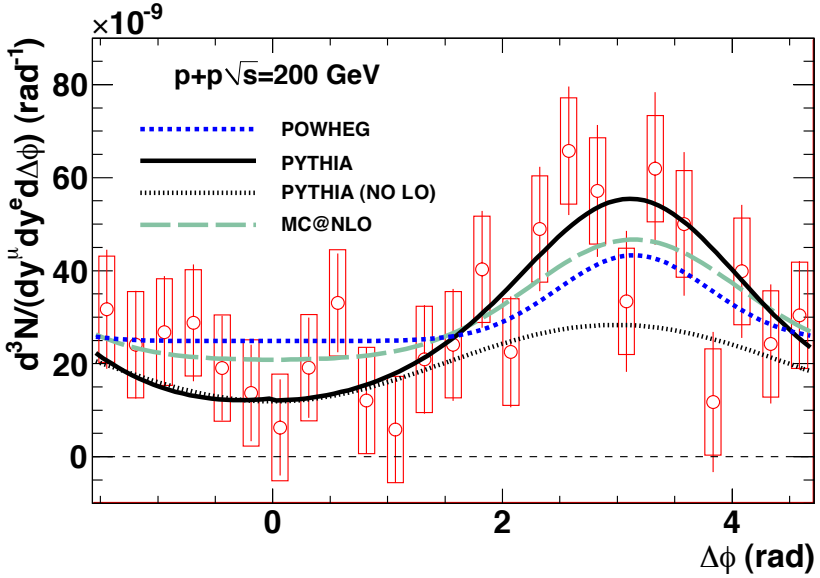
p + p equivalent extracted cross-sections:

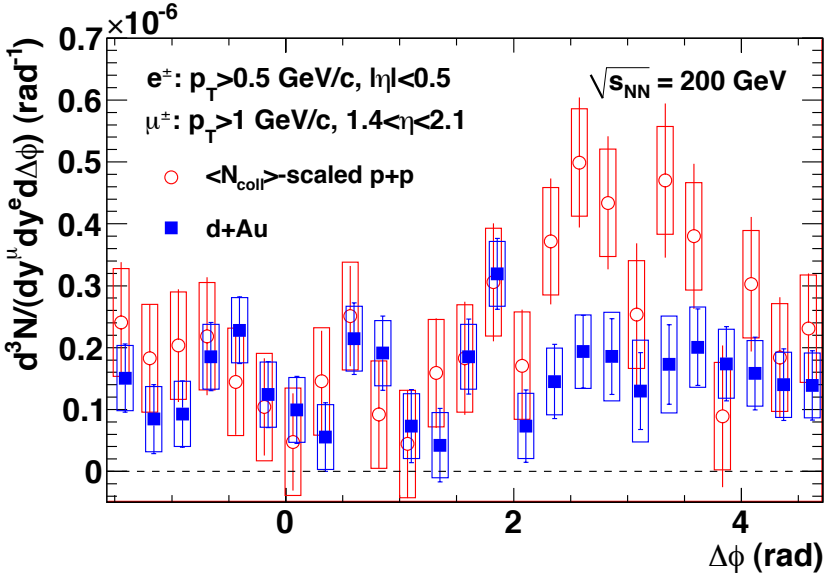
- $c\bar{c}$
  - Using MC@NLO $\sigma_{cc} = 958 \pm 96$ (stat) $\pm$ 335 (syst) μb.
  - Using PYTHIA $\sigma_{cc} = 385 \pm 34$ (stat) $\pm$ 119 (syst) μb.
- $b\bar{b}$
  - $\sigma_{bb} = 3.4 \pm 0.28$ (stat) $\pm$ 0.46 (syst) μb.

The difference between MC@NLO and PYTHIA extracted $b\bar{b}$ cross-sections are less than 2%.

$e - \mu$ *correlations in* p + p *and* d + Au *collisions*

Phys. Rev. C 89, 034915 (2014)





- Like-sign subtracted $e - \mu$ correlations predominantly from $c\bar{c}$ decays.
- PYTHIA: $\sigma_{c\bar{c}}$ =340 $\pm$ 29(stat) $\pm$ 114(sys)$\pm$ μb.
- POWHEG: $\sigma_{c\bar{c}}$ =511 $\pm$ 44(stat) $\pm$ 198(sys)$\pm$ μb.
- MCNLO: $\sigma_{c\bar{c}}$ =764 $\pm$ 64(stat) $\pm$ 284(sys)$\pm$ μb.

- Suppression of $e - \mu$ correlations in d + Au collisions.
- Indicates the modification of $c\bar{c}$ correlation by nuclear effects.
- Suppression might be from shadowing, or gluon saturation?

