Heavy Flavor Overview

Krista Smith
for the PHENIX Collaboration

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PHENIX Systems Overview

PHENIX

During the last few years of operation, PHENIX collected data in a wide range of different collision systems:

- 2013 $p+p$ at $\sqrt{s} = 510$ GeV
- 2014 ^{3}**He+Au, Au+Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2015 $p+p$, p+**Al**, p+**Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2016 d+**Au**, **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV

PHENIX recorded heavy-ion data for 16 years, recently ending its run in 2016. Although PHENIX is no longer actively recording data, analysis continues with the primary focus on these most recent data sets.

PHENIX Heavy Flavor Overview

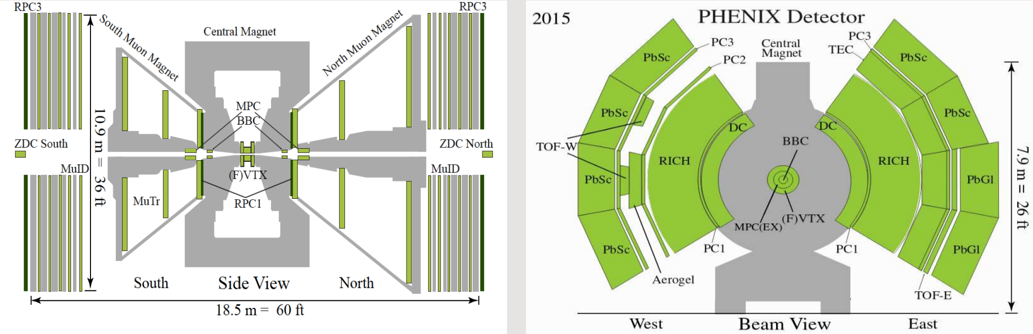
PHENIX

Four recent PHENIX analyses focus on the following collision systems and investigate the following:

- 2013 $p+p$ at $\sqrt{s} = 510$ GeV
- 2014 ^{3}**He+Au, Au+Au** at $\sqrt{s_{NN}} = 200$ GeV
- 2015 $p+p$, $p+$**Al**, $p+$**Au** at $\sqrt{s_{NN}} = 200$ GeV

1. Is $b\bar{b}$ cross section at RHIC energies consistent with pQCD calculations?
2. If QGP is present in small systems, does it affect Charmonium production?
3. Is there evidence of mass ordering for heavy quark modification?
4. Is bottom electron v_2 smaller than charm electron v_2?

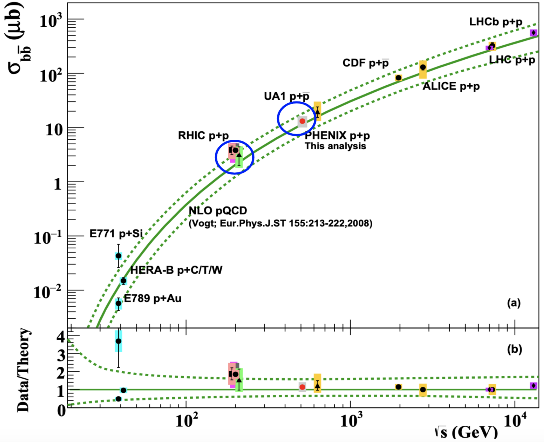
PHENIX Muon and Central Arms



- Muon arms measure muons and inclusive charged hadrons
- Mid-rapidity arms measure electrons, photons and identified hadrons

Heavy Flavor Results

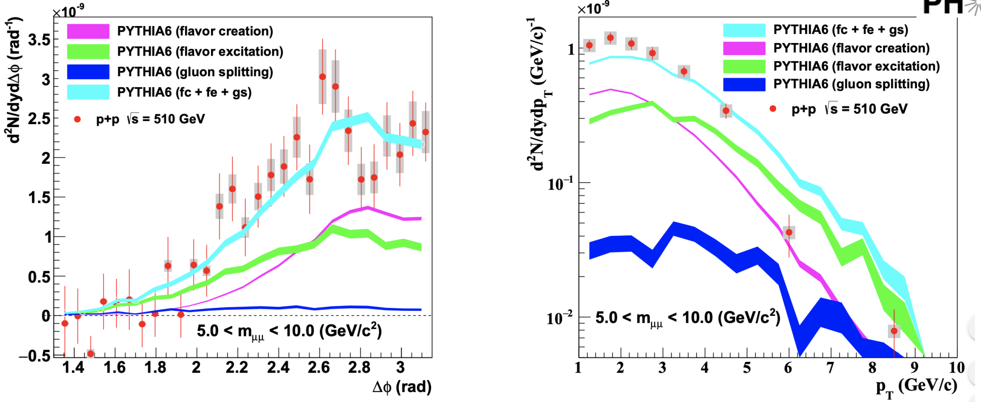
PHENIX $\sigma_{b\bar{b}}$ vs. $\sqrt{s}$ in $p+p$



