PHENIX Results on Heavy-Flavor Yields at Forward Rapidity

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Open and Closed Heavy Flavor Production

Factorize Production:
• pQCD to calculate cc production
• cc propagation and hadronization
Open and Closed Heavy Flavor Production

Factorize Production:
- pQCD to calculate cc production
- c\bar{c} propagation and hadronization

Initial-State modifications beyond p-p extrapolation:
- Parton Distribution Functions modified in nucleus
- Energy loss of partons traversing nucleus
- Cronin modification of p_T spectra

Propagation and hadronization can include suppression from:
- Breakup of charmonia in cold nucleus
- Suppression of charmonia due to interactions with co-movers

QGP-Specific effects: radiative energy loss, Debye screening
Rapidity Dependencies

• Exploit rapidity dependencies to help separate hot and cold nuclear matter effects

- Larger x of A nucleus
  - E-loss smaller
  - Longer time in nucleus
  - Larger dN/dη

- Small x of A nucleus
  - Initial-state E-loss effects larger
  - Shorter time in nucleus
  - Smaller dN/dη

QGP effects slightly stronger at mid-rapidity in symmetric A+A
CNM effects stronger at forward/backward rapidity in symmetric A+A
The PHENIX Detector

Muon Arms:
- $J/\psi \rightarrow \mu^+\mu^-$
- $D, B \rightarrow X+\mu$

Central Arms:
- $J/\psi, \psi' \rightarrow e^+e^-$
- $D, B \rightarrow X+e$

With FVTX:
- $\psi' \rightarrow \mu^+\mu^-$
- $B \rightarrow J/\psi$
- Separate $D, B$

$p, d, Cu, Au$

$\mu^-$

$\approx 8 \times 10^{-2}$ Anti-shadowing region

$\approx 5 \times 10^{-3}$ Shadowing region

$Au, Al$
Results: $p+p$, $p+A$ and $d+Au$
Results: p+p and d+Au

- Open heavy flavor $R_{dAu}$ shows a different rapidity dependence from $J/\psi$
- Similar suppression at forward rapidity – initial state effects (shadowing, e-loss)
- Enhancement at backward – incoherent multiple scattering* gives Cronin-type behavior
- Divergence at mid/backward rapidity – breakup in CNM, comovers
- Can we quantify different cold nuclear matter effects better?

* Kang et al, PLB 740 (2015)
Initial State Partonic E-Loss

- FNAL E906 - unique access to unambiguous CNM partonic energy loss – kinematic region where shadowing would be minimal, no final-state effects with DY
- First data collected with initial results produced
- We can use these measurements to constrain CNM at RHIC

SeaQuest Preview

-Mass > 4.2 GeV
-\( x_{\text{Target}} > 0.15 \)

First preliminary results from subset of data
ψ':J/ψ, Central Rapidity, d+Au

(more details in Tony Frawley's talk)

• PHENIX ψ' suppressed more than J/ψ at central rapidity, in d+Au. Time spent in nucleus (breakup) does not by itself explain PHENIX data.
$\psi':J/\psi$, Central Rapidity, $d+Au$

(more details in Tony Frawley's talk)

- PHENIX $\psi'$ suppressed more than $J/\psi$ at central rapidity, in $d+Au$. Time spent in nucleus (breakup) does not by itself explain PHENIX data.
- Interactions with co-movers reproduces suppression pattern at this rapidity
- Can we fill out the $dN/d\eta$ dependence more and see if co-mover model holds?

![Breakup by nucleus](image-url)
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Forward Rapidity $\psi':J/\psi$ in $p+p$

(new results)

- Run 13 510 Gev, Run 15 200 GeV
- FVTX Detector allows clean separation of $J/\psi$, $\psi'$ peaks, rejects hadronic backgrounds
- Extract total $\psi':J/\psi$ and $p_T$-dependence (200 GeV)
Forward Rapidity $\psi':J/\psi$ in $p+Al$, $p+Au$
(new results)

- Run 15 $p+Al$ and $p+Au$ 200 GeV runs analyzed at forward and backward rapidity.
- Suppression in the A-going direction but not p-going $\rightarrow$ interaction with co-movers?
- A-going formation time allows some nuclear medium interaction, but should be relatively small.
- In progress: FVTX can also provide $\psi':J/\psi$ versus event multiplicity.
Suppression of both open and closed heavy flavor at similar levels at forward rapidity indicates initial state CNM effects.

Backward rapidity shows enhancement of open heavy flavor which can be reproduced by incoherent multiple scattering effects.

Increased suppression of $J/\psi$ w.r.t. open heavy flavor at backward rapidity indicates some breakup of $J/\psi$, consistent with co-mover effects.

$p$-$A$ suppression of $\psi'$ w.r.t. $J/\psi$, rapidity-dependence could also be explained by co-mover effects.

