Heavy Flavor Measurements at STAR

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for the STAR collaboration

Nuclear Physics Institute
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Heavy flavor physics at STAR

- sQGP signatures and properties using heavy quarks (c, b)

1. Open Heavy Flavor
2. Quarkonia

- p+p 200 and 500 GeV
- d+Au 200 GeV
- Au+Au 39, 62.4 and 200 GeV
- U+U 193 GeV

...many more not covered

- Outlook: data analysis with the newly installed HFT and MTD
1. Open heavy flavor

- Heavy quarks c, b
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalization
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- Semi-leptonic decays
  - Higher branching ratio, easy to trigger on
  - Indirect access to kinematics, mixture of c and b contributions

- Hadronic reconstruction
  - Direct access to kinematics
  - Large combinatorial bg., difficult to trigger
**RHIC/STAR**

- **TPC**
  - dE/dx PID
  - Large acceptance, uniform in a wide energy range

- **TOF**
  - PID using flight time

- **BEMC**
  - High-$p_T$ trigger
  - PID using $E/p$ ratio

- **VPD**
  - Trigger minimum bias events
D⁰ and D* production in p+p

p+p 200 GeV

- Essential as a baseline for A+A
- Consistent with FONLL upper limit
- New point at 0<p_T<0.7 GeV/c
  → Lévy fit describes data well
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New 500 GeV measurement
- Consistent with NLO calculations
Total cross section scales with the number of binary collisions.
D⁰ production in Au+Au

Total cross section scales with the number of binary collisions

Charm is mostly produced in initial hard processes
D⁰ suppression in Au+Au

- Strong suppression in central collisions at p_T>2 GeV/c
  - Identical to that observed for pions

- Enhancement at 1<p_T<2 GeV/c
D⁰ suppression and models

- Strong suppression in central collisions at $p_T > 2$ GeV/c
  - Identical to that observed for pions
- Enhancement at $1 < p_T < 2$ GeV/c
- Understanding from models:
  - Characteristic low-$p_T$ “hump” is described by models that include charm–light quark coalescence
  - High-$p_T$ suppression is consistent with strong charm–medium interaction
  - CNM effects may be important

→ Call for a high-statistics $p+A$ (d+A) run

arXiv:1404.6185 (submitted to PRL)
D⁰ in U+U collisions

- Trend in Au+Au continued in U+U
- Increasing suppression with N_{part}

U+U collisions reach ~20% higher Bjorken energy density than Au+Au
Non-photonic electrons in 200 GeV Au+Au

**Suppression**
- Significant suppression of NPE in central collisions \( p_T > 4 \text{ GeV/c} \)
- Similar to that of \( D^0 \) and light hadrons
- Radiation energy loss alone not enough to explain suppression

**Anisotropy (v\(_2\))**
- Substantial elliptic flow of NPE is seen in 200 GeV Au+Au collisions

Note: it’s challenging for models to describe suppression and flow at the same time
Non-photonic electrons: 39, 62.4 GeV

**Suppression**
- No sign of suppression of NPE in 62.4 GeV Au+Au collisions

Note: pQCD-scaled p+p reference

**Anisotropy ($v_2$)**
- NPE in 39 and 62.4 GeV Au+Au collisions consistent with no flow ($p_T<1$ GeV/c)
2. Quarkonia

Quarkonia probe thermal properties of the sQGP
- J/ψ suppression due to color screening
- Sequential melting of states $\rightarrow$ sQGP thermometer

However: picture is complicated by…
- Cold nuclear matter effects
- Co-mover absorption
- Regeneration in the sQGP…

Mócsy, Petreczky, PRD 77, 014501
2. Quarkonia

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However: picture is complicated by…

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Precise measurements to disentangle various effects

- p+p → reference
- d+Au → CNM effects
- Vary collision energy: 39 GeV, 62.4 GeV, 200 GeV
- Vary colliding systems: U+U vs. Au+Au
- High-\(p_T\) J/ψ → suppress CNM and regeneration
- \(Υ\) → negligible recombination and co-mover absorption

