HEAVY QUARKS AND QUARKONIA FROM PHENIX

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Rencontres de Moriond
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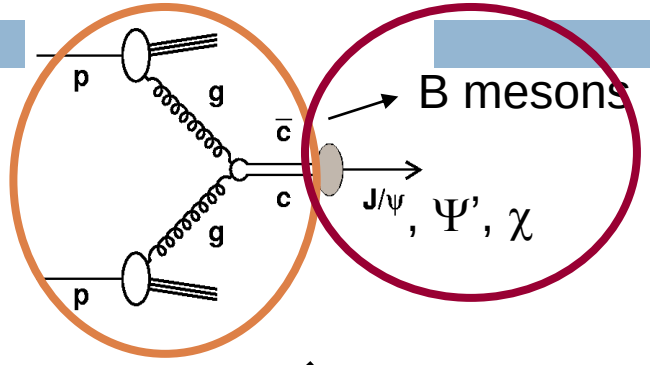
Outline

- Introduction
- Recent quarkonia results
  - J/Psi in Cu+Au collsions at $\sqrt{s_{NN}}$=200 GeV
  - Upsilon in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- Recent open heavy flavor results
  - Yield and elliptic flow of heavy quarks from Au+Au collisions at $\sqrt{s_{NN}}$=62 GeV
  - $b\bar{b}$ cross-section from e^+e^- channel in d+Au at $\sqrt{s_{NN}}$=200 GeV
- Summary and outlook

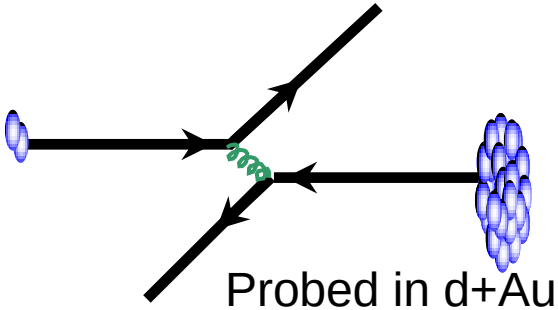
Heavy flavor production at RHIC

- Heavy quarks produced early in the collision
  → probe the evolution of the matter
- Quarkonia at RHIC dominantly produced through gluon fusion

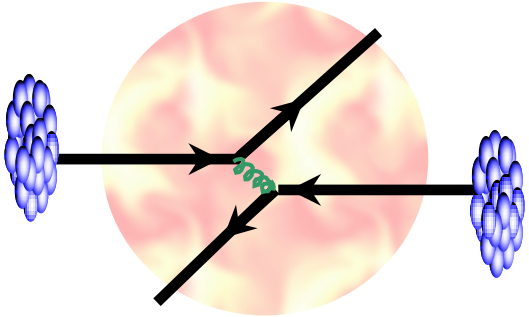


Possible modifications in cold-nuclear matter:

- Nuclear modification of parton distribution functions?
- Energy loss of partons traversing nucleus
- Cronin modification of p_T spectra
- Nuclear breakup of quarkonia



Probed in d+Au

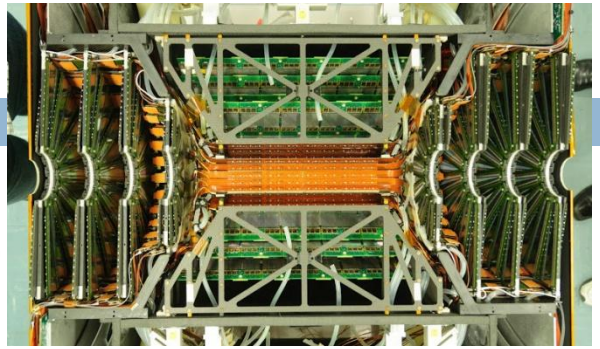


Probed in A+A

Possible modifications in QGP:

- Energy loss of partons traversing QGP
- Screening of quarkonia by QGP
- Charmonium production through coalescence

Detection of heavy flavor in PHENIX



Central Arms:

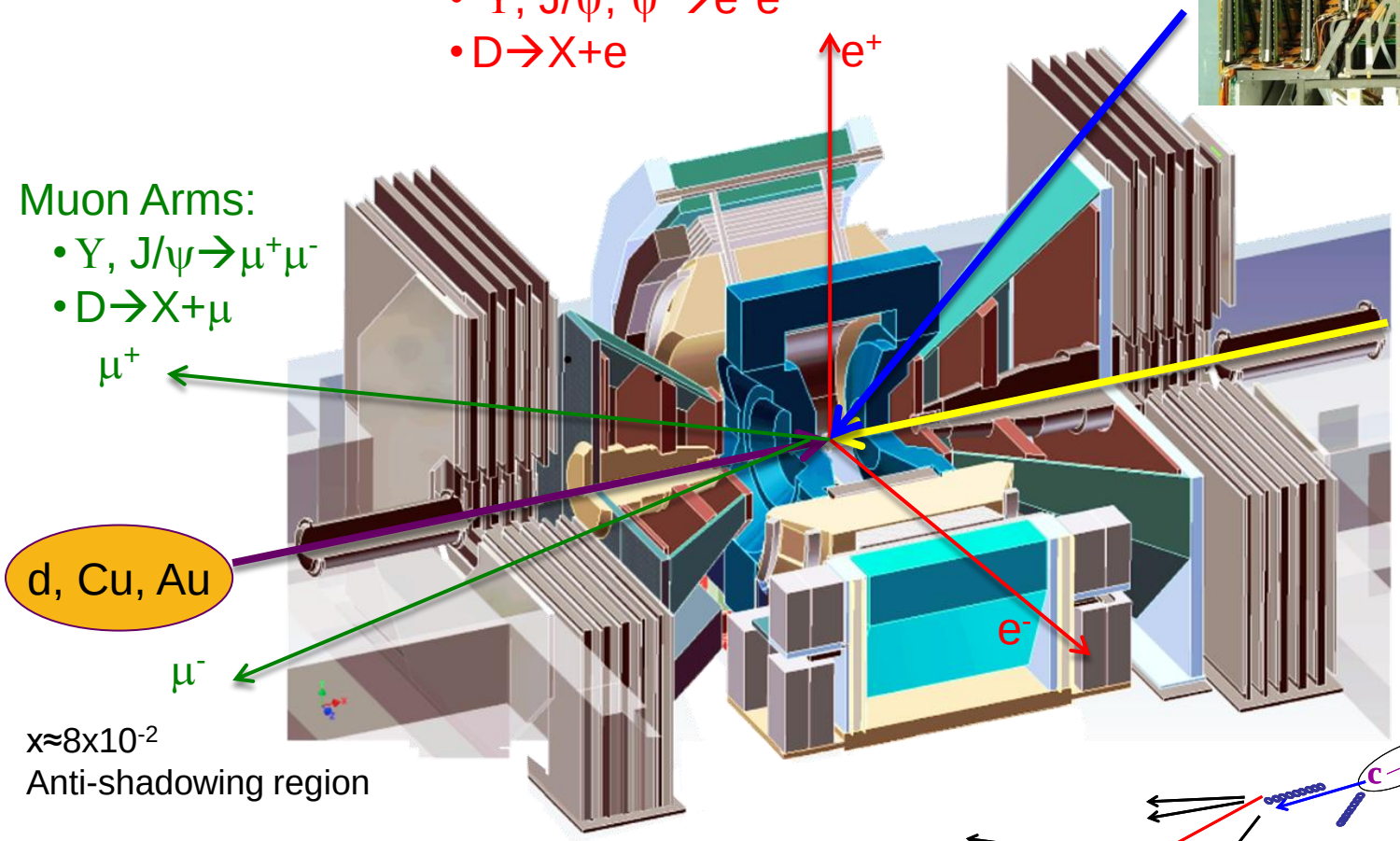
- Υ, J/ψ, $\psi' \rightarrow e^+e^-$
- $D \rightarrow X + e$

