The Charm (and Beauty) of RHIC

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- Heavy flavor in nuclear collisions
- Open heavy flavor at RHIC: PHENIX & STAR
- Selected results
  - pp: reference
  - dAu: cold nuclear matter effects
  - AuAu: probing the hot medium
- Heavy quarkonia (J/ψ) at RHIC: PHENIX
  - snapshot of current results and future attractions
- Summary

Why is heavy flavor interesting?

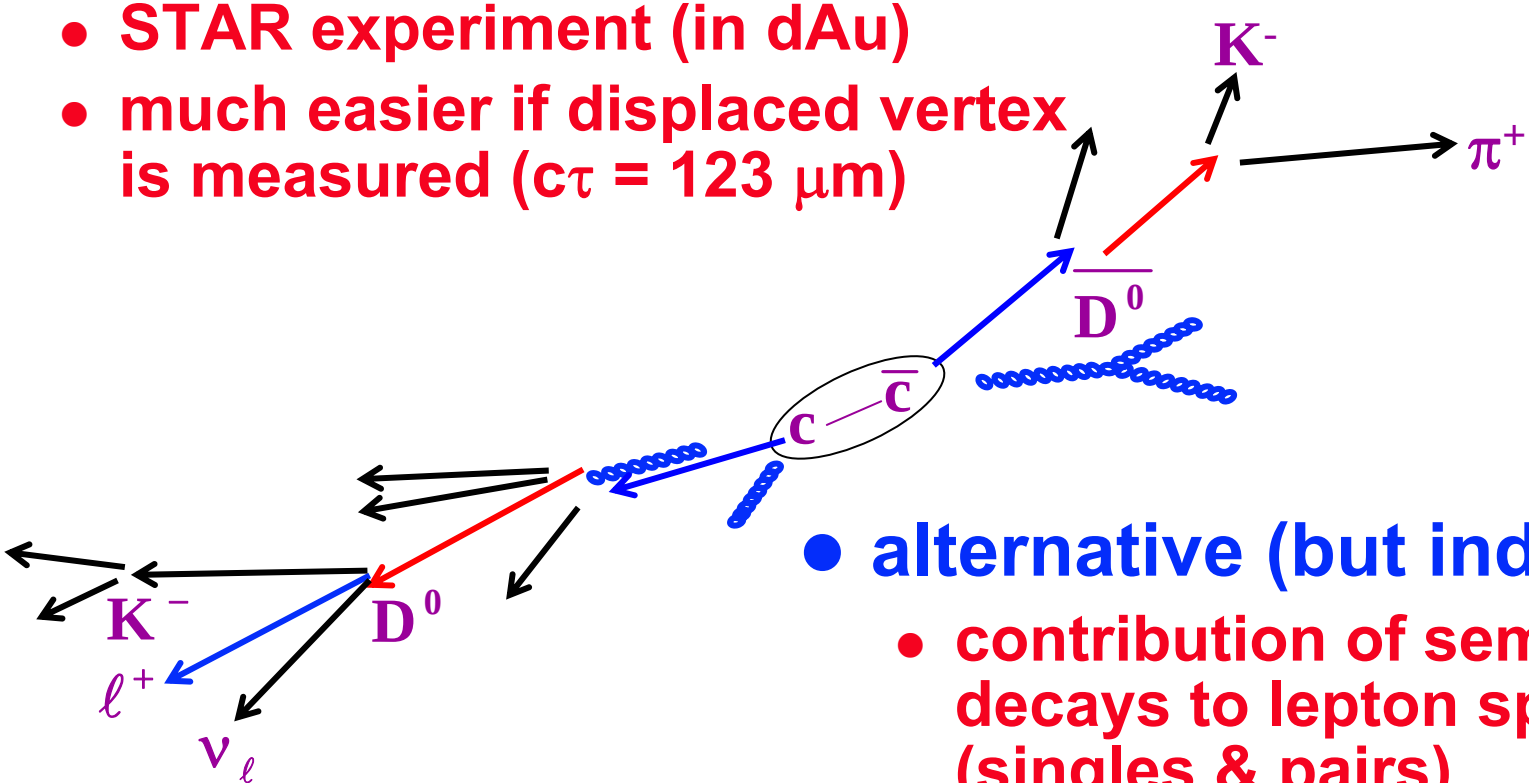
- production of heavy quark-antiquark pairs: $c\bar{c}$ ($b\bar{b}$)
  - dominated by gluon-gluon hard scattering
    - sensitive to initial gluon density (and spin)
  - additional thermal production → enhancement?
    - sensitive to initial temperature
- propagation through dense medium
  - energy loss or thermalization → softening of spectra?
    - sensitive to properties of the produced nuclear medium
  - does charm flow?
    - sensitive to collectivity on parton level
- quarkonia (J/ψ) in dense medium
  - suppression via color screening?
  - enhancement via coalescence?

