Open heavy flavor measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the STAR Heavy Flavor Tracker

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Kent State University
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Outline

• Motivation

• STAR experiment
  • HFT subsystem design & performance

• Heavy flavor measurements
  • $D^0 R_{AA}$
  • $D$ Meson $v_2$

• Model comparisons

• Outlook

• Summary
Motivation

Charm quarks:

- Produced early in heavy ion collisions at RHIC, through hard scattering
- Experience the whole evolution of the system -> good probe for medium properties

Physics interest:

- High $p_T$: test different energy loss mechanisms: radiative vs collisional
- At low $p_T$: extract medium properties from motion of heavy quarks in medium (Brownian motion), e.g. diffusion coefficient

Recent developments and understanding

• RHIC and LHC: $D$-meson $R_{AA}$ suppression at high $p_T$: strong charm-medium interactions

• $D^0$ $v_2$ LHC results are compatible with light flavor $v_2$, charm thermalized?

• $v_2$ and $R_{AA}$ can be used simultaneously to constrain models

• What is occurring at low $p_T$ at RHIC?

• Low $p_T$ $v_2$ is especially sensitive to the partonic medium: scattering strength, transport properties

STAR:PRL 113 (2014) 142301
ALICE: PRL 111 (2013) 102301
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Excellent PID and tracking
Full azimuthal coverage at mid rapidity
-1 < \( \eta \) < 1
STAR Heavy Flavor Tracker (HFT)

TPC – Time Projection Chamber (main tracking detector in STAR)

HFT – Heavy Flavor Tracker

- SSD – Silicon Strip Detector
- IST – Intermediate Silicon Tracker
- PXL – Pixel Detector

Tracking inwards with gradually improved resolution:

Acceptance coverage:
-1 < $\eta$ < 1
0 < $\phi$ < $2\pi$

- SSD $r = 22$
- IST $r = 14$
- PXL $r_1 = 8, r_2 = 8$

$\sigma = \sim 1 \text{ mm}$
$\sigma = \sim 300 \mu\text{m}$
$\sigma = \sim 250 \mu\text{m}$
$\sigma = < 30 \mu\text{m}$

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• Kaon track pointing resolution exceeds the requirement <55 μm at 750 MeV/c
• Pointing resolution in the region with Al-cables ~ 45 μm
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Particle Identification

- Excellent long-lived hadron and electron identification
- Secondary vertex reconstruction with HFT → Full kinematic reconstruction of charmed hadron
Topological reconstruction with HFT

- Greatly reduced combinatorial background (4 orders of magnitude)
- Highly improved S/B

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STAR Preliminary
Au+Au √sNN = 200 GeV
RHIC Run 2014

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6/7/16
Invariant yields

STAR:D^0 @ Au+Au 200 GeV

Au+Au 0-10%
- D^0 2014 [/20]
- D^0 2010/11 [/20]

STAR Preliminary

- p+p D^0+D^*
- p+p Levy scaled by <N_{bin}>

[High p_T] Consistent with published result, with improved statistical precision
- Finalizing systematic uncertainties for p_T < 2 GeV/c and in peripheral collisions
Nuclear Modification Factors

- High $p_T$: significant suppression in central Au+Au collisions. New results have improved precision.

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$D^0$ vs. $\pi$

- $R_{AA}(D) \sim R_{AA}(p)$ at $p_T > 4$ GeV/c

Similar suppression for light partons and charm quarks at high $p_T$
RHIC vs. LHC

- $R_{AA}@\text{RHIC} \sim R_{AA}@\text{LHC}$

strong charm-medium interaction at RHIC and LHC

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ALICE: arXiv: 1509.06888

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\( D^0 \) azimuthal anisotropy significantly different from zero for \( p_T > 2 \) GeV/c 
\( (\chi^2/n.d.f. = 17.5/4) \)

- \( B \rightarrow D \) feed down is negligible at RHIC energies (<5% relative contribution)
**D Meson $v_2$**

- Good agreement between EP and 2 PC methods within systematics
$D$ Meson $v_2$

- $D^{+/−} v_2$ compatible with $D^0$ albeit within large error bars
- First measurement of $D_s v_2$ in heavy-ion experiment, limited statistics
Mass effect

- Systematically below results obtained for light hadrons
  - Need better statistics for a firm conclusion

Suggests something beyond hydro
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  - $D$ Meson $\nu_2$
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Model comparison: TAMU

- Full T-matrix treatment, non-perturbative model with internal energy potential
- Diffusion coefficient extracted from calculation $2\pi T \times D = 2-10$
- Good agreement with $D^0$ meson $v_2$ at low $p_T$, data favor model including $c$ quark diffusion in the medium
  - (w/ c diff. $\chi^2$/n.d.f. = 1.8/5)
  - (w/o c diff. $\chi^2$/n.d.f. = 7.4/5)
  - $\chi^2$ tests done to $v_2$