Adding FVTX:

- $\psi' \rightarrow \mu^+\mu^-$
- D, B

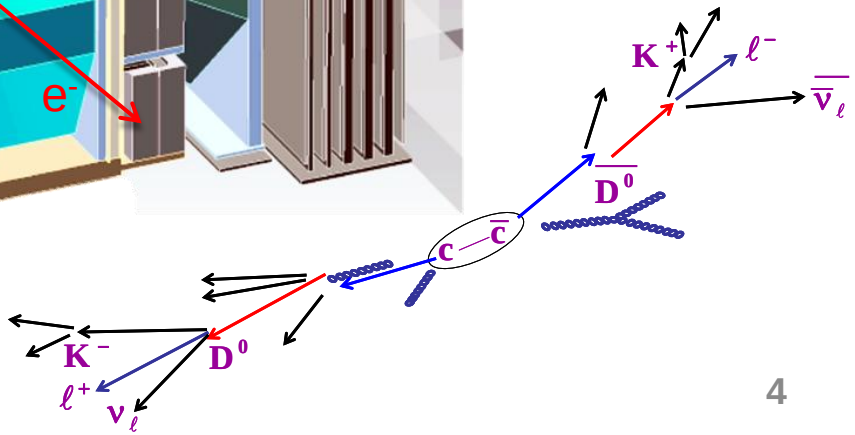
Muon Arms:

- Υ, $J/\psi \rightarrow \mu^+\mu^-$
- $D \rightarrow X + \mu$



$x \approx 5 \times 10^{-3}$
Shadowing region

$x \approx 8 \times 10^{-2}$
Anti-shadowing region



PHENIX data sets

Quarkonia

p+p (200 and 510 GeV)

- J/ψ, ψ', Υ at mid- and forward rapidities

d+Au (200 GeV)

- J/ψ, ψ', χ_c, Υ at mid-rapidity
- J/ψ, Υ at forward/backward rapidities

A+A (200 GeV)

- CuCu, J/ψ R_{AA} at forward rapidities
- AuAu, J/ψ R_{AA} at mid- and forward rapidities
- **CuAu, J/ψ R_{AA} at forward/backward rapidities**
- **AuAu, Υ at mid-rapidity**
- UU, J/ψ R_{AA} at 193 GeV at forward rapidities, preliminary result

A+A (62 GeV, 39 GeV)

- AuAu J/ψ R_{cp} at 39 and 62 GeV, forward rapidities

Open heavy flavor

p+p (200 GeV)

- Open heavy flavor baseline

d+Au (200 GeV)

- Open heavy flavor R_{dA}
- **bb cross section at mid-rapidity**

A+A (200 GeV)

- CuCu, open heavy flavor R_{AA}
- AuAu, open heavy flavor R_{AA} and v_2

A+A (62 GeV)

- **AuAu open heavy flavor R_{AA} and v_2**

Recent quarkonia results

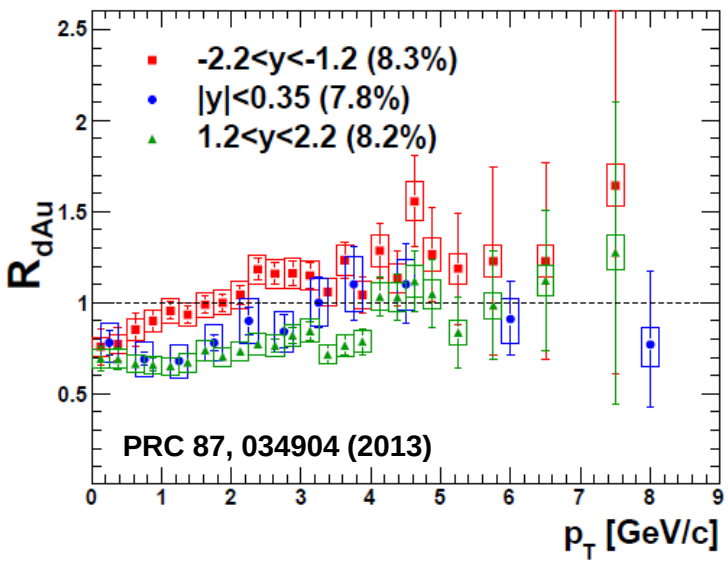
J/ψ in Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV

Y in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

J/ψ in cold and hot nuclear matter

- d+Au collisions at $\sqrt{s_{NN}}$=200GeV:

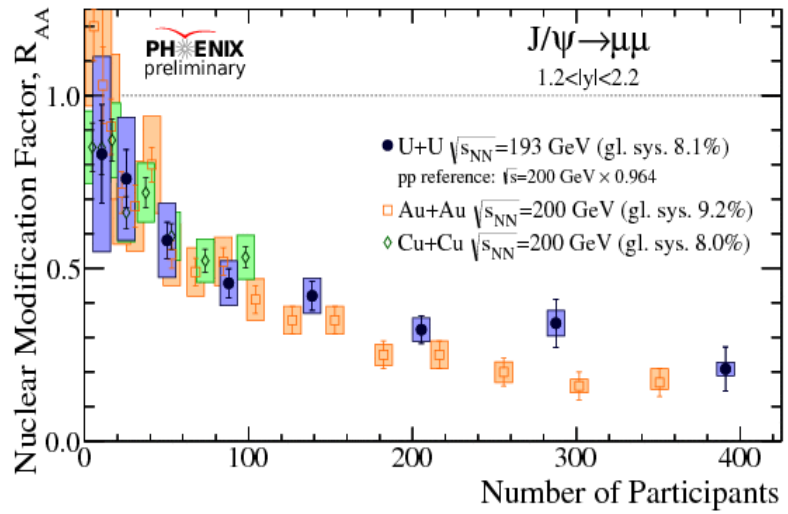
$$R_{dAu} = \frac{dN/dy_{dAu}}{\langle N_{coll}\rangle dN/dy_{pp}}$$



- Different suppression /enhancement pattern in d-going and Au going direction → probing different x in Au nucleus
- Gluon shadowing?