→heavy quarks = rich probe of the nuclear medium

→study of yields & spectra in pp, dAu, and AuAu

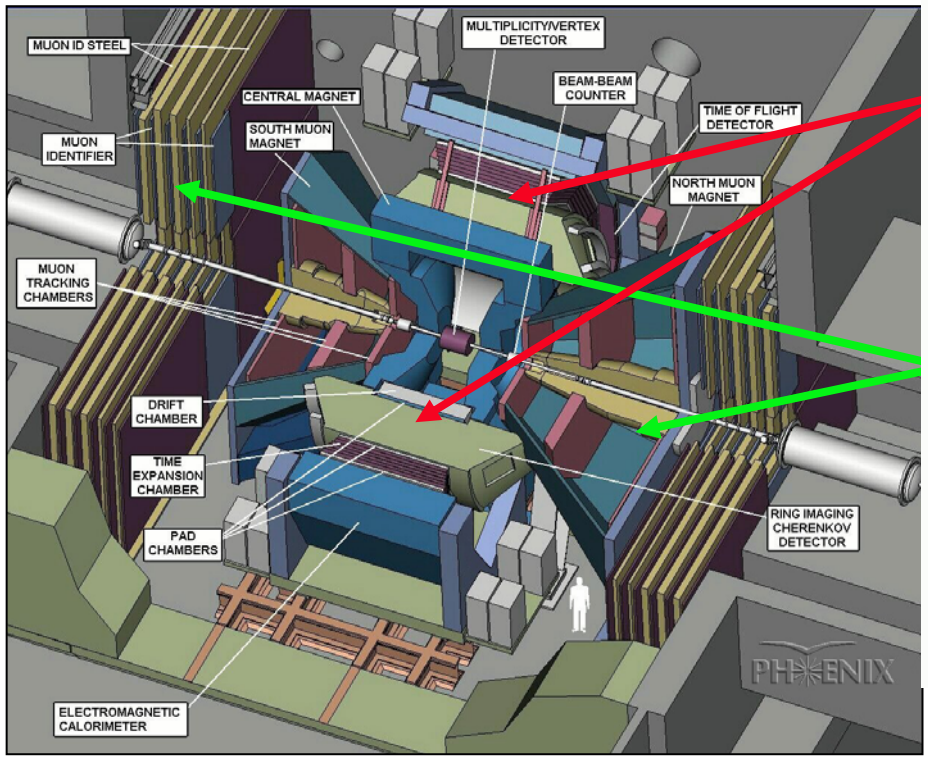
Open heavy-flavor measurements

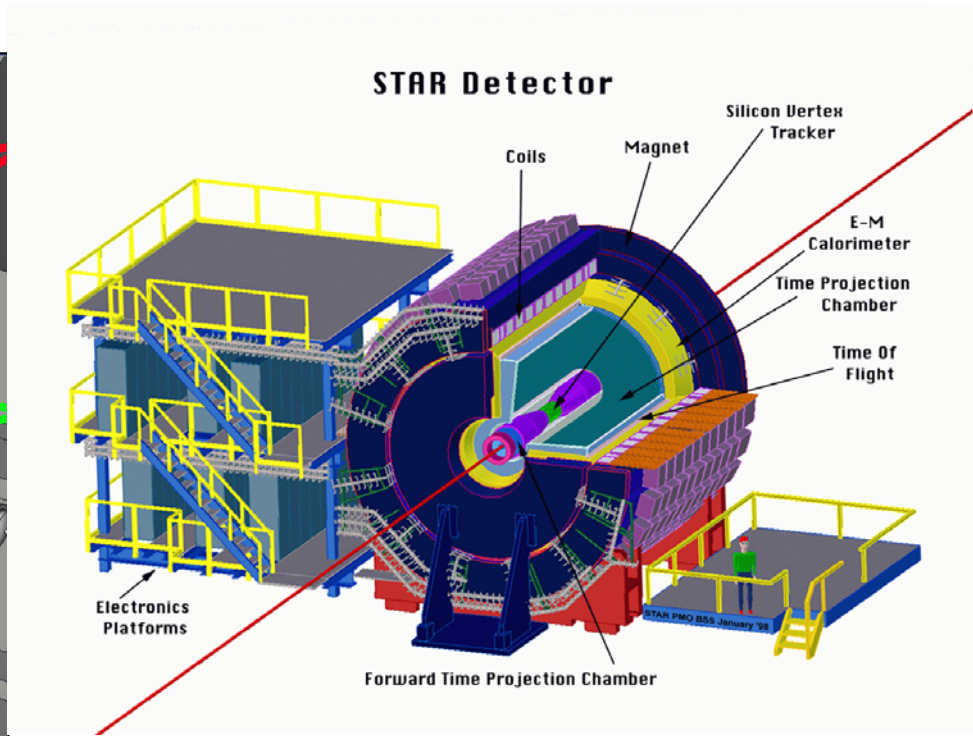
- ideal (but very challenging in HI environment)
  - direct reconstruction of charm decays (e.g. $\bar{D}^0 \rightarrow K^- \pi^+$)
  - STAR experiment (in dAu)
  - much easier if displaced vertex is measured ($c\tau$ = 123 μm)



- alternative (but indirect)
  - contribution of semileptonic decays to lepton spectra (singles & pairs)
  - PHENIX experiment (in pp, dAu, AuAu)
  - STAR experiment (pp, dAu)

