Recent Open Heavy Flavor Results from PHENIX

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Why Open Heavy Flavor

- Heavy flavors are primarily produced via gluon fusion in initial stage of the collision
  - Travel through the created medium.
  - Almost no interaction with hadronic phase.
  - No breakup effects like quarkonium productions.

- **Mass-dependence** of cold/hot nuclear matter (CNM/HNM) effects. Heavy ion collisions are mixed of both effects.
  - **CNM effects**
    - Cronin effects
    - Gluon shadowing/anti-shadowing effects
    - Initial state energy loss prior the formation of hot matter
    - Gluon saturation (CGC)
  - **HNM effects**
    - Radiative energy loss
    - Collisional energy loss
    - Recombination of quarks
    - Dissociation and fragmentation of heavy-flavor mesons

Good probe
Use Various System Size

- Use various system size to study CNM/HNM effects
  
  - p+p collisions
    - Baseline for heavy ion collisions
  
  - p+A collisions
    - By reducing system size, no sizable volume of hot matter $\rightarrow$ CNM effects
  
  - Heavy ion collisions (A+A)
    - Formed hot matter $\rightarrow$ CNM + HNM effects

- d + Au (CNM) $\quad 3 < N_{\text{coll}} < 15$
- Cu + Cu (transition region between dominance of CNM and HNM $\quad 5 < N_{\text{coll}} < 180$
- Au + Au (HNM dominance) $\quad 15 < N_{\text{coll}} < 1000$
Use Various Rapidity Range

- Variation of rapidity and energy probe different kinematic regions inside the nucleus

- e.g.
  - Probe CNM effects (shadowing) in p + A collisions

![Diagram showing rapidity regions in proton + nucleus collisions](image)
Open Heavy Flavor Results from PHENIX

- **d + Au** collisions (200GeV)
  - Modification factor, $R_{dAu}$, of heavy flavor $\mu$
    - Forward/Backward rapidity
  
- **Cu + Cu** collisions (200GeV)
  - Modification factor, $R_{CuCu}$, of heavy flavor $e$
    - Mid-rapidity

- **Au + Au** collisions (62.4GeV)
  - Elliptic flow of heavy flavor $e$ and $R_{AuAu}$
    - Mid-rapidity

CNM effects

Transition region between dominance of CNM and HNM effects

Energy dependence of CNM and HNM effects
Heavy Flavor $\mu^-$ at forward and backward rapidity in d+Au (200GeV)

- Negative muons are used.
  - S/N is better than positive muons
  - $\mu^-$: $1 < p_T < 6$ GeV/$c$, $1.4 < |\eta| < 2.0$

Forward:
- $1.4 < |\eta| < 2.0$

Backward:
- $-2.0 < |\eta| < -1.4$

CNM: shadowing   anti-shadowing
Modification factor for $\mu^-$ at forward and backward rapidity

- **Peripheral collisions**: No significant modifications in forward and backward rapidity.
- **Central collisions**: Suppression at forward rapidity, Enhancement at backward rapidity.
- EPS09s nPDF based calculation doesn't reproduce data at backward rapidity.

Require other CNM effects parton recombination in final state
Comparison with $R_{dA}$ of $\psi$

- Compared with $R_{dA}$ of $\psi$
- Should be sensitive to the same effect on heavy-flavor productions
- $\psi$ production has additional effect of breakup in nuclear matter

Comparison shows the breakup of $\psi$ into heavy-meson pairs has a significant effect in quarkonium productions.
Heavy Flavor e at mid-rapidity in Cu+Cu (200GeV)

Cu + Cu system can be bridge between d + Au system and Au + Au system (CNM dominance region and HNM dominance region)

$R_{AA}$ comparison between different systems

- Clear enhancement in d + Au
- Large suppression in Au + Au
- Cu + Cu system: intermediate $R_{AA}$ between that in d + Au and Au + Au
Comparison within different collision systems in similar $<N_{part}>$