- A+A collisions at $\sqrt{s_{NN}}$=200GeV:

$$R_{AA} = \frac{dN/dy_{AA}}{\langle N_{coll}\rangle dN/dy_{pp}}$$

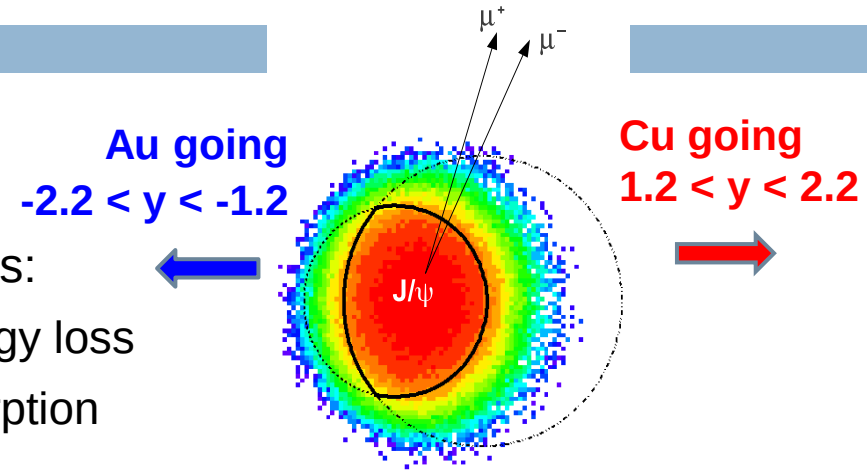


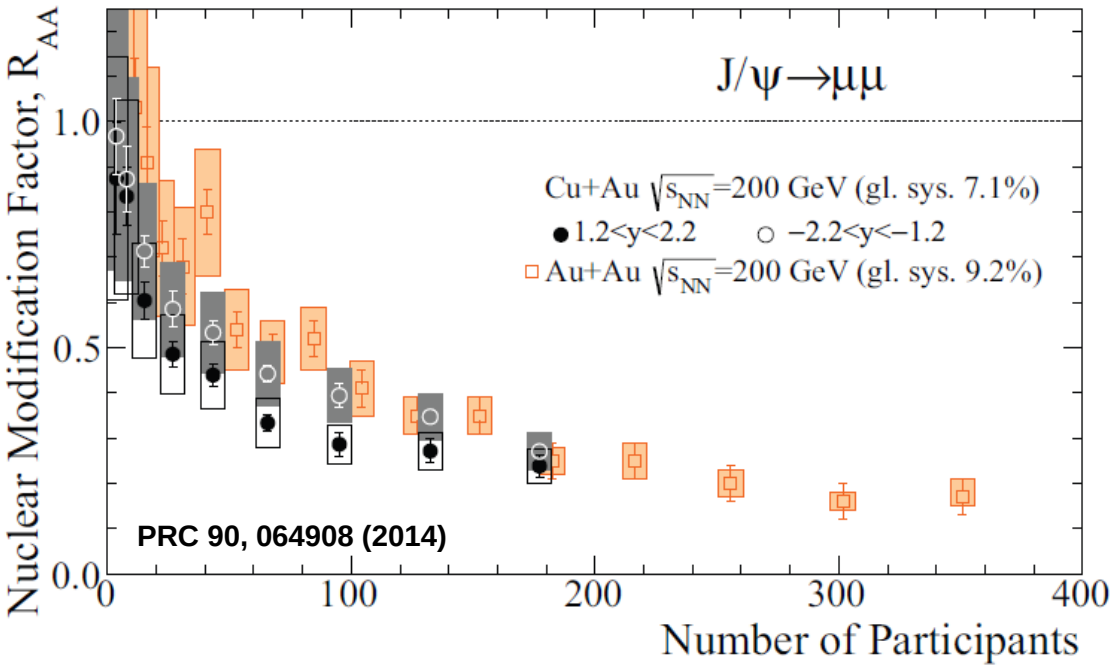
- Nuclear modification following the same trend vs. N_{part} for various systems

What will happen in Cu+Au collisions?

J/ψ in Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV

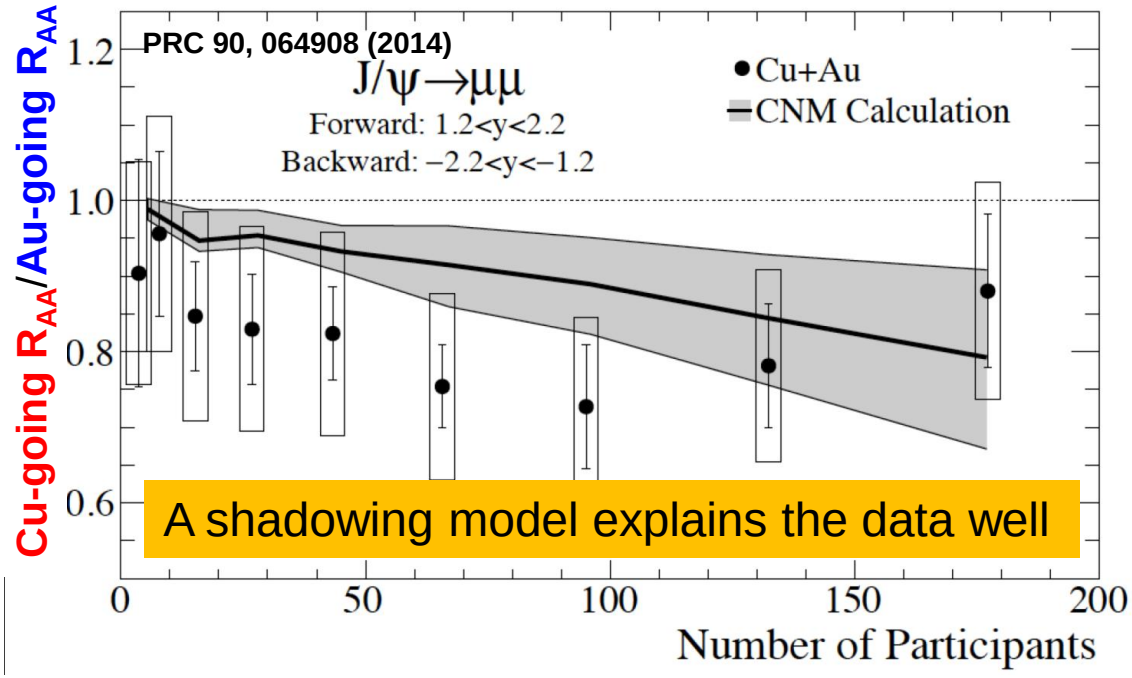
- Interplay between hot and cold nuclear matter effects
- Helps to disentangle the CNM effects:
  - short crossing time → probes energy loss
  - long crossing time → probes absorption