PHENIX & STAR at RHIC



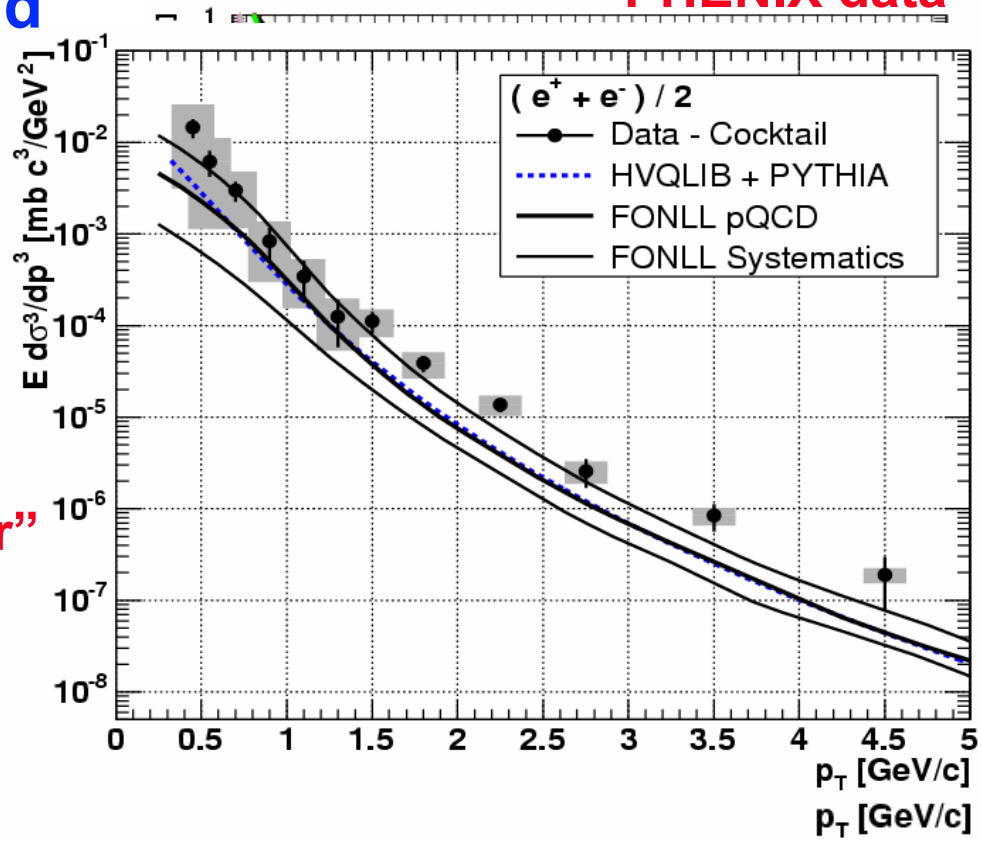


- **electrons in central arms**
  - tracking
  - electron ID:
    - RICH + EMC
- **muons in forward arms**
  - tracking
  - muon ID:
    - "absorber"
- **large acceptance ($|\eta| < 1$) tracking detector: TPC**
  - hadrons:
    - TPC (dE/dx)
    - Time-of-Flight detector
  - electron ID:
    - EMC ($0<\eta<1$) in addition

pp @ √s = 200 GeV

- subtract $e^{\pm}$ from background sources (*cocktail*) from inclusive $e^{\pm}$ spectrum
  ➔ $e^{\pm}$ from heavy flavor
- comparison with PYTHIA (tuned to available data)
  - p_T < 1.5 GeV/c: reasonable
  - p_T > 1.5 GeV/c: spectra "harder" than PYTHIA
    - bottom enhancement?
    - hard fragmentation?
- comparison with FONLL
  - Fixed Order Next-to-Leading Log pQCD calculation (M. Cacciari, P. Nason, R. Vogt hep-ph/0502203)
  - good description of spectral shape
  - barely in agreement with data (within errors)

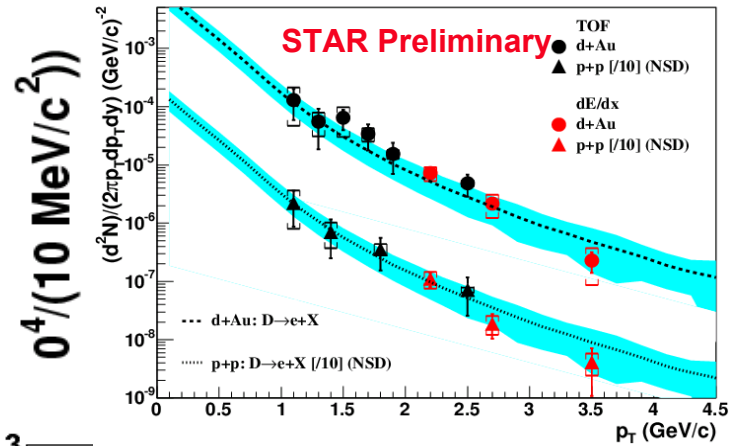
PHENIX data

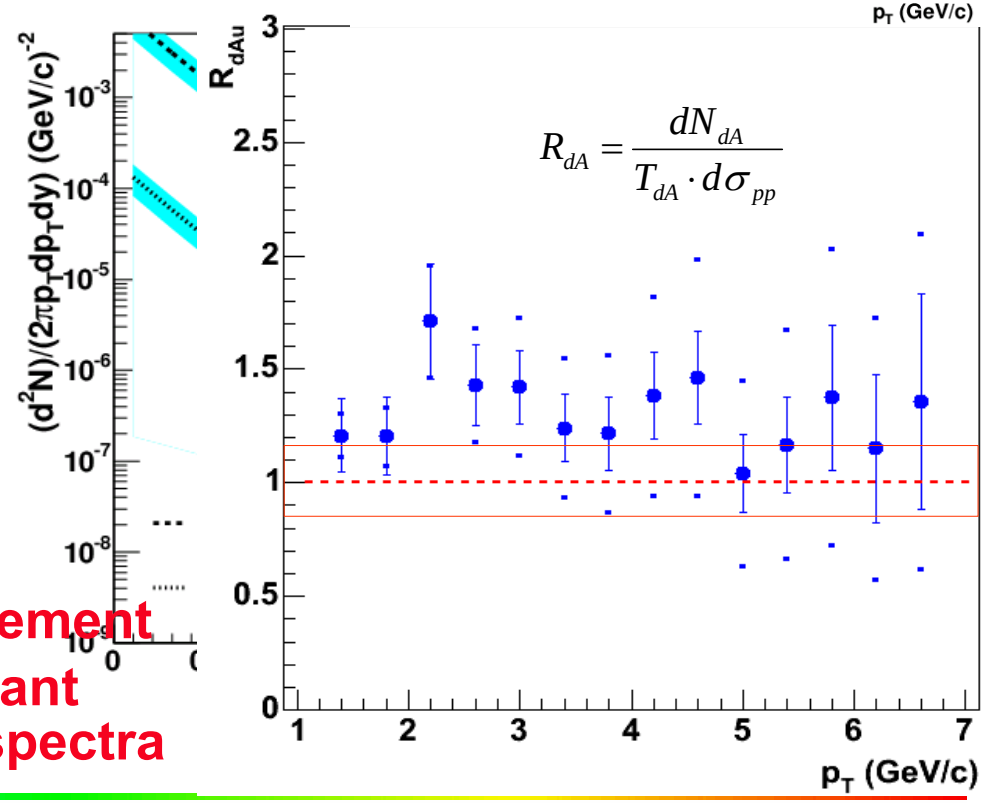


- STAR: consistent results (PRL 94, 062301 (2005))
  - slightly larger cross section
  - agreement within errors

