Open Heavy Flavor Results from RHIC and the LHC

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Why Study Heavy Quarks?

- Charm ($m_c \sim 1.5$ GeV) & Bottom ($m_b \sim 5$ GeV)

- $m_{c,b} >> \Lambda_{QCD}$
  - Large mass $\rightarrow$ short formation time
  - Medium doesn’t change flavor, but can modify phase-space distribution
  - Difficult to destroy or create in medium

- Experience full evolution of medium
  - Describe medium and interaction
  - Measure intrinsic transport properties
The Role of Heavy Quarks: \( p+p \) collisions

- Test pQCD predictions
  - Results in good agreement w/FONLL predictions
- Baseline for \( p(d)+A \) and \( A+A \) collisions

PRC 84(2011)084905
The Role of Heavy Quarks: A+A collisions

- Energy loss in the medium
- "Dead cone" effect
  - $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Collectivity
  - Heavy quarks flow
  - Thermalization

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}}{\langle N_{coll} \rangle \times dN_{pp}}$$

PRC 84, 044905 (2011)
The Role of Heavy Quarks: p(d)+A collisions

- Another baseline system?
- Cold nuclear matter effects?

Modification to the nPDF

p_T broadening
Measuring Heavy Flavor
Measuring Heavy Flavor

- **Direct**
  - Full hadron kinematics
  - Hard to trigger
  - Large combinatorial background
Measuring Heavy Flavor

- **Direct**
  - Full hadron kinematics
  - Hard to trigger
  - Large combinatorial background

- **Indirect**
  - Kinematic smearing
  - Easy to trigger – high statistics
  - Lots of background sources
  - Branching ratios ~10%
p+p collisions
Charm in p+p

- Data consistent with pQCD FONLL calculations
  - Multiple $\sqrt{s}$ energies, experiments, rapidities
Bottom in p+p

- Data consistent with pQCD FONLL calculations
  - Multiple $\sqrt{s}$ energies, experiments, rapidities

PRL 103(2009)082002

PLB 738(2014)97

PLB 708(2012)265
Data consistent with pQCD FONLL calculations
A+A collisions
• Total charm cross section (RHIC mid-rapidity) scales with number of binary collisions
Heavy flavor leptons in A+A

- Significant energy loss in the medium
  - $R_{AA} < 1$ for $p_T > 2$GeV/c
  - $R_{AA}(HF) \sim R_{AA}(LF)$

- $R_{AA}(e) \sim R_{AA}(\mu)$
  - No rapidity dependence

*Phys. Rev. Lett. 98, 172301 (2007)*
Charm modification

- High $p_T$: $R_{AA}(D) \sim R_{AA}(e)$
- Low $p_T$ at RHIC: Enhancement
Charm modification

- **High $p_T$:** Similar suppression at RHIC & LHC
- **Low $p_T$:** CNM?
  - Probing different $x$-regions ($\sim 10^{-3}$ LHC & $10^{-2}$ RHIC)
  - Charm flow?

![Graph showing Charm modification](image)
• Possibly with the medium
• Need better precision data at low $p_T$
Suppression across systems

- $R_{AA}^{(HF)} \sim R_{AA}^{(LF)}$
- $R_{AuAu} \sim R_{UU}$ for similar $N_{\text{part}}$
- Several models consistent with the data
  - Should also describe $v_2$ and correlations
Dependence on collision energy

- No suppression at high $p_T$ observed
  - $\pi^0$ still suppressed
- $v_2(62.4/39 \text{ GeV}) < v_2(200 \text{ GeV})$
  - Reduced/no strong interaction with the medium?

$p+p$ reference from ISR data

arXiv:1405.6348v1

PRC 91, 044907 (2015)
p(d)+A collisions
What about the other “small” systems? $p(d)+A$

- RHIC
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- RHIC
  - Mid-rapidity
    - No modification
What about the other “small” systems? $p(d)+A$

- **RHIC**
  - Mid-rapidity
    - No modification
  - Forward rapidity
    - Shadowing
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What about the other “small” systems? $p(d)+A$

- **RHIC**
  - Mid-rapidity
    - No modification
  - Forward rapidity
    - Shadowing
  - Backward rapidity
    - Anti-shadowing

- **LHC**
  - Mid-rapidity: low-$x$
RHIC mid-rapidity d+Au

- Peripheral $R_{dA} \sim 1$
- Central $R_{dA} > 1$
- CNM effects?
  - Cronin?
  - $p_T$ broadening?

