# Charm production in high-energy p+A & A+A collisions

1. Cold nuclear matter effects from SPS to RHIC
2. Charm in heavy ion collisions

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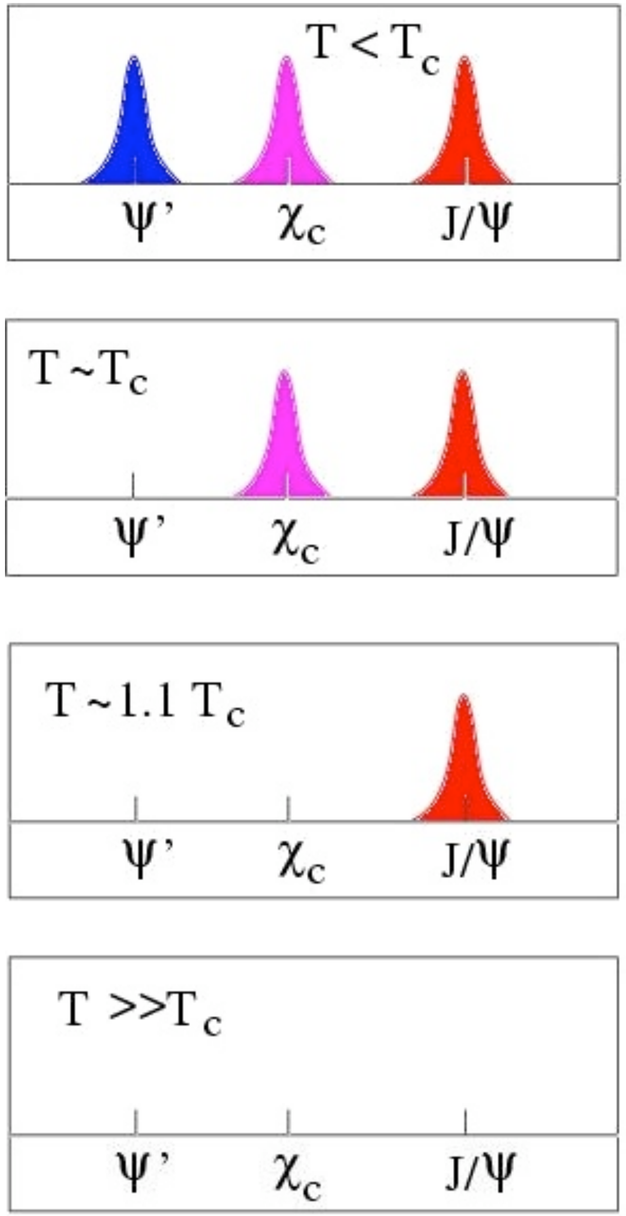
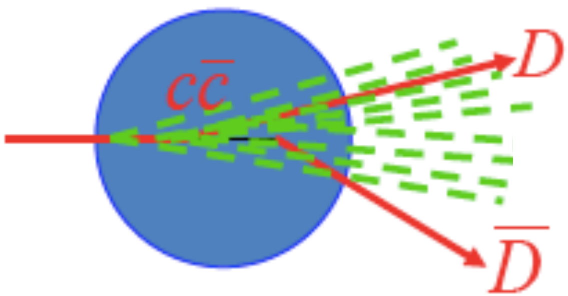
# Motivation

- Charm as a probe of the QGP
  - J/ψ suppression: golden signature of the QGP
  - Charmonia as thermometer
  - Open charm
    - Heavy quark energy loss in medium
    - Reference for charmonium suppression
- Cold nuclear matter effects important for interpretation of HI measurements
  - Nuclear PDFs, initial state parton energy loss, final state absorption ($\sigma_{abs}$), etc.

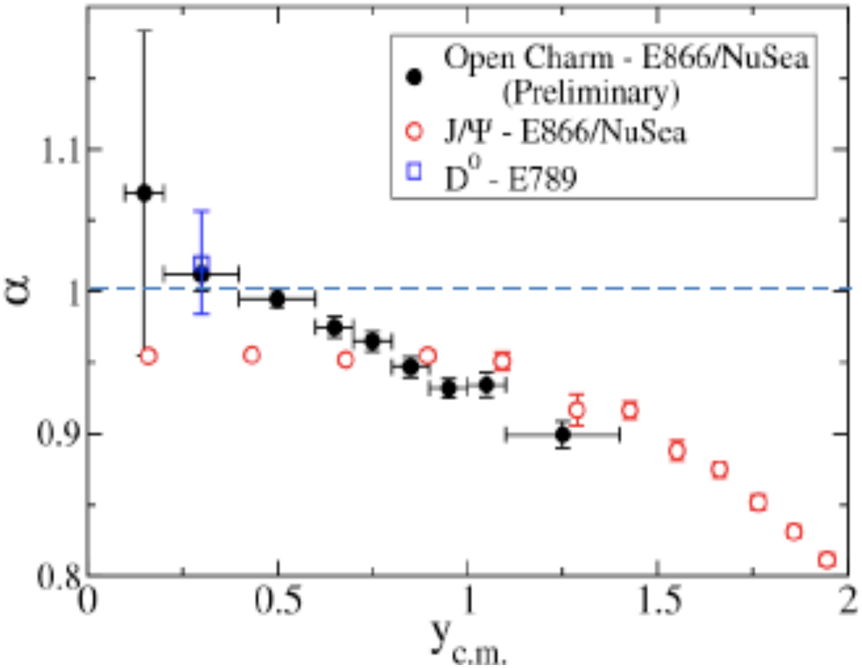


# 1. Cold nuclear matter effects from SPS to RHIC

# Charm production at E866…

- Fixed target p-A collisions at 800 GeV
- Broad rapidity coverage




$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

<u>Mid-rapidity (y<0.5):</u>

- J/ψ strongly absorbed
- No nuclear effects on open charm

→ At mid-rapidity, final state effects dominate the changes to the per-nucleon cross sections (and kinematics)

<u>Forward rapidity:</u>

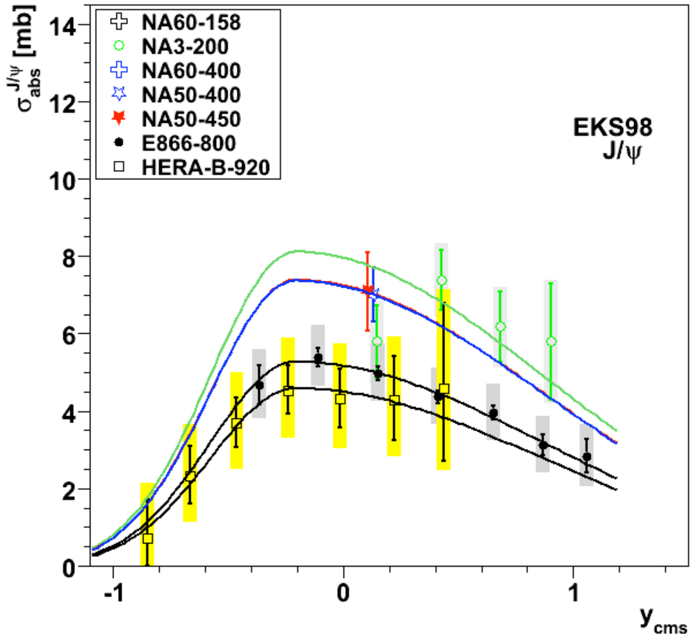
- Strong reduction of the J/ψ and open charm per-nucleon production cross sections

→ Strong indication of initial state effects
  - Nuclear modification of PDFs?
  - Initial state gluon energy loss?