dAu @ $\sqrt{s_{NN}}$ = 200 GeV

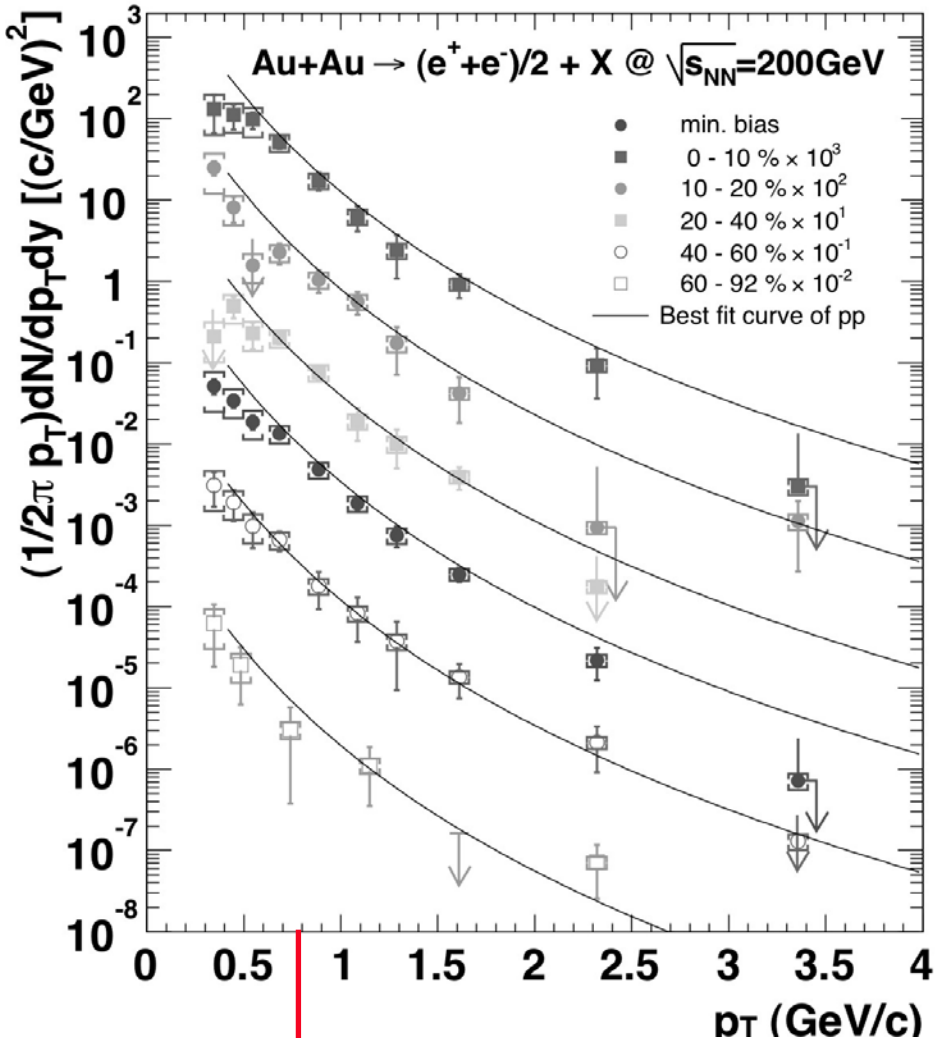
- STAR: 1st direct reconstruction of charmed hadrons at RHIC (PRL 94, 062301 (2005))
  - $D^0 \rightarrow K^- \pi^+$ (and charge conjugate)
  - $D^\pm$, D^* as well
- D spectra confirm failure of tuned PYTHIA
- D and $e^\pm$ measurements are consistent
  - with each other
  - with PHENIX $e^\pm$ data in dAu
- medium effects?
  - R_{dA} is consistent with binary scaling (within errors)
  - indication for Cronin enhancement
  - PHENIX observes no significant centrality dependence of $e^\pm$ spectra



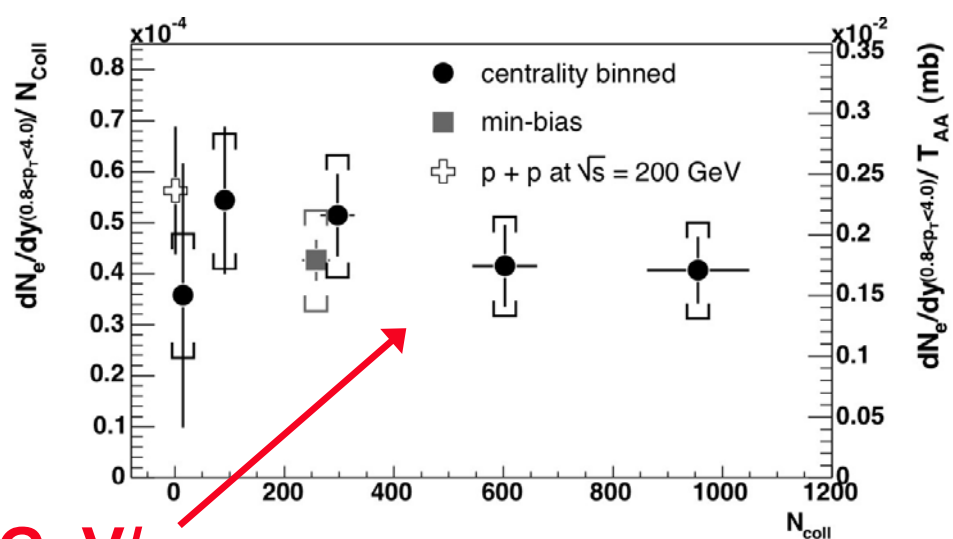


AuAu @ $\sqrt{s_{NN}}$ = 200 GeV: yields

PHENIX: PRL 94, 082301 (2005)