Phys. Rev. D 102, 092002 (2020)

- PHENIX measurement fills gap between fixed target and TeV energy ranges
  - Extrapolated to full phase space due to limited kinematic coverage
- Cross section measurement consistent with world data and pQCD calculations [1]

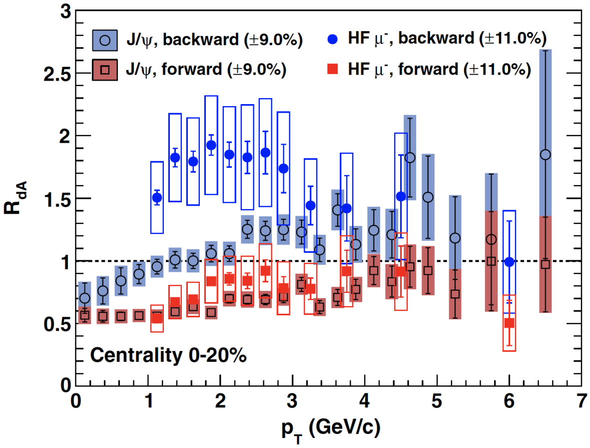
$b\bar{b}$ Invariant Yields in $p+p$



Phys. Rev. D 102, 092002 (2020)

- Extracted using like-sign muon pairs, without the need for a precision vertex detector
- Comparison of PYTHIA6 models based on different $b\bar{b}$ production mechanisms
  - At RHIC energies, gluon splitting less significant than at LHC energies

J/ψ Nuclear Modification (2014)

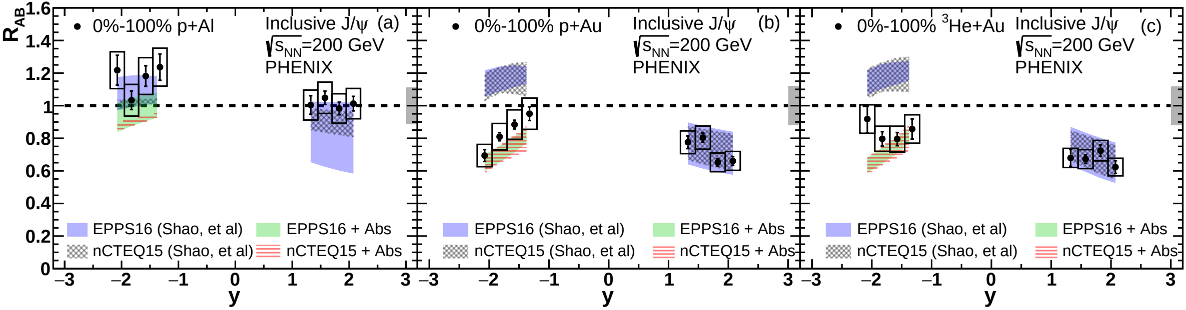


Phys. Rev. Letters 112, 252301 (2014)

- Forward rapidity: J/ψ suppression similar to open charm suppression
  - Consistent with shadowing and/or parton energy loss
- Backward rapidity: J/ψ suppressed relative to open charm
  - Expect open charm enhanced by anti-shadowing
  - J/ψ suppression consistent with absorption from collisions with nucleons in target
  - Possible contribution also from co-movers

J/ψ Nuclear Modification (2020)

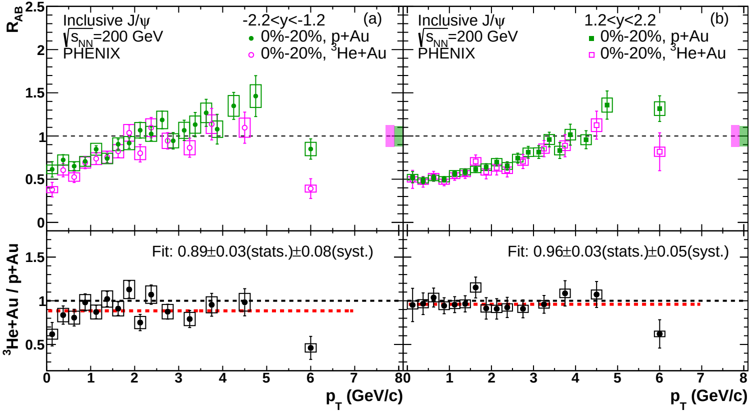
p+Al p+Au ^{3}He+Au



Phys. Rev. C 102, 014902 (2020)