Summary

$A + A$

- Large open HF suppression at high p_T in $A + A$ for $\sqrt{s_{NN}}$ = 200 GeV.
- Charm modification in Au + Au looks different at 62 GeV and 200 GeV.
- J/ψ more suppressed at forward rapidity.

d + Au

- Large CNM effects on open HF electrons.
- J/ψ more suppressed than HF at mid- and backward. Hints for final state effects.
- ψ' relative suppression suggests nuclear absorption from co-movers.

System size

- A decreasing trend of R_{AA} with increasing system size, after the enhancement in d + Au and peripheral $Cu + Cu$ collisions.

dilepton correlations

- $b\bar{b}$ cross-section measured precisely via e^+e^- m,p_T spectrum.
- $e - \mu$ correlation show away-side suprresion in d + Au.

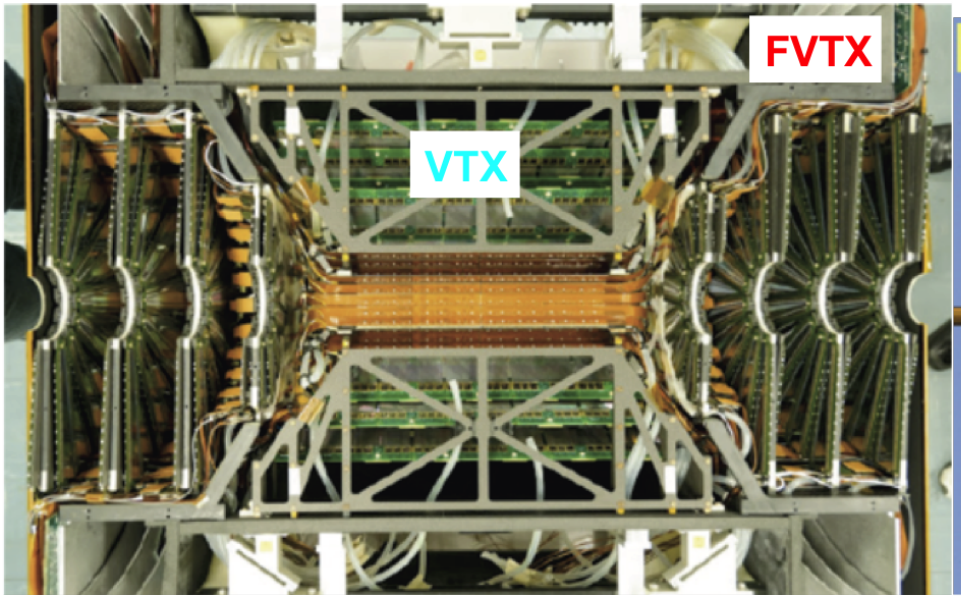
Topics not covered

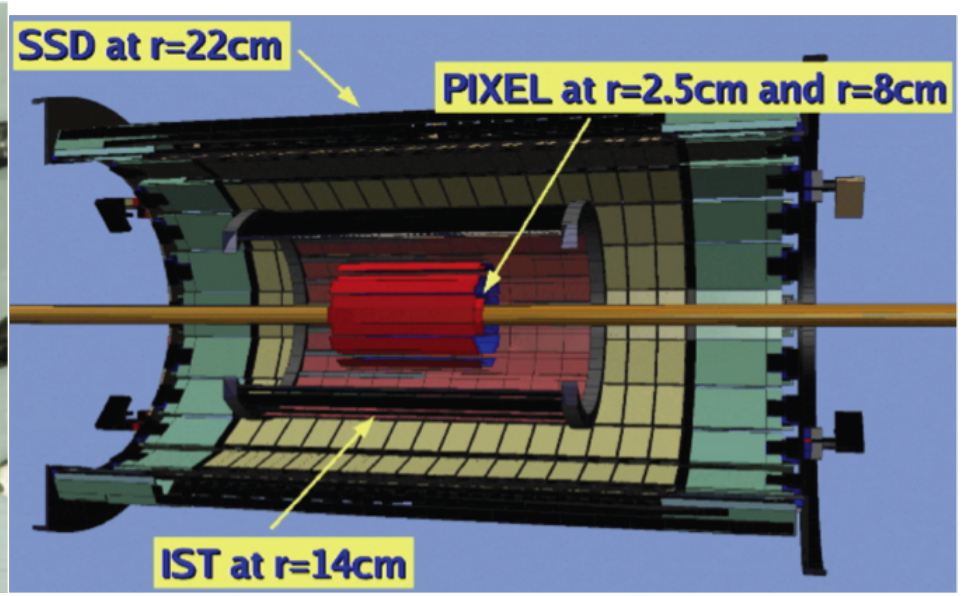
- Flow, Asymmetric collisions, Υ in $U + U$.