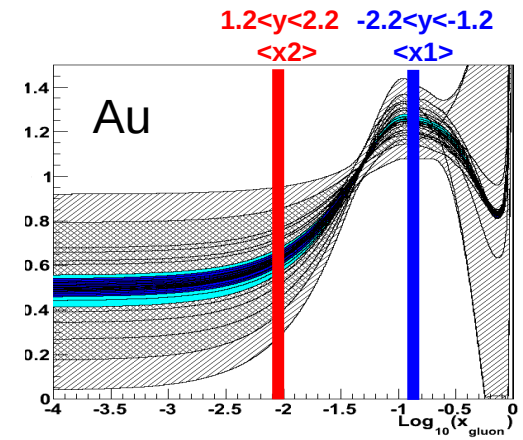


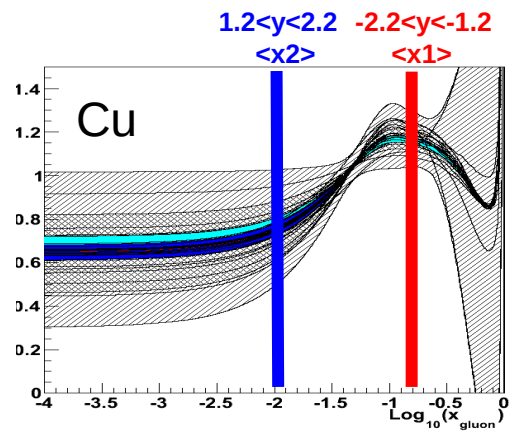


Higher suppression in region of lower particle density
→ QGP would have the opposite effect.
→ Similar to d+Au

J/ψ in Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV





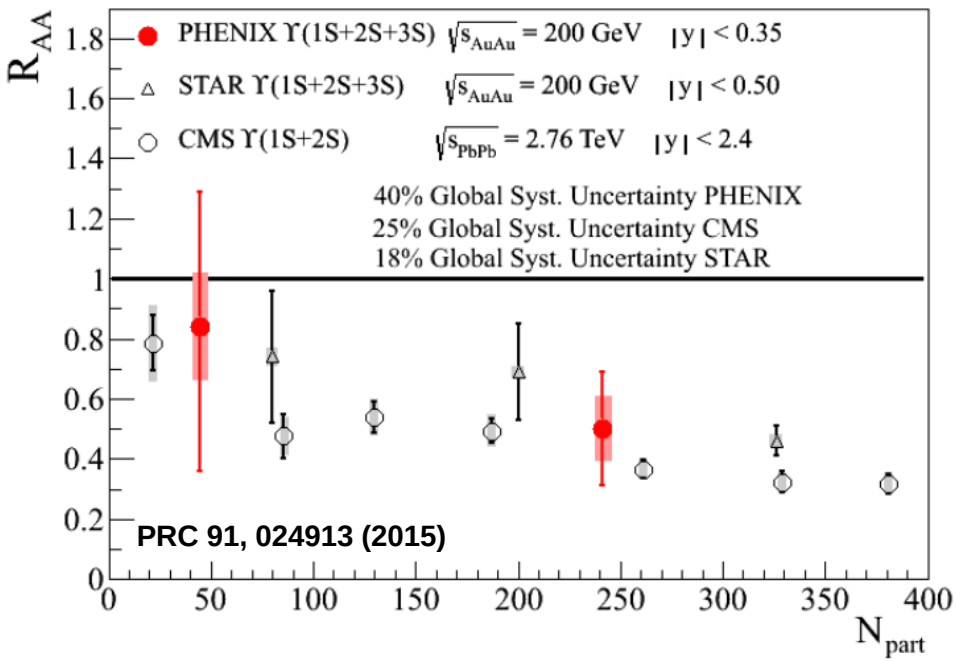


Au-going direction: low-x partons in Cu nucleus + high-x partons in Au nucleus

Cu-going direction: low-x partons in Au nucleus + high-x partons in the Cu nucleus

Υ in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

- PHENIX measured inclusive states Υ(1S+2S+3S) via e^+e^- channel at mid-rapidity
- **R_{AA} for min. bias collisions: 0.58+-0.17(stat)+-0.13(sys)+-0.22(glob)**
- Consistent with suppression of excited states:
  - Expected R_{AA} = 0.65 +- 0.11 (no 2S or 3S)
  - Expected R_{AA} = 0.37 +- 0.09 (no 2S, 3S, or χ_B)
- Compatible with CMS measurement at higher energy



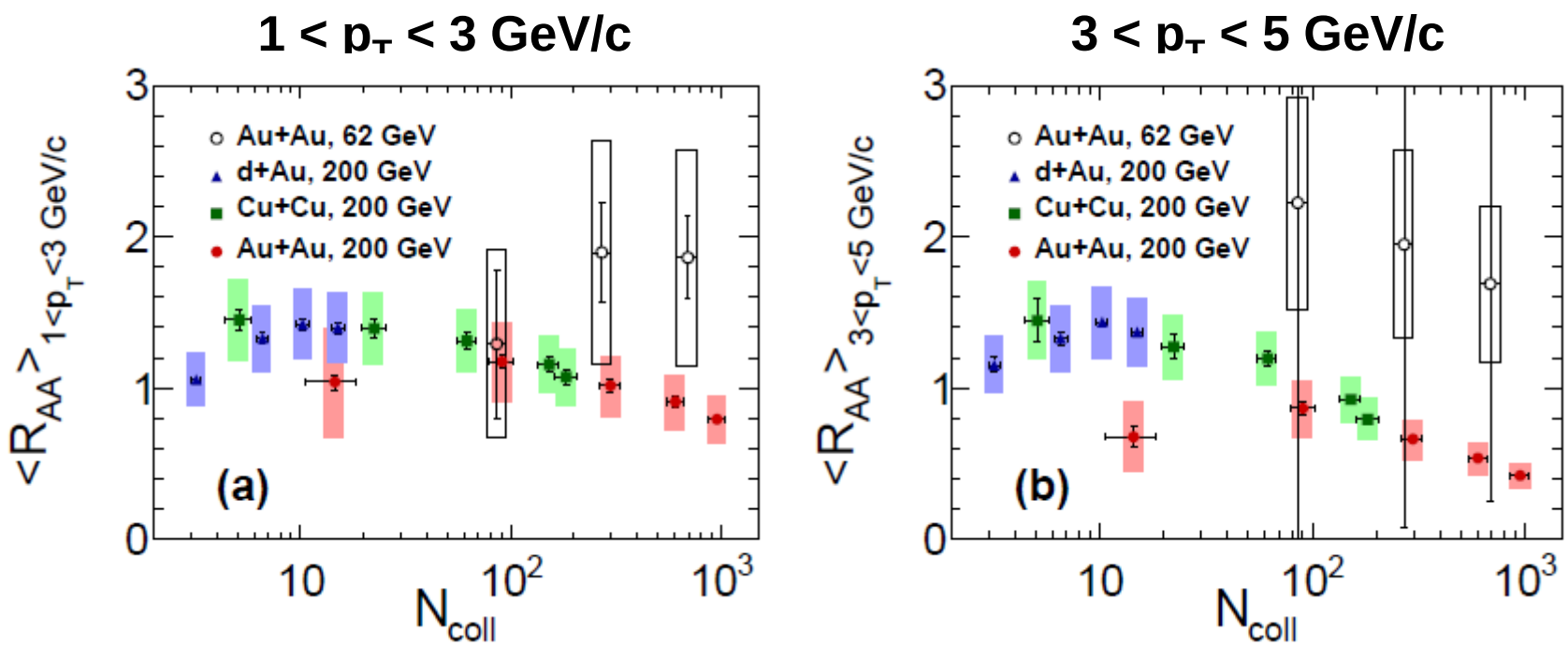
Recent open heavy flavor results

Yield and elliptic flow of heavy quarks from Au+Au collisions at $\sqrt{s_{NN}}$=62 GeV

