Open Heavy Flavor and Quarkonia Results at RHIC

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RHIC Amazing QCD Machine: Many Species and Many Energies!
## RHIC Amazing QCD Machine: Many Species and Many Energies!

| Run   | Species  | Total particle energy [GeV/nucleon] | total delivered Luminosity [µb⁻¹] | Run   | Species  | Total particle energy [GeV/nucleon] | Total delivered luminosity [µb⁻¹] |
|-------|----------|-------------------------------------|-----------------------------------|-------|----------|-------------------------------------|-----------------------------------|
| I (2000) | Au+Au   | 56                                  | < 0.001                           | IX (2009) | p+p    | 500                                  | 110x10⁻⁶                          |
|        | Au+Au   | 130                                 | 20                                |        | +p     | 200                                  | 114x10⁻⁶                          |
| II (2001/2002) | Au+Au | 200                                 | 25.8                              | X (2010) | Au+Au | 200                                  | 10.3x10⁻³                         |
|        | Au+Au   | 19.6                                | 0.4                               |        | Au+Au  | 62.4                                 | 544                               |
|        | p+p     | 200                                 | 1.4x10⁻⁶                          |        | Au+Au  | 39                                   | 206                               |
|        |         |                                     |                                   |        | Au+Au  | 7.7                                  | 4.23                              |
|        |         |                                     |                                   |        | Au+Au  | 11.5                                 | 7.8                               |
| III (2003) | d+Au   | 200                                 | 73x10⁻³                           | XI (2011) | p+p  | 500                                  | 166x10⁻⁶                          |
|        | p+p     | 200                                 | 5.5x10⁻⁶                          |        | Au+Au  | 19.6                                 | 33.2                              |
|        |         |                                     |                                   |        | Au+Au  | 200                                  | 9.79x10⁻³                         |
|        |         |                                     |                                   |        | Au+Au  | 27                                   | 63.1                              |
| IV(2004) | Au+Au  | 200                                 | 3.53x10⁻³                         | XII (2012) | p+p  | 200                                  | 74x10⁻⁶                           |
|        | Au+Au  | 62.4                                | 67                                |        | p+p    | 510                                  | 283x10⁻⁶                          |
|        | p+p     | 200                                 | 7.1x10⁻⁶                          |        | U+U    | 193                                  | 736                               |
|        |         |                                     |                                   |        | Cu+Au  | 200                                  | 27x10⁻³                           |
| V (2005) | Cu+Cu  | 200                                 | 42.1x10⁻³                         | XIII (2013) | p+p  | 510                                  | 1.04x10⁻⁹                         |
|        | Cu+Cu  | 62.4                                | 1.5x10⁻³                          |        | U+U    | 14.6                                 | 44.2                              |
|        | p+p     | 22.4                                | 0.02x10⁻³                         |        | Cu+Au  | 200                                  | 43.9x10⁻³                         |
|        | p+p     | 200                                 | 29.5x10⁻⁶                         |        |        |                                      | 134x10⁻³                          |
| VI (2006) | p+p    | 200                                 | 88.6x10⁻⁶                         | XIV (2014) | p+p  | 200                                  | 282x10⁻⁶                          |
|        | p+p    | 62.4                                | 1.05x10⁻⁶                         |        | p+Au   | 14.6                                 | 44.2                              |
|        |         |                                     |                                   |        | p+Al   | 200                                  | 1.27x10⁻⁶                         |
| VII (2007) | Au+Au | 200                                 | 7.25x10⁻³                         | XV (2015) | p+p   | 200                                  | 3.97x10⁻⁶                         |
|        |        | 9.2                                 | Small                             |        | p+Au   | 200                                  | 282x10⁻⁶                          |
| VIII (2008) | d+Au | 200                                 | 437x10⁻³                         |        | p+Al   | 200                                  | 1.27x10⁻⁶                         |
|        | p+p    | 200                                 | 38.4x10⁻⁶                         |        |        |                                      | 3.97x10⁻⁶                         |
|        | Au+Au  | 9.6                                 | Small                             |        |        |                                      |                                   |
|        |        |                                     |                                   | XIV (2014) | p+p  | 200                                  | 282x10⁻⁶                          |
|        |         |                                     |                                   |        | p+Au   | 14.6                                 | 44.2                              |
|        |         |                                     |                                   |        | p+Al   | 200                                  | 1.27x10⁻⁶                         |
|        |         |                                     |                                   |        |        |                                      | 3.97x10⁻⁶                         |
RHIC Amazing QCD Machine: Many Species and Many Energies!

