Recent Heavy Flavor Results from PHENIX.
A personal review ...

Cesar Luiz da Silva

INT – Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions.
Seattle, Sep-19-2014
high $p_T$ jet

binary collision

bottom quark

charm quark

quark or gluon jet

thermalized QGP

D meson

B meson

numbers from A.Adil, I.Vitev, PLB649 (2007)
Multiple interactions
Radiation, recombinations
Parton energy loss
Gluon saturation

Quarkonia will be covered by Marzia Rosati

Need several measurements to isolate different effects.

arXiv:1404.2246

Coalescence, Regeneration

Competing effects on Quarkonia $R_{AA}$
Can collide any species combination from proton(polarized) to uranium.
LEPTONS IN PHENIX DETECTOR

\[-2.2 < \eta < -1.2\]
\[\Delta \phi = 2\pi\]

\[1.2 < \eta < 2.2\]
\[\Delta \phi = 2\pi\]

\[|\eta| < 0.35\]
\[\Delta \phi = 2 \times \frac{\pi}{2}\]

9/19/2014

Cesar L. da Silva - LANL - PHENIX HF
Sources of HF at RHIC

From PYTHIA
Heavy Flavor Results in d+Au Collisions

\[ x \sim 10^{-2} \]

PRL109, 242301 (2012)

arXiv:1310.1005

\[ x \sim 8 \times 10^{-2} \]

d+d @ \sqrt{s_{NN}} = 200 \text{ GeV}

Vitev: coherent effect+Croning

Deuteron

Au

9/19/2014

Cesar L. da Silva - LANL - PHENIX HF
Heavy Flavor Results in d+Au Collisions

60-88% centrality

- $R_{dA}$ vs. $p_T$ (GeV/c)

- Blue dots: $HF\mu^+$, $-2.0 < y < -1.4$
- Red dots: $HF\mu^+$, $1.4 < y < 2.0$

Cesar L. da Silva - LANL - PHENIX HF
Heavy Flavor Results in d+Au Collisions

40-60% centrality

\( R_{dA} \)

- \( \mu^- \), \(-2.0 < y < -1.4\)
- \( \mu^- \), \(1.4 < y < 2.0\)

\( p_T \) (GeV/c)
Heavy Flavor Results in d+Au Collisions

![Diagram of Au nucleus and leptons](image)

**0-20% centrality**

- HF $\mu^-$, $-2.0 < y < -1.4$
- HF $\mu^-$, $1.4 < y < 2.0$

$p_T$ (GeV/c) vs. $R_{dA}$

Cesar L. da Silva - LANL - PHENIX HF
d+Au Heavy Flavor Comparison with EPS09s

$R_{dA}$

- PYTHIA + EPS09s LO, $D \rightarrow \mu$
- HF $\mu^-$, $-2.0 < y < -1.4$
- PYTHIA + EPS09s LO, $D \rightarrow \mu$
- HF $\mu^-$, $1.4 < y < 2.0$

0-20% centrality

$\sqrt{s} = 200$ GeV

arXiv:1310.1005

9/19/2014

Cesar L. da Silva - LANL - PHENIX HF
Not a surprise given the limited CNM coverage of DIS in EPS09.
JdA(2.7<\Delta \phi<3.2) = 0.433 \pm 0.087 \text{ (stat)} \pm 0.135 \text{ (syst)}

Back-to-back dominated by gluon fusion.
Continuum dominated by flavor excitation, gluon splitting.
Suppression in JdA stronger than in smaller $x$ single muons. HF from gluon fusion has a stronger suppression.
Light/Heavy quark comparison

$d+Au \at \sqrt{s_{NN}} = 200 \text{ GeV}$

a) 0-20%

$R_{dA}$

$0-20\%$

$\pi^0$

$R_{AA}: 0-10\%$

$Au+Au \at \sqrt{s_{NN}} = 200 \text{ GeV}$

PRL 98, 172301 (2007)

Point-by-point error
Scaling error
Uncertainty in $T_{AA}$
$\pi^0$ without scaling error
$\eta$ without scaling error
$e^+$ from heavy flavor

$R_{dA}$ vs. $p_T$ [GeV/c]

$R_{AA}$ vs. $p_T$ [GeV/c]
Final state modification of light and heavy quarks are consistent within uncertainties.
Is $(R_{dA})^2$ a valid representation of CNM effects in A+A?
Modification in Cu+Cu is an interplay between d+Au and Au+Au mid-rapidity results.