- Predictions for $p/^3$He+Au based on Bayesian reweighting method using J/ψ constraints from p+Pb data at the LHC [2],[3]
  - Added PHENIX nuclear absorption estimate at backward rapidity [4]

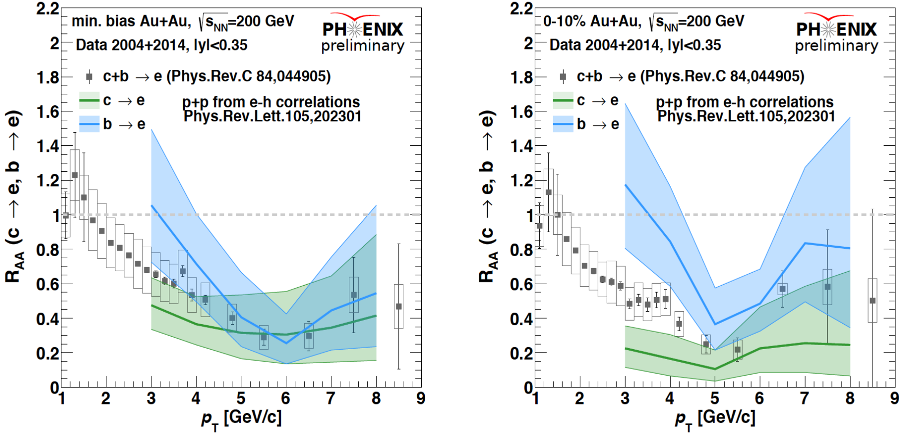
J/ψ Modification Ratio for ^{3}He+Au to p+Au (0-20%)



Phys. Rev. C 102, 014902 (2020)

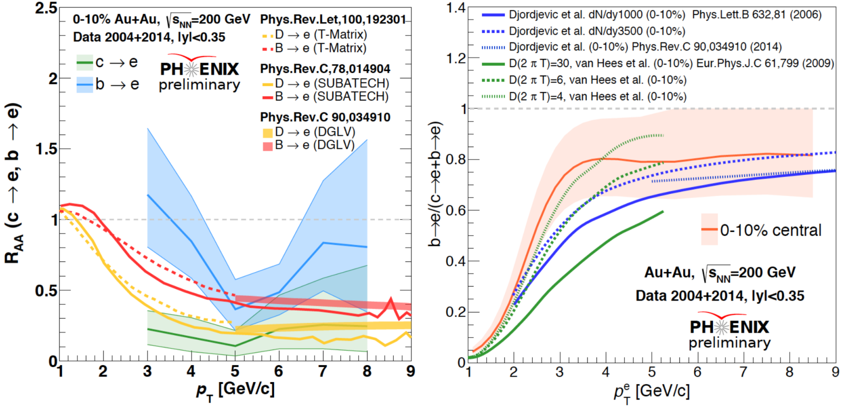
- Stronger suppression in ^{3}He+Au than p+Au at bkwd rapidity with significance 1.3σ
  - No final state effect at fwd rapidity, small final state effect at bkwd rapidity