# …at SPS and HERA-B…

- NA3, NA50, E866, HERA-B (200, 400/450, 800, 920 GeV)
- Similar J/ψ trend as E866 in p-A:
  - Changes with J/ψ rapidity & collision energy

JHEP 02 (2009) 014



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JHEP 02 (2009) 014

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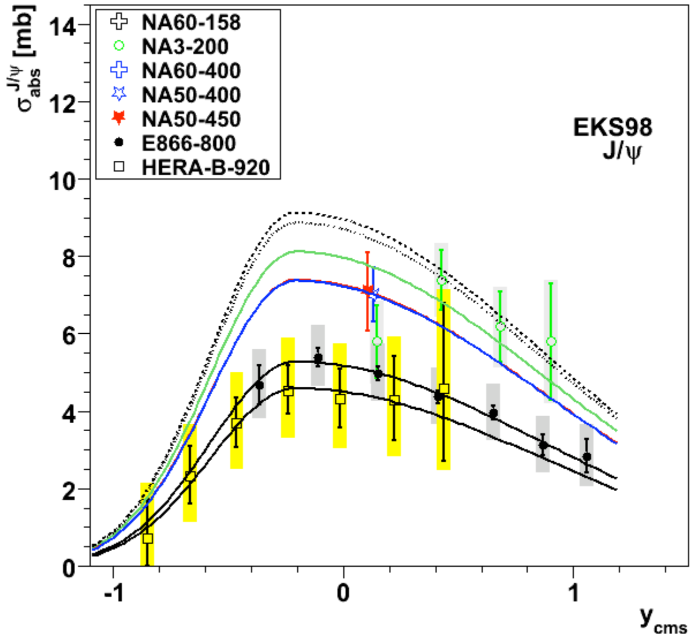
  - Prediction for 158 GeV shown as black dotted line



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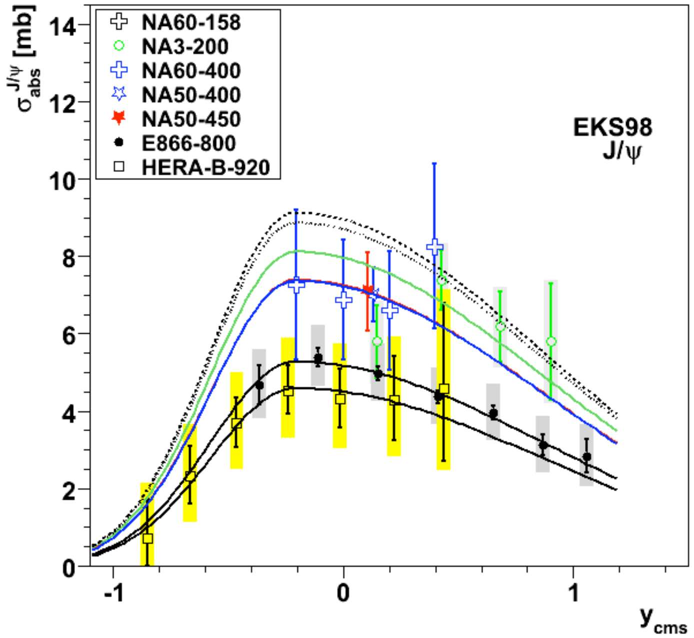

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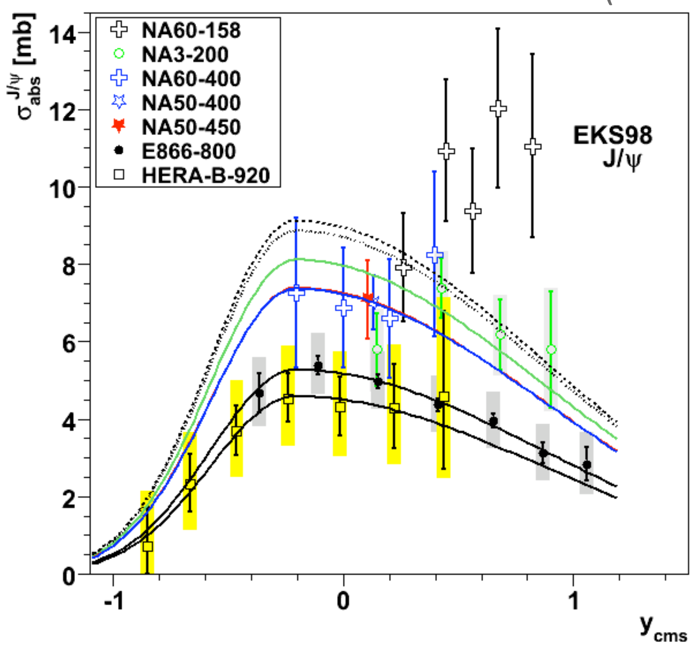


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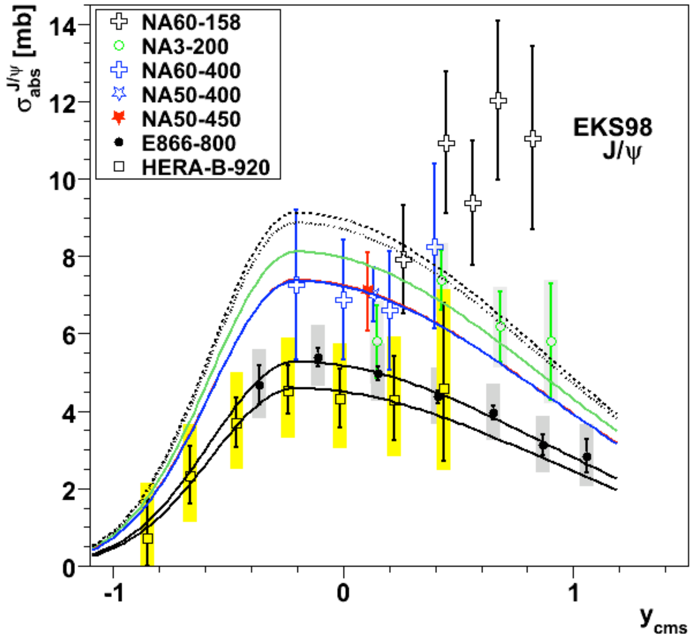
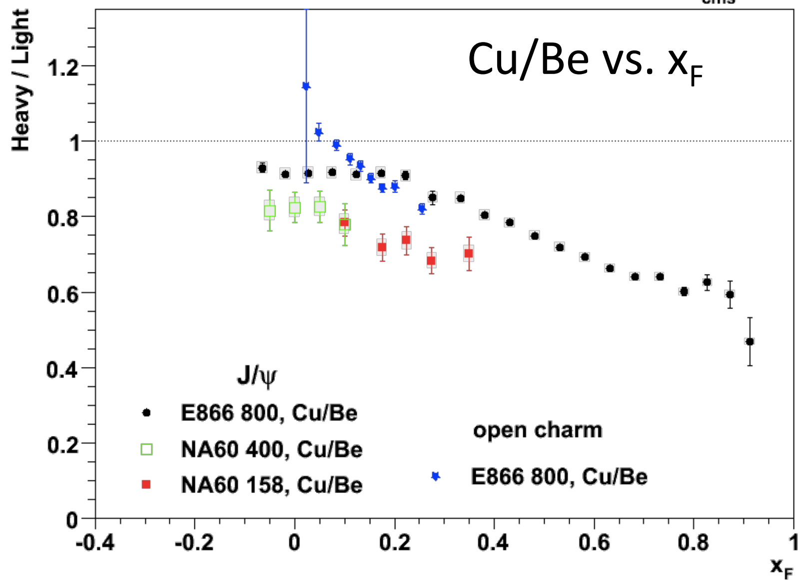
  - NA60 data at 158 GeV are generally higher than expected (besides the first point)
  - → Different physics at forward rapidity than just nuclear absorption?
    - But similar trend also observed for open charm, ergo initial state effects…?