STAR: PRL 113 (2014) 142301

* See talk by R. Rapp, Plenary II
Model comparison: SUBATECH

- pQCD+HTL calculation with latest EPOS3 initial conditions
- Diffusion coefficient extracted from calculations \(2\pi T \times D \sim 2-4\)
- Good agreement between model and experiment for both \(v_2\) and \(R_{AA}\) in entire \(p_T\) range
  \((\chi^2/n.d.f. = 2.8/5)\)
  - \(\chi^2\) tests done to \(v_2\)

STAR: PRL 113 (2014) 142301

* See talk by PB Gossiaux, HF Workshop
Model comparison: Duke

- Diffusion coefficient is a free parameter, fixed by fitting to $R_{AA}$ at high $p_T$.
- Input value for diffusion coefficient $2\pi T \times D = 7$ fixed to fit LHC results.
- Model with $2\pi T \times D = 7$ doesn’t describe the magnitude of $v_2$ in experimental data.

STAR: PRL 113 (2014) 142301

* See talk by S. Cao, HF Workshop
Charm diffusion coefficient

- Scan different values of the diffusion coefficient to find best agreement to data
- Best agreement for diffusion coefficient $2\pi T \times D = \sim 1 - 3$
- This model seems to underestimate the data for $p_T > 3$ GeV/c

Diffusion coefficient

- Compatible with models predicting a value of diff. coefficient between 2 to ~10
- Lattice calculations, although with large uncertainties, are consistent with values inferred from data

<table>
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<tr>
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<th>Diffusion coef.</th>
<th>$\chi^2$/n.d.f. (to $v_2$)</th>
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<tbody>
<tr>
<td>TAMU</td>
<td>2-10</td>
<td>1.8/5</td>
</tr>
<tr>
<td>SUBATECH</td>
<td>2-4</td>
<td>2.8/5</td>
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<tr>
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<td>7</td>
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Outlook

• Run 14:
  • Full statistics available soon

• Run 15:
  • Full aluminum cables for inner layer of PXL
  • p+p and p+A data sets with HFT

• Run 16:
  • Full aluminum cables for inner layer of PXL
  • Factor 2-3 improvement for $D^0$ significance @ 1 GeV -> centrality dependence for $\nu_2$

<table>
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<th>Year</th>
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<th>Events(MB)</th>
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<tbody>
<tr>
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<td></td>
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<tr>
<td></td>
<td>Au+Au</td>
<td>1.2 B</td>
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<td>Run 15:</td>
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<tr>
<td></td>
<td>p+p</td>
<td>1 B</td>
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<tr>
<td></td>
<td>p+Au</td>
<td>0.6 B</td>
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<td>Run 16:</td>
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<tr>
<td></td>
<td>Au+Au</td>
<td>1.5 B *</td>
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<tr>
<td></td>
<td>d+Au</td>
<td>~0.3 B</td>
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* Up to Date
Future HFT+ Upgrade plan (2021-2022)

HFT+ upgrade motivation:
• Measure **bottom quark hadrons** at the RHIC energy
• Take data in **higher luminosity** with high efficiency

HFT+ detector requirements:
• **Faster** frame readout of 40 µs or less
• **Similar or better**: pointing resolution
  S/N ratio
  Total power consumption
  Radiation length
• **Compatible** with the existing insertion mechanism, support structure, air cooling system

HFT+ read-out electronics requirements:
• **Compatible** with STAR DAQ system and trigger

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Summary

• The STAR HFT has been successfully installed and taking data in 2014-2016

• State-of-the-art MAPS technology proved to be suitable for vertex detector application

• The HFT enabled STAR to perform a direct topological reconstruction of the charmed hadrons – factor 4 improvement in $D^0$ significance

• A faster HFT+ has been planned in order to measure the bottom quark hadrons at the top RHIC energy

• Presented first results of charmed meson $R_{AA}$ and $v_2$ using the HFT

• $D^0$ is significantly suppressed for high $p_T$ in 0-10% Au+Au collisions
• $D^0 \nu_2$ is finite for $p_T > 2.0$ GeV/c and lower than light hadrons for $1 < p_T < 4.0$ GeV/c

• Data favor model scenario where charm quarks flow

• $D^0 \nu_2$ and $R_{AA}$ can be described simultaneously by models and are consistent with values of $2\pi T x D$ between 2 and $\sim 10$

• Looking forward to improved baseline from 2015 and statistics in year 2016
Thank you!
HFT Subsystems