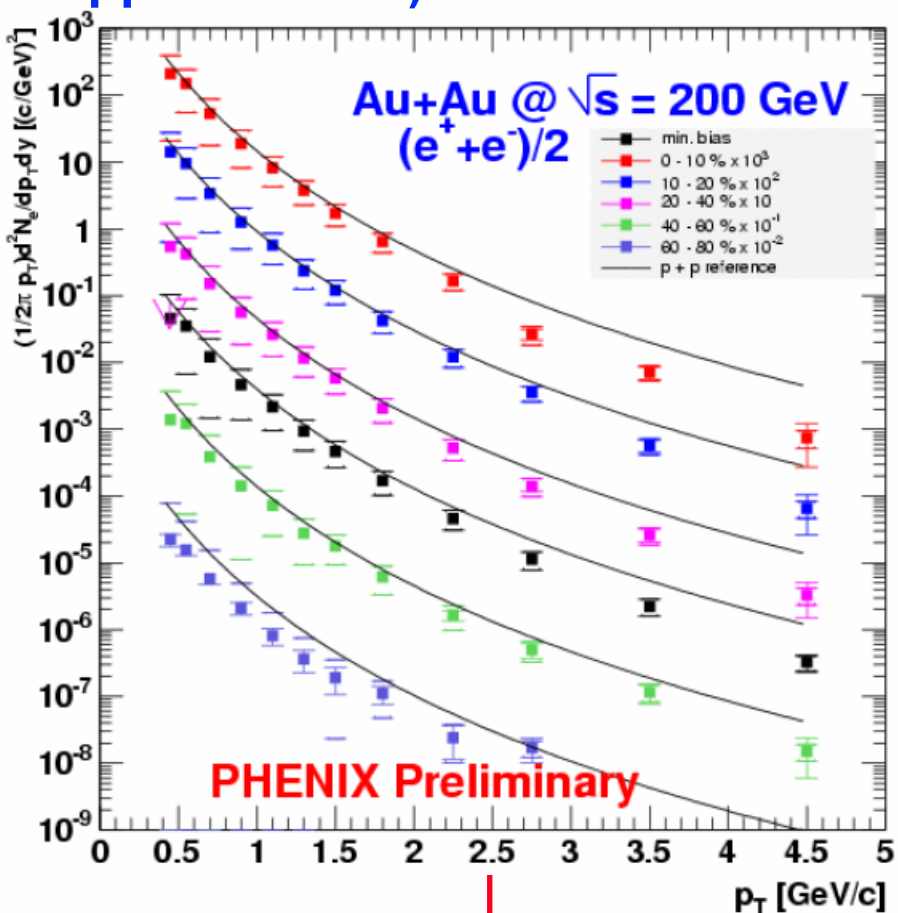
- heavy flavor $e^{\pm}$ inv. differential multiplicity as function of collision centrality
- insufficient statistics at p_T > 1.5 GeV/c to study modification of spectral shape
- total charm yield in AuAu agrees with binary scaled pp yield (as expected for point-like pQCD process)!



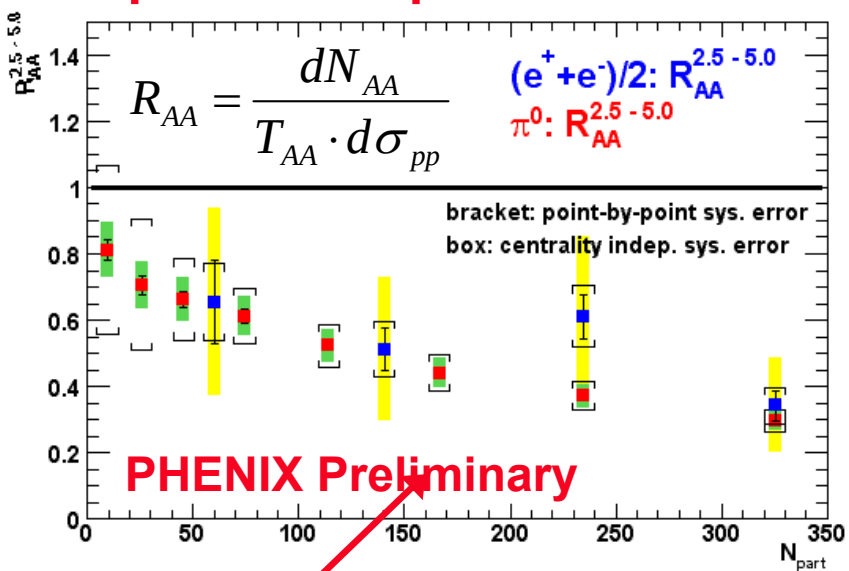
total yield at p_T > 0.8 GeV/c

AuAu @ $\sqrt{s_{NN}}$ = 200 GeV: spectra

- full statistics cocktail analysis
- indication for suppression at high p_T (relative to binary scaled pp reference)



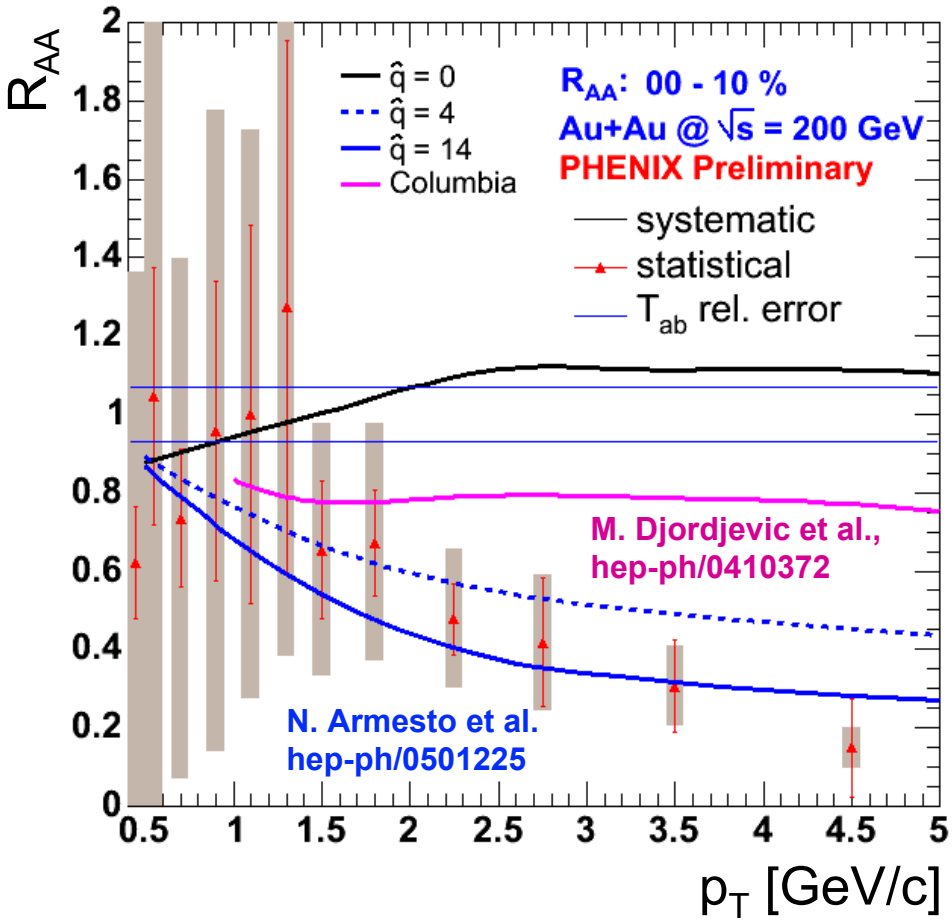
- nuclear modification factor R_{AA} of $e^{\pm}$ from heavy flavor is compatible with R_{AA} of π^0
- present precision insufficient to examine centrality dependence
- strong medium modification of spectral shape is observed!