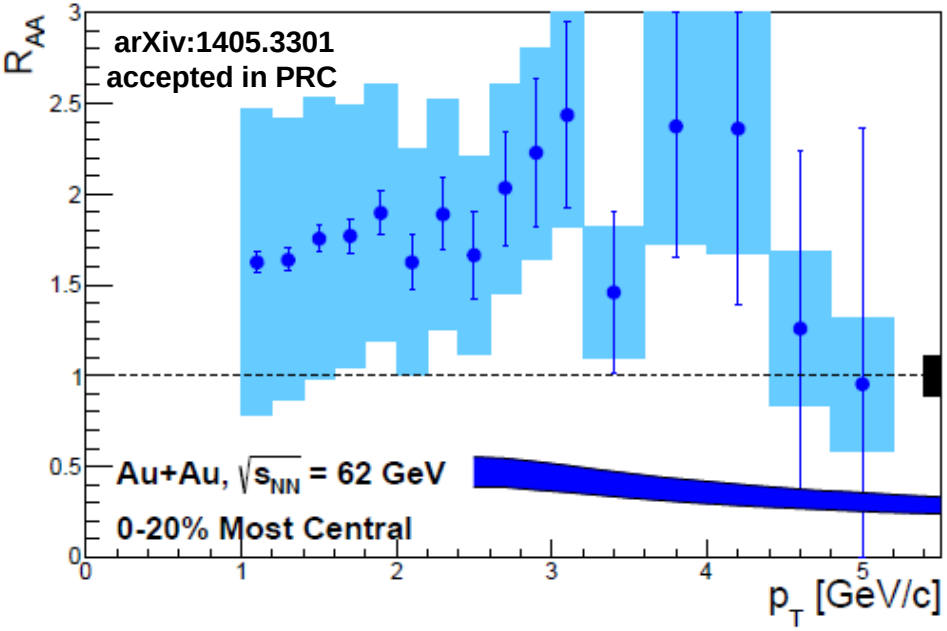
bb cross-section from e^+e^- channel in d+Au at $\sqrt{s_{NN}}$=200 GeV

Open heavy flavor at $\sqrt{s_{NN}}$=62 GeV

- Electrons from semi-leptonic decays of heavy flavored mesons (D, B) at mid-rapidity
- R_{AA} modification factor, using p+p baseline from ISR experiment



Compare modification with theory

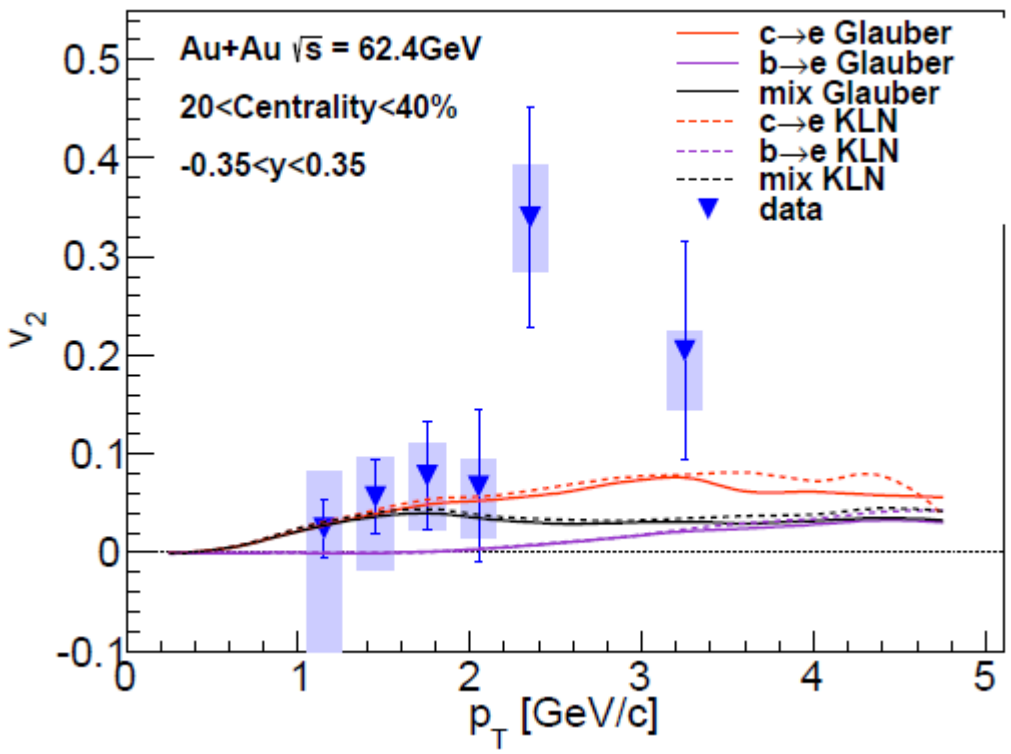


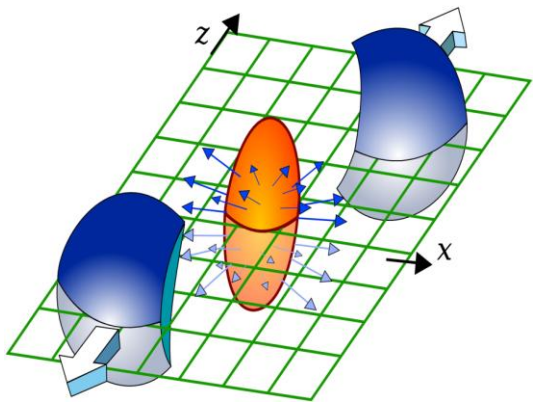
In contrast with R_{AA} at 200 GeV which is < 1

Theoretical calculation including partonic energy loss and dissociation of D and B mesons
→ describes the suppression at 200 GeV
→ underpredicts 62.4 GeV data

Compatible with dAu result?
Larger Cronin enhancement?
Smaller energy loss?
Both?