Lattice QCD

RHIC QCD Machine

RHIC energies, species combinations and luminosities (Run-1 to 16)

Center-of-mass energy $\sqrt{s_{NN}}$ [GeV] (scale not linear)

Species combination
- $p + p$
- $p + Al$
- $p + Au$
- $d + Au$
- $h + Au$
- $Cu + Cu$
- $Cu + Au$
- $Au + Au$
- $U + U$

Average store luminosity $L_{NN}$ [10^{33} cm^{-2} s^{-1}]

Derek B. Leinweber
The RHIC Facility Today

PHENIX

STAR
We study QCD matter (Hot vs Cold) through heavy flavor production:

1) Open Heavy Flavor  
2) Quarkonia

System Size/Collision Asymmetry  
Centrality  
Change the relative contributions of Cold and Hot nuclear matter effects  
Suppression vs path length

Collision Energy  
Change system energy density

Momentum  
Rapidity  
Hard collision dynamics  
Probes different gluon (anti)shadowing

Heavy/Light  
Particle Species  
Mass ordering of suppression  
Break-up, Temperature?  
Each parameter probes different admixtures of nuclear modification
Heavy Flavor: Ideal Probe of QCD Matter

**Theoretical motivation**

- **Symmetry breaking**
  - **Higgs mass:** electroweak symmetry breaking → current quark mass
  - **QCD mass:** chiral symmetry breaking → constituent quark mass

- Charm and beauty quark masses are not affected by QCD vacuum → ideal probes to study QGP

- **Heavy quarks** (c¯c, b¯b)
  - Bound states (J/ψ, Υ)

- Due to their mass (m_Q >> T_{cri}, Λ_{QCD}) → higher penetrating power

- Gluon fusion dominates → sensitive to initial state gluon distribution

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B. Muller, Nucl. Phys. A750 (2005) 84

M. Gyulassy and Z. Lin, Phys. Rev. C51 (1995) 2177
Measuring Heavy Flavor in PHENIX

Mid-rapidity \( J/\psi, \gamma \rightarrow e^+ e^- \) RICH EMCal PC DC Si-VTX MuID MuTr

Forward rapidity: \( J/\psi, \gamma \rightarrow \mu^+ \mu^- \) Si-FVTX

1.2 < |y| < 2.2

\( y = |0.35| \)
VTX detector: 4 barrels of silicon

DCA$_T$ Distributions: b/c separation

- VTX: $|\eta| < 1.2$
- Au+Au 200 GeV: DCA$_T$ resolution $\sim 60 \mu m$

Life time ($c\tau$)
- $D^0: 123 \mu m$
- $B^0: 464 \mu m$

$1.50 < p_T < 2.00$
VTX detector: 4 barrels of silicon

DCA$_T$ Distributions: b/c separation

- VTX: $|\eta| < 1.2$
  - Au+Au 200 GeV: DCA$_T$ resolution $\sim 60 \mu m$

**Lifetime ($c\tau$)**

\[
\begin{align*}
D^0 &: 123 \mu m \\
B^0 &: 464 \mu m
\end{align*}
\]

**Backgrounds**

PHENIX: PRC 93, 034904 (2016)
PHENIX Forward Heavy Flavor Tracker (FVTX)

FVTX detector:

- **FVTX:**
  - Forward rapidity - $1.2 < |\eta| < 2.2$
  - Improved muon momentum resolution & precise tracking

$DCA_R$ Distributions: b/c separation

- **Data-BG**
- **prompt J/\psi**
- **B\rightarrow J/\psi**
- **Total signal**
Measuring Heavy Flavor in STAR

TPC/TOF/BEMC: $|\eta| < 1$

HFT: $|\eta| < 1$

MTD: $|\eta| < 0.5$
First application of Monolithic Active Pixel Sensor technology in collider experiments. DCA resolution <50 μm for $p_T=750$ MeV/c Kaon.

- Recorded about 3B Minimum Bias 200 GeV Au+Au events for $D^0$, $D^\pm$, $D_s$

- Results presented today are based on partial 2014 MB data.
• Precise timing info (~100 ps) for $p_T > 1.2$ GeV/c; muon online triggering and offline identification.

• Recorded 28 pb$^{-1}$, 120 pb$^{-1}$, 400 nb$^{-1}$ and 22 nb$^{-1}$ dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au data for $J/\psi$ and $\Upsilon$ studies.

• Results presented today are based on 28 pb$^{-1}$ p+p 500 GeV (63% MTD) and 14.2 nb$^{-1}$ Au+Au 200 GeV data.
Where does all the heavy flavor go?

Courtesy of Kai Schweda (SQM2016)

Open Heavy Flavor
Open Heavy Flavor with VTX in PHENIX

Results from PHENIX VTX: b/c separation

Invariant yield compared to previous published results

The unfolding results are consistent with the previous published inclusive heavy flavor electron invariant yields.
We see that around $p_T < 4$ GeV the electrons from bottom experience much less suppression than electrons from charm.

**Stay Tuned:**
- 2014 data set x10 better statistics than 2011
  - Decrease uncertainties
  - Increase $p_T$ reach
  - Centrality separation
- Good 2015 p+p and p+Au data sets
Open Heavy Flavor with FVTX in PHENIX

Results from FVTX: B-meson → J/ψ in p+p 510 GeV

The fraction of B-mesons in J/ψ yields is of around 10%, in accordance with world data.
Results from FVTX: B-meson $\rightarrow$ J/$\psi$ in Cu+Au at 200 GeV

Nuclear Modification factor Cu+Au at 200 GeV: $R_{AA} (B\rightarrow J/\psi)$

$R_{CuAu}^{B\rightarrow J/\psi} = \frac{F_{CuAu}^{B\rightarrow J/\psi}}{F_{pp}^{B\rightarrow J/\psi}} R_{CuAu}^{inc. J/\psi}$

- The $B \rightarrow J/\psi$ fraction measured in the Cu+Au collisions at PHENIX is much larger than the LHC results.
- Assuming the fraction is 0.1 in 200 GeV p+p collisions, the $R_{CuAu}$ defined as is less suppressed.
- PHENIX and LHC $R_{AA}$ follow the same trend.
• $R_{AA}(D) > 1$ for $p_T \sim 1.5$ GeV/c
  
  Charm coalescence

• High $p_T$: significant suppression in central Au+Au collisions.
  
  Strong charm-medium interaction

• $R_{AA}(D) \sim R_{AA}(\pi)$ at $p_T > 4$ GeV/c
  
  Similar suppression for light partons and charm quarks at high $p_T$
- $R_{AA}(D)>1$ for $p_T\sim 1.5$ GeV/c

  Charm coalescence

- High $p_T$: significant suppression in central Au+Au collisions.

  Strong charm-medium interaction

- $R_{AA}(D) \sim R_{AA}(\pi)$ at $p_T>4$ GeV/c

  Similar suppression for light partons and charm quarks at high $p_T$

**Significant $v_2$ for D’s at RHIC**

- Non-zero $v_2$ for $p_T>2$ GeV/c

  Favors charm quark diffusion
Quarkonia!