Charm and Bottom Modification in Au+Au



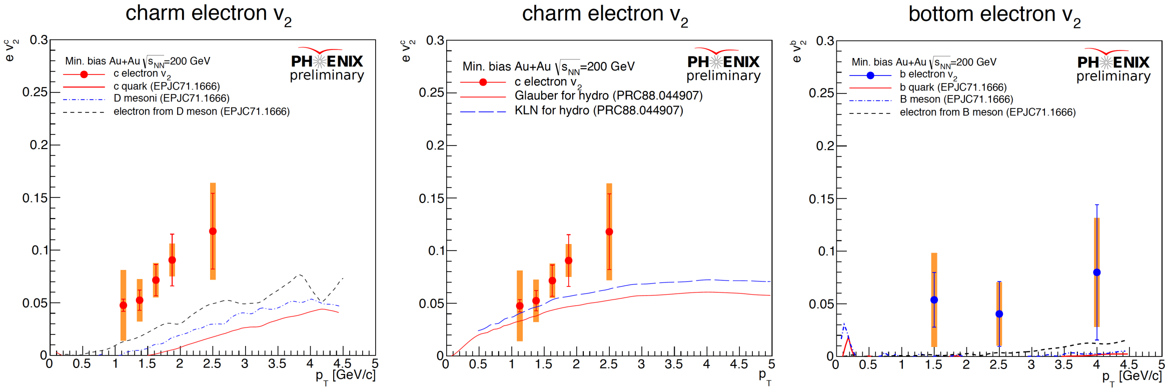
- Stronger suppression observed for c→e than b→e around the range 3-5 GeV/c
  - In 0-10% most central events, clear separation of charm and bottom at low p_T

Charm and Bottom Modification in Au+Au (0-10%)



- Data shows a flavor dependent modification ($R^c_{AA} < R^b_{AA}$) consistent with the models
- Diffusion constant D(2πT)=4 consistent with b-fraction results in most central events
  - Smaller diffusion constant indicates more strongly coupled QGP [5]

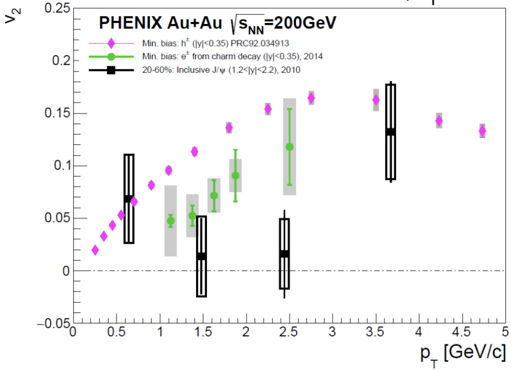
Charm and Bottom v_2 in Au+Au



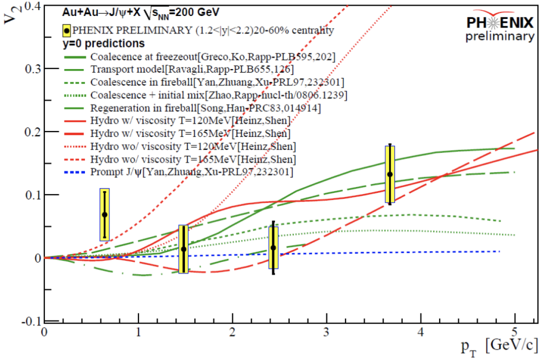
- Models including coalescence show better agreement with the data
- Bottom electron v_2 with large uncertainty (plan to combine 2014, 2016 data sets)
  - Current data set 5x larger than data set used for preliminary results

Flow of Electrons from Charm and J/ψ in Au+Au

charm electron vs J/ψ



J/ψ v2



- Charm electron $v_2 > J/\psi\ v_2$ at mid p_T (1-3GeV/c) with significance 0.7σ
- $J/\psi\ v_2$ model comparisons inconclusive (plan to combine 2014, 2016 data sets)
  - Current data set 5x larger than data set used for preliminary results

PHENIX Heavy Flavor Summary

PHENIX

1. p+p at $\sqrt{s}$ =510 GeV
   - $b\bar{b}$ cross section at RHIC energies consistent with pQCD calculations
   - $b\bar{b}$ invariant yields consistent with simulations including all three production mechanisms (flavor creation, flavor excitation and gluon splitting)
2. p+Al, p+Au, ^{3}He+Au at $\sqrt{s_{NN}}$ =200 GeV
   - J/ψ nuclear modification in small systems best described by nPDF's with nuclear absorption model included at backward rapidity
   - Small increase in J/ψ suppression for ^{3}He+Au vs. p+Au at backward rapidity
3. Au+Au at $\sqrt{s_{NN}}$ =200 GeV
   - Stronger suppression for $c \to e$ than $b \to e$ for mid p_T
   - non-zero charm electron v_2 observed
   - b-fraction results consistent with strongly coupled QGP model

Theory References

[1] Vogt, Ramona
The total charm cross section
Eur. Phys. J. Special Topics 155, 213 (2008).