R_{AA} with yield above 2.5 GeV/c

AuAu @ $\sqrt{s_{NN}}$ = 200 GeV: energy loss

- comparison of R_{AA} of $e^{\pm}$ from heavy flavor for central AuAu collisions with theoretical predictions



- measured suppression pattern at high p_T
  - is in reasonable agreement with theoretical models incorporating heavy quark energy loss
  - can differentiate between different scenarios
- caveat
  - currently compared to charm calculations only
  - data contain *significant* contribution from b decays for $p_T \geq 4$ GeV/c

- heavy quarks DO interact strongly with the medium!

AuAu @ $\sqrt{s_{NN}}$ = 200 GeV: elliptic flow

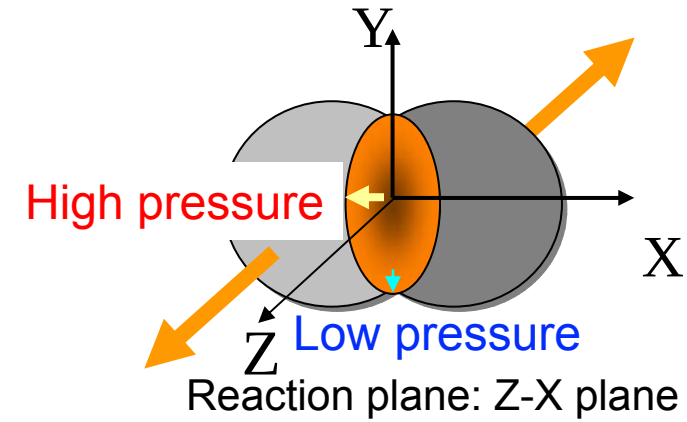
- spatial anisotropy in initial stage

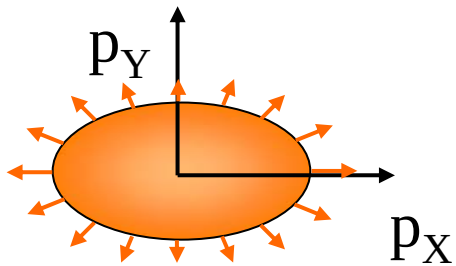
pressure gradients (early)

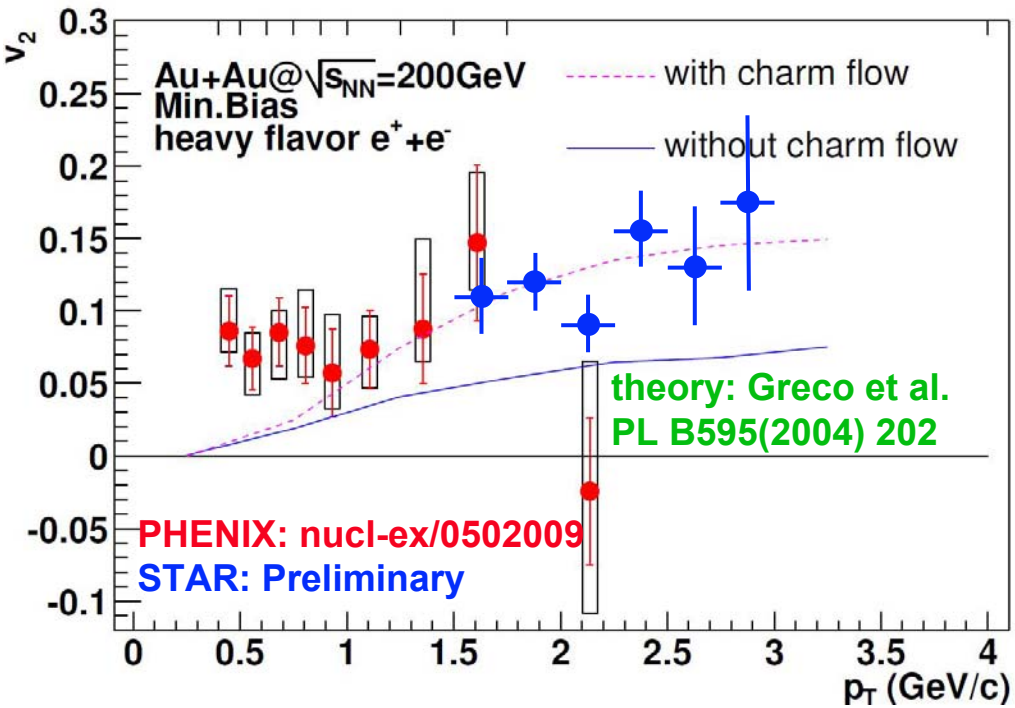
- momentum anisotropy in final stage

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$

- elliptic flow strength $v_2 = \left\langle \cos 2\left(\varphi - \Psi_R\right)\right\rangle$