- Non-trivial cocktail of initial and final state effects

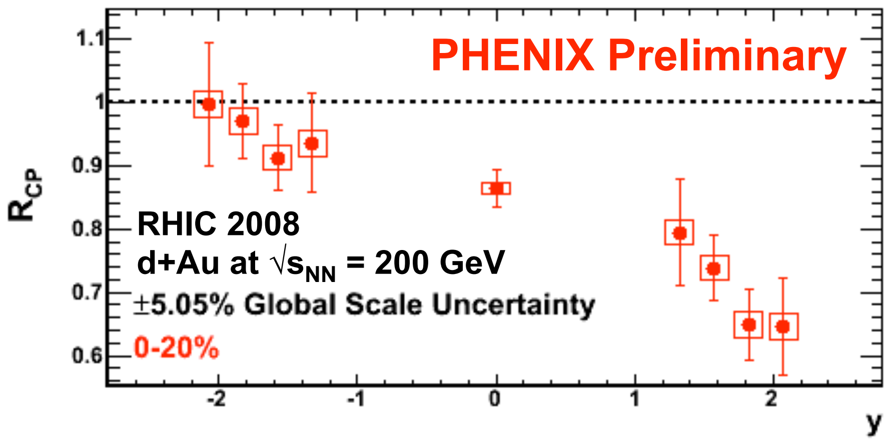


# …and at RHIC?

- Collider with √s = 200 GeV
  p+p, d+Au (+heavy ions)

- J/ψ in d+Au central vs. peripheral shows significant increase of "absorption" at forward rapidity
  - As seen by E866, NA3, …
    → energy loss as well?



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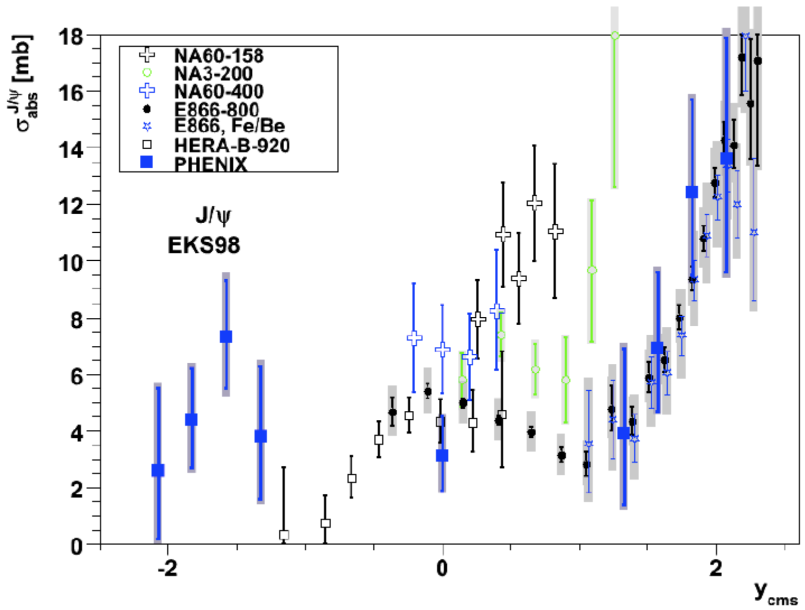

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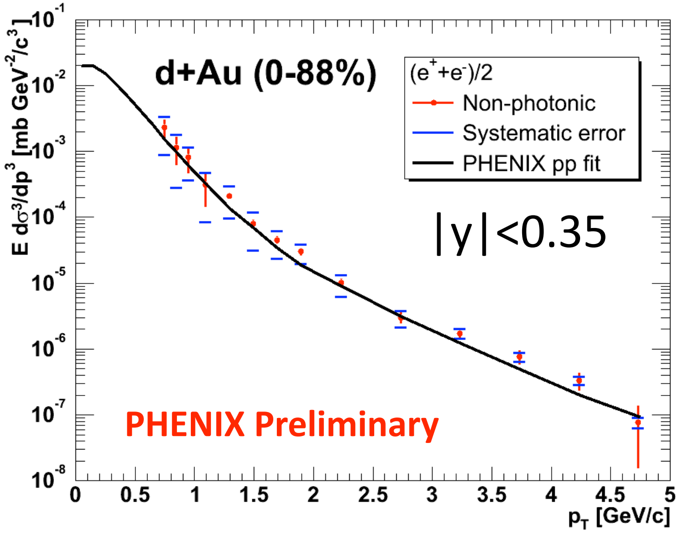
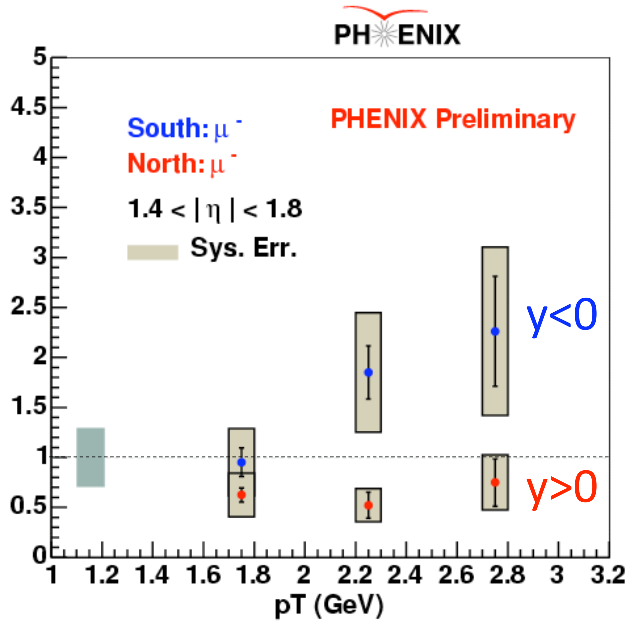
  - As seen by E866, NA3, ...
    → energy loss as well?
  - If so, should also affect open charm
  - Existing data of non-photonic leptons from semi-leptonic open charm decays have large uncertainties, but indicate the same trend
  - Should be seen in new data (Run 8) analysis is ongoing