Elliptic flow of open heavy flavor at mid-rapidity



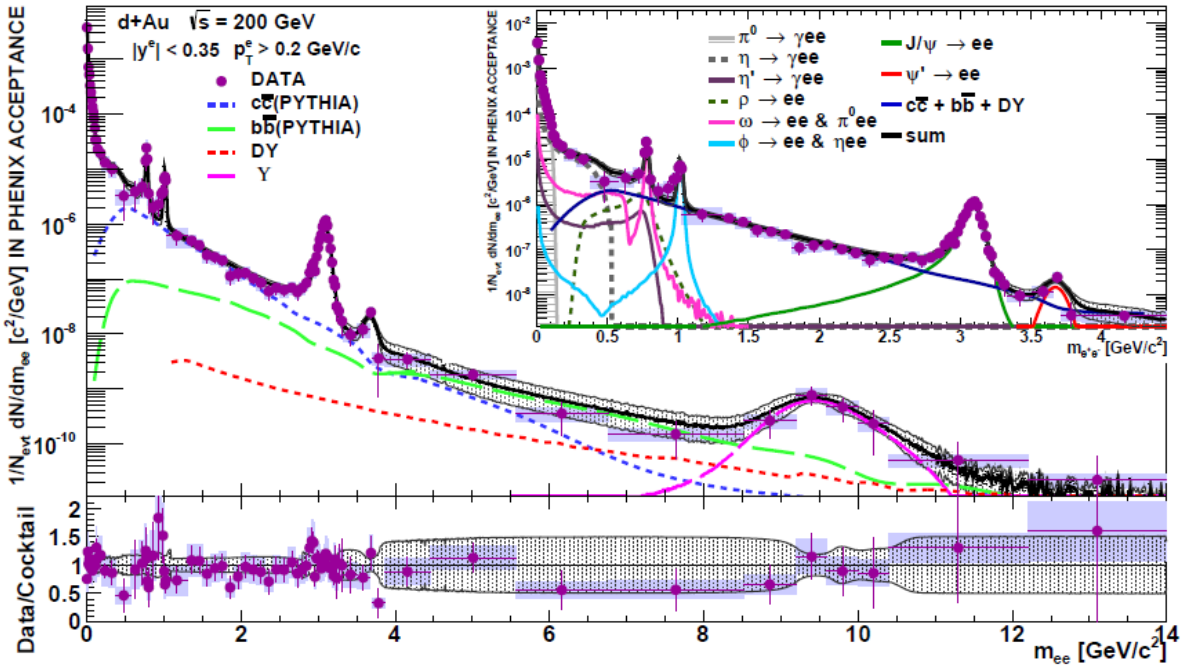


- Non-zero v_2 in 62 GeV Au+Au
- Compatible with 200 GeV Au+Au results
- Models describe data below p_T of 2 GeV/c

Collective motion of charmed hadrons through recombination with flowing light partons?

bb cross-section in d+Au at $\sqrt{s_{NN}}$=200 GeV

- Dielectron invariant mass in agreement with hadronic cocktail
- Subtract the cocktail of pseudoscalar and vector mesons + Drell-Yan
- Remaining yield is from heavy flavor decays
- Simulations suggest:
  - Charm dominates at low mass and low p_T
  - Bottom dominates at low mass and high p_T, as well as high mass and low p_T



→dielectron channel allows separation of charm and bottom contributions in m_{ee} – p_T space

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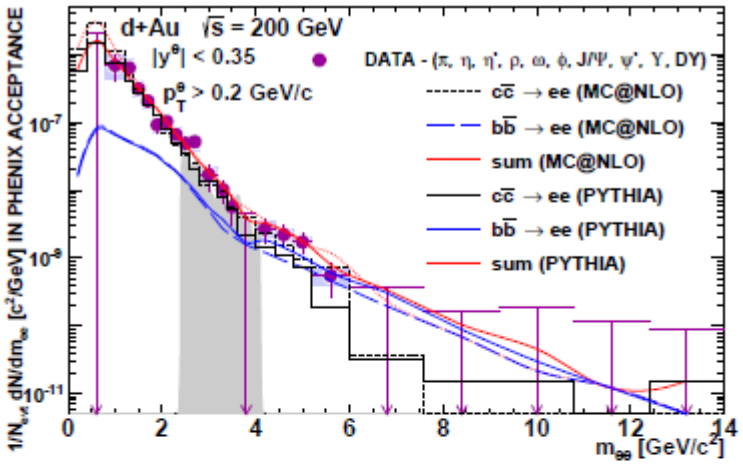
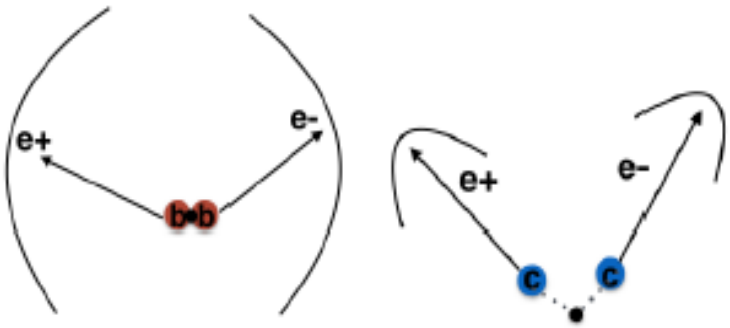
bb cross-section in d+Au at $\sqrt{s_{NN}}$=200 GeV

- Perform PYTHIA and MC@NLO simulations in mass and p_T
- Fit the simulated shapes to the data
- **Both simulations describe the data equally well**, although different underlying mechanisms
- → Extracted $c\bar{c}$ cross-section in PYTHIA and MC@NLO significantly different, due to strong model dependence
- Expect weaker model dependence for $b\bar{b}$
  - M_b>>p_b, so e^+e^- pairs will come out ~isotropically
  - Not the case for e^+e^- pairs from $c\bar{c}$, which are boosted along the pair momentum





bb cross-section in d+Au at $\sqrt{s_{NN}}$=200 GeV

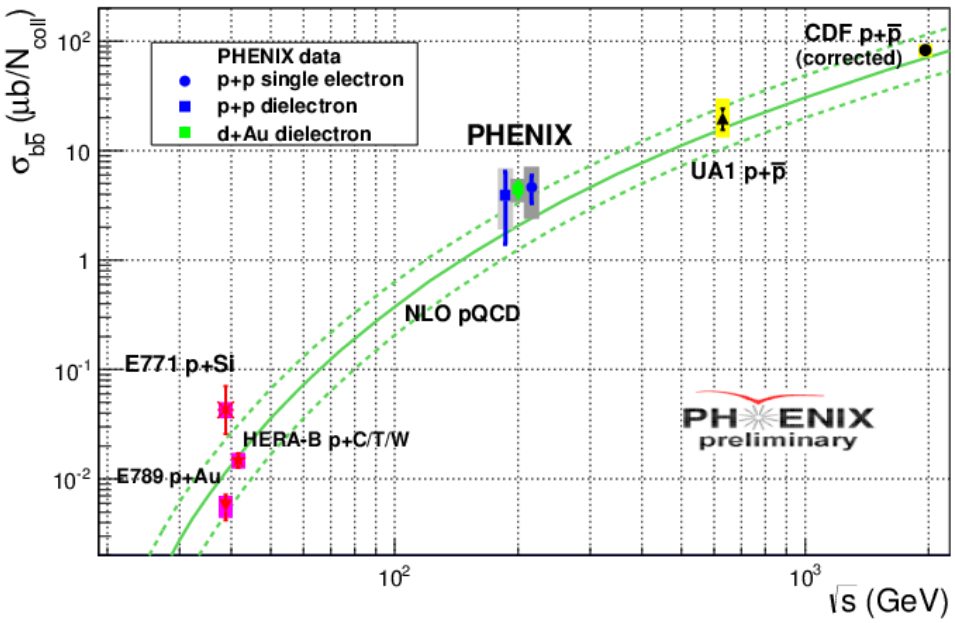
- For $b\bar{b}$, the difference between PYTHIA and MC@NLO < 2%
- Allowes extraction of the $b\bar{b}$ cross section in d+Au:

$$\sigma_{b\bar{b}}^{dAu} = 1.27 \pm 0.28(stat) \pm 0.46(syst) \text{ mb}$$

- In terms of nucleon-nucleon equivalent cross-section:

$$\sigma_{b\bar{b}}^{NN} = 3.4 \pm 0.8(stat) \pm 1.1(syst) \ \mu\text{b}$$

Nucleon-nucleon equivalent bb cross-section



Summary

- J/ψ in Cu+Au collisions
  - Suppression more compatible with d+Au than Au+Au
  - Trend is comparable with the calculations using EPS09
- Inclusive Y at mid-rapidity in Au+Au – suppression consistent with disappearance of Y 2S+3S(+χ_B) states
- Open heavy flavor at 62.4GeV
  - enhancement of yield, contrast to 200 GeV Au+Au data
  - non-zero v_2
- Dielectron channel in d+Au at 200 GeV
  - High quality data allowed separation of $c\bar{c}$ and $b\bar{b}$ contributions and extraction of the $b\bar{b}$ cross-section

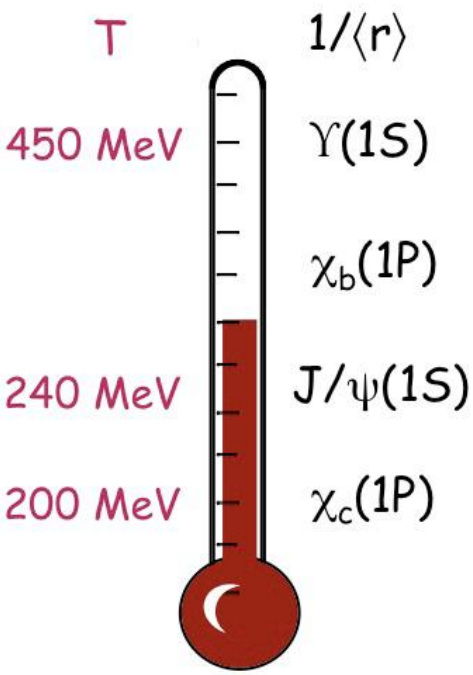
Outlook

- Analysis underway:
  - J/ψ : ψ' ratio in CuAu and AuAu at forward rapidity – will we see any ψ'?
  - Dielectron channel in p+p collisions to separate cc and bb contributions – comparison with d+Au to explore CNM effects
- VTX and FVTX allow separation of quarkonia states, enable higher precision analysis of the heavy flavor
- Run-15 p+A measurements to further explore the CNM effects.
- Possible stronger coupling near T_c drives interest in Au+Au and p+p at $\sqrt{s_{NN}}$ = 62.4 GeV for 2016 Run

BACKUP

The role of heavy quarks in heavy-ion collisions

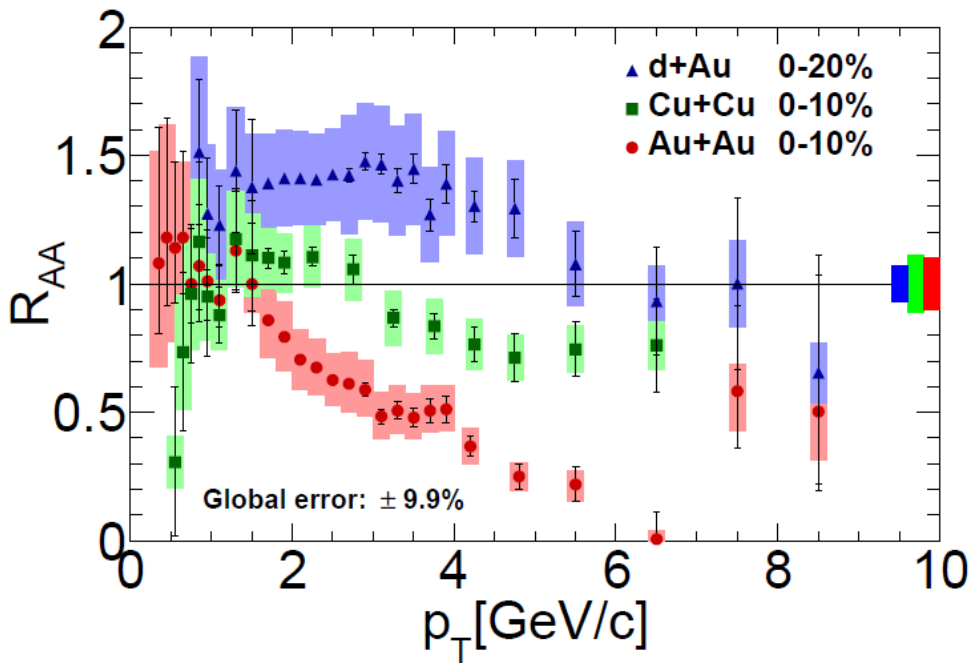
- Heavy quarks produced early in the collisions → auto-generated probes
- Quarkonia states have different binding energies:
  - Probe QGP - suppression of individual states due to screening provides a "thermometer"
  - Probe CNM: natural length (quarkonia size) & time scales (quarkonia momentum)
- Modification of nPDFs, Energy loss and Cronin affect both quarkonia and OHF
- Nuclear absorption (break-up) affects quarkonia only.



Heavy flavor electrons at mid-rapidity

Cu + Cu system can be bridge between d + Au system and Au + Au system (CNM dominance region and HNM dominance region)

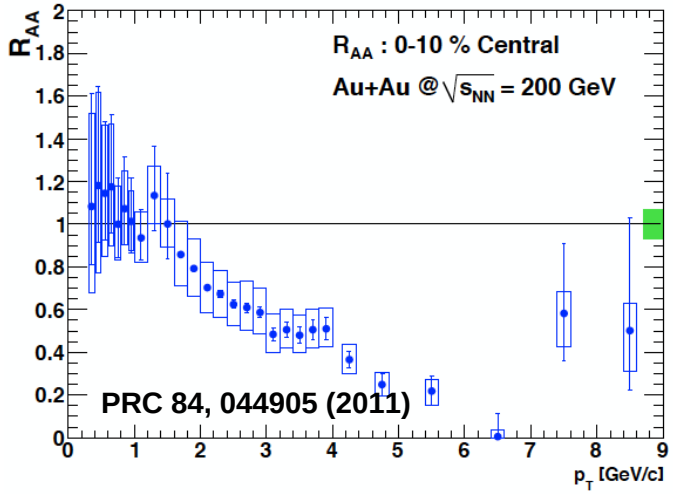
R_{AA} comparison between different systems