**d+$A$, p+$A$ Conclusions**
New Forward Rapidity Open Charm/Beauty Measurements in Progress
Understanding Large Suppression in A+A, c/b components
Heavy Flavor Measurements With FVTX

Two Methods for Measuring D/B:
- Direct measurement of $B \rightarrow J/\psi$
- Separation of D/B components in single muon spectra

Heavy Flavor Extraction Method:
- Precision vertex determined with combination of FVTX+VTX detectors
- Muon system tracks projected to FVTX, select best candidate track within a search window
- Perform combined fit of MuTr + FVTX hits and project to vertex
- $Dca_r$ distributions different for prompt, short- and long-lived decays
Work in Progress: $B \rightarrow J/\psi$
(forward rapidity)

Method:
- select good $J/\psi$s, matched to the FVTX detector, and plot muon dca
- Model prompt $J/\psi$, $B \rightarrow J/\psi$, and any background dcas (combinatorial, mismatched)
- Deconvolute the multi-component dca distribution contributions
- Correct for $J/\psi$, $B \rightarrow J/\psi$ acceptance*efficiencies

Status
- Modeled dcas, Good matching between MC and real data
- P+p extracted and fit
- Cu+Au extracted and fit
- Systematic Error checks underway
- Expect results soon

Open HF analysis with single $\mu$
also underway
(very similar methods)
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Additional Conclusions

• Coming soon: Forward/backward $B \rightarrow J/\psi$ and separation of $D/B \rightarrow \mu+X$ for $p+p$, $p+A$, Cu+Au, Au+Au

Thank you
BACKUPS
Results: p+p and d+Au

- Forward rapidity results consistent with models which include shadowing, Cronin and initial-state e-loss
- Model with incoherent multiple scattering better describes backward rapidity data
Enhancements With FVTX

General:
- Contribute to measurement of event vertex(es)
- Provide reaction plane measurement
- Provide relative luminosity measurement in p-p
- Provide multiplicity trigger

Enhance Forward Muon Arm Analyses
- Opening angle measurement before absorber improves dimuon mass resolution
- Combined FVTX-MuTr track fit, DCA cuts provide rejection of some hadronic backgrounds
- Isolation Cuts to enhance signal:background
- DCA measurement to separate prompt particles from non-prompt decay particles
Open Heavy Flavor in A+A

- Open heavy flavor also shows significantly more suppression at forward rapidity than central rapidity in CuCu collisions→large CNM effects?
- In AuAu collisions, central rapidity starts to be highly suppressed
- What will forward rapidity show?
- What will we learn by separation of c, b?

Central Rapidity vs. Species

Central and Forward Rapidity CuCu

Global error: ± 9.9%
\( J/\psi \) in A+A

- \( J/\psi \) in CuCu consistent with CNM extrapolations
- \( J/\psi \) in CuAu rapidity dependence more consistent with CNM effects than QGP effects
- \( J/\psi \) in AuAu has larger suppression at forward rapidity than central rapidity, perhaps indicating strong CNM effects again
- How well can we separate any residual QGP effects from CNM?
Work in Progress: $B \rightarrow J/\psi$
(forward rapidity)

- **Method:**
  - select good $J/\psi$’s, matched to the FVTX detector, and plot muon dca
  - Model prompt $J/\psi$, $B \rightarrow J/\psi$, and any background (combinatorial, mismatched)
  - Deconvolute the multi-component dca distribution contributions
  - Correct for $J/\psi$, $B \rightarrow J/\psi$ acceptance*efficiencies

- **Status**
  - Good matching between MC and real data distributions
  - Systematic Error checks underway
  - p+p and Cu+Au

- Open HF analysis with single $\mu$ also underway
  (very similar methods)
Forward Rapidity $\psi'$ : $J/\psi$ in p+Al, p+Au (new results)

- Run 15 p+Al and p+Au 200 GeV runs analyzed at forward and backward rapidity
- Suppression in the A-going direction but not p-going → interaction with co-movers? Other?
- $p_T$ dependence statistically limited
- FVTX can provide event multiplicity

![Graph showing data and annotations](image_url)

**Table 1.** Boost and formation-time $y$-dependence in the Au rest frame of the $\psi$ at $\sqrt{s_{NN}}$ = 200 GeV.
Results: $x_2$ Dependence

- We do not see $x_2$ scaling, which would be indicative of gluon shadowing.
- Initial-state energy loss ($x_1$-dependent) and final-state effects?
- Difficult to separate initial state effects at RHIC.
ψ’: J/ψ, Central Rapidity, d+Au

(more details in Tony Frawley’s talk)

• PHENIX ψ’ suppressed more than J/ψ at central rapidity, in d+Au. Time spent in nucleus (breakup) does not by itself explain PHENIX data.
• Universal trend with dN_{ch}/dη for several systems, up to 200 GeV
• Is this effect of co-movers? Other?
• Can we fill out the dN/dη dependence more?
Results: p+p and d+Au

- Open heavy flavor $R_{dAu}$ shows a different rapidity dependence from $J/\psi$
- Similar suppression at forward rapidity – initial state? (shadowing, e-loss, etc.)
- Divergence at central/forward rapidity – final state?