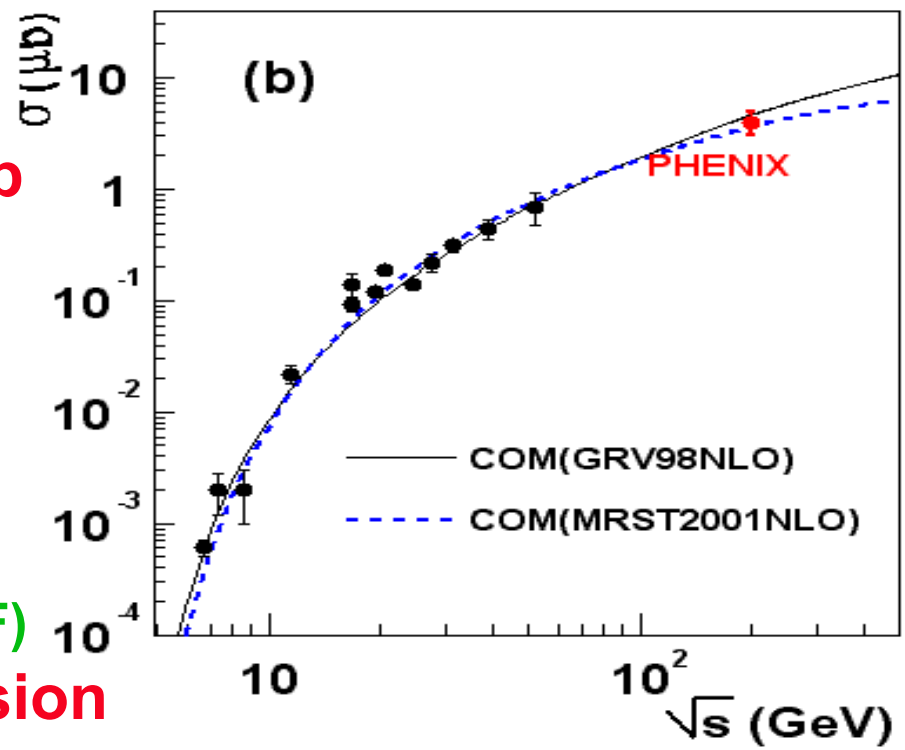




- data show v_2(electron) > 0 ➔ v_2(D meson) > 0
- interaction of heavy quarks with the medium, possibly thermalization

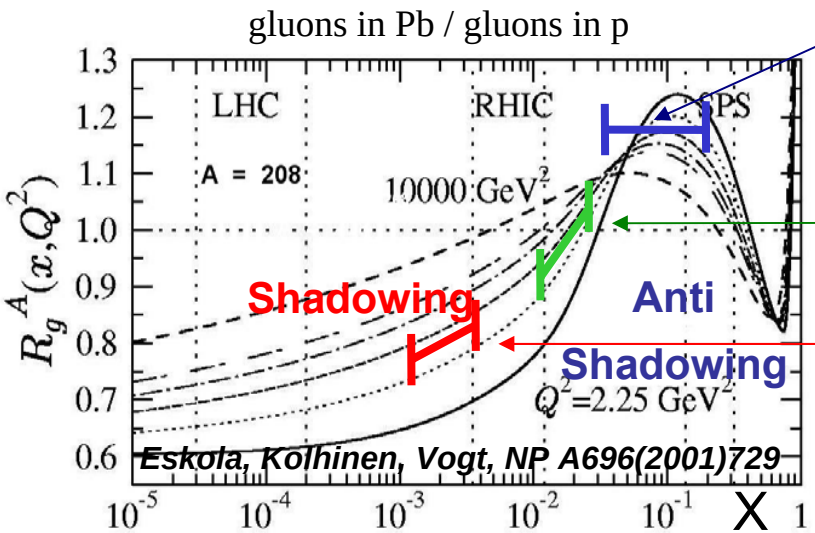
J/ψ: the other heavy flavor probe at RHIC

- PHENIX measurements in pp, dAu, AuAu (CuCu currently in progress) at 200 GeV
  - $J/\psi \rightarrow e^+e^-$ at midrapidity
  - $J/\psi \rightarrow \mu^+\mu^-$ at forward and backward rapidity
- pp reference
  - total cross section $\sigma_{J/\psi} = 2.69 \pm 0.23 \pm 0.33\ \mu b$
  - consistent with predictions from
    - Color Octet (COM) and Color Evaporation (CEM) model calculations
    - using "typical" parton distribution functions (PDF)
  - consistent with gluon-fusion picture of J/ψ production