**Silicon Strip Detector (SSD)**
- Double sided silicon strip modules with 95 μm pitch
- Existing detector with new faster electronics
- Radius: 22 cm – Length: ~106 cm

**Intermediate Silicon Tracker (IST)**
- Single sided double-metal silicon pad with 600 μm x 6 mm pitch
- Radius: 14 cm – Length: ~50 cm

**PiXeL detector (PXL)**
- *Monolithic Active Pixel Sensor* technology
- 20.7 μm pitch pixels
- Radius: 2.8 and 8 cm – Length: ~20 cm

First MAPS-based vertex detector at a collider experiment
HFT Status in 2014 and 2015 Run

• Collected minimum bias events in HFT acceptance:
  • 2014 Run: 1.2 Billion Au+Au @ $\sqrt{s_{NN}} = 200$ GeV
  • 2015 Run: \[\begin{array}{c}
    \sim 1\text{ Billion } p+p \\
    \sim 0.6\text{ Billion } p+Au
  \end{array}\] @ $\sqrt{s_{NN}} = 200$ GeV

• Typical trigger rate of ~0.8kHz with dead time <5%

• Sub-detector active fraction
  • PXL
    • > 99% operational at the delivery
    • 2015 Run ended with 5% dead sensors (6 damaged sensors + 1 outer ladder off)
  • IST
    • 95% channels operational, stable
  • SSD
    • 80% channels operational (one ladder off)
Topological reconstruction

- Direct topological reconstruction through hadronic channels, for instance:

\[ D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm \]

B.R. 3.9% \( c\tau \sim 120 \, \mu m \)

- Greatly reduced combinatorial background (4 orders of magnitude)

- Topological cuts optimized using TMVA (Toolkit for Multivariate Analysis)
$D^0$ reconstruction using HFT

- Significance greatly enhanced compared to STAR previous, 2010+2011 results.

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6/7/16
Diffusion Coefficient from DUKE

\[ \chi^2 \]

\[ \chi^2_{\text{min}} + 1 \]

\[ \chi^2_{\text{min}} \]

\[ D (2\pi T) \]

STAR Preliminary
Comparison to ALICE

STAR Preliminary

Transverse Momentum $p_T$ (GeV/c)

$V_2$

- $D^0$ STAR 0-80%
- ALICE 0-10%

STAR Preliminary

Transverse Momentum $p_T$ (GeV/c)

$V_2$

- $D^0$ STAR 0-80%
- ALICE 0-10%

STAR Preliminary

Transverse Momentum $p_T$ (GeV/c)

$V_2$

- $D^0$ STAR 0-80%
- ALICE 10-30%

STAR Preliminary

Transverse Momentum $p_T$ (GeV/c)

$V_2$

- $D^0$ STAR 0-80%
- ALICE 30-50%

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$v_2$: Event plane method

- Event plane reconstructed using charged hadrons within STAR TPC acceptance ($|\eta|<1$)
- Corrected for detector acceptance
- Yields in $\phi$–$\Psi$ bins corrected for event plane resolution

$$v_2 = v_2^{obs} \times \left\langle \frac{1}{\text{E.P. Resolution}} \right\rangle$$

- $\Delta\eta$ gap of ~0.15 used in event plane reconstruction

$$v_{2,\text{nonFlow}} = \frac{\langle \sum_h \cos(2(\phi_{D^0} - \phi_h)) \rangle}{M v_2^h}$$

- Non-flow estimated from measured D-h correlations in p+p 200GeV

\( v_2: \) Two particle correlation

- Event by event \( v_2 \) for foreground and background

\[
< \cos(2\varphi_{h1} - 2\varphi_{h2}) > = (v_2^h)^2
\]

\[
\nu_2^D = \frac{< \cos(2\varphi_D - 2\varphi_h) >}{\sqrt{< \cos(2\varphi_{h1} - 2\varphi_{h2}) >}}
\]

- \( h_1 \) in \( \eta < 0 \), \( h_2 \) in \( \eta > 0 \)

- Statistically subtract background from foreground to obtain \( D^0 v_2 \)

- Corrected for detector acceptance


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Comparison to experiment

- $D^0 v_2$ is below light hadrons for $1 < p_T < 4$ GeV/c
  - ($\chi^2$/n.d.f. = 9.6/3 )
Efficiency: fast vs. slow HFT

- HFT (~200 µs) → HFT+ (≤40 µs)

The planned HFT+ program (2021-2022) is complementary to sPHENIX at RHIC and ALICE HF program at LHC

HFT+ flagship measurements

- $R_{AA}$ for $J/\psi$ and $D^0$ from $B$, and $b$-jets