Heavy-Flavor flow and transport in the QGP at RHIC with STAR

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Heavy Flavors in Heavy Ions

- Heavy quarks produced early: initial hard parton collision
- Total charm/bottom yield is conserved throughout QGP evolution in AA collisions
  - $m_c, m_b \gg T_{QGP}$
  - Momentum spectrum is modified in QGP
    - Collisional, radiative energy loss for heavy quarks
    - Study via Nuclear modification factor of $D^0$ mesons.
- Low $p_T$: Momentum transfer from thermal medium is small compared to heavy quark momentum
  - Brownian motion in an expanding QGP
- Insight into dynamics, transport properties of QGP
  - Moore, Teaney PRC71 (2005) 064904
- Experimental study using azimuthal momentum distributions, “elliptic flow” ($v_2$), of $D^0$ mesons.
Azimuthal anisotropy: Elliptic flow, $v_2$

- AA collision region: overlap of two spherical nuclei, ellipsoid
  - Fourier expansion of azimuthal distribution wrt reaction plane ($\Psi_n$)
    \[ \frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_n)] \]
    - 2nd coefficient, $v_2$, well described using relativistic hydrodynamics
      - "Elliptic flow"
      - Light hadron $v_2$: scales with number of constituent quarks.

- Charm hadron $v_2$:
  - Test particle inside QGP fluid
  - Insight into transport properties of QGP

As seen in atomic systems: Science, 298, (2002) 2179
STAR Heavy Flavor Tracker

- Pixels
  - $r \sim 2.8$, 8 cm

- Intermediate Silicon Tracker (IST)
  - $r \sim 14$ cm

- Silicon Strip (SSD)
  - $r \sim 22$ cm

Allows direct topological reconstruction of charmed hadrons in the challenging heavy ion environment
DCA$_{xy}$ resolution $\sim$ 30-40 $\mu$m at $p\sim$1 GeV/c

- **D$^0$** analysis with HFT:
  - Background rejection by 4 orders of magnitude
- Signals for D$^\pm$ and D$_s$ observed

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Good signal significance
- Great improvement over 2010-2011 STAR: PRL 113 (2014) 142301
- Signal significance allows study of azimuthal anisotropy vs. $p_T$
D₀ Nuclear Modification, \( R_{AA} \)

- \( R_{AA} \): Quantify deviations from pp behavior
  \[
  R_{AA} = \frac{1}{N_{\text{bin}}} \frac{dN_{AA}}{dp_T} \bigg/ \frac{dN_{pp}}{dp_T}
  \]

- If AA is a superposition of \( N_{\text{bin}} \) nucleon-nucleon collisions: \( R_{AA} = 1 \)

- Central collision data:
  - \( R_{AA}(D) > 1 \) @ \( p_T \sim 1.5 \) GeV
    - Evidence of charm coalescence with light quarks expanding from bulk QGP medium

- \( R_{AA}(D) \) for higher \( p_T \): significant suppression
  - Significant interaction of c quarks with medium, c quark energy loss
  - Suppression of D₀ is similar to that of mesons containing light quarks

STAR D0 (2010-11 data): PRL 113 (2014) 142301
STAR π : PLB 655 (2007) 104
Azimuthal Anisotropy via Event Plane Method

- Measure $D^0 \phi$ distribution wrt event plane
- Fit: $N(1+2v_2\cos(2(\phi-\Psi)))$
  - Extract $v_2\{\text{EP}\}$
    - Require rapidity gap ($\Delta\eta \sim 0.15$) between $D^0$ and particles used to measure event plane.
    - Reduce background, e.g. from di-jets, resonance decays.
  - Alternate method, $v_2\{2\}$: 2-particle correlation between $D^0$ and all other hadrons. (not shown)
    - Different systematics.

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**D^0 azimuthal anisotropy, v_2**

- **Observe finite v_2 for charm mesons**
  - D^0 v_2 > 0 @ p_T > 2

**Remarks:**
- B feeddown contribution is small at RHIC, < 5%
- Estimate contributions unrelated to reaction plane azimuthal correlation ("non-flow") using D*-h correlations in pp @ 200 GeV
Comparison with light flavor $v_2$

- Hadrons including u,d,s quarks:
  - Show similar $v_2$ behavior when scaled by Number of Constituent Quarks
  - Evidence of light-quark collective behavior in a QGP

- Compare $D^0$ to light quark hadrons
  - scaled $D^0$ $v_2$ smaller than light flavor hadrons
  - Indication that charm is not fully thermalized
D⁰ elliptic flow and c-quark diffusion

- Compare to calculations with/without c-quark diffusion.
  - TAMU transport model:
    - T-Matrix, non-perturbative

Calculation with diffusion is favored
- $\chi^2/\text{ndf} \sim 2.1/5$, vs. 7.4/5

D⁰ R_{AA} and ν₂ comparison

Diffusion calculations:

- **TAMU:**
  \[ 2\pi T D_s = 2 - 7 \]

- **Subatech:**
  - Gossiaux et al.
  - pQCD + hard thermal loop
  \[ 2\pi T D_s = 2 - 4 \]

- **Duke:**
  - Cao et al. PRC92 (2015) 024907
  - Constant Ds, fit to LHC high p_T R_{AA}
  \[ 2\pi T D_s = 7 \]

- **PHSD: Parton-Hadron-String Dynamics**
  - Berrehrah et al. PRC90 051901 (2014)
  - Transport model
  \[ 2\pi T D_s = 5 - 12 \]

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Models incorporating charm diffusion are consistent with STAR $R_{AA}$ and new $v_2$ results.

\[ 2\pi T D_s \sim 2 - 10 \]

Lattice calculations are consistent with this range of values inferred from STAR $D^0$ data.
**D_s results from STAR HFT**

- Expect enhancement of D_s in AuAu
  - More abundant s-quark production compared to pp

- Observe larger D_s/D_0 ratio in AuAu compared to PYTHIA pp simulation.
Outlook for $D^0$ and HFT in STAR

- **Run 14 AuAu:**
  - Prelim. results based on $\sim$70% of available stats.
  - Full statistics coming soon.

- **Run 15 data:**
  - $p+p$: baseline measurements
  - $p+Au$: study Cold Nuclear Matter effects

- **Run 16 AuAu:**
  - Expect 2B events (compared to 1.2 B in Run 14)
  - Al cables for inner layer of Pixel detector
    - 0.5% $\rightarrow$ 0.4% $X_0$.
    - Factor 2-3 improvement in significance for $D^0$
    - Allow study of centrality dependence

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Summary

- STAR HFT: measurement of $D^0$ mesons
  - Observe modifications of $p_T$ spectrum
    - Transverse flow and charm energy loss:
      - charm has significant interactions with produced medium.
  - Observe finite $D^0$ azimuthal anisotropy $v_2$.
    - Suggests collective behavior of charm quarks
    - Measurements can provide information on diffusion coefficient of QGP medium
      - Models with $2\pi$TDs $\sim 2 - 10$ are consistent with our data

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Backup
D meson $R_{AA}$ at RHIC is similar to LHC for $p_T > 4$ GeV/c
D⁰ v₂ Comparison with LHC

- D⁰ v₂ LHC results:
  - similar to v₂ for light flavors.

- D⁰ v₂ STAR results:
  - lower than v₂ for light flavors

- Indications that charm is fully thermalized at LHC but not at RHIC

- Need systematic theoretical studies of heavy flavor production at both energies