Measurements of open heavy-flavor hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR experiment

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Outline

• Motivation – probing quark-gluon plasma
• The Solenoid Tracker At RHIC
• Heavy flavor energy loss in Au+Au collisions
• Directed and elliptic flow of charm quarks in Au+Au collisions
• Hadronization of charm quarks in Au+Au collisions
Heavy-flavor quarks as a probe of quark-gluon plasma (QGP)

- QGP is hot and dense medium produced in **heavy-ion collisions**
- HF quarks possess **large masses**
  → they are produced primarily at the **early stages of nuclear collisions**
  → they experience the **whole evolution of the system including the QGP phase**
- HF hadrons allow to probe **the quark mass dependence of energy loss** in the QGP
- **Collective behavior** of heavy-flavor quarks
  → sensitive to the degree of thermalization in the QGP
  → constrain the heavy-flavor quark diffusion coefficient

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Open charm hadrons are studied via hadronic decays:

- $D^+(c\bar{d}) \to K^-\pi^+\pi^+$, **branching ratio (BR) = (8.98 ± 0.28) %**
- $D^0(c\bar{u}) \to K^-\pi^+$, **$BR = (3.93 ± 0.04) %$**
- $D_s^+(c\bar{s}) \to \Phi\pi^+$, $\Phi \to K^-K^+$, **$BR = (2.27 ± 0.08) %$**
- $\Lambda_c^+(udc) \to K^-\pi^+p$, **$BR = (6.35 ± 0.33) %$**
The **Solenoid Tracker At RHIC**

- Situated at **Relativistic Heavy-Ion Collider at Brookhaven National Laboratory (BNL) in the USA**
- Designed to study the strongly interacting matter
- Excels in **tracking and identification of charged particles** at mid-rapidity with full azimuthal coverage
- Most of the subsystems are immersed in 0.5 T solenoidal magnetic field
The Solenoid Tracker At RHIC

**Time Projection Chamber (TPC)**
- Main tracking device; momentum determination
- Particle identification via specific energy loss $dE/dx$
Time Of Flight (TOF)

- Measures particle velocity $\beta$
- Improves particle identification in the momentum range of 0.6–3 GeV/c
The **Solenoid Tracker At RHIC**

**Forward Meson Spectrometer**
- $2.5 < \eta < 4$
- Event plane measurements for flow studies

**Barrel ElectroMagnetic Calorimeter**
- Trigger on and identify high transverse momentum ($p_T$) electrons
The Solenoid Tracker At RHIC

Heavy Flavor Tracker (HFT)
- Inner tracking system
- First application of MAPS in collider experiments
- Excellent $DCA_{xy}$ and $DCA_z$ resolution: $\sim 50 \, \mu m$ for kaons at $p_T = 750 \, \text{MeV}/c$
- Significantly improves the signal/background for open HF reconstruction

Energy loss in Au+Au collisions: D⁰

- Nuclear modification factor $R_{AA}$:

$$ R_{AA} = \frac{dN_{AA} / dp_T}{\langle T_{AA} \rangle d\sigma_{pp} / dp_T} $$

- Yields at high $p_T$ are greatly suppressed in central collisions
- Suppression at high $p_T$ decreases towards more peripheral collisions
- No significant centrality dependence for D⁰ suppression at low $p_T$
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- Suppression at high $p_T$ decreases towards more peripheral collisions
- No significant centrality dependence for D⁰ suppression at low $p_T$

- D⁰ shows **similar suppression to light mesons** at high $p_T$
- D⁰ $R_{AA}$ is **comparable to that from the LHC** measurements in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Models that include both collisional and radiative losses are consistent with data at $p_T > 3$ GeV/c

- Charm quarks lose significant amount of energy when traversing through the QGP

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**STAR**

Energy loss in Au+Au collisions: $D^0$

- Nuclear modification factor $R_{AA}$:
  \[
  R_{AA} = \frac{dN_{AA}}{d\rho_T} \cdot \frac{1}{\langle T_{AA} \rangle} \cdot \frac{d\sigma_{pp}}{d\rho_T}
  \]

- Yields at high $p_T$ are **greatly suppressed** in central collisions
- Suppression at high $p_T$ decreases towards more peripheral collisions
- No significant centrality dependence for $D^0$ suppression at low $p_T$

- $D^0$ shows **similar suppression to light mesons** at high $p_T$
- $D^0$ $R_{AA}$ is **comparable to that from the LHC** measurements in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- Models that include both collisional and radiative losses are consistent with data at $p_T > 3$ GeV/c