PRL 109, 242301 (2012)
RHIC mid-rapidity d+Au

- Peripheral $R_{dA} \sim 1$
- Central $R_{dA} > 1$
- CNM effects?
  - Cronin?
  - $p_T$ broadening?
- Or a small drop of HNM?
LHC heavy flavor in p+Pb

- $R_{pPb}$ consistent w/ 1
  - Systematically higher
- $R_{pPb} \sim R_{dAu}$
- Pb+Pb suppression mainly a final state effect

PRL 113, 232301 (2014)
Forward Rapidities: RHIC d+Au

- Peripheral
  - $R_{dA} \sim 1$ for all rapidities

PRL 112, 252301 (2014)
Forward Rapidities: RHIC d+Au

- **Peripheral**
  - $R_{dA} \sim 1$ for all rapidities

- **Central**
  - **Forward**: $R_{dA} < 1$
    - Consistent with pQCD + shadowing
  - **Backward**: $R_{dA} > 1$
    - Consistent with additional $k_T$ broadening
  - Backward & Forward not described simultaneously
Forward Rapidities: LHC p+Pb

- **Forward:** $R_{ppb} \sim 1$
  - No modification
Forward Rapidities: LHC p+Pb

- **Forward:** $R_{p\text{Pb}} \sim 1$
  - No modification

- **Backward:** $R_{p\text{Pb}}$ slightly larger than 1 at low $p_T$
Forward Rapidities: LHC p+Pb

- **Forward:** $R_{pPb} \sim 1$
  - No modification

- **Backward:** $R_{pPb}$ slightly larger than 1 at low $p_T$

- Consistent with RHIC results
- Consistent with pQCD models that include CNM effects
System Size Dependence

- **Suppression**
  - Central Cu+Cu & Au+Au

- **Enhancement**
  - Central d+Au & Peripheral Cu+Cu
System Size Dependence

- **Suppression**
  - Central Cu+Cu & Au+Au

- **Enhancement**
  - Central d+Au & Peripheral Cu+Cu

- Same trend for similar $N_{\text{part}}$
Smooth trend from enhancement (central d+Au, peripheral Cu+Cu) to suppression (central Cu+Cu and Au+Au)
B mesons in p+Pb

- p+p reference from FONLL
- $R_{pPb} \sim 1$
- Pb+Pb suppression not coming from CNM effect
Summary

- Open heavy flavor (direct & indirect) give us insight into the medium produced in heavy-ion collisions
  - Energy loss in the medium
    - $R_{AA}(HF) \sim R_{AA}(LF)$
  - Charm quark flow
- $p(d)+A$
  - Evidence for CNM at RHIC (enhancement in mid & backward rapidities, suppression at forward rapidity)
  - No modification at mid-rapidity at LHC
    - Consistent with A+A suppression coming from HNM
- Where do we go from here?
  - Better precision, statistics, extended $p_T$ range,
    - LHC Run II and RHIC Run 14 & 15
    - Upgrades at both the LHC & RHIC
High $p_T$ - Flavor dependence of $R_{AA}$ – “dead-cone” in pQCD
- $R_{AA}(e_D)$ vs. $R_{AA}(e_B)$ indicates bottom suppression in central A+A at RHIC/LHC
- Need precision measurement on both $R_{AA}(D)$ and $R_{AA}(B)$
R_{AA} of b-jets at p_{T}>80 \text{ GeV/c} comparable to that of light jets

\text{caveat: sizable gluon splitting contribution}

Suppression hierarchy between R_{AA}(J/\psi^{B}) and R_{AA}(D)

\text{– consistent with pQCD calculations}