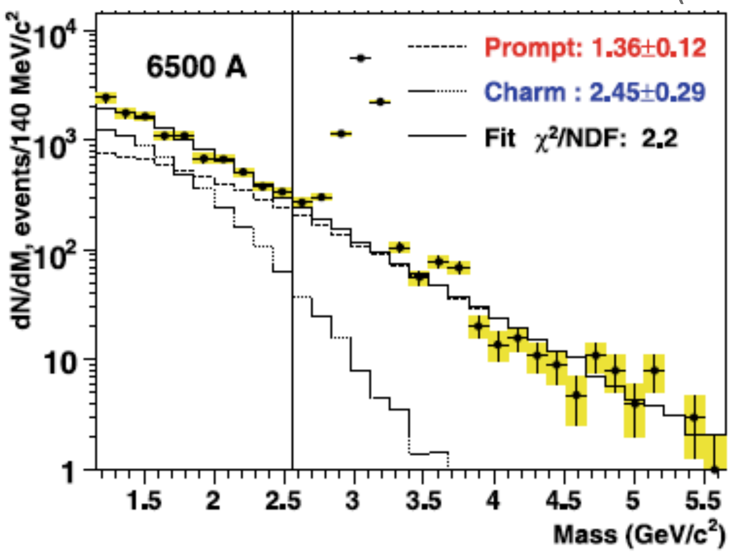



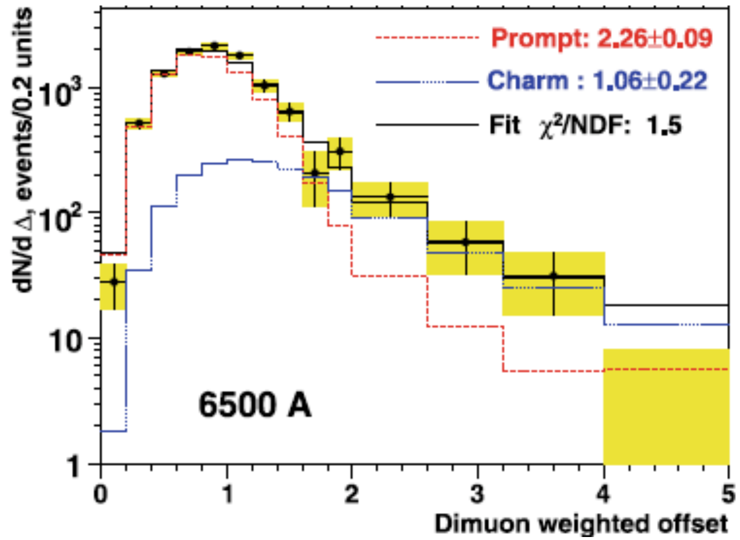
# 2. Charm in heavy ion collisions

# NA60: open charm in In-In

EPJ C 59 (2009) 607

- NA60 measured dimuon continuum in In-In collisions at the SPS at 158 GeV
- With vertexing able to distinguish non-prompt from prompt dimuons in the intermediate mass region (1.16–2.56 GeV)
- Non-prompt:
  - From simultaneous semi-leptonic decays of charmed mesons
  - Two times larger charm cross section than the world average (based on fully reconstructed D → π K decays)
  - Open charm in p-p needed



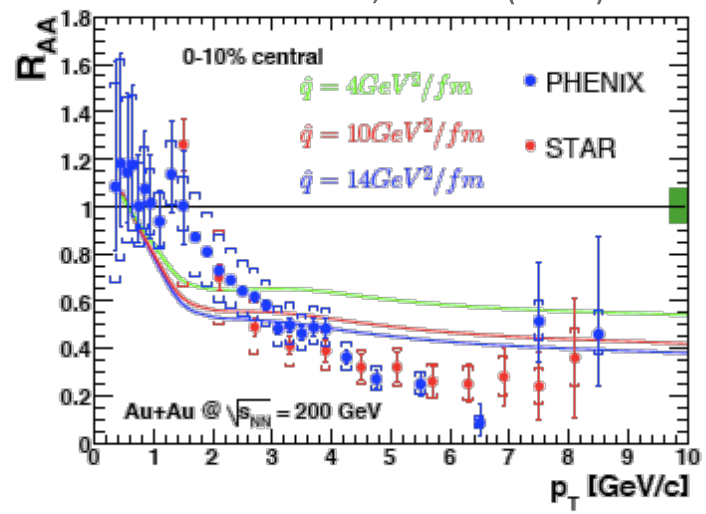



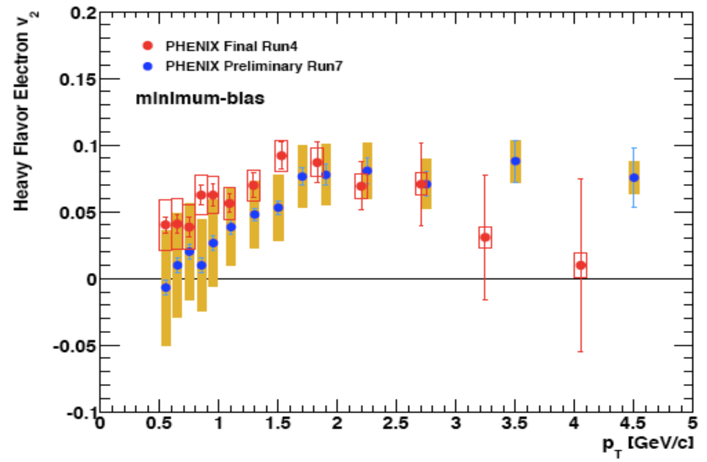
# RHIC: open charm in Au+Au

PHENIX, PRL 98 (2007) 172301
STAR, PRL 98 (2007) 192301

- PHENIX & STAR have measured non-photonic single electrons in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- STAR measures 2× larger open charm cross section than PHENIX both in p+p and Au+Au (cancels in $R_{AA}$)
- Both measure high $p_T$ suppression of electrons from semi-leptonic open charm (& beauty?) decays
- Significant elliptic flow

→ Final state effect: strong coupling of heavy quarks to the medium



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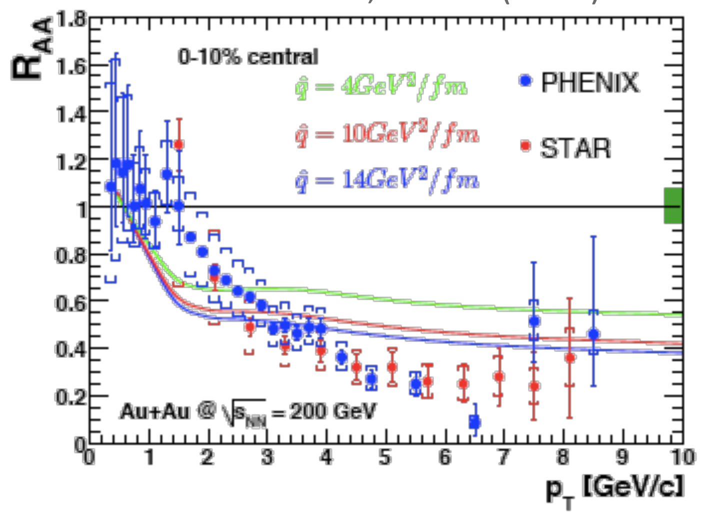
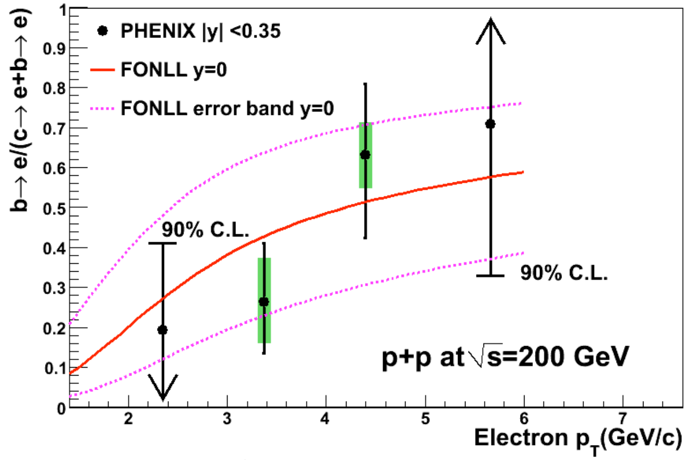
- Where does beauty become important?
- b/(c+b) measured via e-h correlations in p+p