- **Charm quarks lose significant amount of energy when traversing through the QGP**
- $p_T$-integrated $D^0$ cross-section is independent of centrality, and smaller than that in p+p collisions
Energy loss in Au+Au collisions: D±

- Similar level of suppression and centrality dependence for D± and D⁰ mesons
- D±/D⁰ yield ratios are compatible with PYTHIA
Energy loss in Au+Au collisions: heavy-flavor decayed electrons

- Measurement of electrons from **charm and beauty** hadron decays
- Extract charm and bottom decayed **electron fractions**
  - background from photonic electrons and hadrons
  → template fitting to Distance of Closest Approach (DCA) distribution (enabled thanks to HFT)

- Charm-decayed electrons show suppression at high-$p_T$ of $R_{AA} \sim 0.4$
- Data consistent with DUKE model prediction
- Beauty-decayed electrons suppression is smaller than charm-decayed electrons with ≥ 3σ significance
  - **Evidence of mass dependence of energy loss**
\( \Lambda_c/D_0 \) yield ratio in Au+Au collisions

- Helps to understand charm quark hadronization
- \( \Lambda_c/D_0 \) is comparable with baryon-to-meson ratios for light and strange flavor hadrons
- Data can be used to constrain model calculations

- Increase towards more central collisions:
  - Similar to those for light and strange-flavor hadrons
  - Consistent with the Catania model calculation including both coalescence and fragmentation hadronization
D_s/D_0 yield ratio in Au+Au collisions

- D_s/D_0 yield ratio probes **strangeness enhancement** and **coalescence of charm** quarks with strange quarks in QGP

- Significantly larger than fragmentation baseline (PYTHIA p+p)
- No significant centrality dependence

- PYTHIA calculation consistent with ALICE p+p results at $\sqrt{s} = 7$ TeV
- STAR measurements at high $p_T$ are consistent with ALICE Pb+Pb results at $\sqrt{s_{NN}} = 5.02$ TeV
**$D_s/D_0$ yield ratio in Au+Au collisions**

- $D_s/D_0$ yield ratio probes **strangeness enhancement and coalescence of charm** quarks with strange quarks in QGP

- Significantly larger than fragmentation baseline (PYTHIA $p+p$)
- No significant centrality dependence

- Catania model calculation with only coalescence hadronization describes data for $p_T > 4$ GeV/$c$
- Catania model calculation with both coalescence and fragmentation hadronization describes data for lower $p_T$
- **Tsinghua model with sequential coalescence hadronization** qualitatively describes data

- Enhancement of $D_s$ meson in Au+Au collisions suggests that **charm quarks also participate in coalescence hadronization** in the QGP
The charm quark cross-section in \textbf{Au+Au collisions}, scaled by the number of binary nucleon-nucleon collisions, is consistent with that measured in \textbf{p+p collisions} within the uncertainties.

\begin{itemize}
  \item Redistributed of charm quarks among open-charm hadron species.
\end{itemize}
Fourier expansion of the particle yield with respect to the event plane:

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{dp_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos \left[ n(\phi - \psi_{RP}) \right] \right)
\]

- Light flavor \( v_2 \) suggests hydrodynamic behavior of a strongly interacting matter

- \( p_T < 2 \text{ GeV/c} \): clear mass ordering of \( v_2 \)
- \( p_T > 2 \text{ GeV/c} \): \( D^0 v_2 \) consistent with light mesons

- \( D^0 v_2 \) follows number of constituent quarks scaling → suggesting that charm quarks flow with the QGP
Charm-decayed electrons

- Measured $D^0 \nu_2$ folded to decayed electron $\nu_2$ with semi-leptonic decays simulated in EvtGen
- **Charm electron $\nu_2$ consistent with folded $D^0 \nu_2$** and DUKE model

Beauty-decayed electrons

- First observation of **non-zero bottom electron $\nu_2$**
  - TPC event plane measurement with full non-flow subtraction significant at $3.4\sigma$
- Forward Meson Spectrometer ($2.5 < \eta < 4$) as event plane detector reduces non-flow to 0.5%
Comparison of HF decayed electron $v_2$ in Au+Au collisions at $\sqrt{s_{NN}} = 27, 54.4$ and $200$ GeV

- Results in 54.4 GeV Au+Au collisions show $v_2$ comparable to that in 200 GeV
- Hint for lower $v_2$ in Au+Au collisions at 27 GeV than those at 54.4 and 200 GeV

- Comparable to light flavor meson $v_2$ at 54.4 GeV

- HF quarks interact strongly with the medium in 54.4 GeV Au+Au collisions
Charm quark directed flow $\nu_1$