Mócsy, Petreczky, PRD 77, 014501
J/ψ suppression: 39, 62.4, 200 GeV

Suppression

- Similar to light hadrons
- Similar in central collisions from 39 thru 62.4 up to 200 GeV

Note: 39 and 62.4 GeV CEM references have large uncertainties

- Similar in U+U and Au+Au
- Model with prompt production and regeneration consistent with data
J/ψ suppression and flow in Au+Au

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Anisotropy ($v_2$)
- J/ψ $v_2$ consistent with non-flow ($p_T > 2$ GeV/c; unique among hadrons)
- Model with thermalized charm quark coalescence disfavored

[32] Zhao, Rapp, PLB 655 (2007) 126
[33] Liu,Xu,Zhuang, NPA834 (2010) 317c
[34] Heinz, Chen (2012)
High-$p_T$ $J/\psi$ in $Au+Au$

- CNM effects are small
- Less regeneration
- Suppression of high-$p_T$ $J/\psi$ in central collisions

$\sqrt{s_{NN}} = 200$ GeV

$A+A \rightarrow J/\psi+X$

STAR Au+Au

STAR ($p_T > 5$ GeV/c)

PHENIX Au+Au ($|y|<0.35$)

Zhao, Rapp

Zhao, Rapp ($p_T > 5$ GeV/c)

Liu et al.

Liu et al. ($p_T > 5$ GeV/c)

$R_{AA}$ vs $N_{part}$

Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010), PLB 664, 253 (2008)
High-$p_T$ $J/\psi$ in Au+Au

- CNM effects are small
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- Suppression of high-$p_T$ $J/\psi$ in central collisions

High-$p_T$ $J/\psi$ suppression is clearly an sQGP effect
Upsilon in A+A

- Co-mover absorption and recombination negligible at RHIC

- Suppression in 200 GeV central Au+Au

- Trend continues in 193 GeV U+U (20% more energy density)

Model calculations:

- Potential based on internal energy assumes 428<T<443 MeV
  

- Strong binding scenario, CNM effects included

Excited Y states in Au+Au

Central Au+Au:
- No evidence of excited states $\Upsilon(2S)$ and $\Upsilon(3S)$
- $\Upsilon(1S)$ suppression is similar to high-$p_T$ $J/\psi$

Suppression of $Y$ is an indication of color deconfinement
Excited Y states in Au+Au

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However...
- d+Au data indicates that CNM effects can be important
- Models do not explain mid-rapidity d+Au data
  → Better understanding requires high-statistics p+A (d+A)
Outlook: Heavy Flavor Tracker

- Innermost, silicon detectors (3 subsystems)
- Resolves secondary vertex
- Physics goal: **Precision measurement of heavy quark production**

**Complete and taking data in Run14**

- **IST at 14 cm**
- **PXL at 2.9 and 8.2 cm**
- **SSD at 22 cm**

**HFT Design**

Qiu Hao

**Outlook**

- Newly commissioned STAR HFT detector
- 2 layers of thin Silicon pixel (MAPS) 0.4% X_0/layer, 12x12µm, 360M pixels
- 2 layers of Silicon pad/strip detectors fast readout, bridging TPC and PXL
- Stay tuned for greatly improved R_AA and v_2 HF measurements from STAR soon!

**Talk:** Qiu-557; **Posters:** Lomnitz-M13 and Wang-M30

**HFT CDR STAR-sn0600**

**IST at 14 cm**

**PXL at 2.9 and 8.2 cm**

**SSD at 22 cm**

**Anisotropy Parameter v_2 (%)**

- **200 GeV Au+Au Collisions**
  - (D^0: 1B min bias events; |y|<0.5)

<table>
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<tr>
<th>Hydro</th>
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</thead>
</table>

**D^0 v_2 projection**

- Transverse Momentum p_T (GeV/c)
Outlook: Muon Telescope Detector

- Outermost, gas detector
- Physics goal: **Precision measurement of heavy quarkonia through the muon channel**
- Acceptance: 45% in azimuth, |y|<0.5

Complete and taking data in Run14

![Image of the muon telescope detector]

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**33 M Di-muon triggered events**