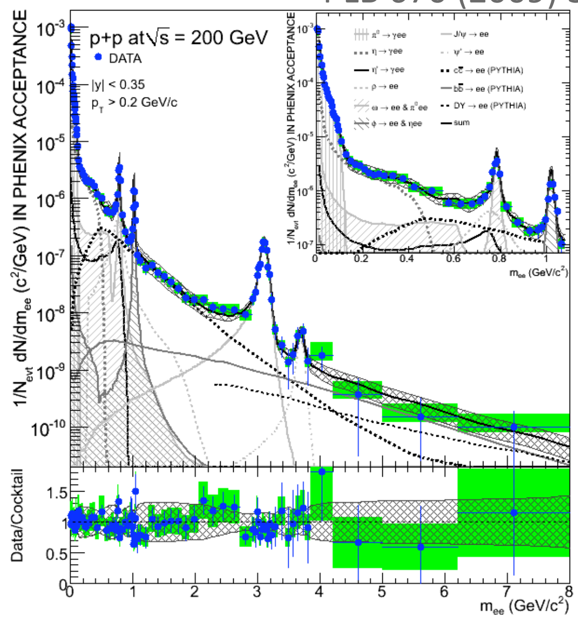



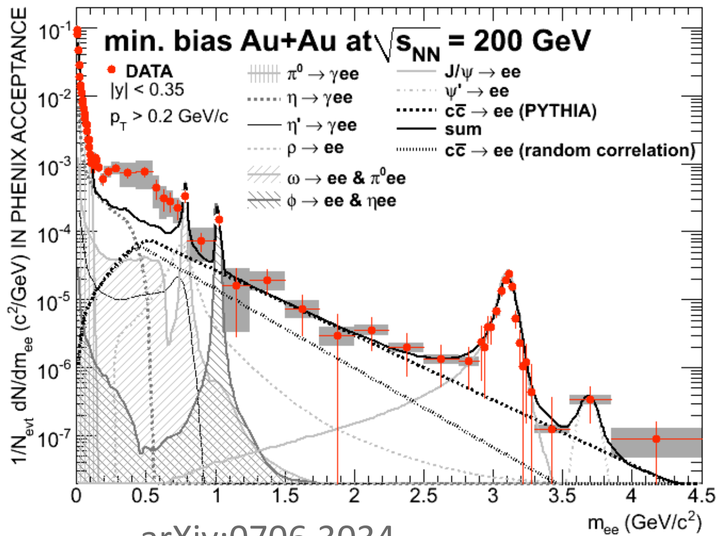

arXiv:0903.4851

# PHENIX: open charm in dielectrons

- PHENIX has measured dielectrons in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- p+p:
  - IMR shape in excellent agreement with PYTHIA
  - Total charm and beauty  cross section:
    $\sigma_{cc}$ = 544 ± 39 (stat) ± 142 (syst) ± 200 (model) μb
    $\sigma_{bb}$ = 3.9 ± 2.5 (stat) $^{+3}_{-2}$ (syst) μb
  - In very good agreement with PHENIX result from non-photonic single electrons:
    $\sigma_{cc}$ = 567± 57 (stat) ± 193 (syst) μb
- Au+Au:
  - IMR in apparent agreement with PYTHIA scaled to total cross section of $\sigma_{cc}$ = 567μb × $N_{coll}$
  - But we know that open charm is heavily modified
  - Toy model: randomized correlation of c and cbar is much softer
  - Would leave room for thermal photons from qqbar
  - We know they should be there, because PHENIX has measured thermal photons at very low mass from qg Compton scattering and NA60 (SPS) has seen them

PLB 670 (2009) 313




arXiv:0706.3034

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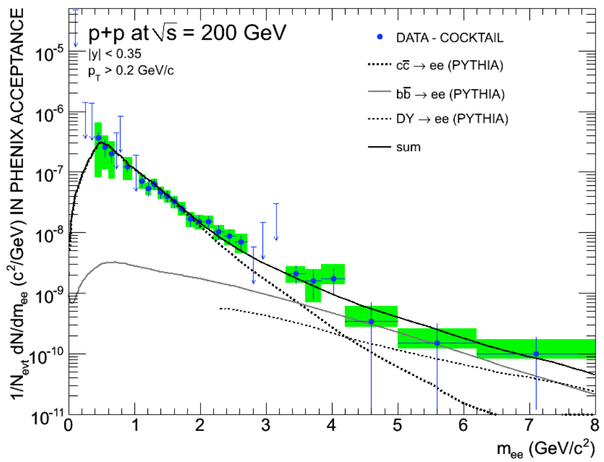
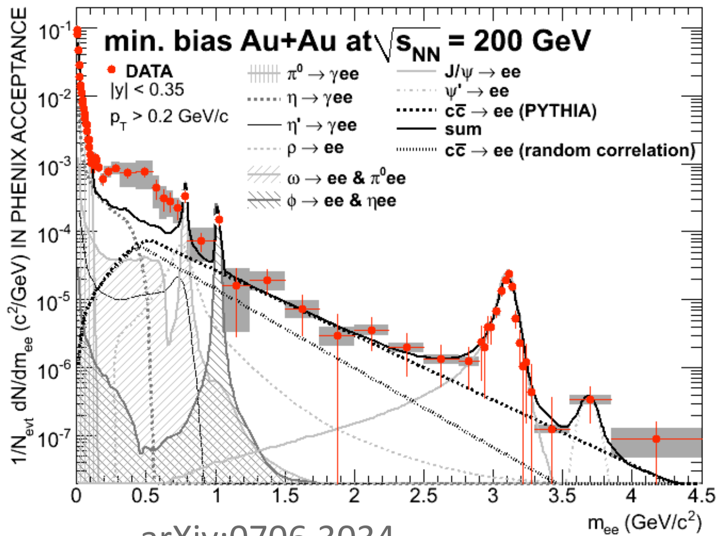



arXiv:0706.3034

# Summary

- Cold Nuclear Matter Effects
  - Charm production in p-A collisions at forward rapidity seems to probe initial state effects (similar behavior of closed and open charm)
  - Mid-rapidity different for open and closed charm

→ shows non-trivial cocktail of initial and final state effects

- Charm in heavy ion collisions
  - Single electrons from semi-leptonic open charm decays suppressed at high $p_T$ in Au+Au collisions at RHIC (+ significant elliptic flow)
    → attributed to heavy quark energy loss in the hot and dense medium
  - Dielectrons in IMR from correlated open charm decays in Au+Au collision consistent with no modification in shape with respect to p+p
    → a fortunate cancelation of modified open charm + thermal radiation from qqbar annihilation?