J/ψ in dAu: cold nuclear matter effects

- **gluon PDF modifications: (anti)shadowing**

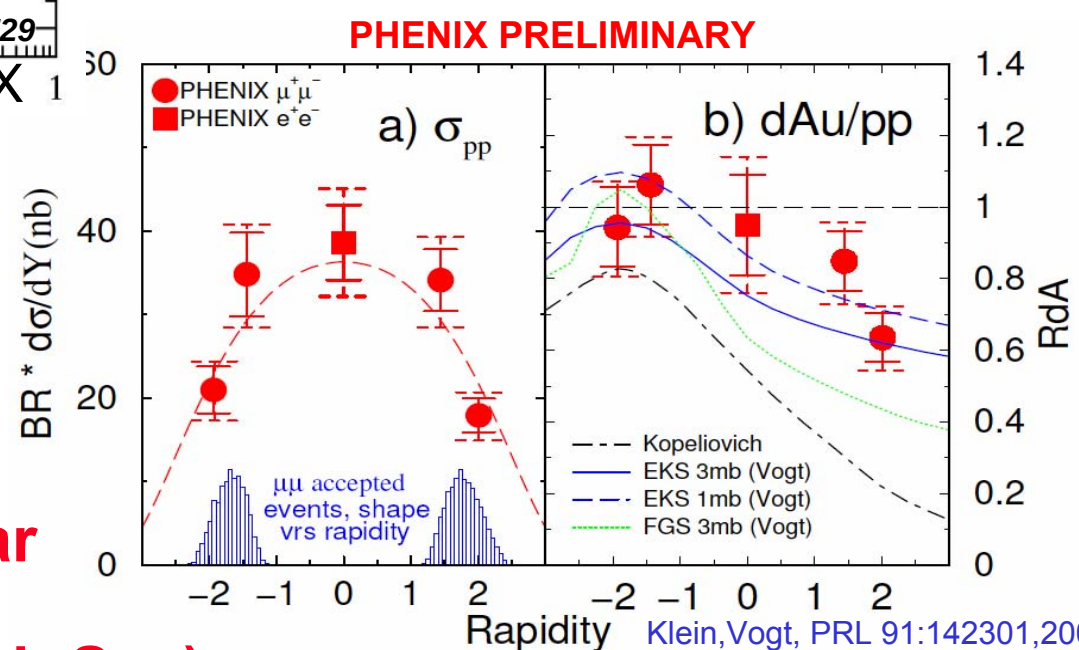


PHENIX North Muon Arm: y < 0

PHENIX Central Arms: y ≈ 0

PHENIX South Muon Arm: y > 0

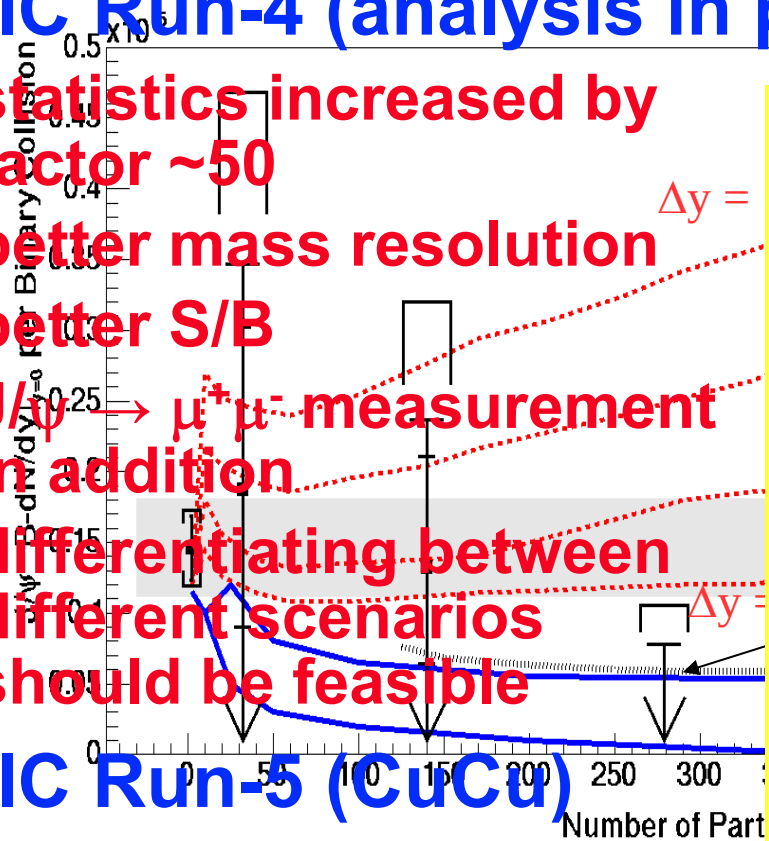
- **data indicate weak (anti)shadowing**
- **also observed**
  - **weak absorption**
  - **p_T broadening similar to measurements at lower energy (E866/NuSea)**

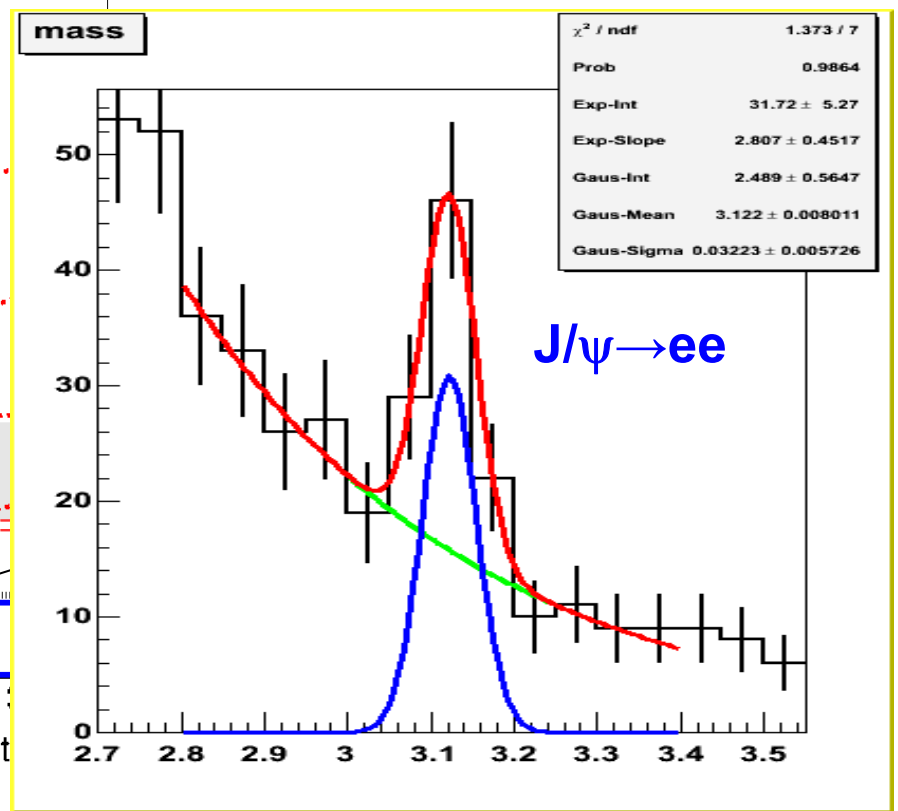


Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

J/ψ in AuAu: suppressed or enhanced?

- RHIC Run-2 (AuAu @ 200 GeV)
  - $J/\psi \rightarrow e^+e^-$ only (~12 counts): PRC69, 014901,2004
  - not conclusive
- RHIC Run-4 (analysis in progress)
  - statistics increased by factor ~50
  - better mass resolution
  - better S/B
  - $J/\psi \rightarrow \mu^+\mu^-$ measurement in addition
  - differentiating between different scenarios should be feasible
- RHIC Run-5 (CuCu)
  - data on A dependence





Summary & Outlook

- Open heavy flavor measurements at RHIC
  - D mesons and single $e^{\pm}$ from heavy flavor decays are measured
  - reference measurement is available for pp @ 200 GeV
    - spectra are harder than PYTHIA prediction
  - cold nuclear matter effects (in dAu) are small
  - heavy flavor in the hot and dense medium (AuAu)
    - yields are consistent with binary scaling (point like pQCD process)
    - high p_T suppression and elliptic flow indicate significant interaction of heavy quarks with a (colored) medium
  - near future
    - increase p_T reach: what happens with beauty?
    - single muon measurement
    - dileptons from correlated heavy flavor decays
- J/ψ at RHIC
  - pp reference is available
  - "normal" nuclear matter effects have been studied in dAu
  - stage is set for nucleus-nucleus collisions
- upgrades (vertex spectrometers) will provide new opportunities