[2] Kusina, Aleksander and Lansberg, Jean-Philippe and Schienbein, Ingo and Shao, Hua-Sheng
Gluon Shadowing in Heavy-Flavor Production at the LHC
Phys. Rev. Lett 121, 052004

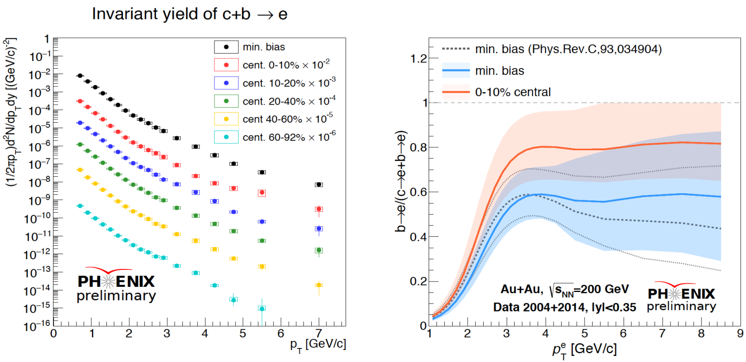
[3] Lansberg, Jean-Philippe and Shao, Hua-Sheng
Towards an automated tool to evaluate the impact of the nuclear modification of the gluon density on quarkonium, D and B meson production in proton–nucleus collisions
Eur. Phys. J. C77, 2017

[4] D. McGlinchey, A.D. Frawley and R. Vogt
Impact-parameter dependence of the nuclear modification of J/ψ production in d+Au collisions at $\sqrt{s_{NN}}$ =200 GeV
Phys. Rev. C 87, 054910 (2013)

[5] H. Van Hees, M. Mannarelli, Vincenzo Greco and Ralf Rapp
T-Matrix approach to heavy quark diffusion in the QGP
Eur.Phys.J.C 61 (2009) 799-806

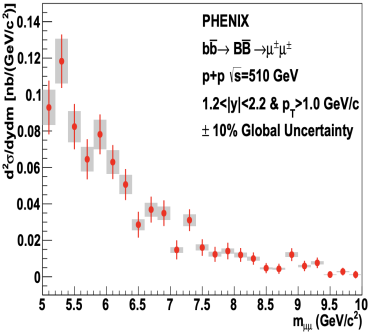
Back-Up

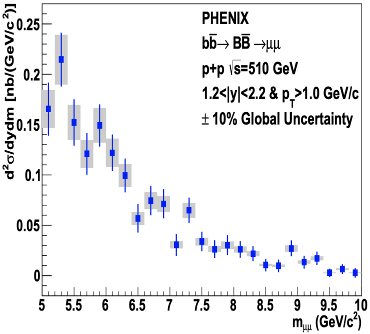
Charm + Bottom Invariant Yields in Au+Au



- In most central collisions, larger contribution from bottom than measured in Min Bias

$\mu^\pm\mu^\pm$ vs. $\mu^+\mu^-$ Mass Distributions in $p+p$

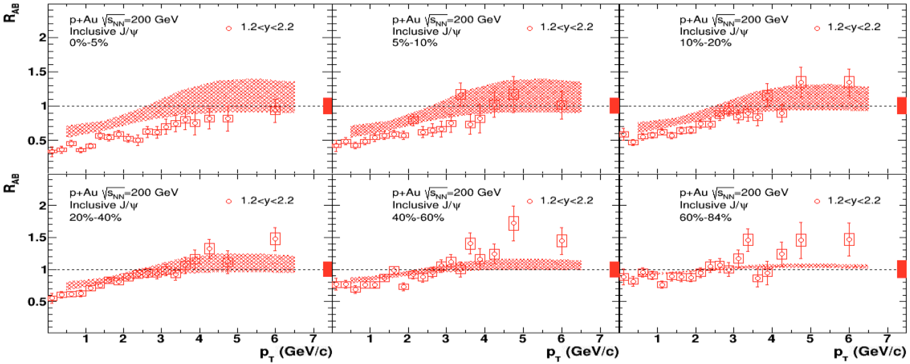




arXiv:2005.14276 (2020)

- $b\bar{b}$ cross section uses like-sign muon pairs for cleaner signal via BB decay (oscillation)
- Comparison with unlike-sign pairs shows similar shape but different normalization

J/ψ Modification in p+Au, Fwd Rapidity



- Transport effects small at forward rapidity
  - EPS09 shadowing dominates model calculations
  - Shadowing not strong enough in central collisions

Phys. Rev. C 102, 014902 (20