# Outlook

RHIC II

- Will provide increased luminosities to study rare processes with higher statistics
- Detector upgrades in PHENIX and STAR will enable vertexing and improved beauty/charm separation
- Will hopefully resolve factor 2 difference in charm cross section measurements by PHENIX and STAR

The LHC

- Higher $\sqrt{s}$ → even higher production rates of rare processes
- Will allow quantitative measurements of the $\Upsilon$ family
- ALICE will measure hadronic decays of D mesons
- CMS will measure beauty through displaced $J/\psi$ over large y range
- Open and closed charm and beauty measurements ($J/\psi$, $\psi'$, $\chi_c$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\chi_b$) will allow us to perform a more systematic study of heavy flavor production and suppression than ever before…

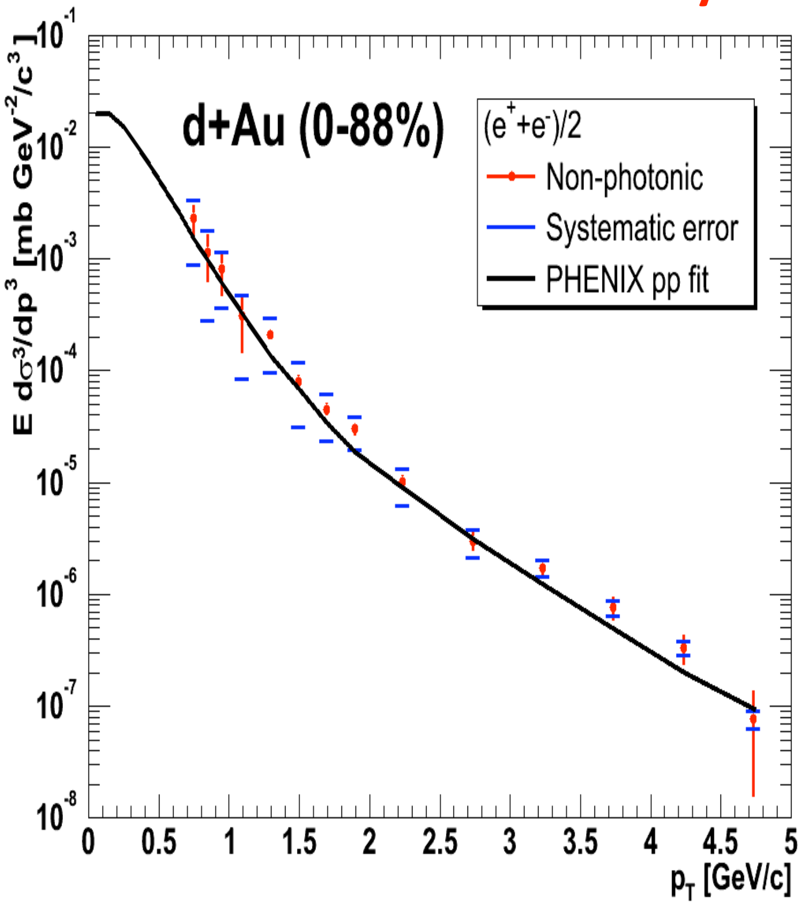
# References

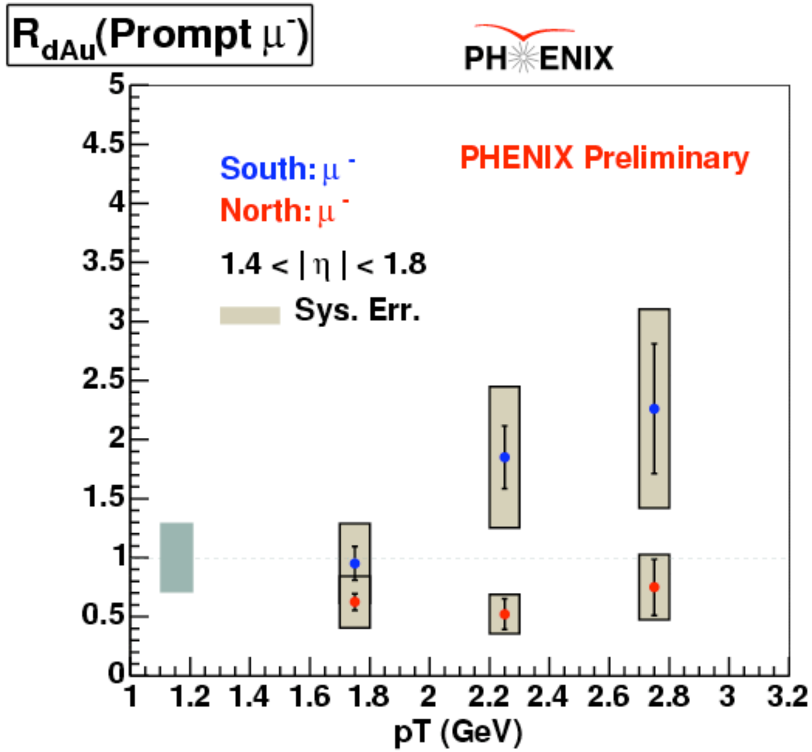

- Lourenço, Vogt, Wöhri, "Energy dependence of J/ψ absorption in proton-nucleus collisions", JHEP 02 (2009) 014
- NA60, *"Evidence for the production of thermal muon pairs with masses above 1 GeV/c$^2$ in 158 A GeV indium-indium collisions "*, EPJ C 59 (2009) 607
- PHENIX, *"Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV "*, PRL 98 (2007) 172301
- STAR, *"Transverse Momentum and Centrality Dependence of High-$p_T$ Nonphotonic Electron Suppression in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV"*, PRL 98 (2007) 192301
- PHENIX, *"Measurement of Bottom versus Charm as a Function of Transverse Momentum with Electron-Hadron Correlations in p+p Collisions at $\sqrt{s}$ = 200 GeV"* (2009), arXiv:0903.4851
- PHENIX, *"Dilepton mass spectra in p+p collisions at $\sqrt{s}$ = 200 GeV and the contribution from open charm"*, PLB 670 (2009) 313
- PHENIX, *"Enhancement of the dielectron continuum in $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions"* (2007), arXiv:0706.3034
- PHENIX, "Enhanced production of direct photons in Au+Au collision sat $\sqrt{s_{NN}}$ = 200GeV" (2008), arXiv:0804.4168