Similar enhancement and suppression are seen for the difference system at similar $<N_{part}>$
Cu + Cu system takes over from CNM dominant region to HNM dominant region
Comparison with $R_{\text{CuCu}}$ of $\mu^-$ for Forward Rapidity

More suppression in $\mu^-$ yield
• Additional CNM effects like shadowing and initial state energy loss

Theoretical calculation:
• partonic energy loss
• suppression due to fragmentation and dissociation of heavy-flavor hadrons
• shadowing effect
• Cronin effect

No theoretical calculation to explain both data
Modification Factor $R_{AA}$ of Heavy Flavor $e^\pm$ at mid-rapidity in Au+Au (62.4 GeV)

200 GeV $d + Au$ and $Au + Au$ Collisions

- Large suppression in 200 GeV $Au + Au$ collisions

62.4 GeV in $d + Au$ Collisions

- In contrast to 200 GeV $Au + Au$ data, show clear enhancement in 62.4 GeV $Au + Au$ collisions
- Due to Less energy loss? Larger Cronin effects? or combination of those factors

- Used $p + p$ data from ISR experiment
Comparison with Theoretical Calculation

Theoretical calculation:

- partonic energy loss
- Dissociation of D and B mesons

Model can describes 200 GeV suppression but it underpredicts 62.4 GeV data.
Elliptic Flow of Heavy Flavor $e$ at mid-rapidity in Au+Au (62.4 GeV)

- Charm still has a positive $v_2$ in 62 GeV Au + Au.
- Collective motion of charm itself?
- Collective motion of charmed hadrons through recombination with flowing light partons?

For further understanding, need more data in Au + Au and d + Au collisions at 62.4 GeV
c/b Separation with VTX/FVTX

- Cover wide rapidity range
- Nuclear modification: c/b separation with displaced vertex measurements
- Collective flow: Good resolution of reaction plane
- VTX/FVTX analysis is ongoing to publish
Run-14 200GeV Au + Au

Run14 ended. 2.6nb^{-1} were accumulated
Simulated Performance in Run-14 200GeV Au + Au

Simulated performance of nuclear modification for VTX and FVTX

Run14 data will be the golden dataset for VTX/FVTX.
Improvement of Reaction Plane Resolution with VTX/FVTX

Efficiency of VTX and FVTX are 85% and 95%, respectively.

VTX and FVTX provides the highest reaction plane resolution.
Calibration of VTX in Run14 is ongoing.

- Alignment of VTX for Run14 is ongoing and almost done.
- DCA resolution with WEST barrel are
  - 80 μm at 1.0 < p_T < 1.5 GeV/c
  - 70 μm at 2.0 < p_T < 2.5 GeV/c

VTX DCA distribution in Run14

1.0 < p_T < 1.5 GeV/c  \( \sigma_{DCA} = 82 \mu m \)

2.0 < p_T < 2.5 GeV/c  \( \sigma_{DCA} = 74 \mu m \)
$p_T$ Dependence of DCA Resolution

Resolution of DCA in X-Y plane versus $p_T$

$\sigma_{DCA}$ ($\mu$m) vs $p_T$ (GeV/c)

$\sim 70 \mu$m at $2 < p_T$
Summary

- **d + Au collisions (200GeV)**
  - Suppression at forward rapidity and enhancement at backward rapidity
  - EPS09s nPDF based calculation doesn’t reproduce data at backward rapidity

- **Cu + Cu collisions (200GeV)**
  - Cu + Cu system takes over from CNM dominant region to HNM dominant region
  - No theoretical calculation to explain both of mid and forward rapidity data.

- **Au + Au collisions (62.4GeV)**
  - In contrast to 200 GeV Au + Au data, show clear enhancement in 62.4 GeV Au + Au collisions
  - Charm still has a positive $v_2$ in 62 GeV Au + Au

- VTX/FVTX measure **nuclear modification and collective flow** of charm and bottom separately with displaced vertex (DCA) measurements.
  - Data analysis is ongoing
  - Run14 data will be the golden dataset for VTX/FVTX