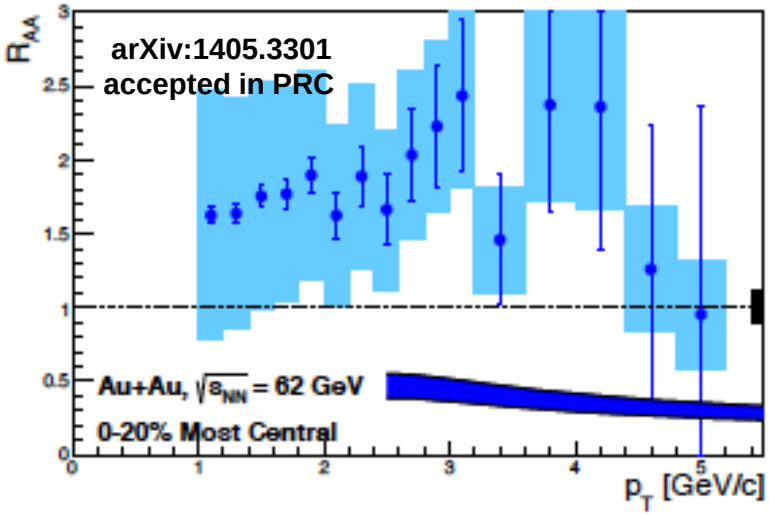
- **Clear enhancement in d + Au**
- **Large suppression in Au + Au**
- **Cu + Cu: intermediate R_{AA} between that in d + Au and Au + Au**

Open heavy flavor modification midrapidity

200 GeV Au+Au



62.4 GeV Au+Au



- Large suppression in 200 GeV Au + Au collisions

- Clear enhancement in 62.4 GeV Au+Au collisions
- Due to less energy loss? Larger Cronin effect? Or a combination of those factors?

bb cross-section in d+Au at $\sqrt{s_{NN}}$=200 GeV

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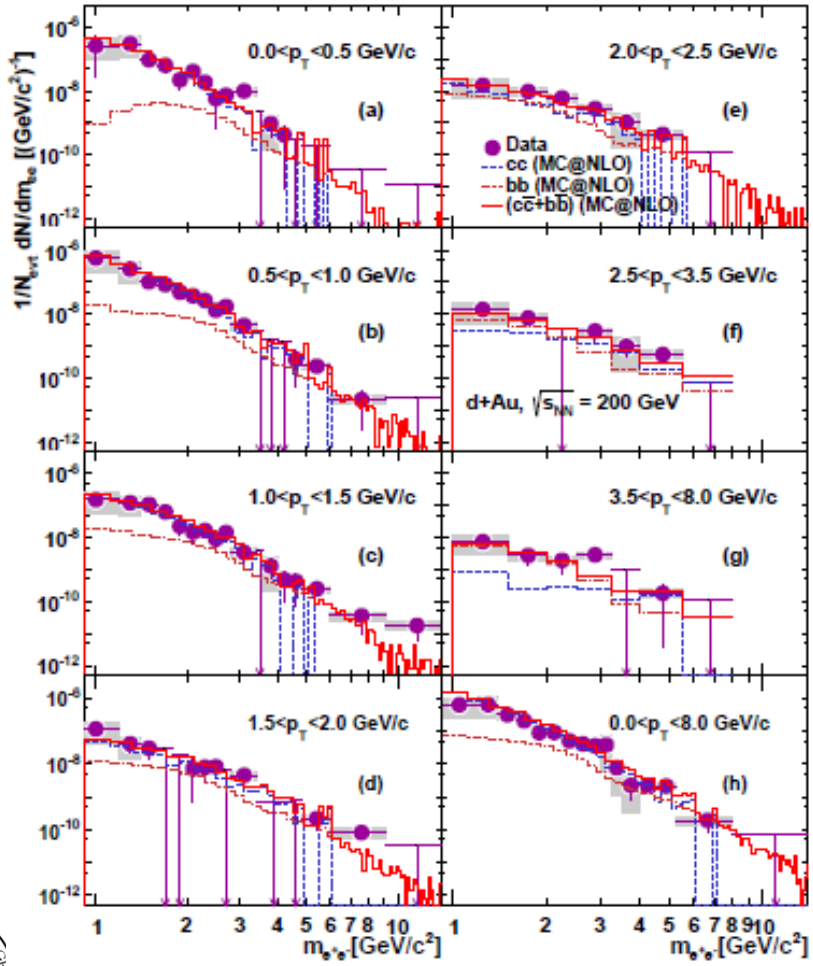
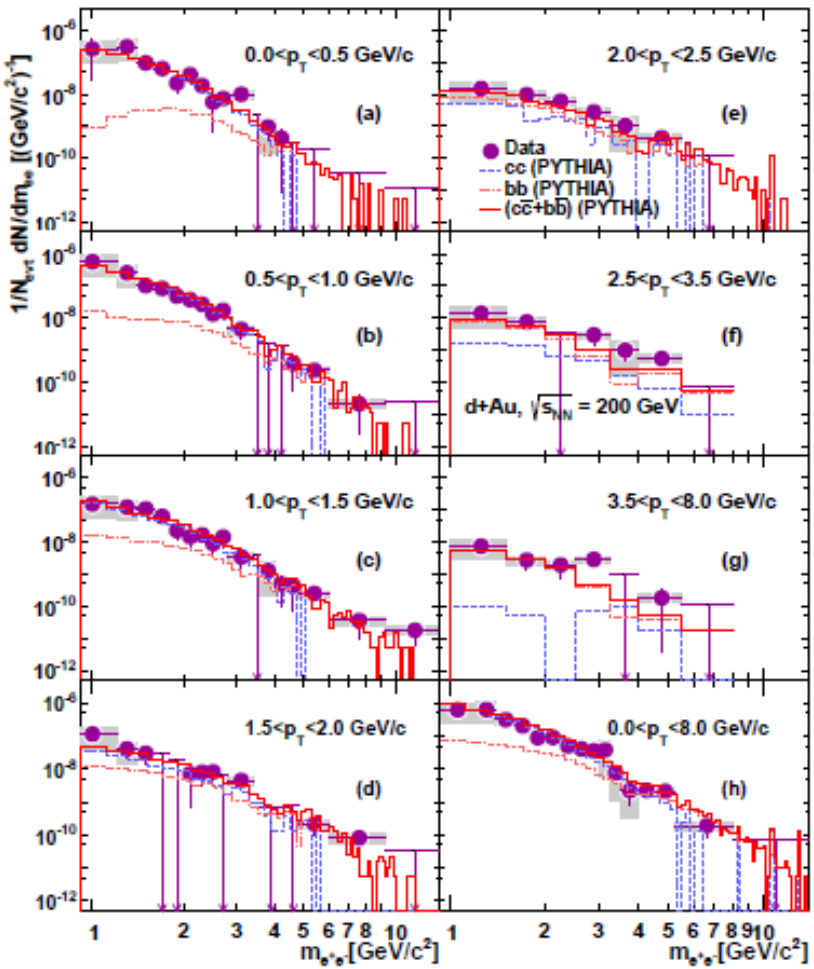
MC@NLO



PYTHIA