# Backup

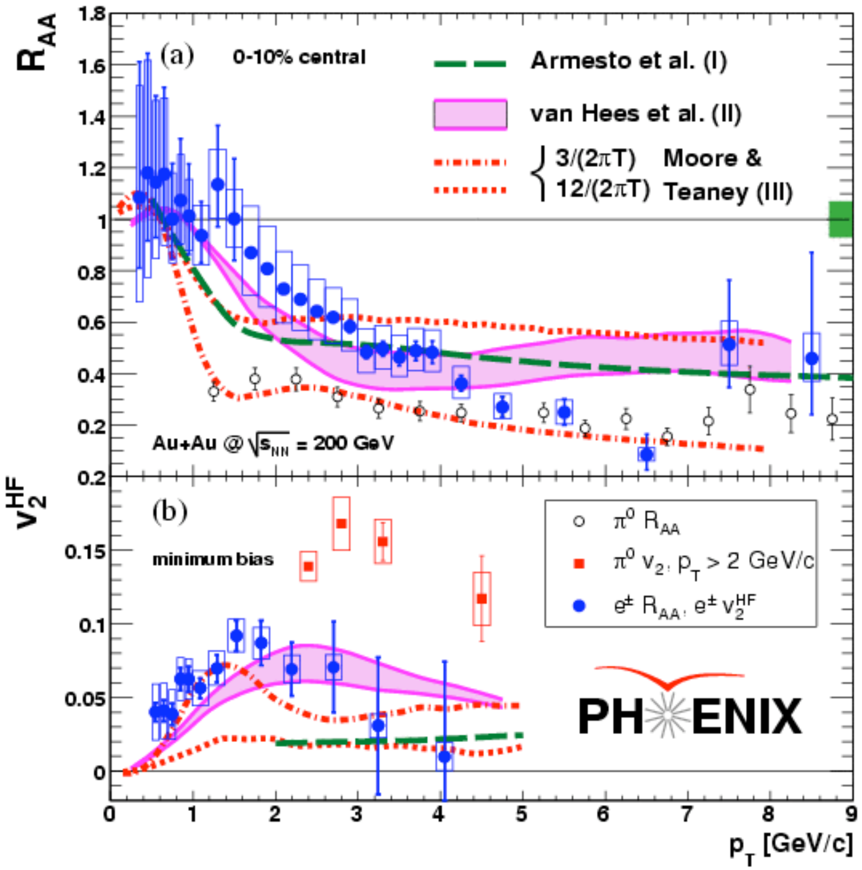
# PHENIX Open Charm ($\mu^{\pm}$)