- Color screening in dense medium can cause disassociation of the bound state
- Should see sequential melting of the different states
- Use quarkonia as a medium thermometer!

... Turns out it’s not that simple!

- Many effects which modify the yield other than disassociation!
  - Regeneration
  - Nuclear shadowing
  - CNM energy loss
  - Nuclear breakup
  - Breakup with co-moving hadrons

We received a letter (Phys. Lett. B178 (1986) 416) that:
J/ψ $R_{AA}$ for $p_T > 0$ GeV/c: RHIC is smaller than LHC -> more recombination at LHC

J/ψ $R_{AA}$ for $p_T > 5$ GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC
STAR: $J/\psi$ $R_{AA}$ in Au+Au at 200 GeV

$J/\psi$ $R_{AA}$ for $p_T > 0$ GeV/c: RHIC is smaller than LHC -> more recombination at LHC

$J/\psi$ $R_{AA}$ for $p_T > 5$ GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC

Transport models with dissociation and recombination qualitatively describe data
PHENIX: Suppression of $\psi'$ in Central $d+Au$ Collisions

**Peripheral**
- $60\text{--}88\%$
- $N_{coll} \sim 3$

**Central**
- $0\text{--}20\%$
- $N_{coll} \sim 15$

Breakup of quarkonia due to interaction with nuclear matters:
1) Large suppression of the weakly bounded state $\psi'$
2) Interaction with nucleus? comovers? or medium?
$\psi'$ broken up in small systems: p+Al, p+Au and d+Au

- comover dissociation model agree qualitatively with data
- Comparison with the QGP model work in progress.

- Similar relative suppression of $\psi'$ at backward rapidity, but larger relative suppression of $\psi'$ at forward rapidity at LHC
Outlook: Y Production in Au+Au at 200 GeV

STAR: Y(2S+3S) from the di-muon channel

- Using STAR MTD
  - Lower brehmsstrahlung compared to dielectron channel.
- Hint of less melting of Y(2S+3S) at RHIC than at LHC?

Future Detector at RHIC: sPHENIX

- sPHENIX being designed with separation of Y states in mind.
- Still exploring tracking options.
Summary

✧ Without Doubt RHIC is Amazing QCD Machine
  ✧ Many Species, Many Energies, and High Luminosity and Stability

➢ Open Heavy Flavor
  ✧ Au+Au at 200 GeV
    - Similar suppression of D mesons and light hadrons (at high-$p_T > 4$ GeV/c)
    - Significant $D^0$ and low-$p_T$ HF electron v2 $\rightarrow$ charm flow
    - Electrons from bottom similarly suppressed to those from charm for $p_T > 4$ GeV/c
  ✧ Cu+Au at 200 GeV
    - $B$-mesons $\rightarrow J/\psi$ at forward-rapidity are less suppressed than prompt $J/\psi$

➢ Quarkonia
  ✧ Small Systems $p+Al$, $p+Au$ and $d+Au$
    - $\psi'$ larger suppression than $J/\psi$ at mid and backward rapidity
      - comover dissociation model agree qualitatively with data
      - Forward rapidity: larger relative suppression of $\psi'$ at LHC compared to RHIC
  ✧ $Y$ in $Au+Au$ at 200 GeV: hint for less $Y(2S+3S)$ suppression at RHIC than LHC.

➢ Stay Tuned …!
  ✧ More statistic: decrease uncertainties, increase $p_T$ reach, centrality separation
    $\rightarrow$ more surprises…
Thank you
The Story so Far — D mesons

STAR: PRL 113 (2014) 142301
PHENIX: PRL 101 (2008) 232301
ALICE: PRL 111 (2013) 102301
arXiv: 1509.06888 (2015)
What NEW on Open Heavy Flavor?

First Results from PHENIX VTX: b/c separation

Invariant yield:

PHENIX unfolded $D^0$ $p_T$ spectra agrees within uncertainties with measurements from STAR.

PHENIX: PRC 93, 034904 (2016)