Looking ahead into the near future

With PHENIX VTX and FVTX and STAR HFT detectors

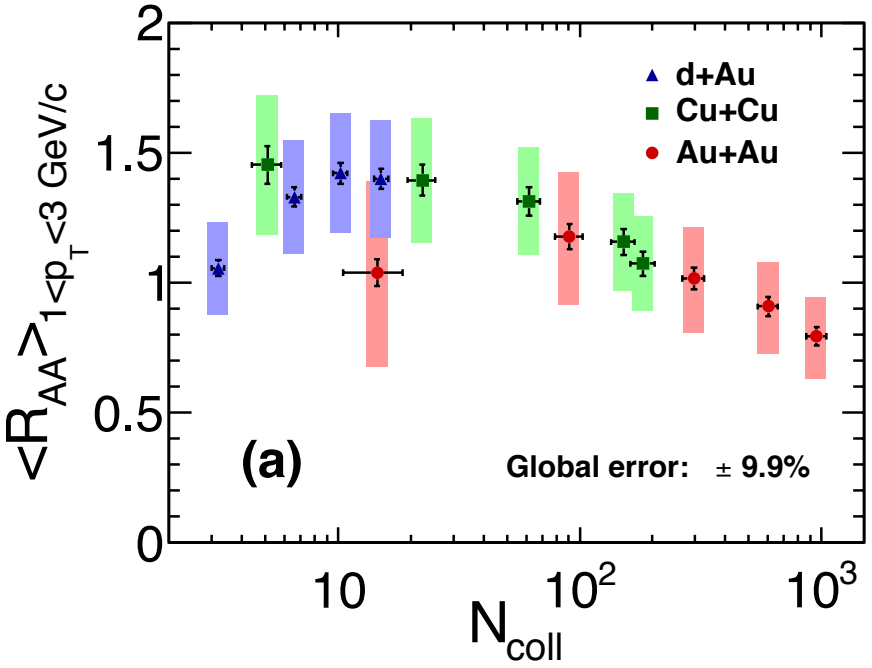
- Separation of c and b.
- Charmed hadrons chemistry.
- b vs c energy loss and flow.