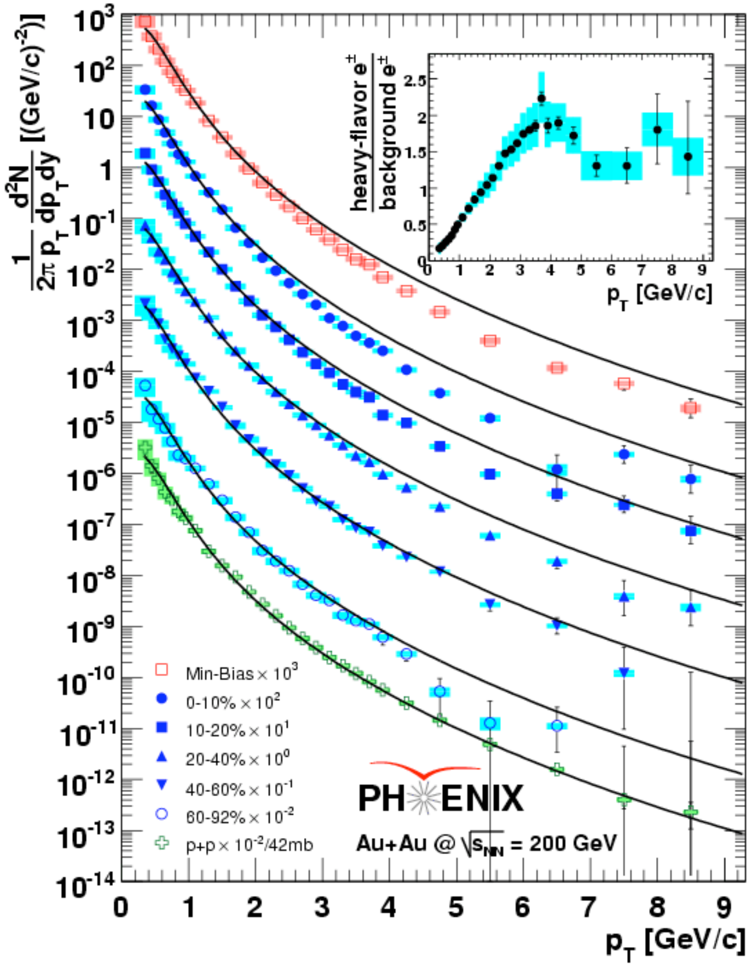
**PHENIX Preliminary**



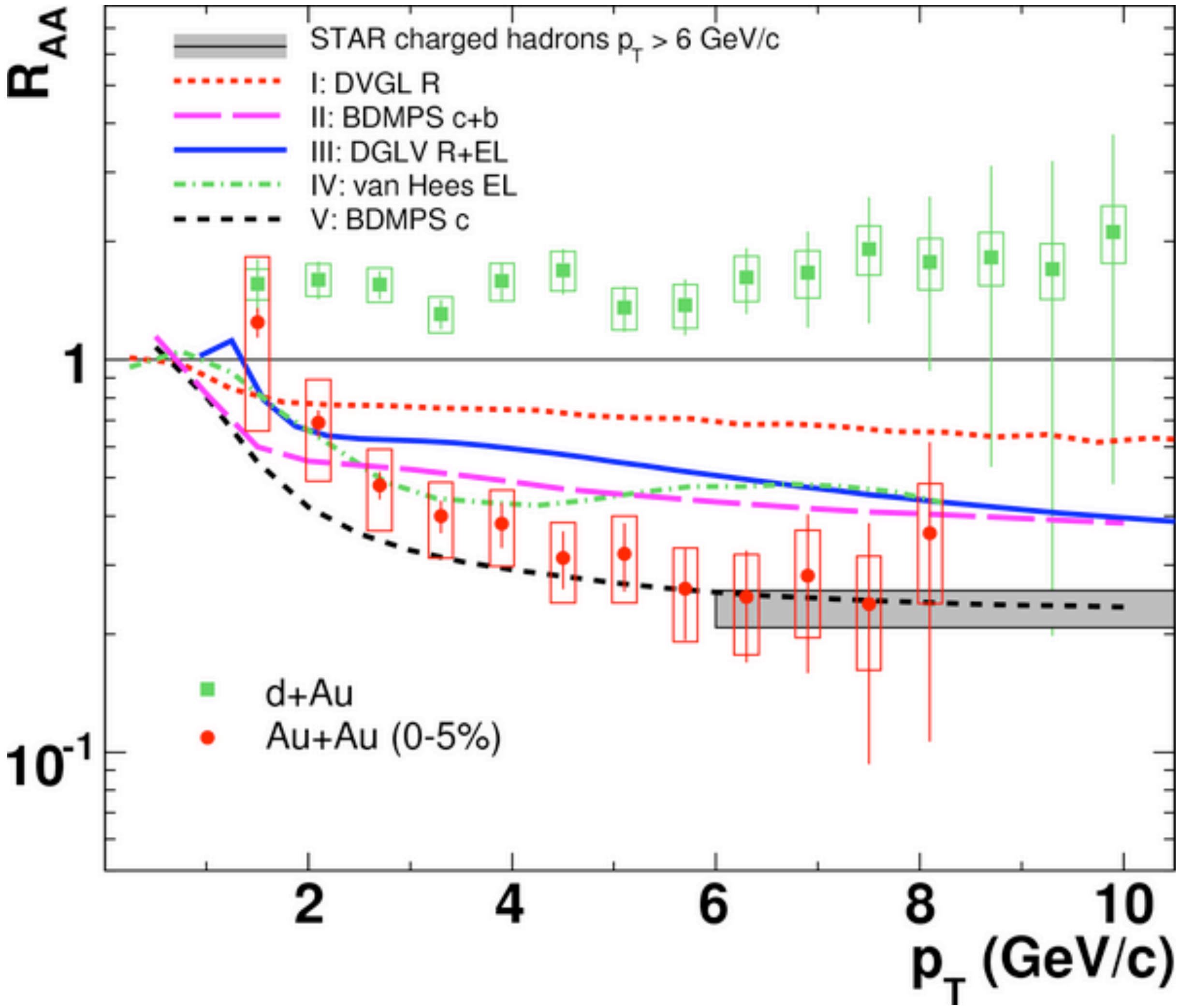



# PHENIX Open Charm ($e^{\pm}$)

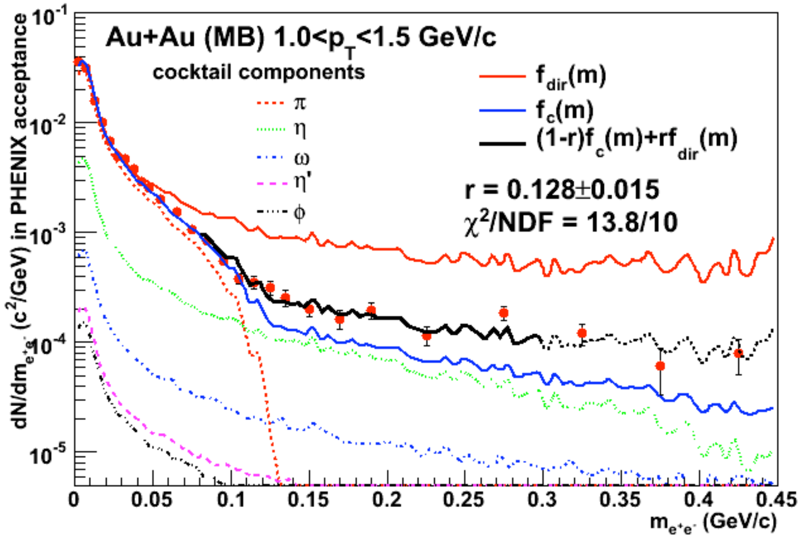


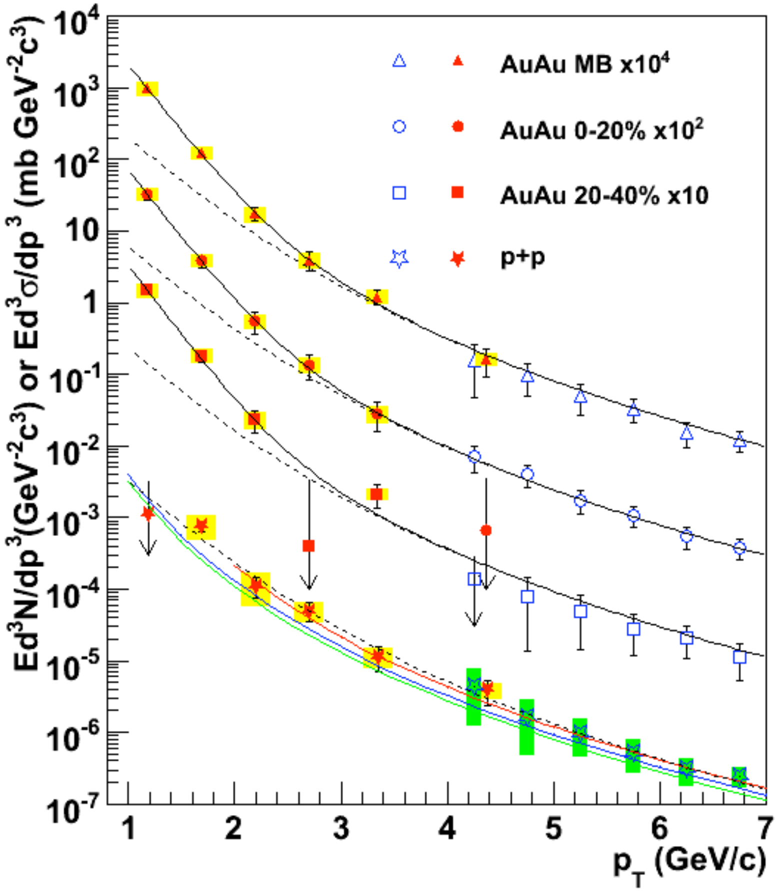



# STAR Open Charm ($e^{\pm}$)



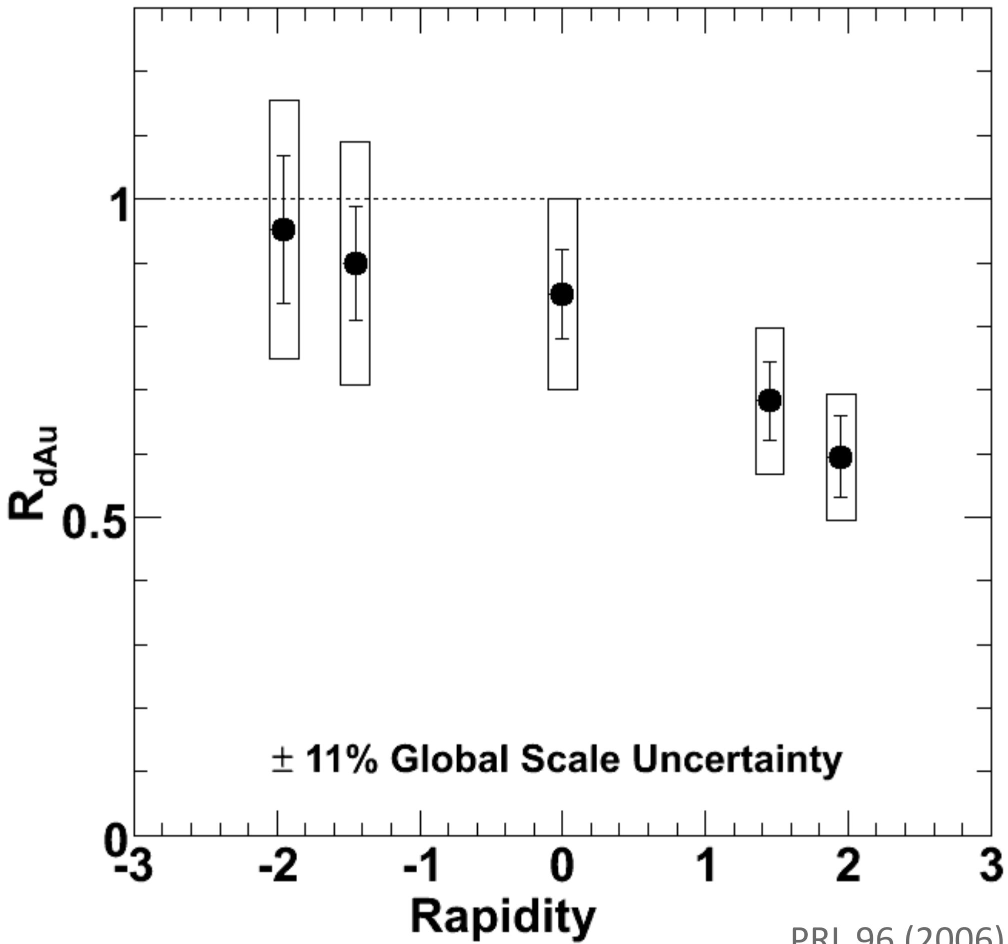
# PHENIX Thermal Photons




arXiv:0804.4168

# PHENIX J/ψ




PRL 96 (2006) 012304