Run 13 p+p @ 500 GeV |y_{\mu\mu}|<0.65

**J/ψ sample data**

- Unlike-sign
- Like-sign
- Signal

**Y projection**

STAR Muon Telescope Detector

60 pb$^{-1}$ p+p, 20 nb$^{-1}$ Au+Au

- Y(1S)$\rightarrow$μ+μ
- Y(2S)$\rightarrow$μ+μ
- Y(3S)$\rightarrow$μ+μ
- Y(1S+2S+3S)$\rightarrow$e+e, |y|<0.5

**M_{ee} (GeV/c^2)**

- Signal

**R_{AA}**

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1

**<N_{part}>**

- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
Open heavy flavor

- Total $D^0$ x-section follows $N_{\text{bin}}$ scaling $\rightarrow$ early charm production
- Low-$p_T$ $D^0$ “hump” $\rightarrow$ suggests charm–light quark coalescence
- High-$p_T$ suppression $\rightarrow$ indicates strong charm–medium interaction
- No 62.4 GeV NPE suppression or flow observed, contrary to 200 GeV

Quarkonia

- $J/\psi$ suppression similar in central 39, 62.4 and 200 GeV collisions
- No $J/\psi$ elliptic flow is observed $\rightarrow$ thermalized $cc$-coalescence unlikely
- Significant high-$p_T$ $J/\psi$ and similar $Y(1S)$ suppression in central A+A, hint for a complete $Y(2S)$ and $Y(3S)$ suppression
  $\rightarrow$ clear signal of a deconfined medium

U+U measurements show similar suppression patterns to Au+Au
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Stay tuned for new great results with HFT and MTD
Thank You!

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UNIVERSITY OF ZAGREB, ZAGREB, HR-10002, CROATIA
$D^0$ in U+U, spectra and $R_{AA}$
D^0, model ingredients

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<th>TAMU</th>
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</table>

Zhenyu Ye, QM2014
Suppression of open charm at high $p_T$ in U+U collisions is similar to and extends the trend as that of open charm and pions in Au+Au collisions.
NPE Au+Au 200 GeV
NPE 62.6 GeV FONLL vs. pQCD

Data/FONLL Au+Au @ $\sqrt{s_{NN}} = 62.4$ GeV
- Min-Bias

Data/pQCD Au+Au @ $\sqrt{s_{NN}} = 62.4$ GeV
- Min-Bias

pQCD: Maciula-Szczurek $k_t$-fact. with Jung CCFM UGDF

STAR preliminary
High-pT J/ψ – motivation

\[ R_{dAu} \sim 1 \text{ at high } P_T \]
\[ \rightarrow \text{CNM effects do not play a strong role} \]

J/ψ vs pT, energy / system

39, 62, 200 GeV Au+Au

U+U vs. Au+Au
$J/\psi$ in $p+p$ 200 GeV

- STAR coverage out to 14 GeV/c
- Prompt NLO CS +CO describes the data
- Prompt CEM better at high-$p_T$
J/ψ in p+p – polarization

- 2<pT<6 GeV/c
- STAR+PHENIX consistent with NLO +CSM
  - Higher statistics needed to discriminate
- p+p 500 GeV results will improve precision for future CNM calculations

\[ \chi^2/\text{ndf} = 1.5/4 \]

\[ \lambda_\theta = -0.16 p_T + 0.18 \]
Heavy Flavor at STAR, R. Vértesi

\( \Upsilon \) in p+p 200 GeV

\[ \Upsilon(1S+2S+3S) \]

\[ B \cdot \frac{d\sigma}{dy} (\text{pb}) \]

\[ \sqrt{s} (\text{GeV})^{1/3} \]

\[ \Upsilon(1S+2S+3S) \rightarrow l^+l^- \]

\[ \text{STAR, p+p, } |y|<1.0 \]

\[ \text{CFS, p+A, E605, p+A, CCOR, p+p, R209, p+p} \]

\[ \text{R806, p+p, UA1, p+\bar{p}, CDF, p+\bar{p}, CMS, p+p} \]

\[ \text{NLO CEM, MRST HO, } m=4.75 \text{ GeV/c}^2, m/\mu=1 \]