- Important to study **initial conditions** of heavy-ion collisions

- **Hydro models:**
  - $\nu_1$ magnitude depends on viscous drag on charm quarks and initial tilt of QGP bulk

- **Initial electromagnetic field:**
  - opposite effects for $c$ and $\bar{c}$
  - induce larger $\nu_1$ for charm quarks than for light flavor quarks, due to the early production of charm quarks
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- Measured $D^0 v_1$ slope is $\sim$5-20 times larger than that for kaons
- Tilted source models **predict the correct sign** of $dv_1/dy$, but the $v_1$ magnitudes are lower than data
  - **Help to constrain initial conditions**
Charm quark directed flow $\nu_1$

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  - Measured $D^0\nu_1$ slope is $\sim$5-20 times larger than that for kaons
  - Tilted source models **predict the correct sign** of $d\nu_1/dy$, but the $\nu_1$ magnitudes are lower than data
    → **Help to constrain initial conditions**
- $\nu_1$ magnitude of **charm-decayed electrons is consistent with $D^0$ mesons**
Charm quark directed flow $v_1$

- $c$ and $\bar{c}$ $v_1$ magnitude probed by both charmed-decayed electrons and $D^0$ mesons
- Within the uncertainties, no splitting due to electromagnetic field

![Graph showing directed flow vs rapidity]
Conclusions

• D meson production is **strongly suppressed** in central Au+Au collisions compared to that in p+p collisions
  → strong charm-medium interactions
  → less suppression of beauty-decayed electrons compared to charm-decayed ones

• $D^0$ meson and charm-decayed electrons exhibit similar $v_2$ as light flavor in Au+Au collisions
  → charm quarks **have gained significant flow** in the QGP
  → charm quarks may have **achieved local thermal equilibrium**

• Directed **flow $v_1$ of $D^0$ is significantly larger** than that for light hadrons
  → constraints for the geometric and transport parameters of the hot QCD medium
  → observed no $c$ and $\bar{c}$ splitting due to electromagnetic field within uncertainties

• Charm quarks participate in **coalescence hadronization** in the QGP
  → Total per-NN charm quark cross section consistent with p+p, but **charm hadrochemistry significantly modified**
Thank you for your attention

STAR at ICHEP 2020:

• Measurements of $J/\psi$ photoproduction in ultra-peripheral collisions at RHIC
  • Jaroslav Adam, 29 July 2020 (Wednesday), 19:18

• Overview of upsilon production studies performed with the STAR experiment
  • Leszek Kosarzewski, 30 July 2020 (Thursday), 09:12

• Measurement of the central exclusive production of charged particle pairs in proton-proton collisions at $\sqrt{s} = 200$ GeV with the STAR detector at RHIC
  • Rafal Sikora, 30 July 2020 (Thursday), 10:25

• Production of D$^+$ mesons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the STAR experiment
  • Jan Vaněk (poster), 30 July 2020 (Thursday), 13:39

• Study of the central exclusive production of $\pi^+\pi^-$, $K^+K^-$ and $p\bar{p}$ pairs in proton-proton collisions at $\sqrt{s_{NN}} = 510$ GeV with the STAR detector at RHIC
  • Tomáš Truhlář (poster), 31 July 2020 (Friday), 13:30

Acknowledgement

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BACKUP
**D⁰ elliptic anisotropy compared to theory**

![Graph showing anisotropy parameter, v₂, as a function of p_T (GeV/c)](graph.png)

- **SUBATECH**: pQCD + hard thermal loops  
  H. Berrehrah et al., PRC 91 054902 (2015)

- **TAMU**: non-perturbative T-matrix approach  
  M. Heet al, EPJ C (2016) 76: 107

- **Linearized Boltzmann Transport (LBT)**: Jet transport model extended to heavy quarks  
  S. Cao et al., PRC 94 014909 (2016)

- **Duke**: transport properties tuned to LHC data  
  S. Cao et al., PRC 92 024907 (2015)

- **Parton-Hadron-String Dynamics (PHSD)**: 
  Effective potential of c-quarks  
  H. Berrehrah et al., PRC 90 051901 (2014)

- **3D viscous hydro**: tuned to light hadrons  

- **TAMU model with no charm quark diffusion and Duke model are inconsistent with data**

- **3D viscous hydro calculation agrees with data, suggesting that charm quarks may have achieved thermal equilibrium**

- **Charm quark diffusion coefficient:**
  \[ (2πT)D_s ≈ 2 - 12 \]
Measurement of electrons from charm and beauty hadron decays

- Goal is to extract beauty and charm-decayed electron from the background of photonic electrons and hadrons
  → template fitting to Distance of Closest Approach (DCA) distribution (enabled thanks to HFT)