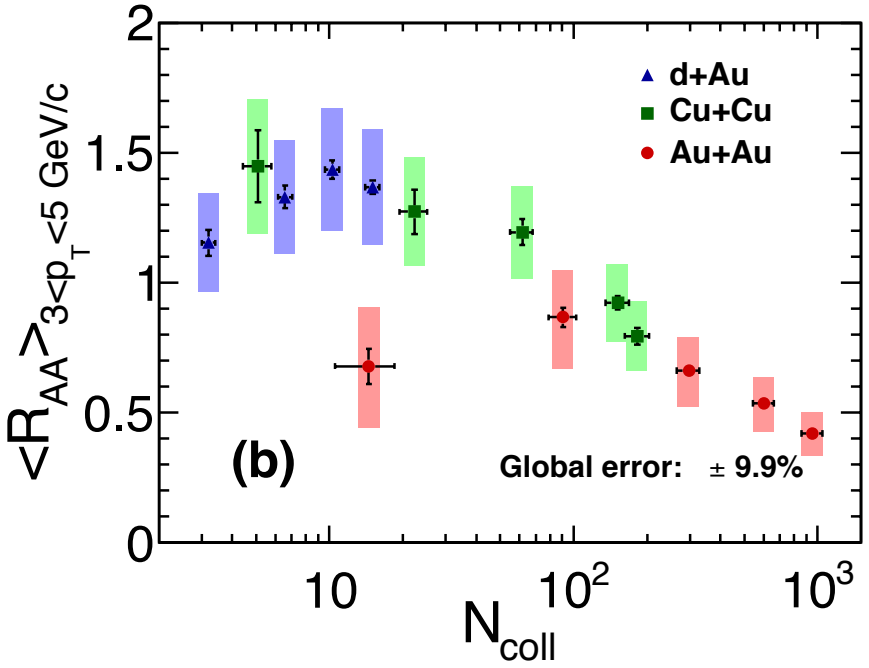




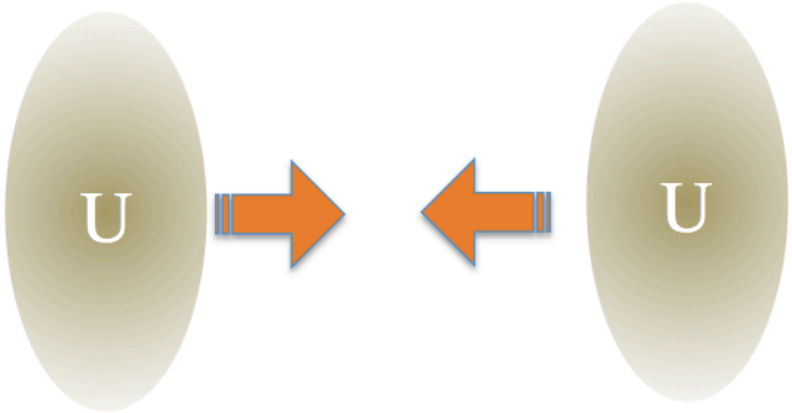
Back-ups

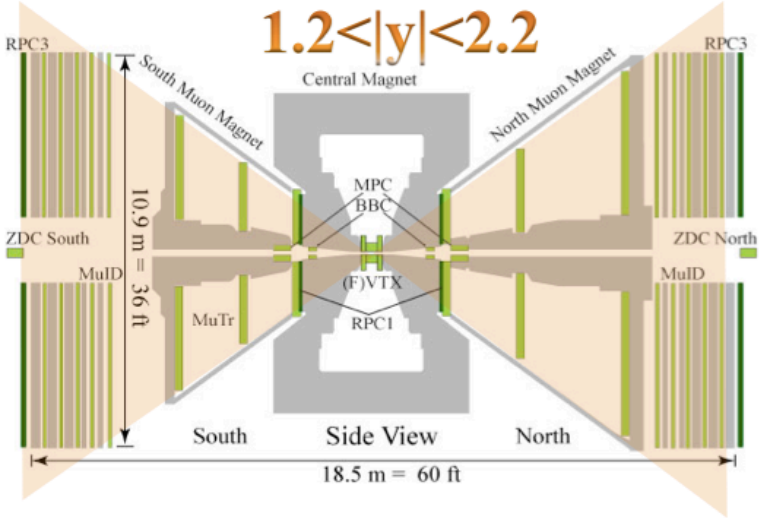
System size as a function of Ncoll



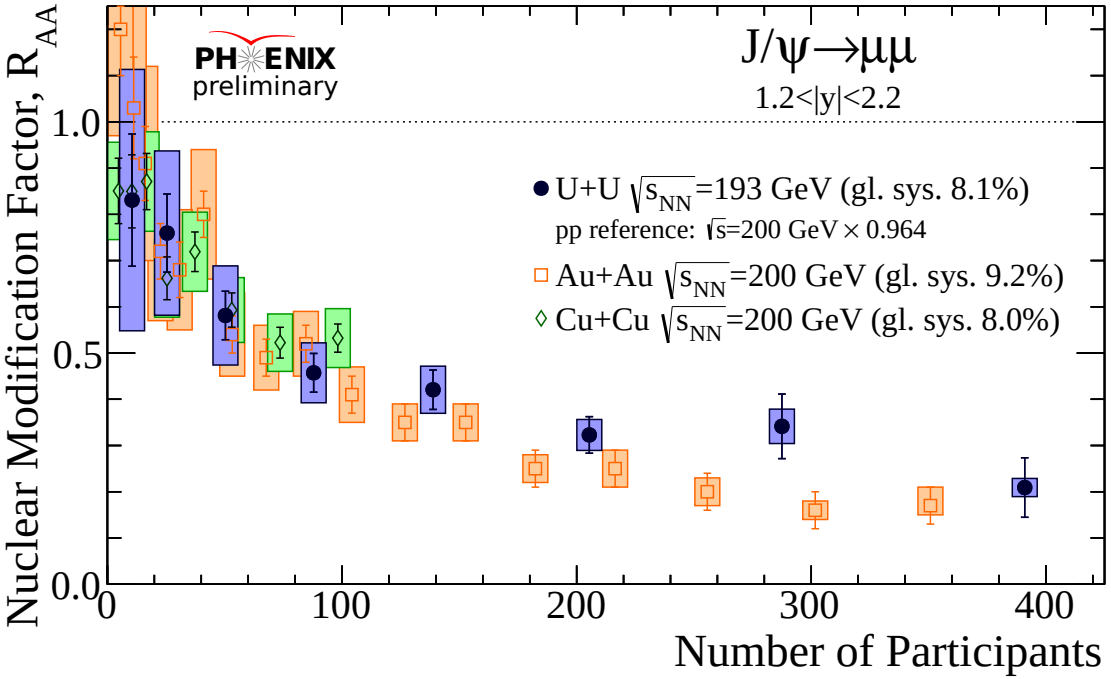


Studying system geometry via J/$\psi \rightarrow \mu^+\mu^-$ in $U + U$





Differences from Au + Au **collisions**

- Maximum number of nucleon participants (15% larger than Au + Au).
- Larger energy denisty.

Consistent between different colliding systems. Differences are $\sim$ 20%.