$R_{AA}(p_T)$ indicates a strong contribution from CNM effects. Model including partonic fragmentation and dissociation E-loss, shadowing and Cronin underestimates low-$p_T$ $R_{AA}$ by at least 20%.
Large HF enhancement when going to lower energies. Largely underestimated by E-loss+shadowing+Cronin based models.
How CNM effects factorize in A+A collisions?

A big challenge when estimating and interpreting RAA.
Rapidity dependence of CNM and QGP effects is not symmetric.

PHENIX is analyzing HF in Cu+Au (no breakup, formation time easier to understand). First FVTX data.
**PERSPECTIVES**

- HF analysis using run11 Au+Au and run12 Cu+Au going on. Will be the first $R_{AA}$ and flow results from separated charm and bottom quarks by PHENIX.

- Run14 Au+Au results are very promising
- More data than all previous runs combined
- Vertex detectors (VTX and FVTX) fully operational.

- Run15 p+A (Al,Cu,Au) can be the basis CNM measurement for high energy hadron collisions
- A-dependence can help distinguish the role of saturation, coherent effects (shadowing) and energy loss
- It will be a better reference for Cronin effect

- Future detectors need to emphasize large coverage and precision in order to disentangle CNM and QGP effects
BACKUP SLIDES
Open and bound $c\bar{c}$ modifications

- $J/\psi$ and open charm have same $p_T$ dependence at forward direction
- Small final state effects.

- Significant breakup of $J/\psi$ at low $p_T$ mid- and backward rapidities
Charmonia suppression in d+Au

PRL111, 202301 (2013)

- $\psi'$ has a binding energy $12\times$ smaller than J/$\psi$
- data suggests $\psi'$ is more sensitive to final state effects
- excellent tool to study charmonium nuclear absorption
- bound $c\bar{c}$ may cross the nucleus as a pre-resonant state
- $J/\psi$ and $\psi'$ should have the same suppression
- data indicates something different

- particle activity can change the relative suppression of $\psi'$
- CMS sees the same behavior for $\Upsilon$ states
- comovers?
- EPS09 cannot describe the difference
- larger $R_{AA}$ may indicates another source of $J/\psi$ (regeneration ?)
Models calculated for $y=0$
Data don’t rule out most of coalescence/regeneration models.
Trend for increasing $v_2$ at high $p_T$?
- break of the rapidity symmetry in
  - parton distribution modifications
  - nucleus crossing time of the $c - \bar{c}$ precursor
  - initial state energy loss
  - breakup in the hadronic phase

- comparisons with $p(d) + A$ results will test CNM + QGP factorization
Is $R_{AA}$ also Asymmetric?

arXiv:1404.1873

$J/\psi \rightarrow \mu\mu$

Cu+Au $\sqrt{s_{NN}} = 200$ GeV (gl. sys. 7.1%)

- $1.2 < y < 2.2$
- $-2.2 < y < 1.2$
Is $R_{AA}$ also Asymmetric?

$J/\psi \rightarrow \mu\mu$

Cu+Au $\sqrt{s_{NN}}=200$ GeV (gl. sys. 7.1%)

- 1.2 < $y$ < 2.2
- -2.2 < $y$ < -1.2

Au+Au $\sqrt{s_{NN}}=200$ GeV (gl. sys. 9.2%)
J/Psi $R_{AA}$ in U+U collisions

U+U allows:
- higher energy density
- more room for recombination
- different geometry
Near Future Results

- charm and bottom nuclear modification factors at mid and forward rapidity
- $\psi'$ measurement at forward rapididy
- heavy flavor $v_2$
- and much more ...
Clear separation of the three states
Large acceptance
Similar statistics to LHC
HF larger than EPS09 at backward direction

$\psi'$ relative suppression suggests nuclear absorption from comover.

$J/\psi$ more suppressed than HF at mid- and backward.
Hint for final state effect.

$J/\psi$ $v_2$ still consistent with many charm coalescence scenarios.
$R_{AA}$

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au $\sqrt{s_{NN}} = 0.2$ TeV

- ALICE $J/\psi \rightarrow \mu^+\mu^-$, $2.5 < y < 4$, centrality 0%–20%
  - Global syst. = ±8%

- PHENIX $J/\psi \rightarrow \mu^+\mu^-$, $1.2 < |y| < 2.2$, centrality 0%–20%
  - Global syst. = ±10%