Measurements of $\Lambda_c^\pm$, $D_s^\pm$, $D^{*\pm}$ and $D^0(\bar{D}^0)$ Production in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR

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Introduction

Heavy quarks: $m_{c/b} \gg \Lambda_{\text{QCD}}, T_{\text{QGP(RHIC)}}$
- Produced early in heavy-ion collisions through hard scatterings
- Experience the whole evolution of the system
  → good probe of medium properties, e.g. transport parameters
- Focus on charm production

Charm Flow: Liang He on 2\textsuperscript{nd} Oct. Bottom production: Xiaolong Chen on 2\textsuperscript{nd} Oct

\[ \frac{2\pi TD_s}{T/T_c} \]

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Contents

- In medium energy loss
  - $D^0 R_{AA}, R_{CP}$

- Hadronization
  - $\Lambda_c, D_s$

- Total charm cross-section

- Possible medium effect of resonance production
  - $D^{*+/-}$

\[ D^0 (D^0) \rightarrow K^+ \pi^- \]
\[ \Lambda^+_c \rightarrow pK^- \pi^+ \]
\[ D_s^+ \rightarrow \phi(1020)\pi^+ \rightarrow K^+K^- \pi^+ \]
\[ D^{*+} \rightarrow D^0 + \pi^+_{soft} \]
**Time Projection Chamber:**
Tracking, PID \((dE/dx)\), \(|\eta|<1, 0<\phi<2\pi\)

**Time Of Flight detector:**
PID \((1/\beta)\), \(|\eta|<1, 0<\phi<2\pi\)
Heavy Flavor Tracker

HFT:
- Silicon Strip Detector: $r \sim 22$ cm
- Intermediate Silicon Tracker: $r \sim 14$ cm
- PIXEL detector: $r \sim 2.8$ & 8 cm, MAPS, 20.7x20.7 $\mu$m², 0.5%$X_0$ (2014), 0.4%$X_0$ (2016), air-cooled

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D⁰ pₜ Spectra

- Precise measurements of D⁰ spectra extended to low pₜ and non-central collisions from 2014 data with HFT
- Results consistent with the re-analyzed 2010/11 TPC-only analysis

Au+Au @ 200 GeV

STAR Preliminary

0-10%  (×20)
10-40%  (×5)
40-80%  (×2)

Levy Fit

Ratio
**D^0 R_{AA}**

- $R_{AA} < 1$ in the 0-10% centrality interval for all $p_T$
- Suppression at high $p_T$ increases towards more central collisions
- Similar trend as D-mesons at LHC and high-$p_T$ pions at RHIC

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Au+Au $\sqrt{s_{NN}} = 200$ GeV
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(a) 0-10%

(b) 10-40%

(c) 40-80%

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**STAR Preliminary**

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Au+Au $\sqrt{s_{NN}} = 200$ GeV
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(a) 0-12%


ALICE: JHEP 03 (2016) 081

DUKE: PRC 92 (2015) 024907

+ private comm
**D⁰ Rₜₚ and D⁰\overline{D⁰} Ratio**

- Significant suppression at high pₜ.
- Reasonable agreement with theoretical calculations.
- D⁰\overline{D⁰} ratio is larger than 1, possibly due to finite baryon density.
D⁰ Cross-section and Blast Wave Fit

- \( p_T \)-integrated \( D^0 \) cross-section is nearly independent of centrality, and smaller than in \( p+p \) collisions. However, for \( p_T > 4 \text{ GeV/c} \) it decreases towards central collisions.

- Blast Wave fits (\( p_T < 5 \text{ GeV/c} \)): suggests earlier freeze-out of \( D^0 \) compared to light flavor hadrons.
**Λc and Heavy Quark Hadronization**

- Strong enhancement of $\Lambda_c/D^0$ ratio seen in Au+Au collisions.
- Enhancement predicted from coalescence hadronization.
- Enhancements relative to PYTHIA also seen in p+p and p+Pb collisions at LHC.

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**QM17**

$\Lambda_c/D^0$ in A+A

$p_T$ and centrality dependence?

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More than 50% improvement in signal significance with TMVA BDT
Also new data from 2016
→ Effectively 4x more data

\((\Lambda_c) = 108 \pm 21\)
Significance = 5.1

\((\Lambda_c) = 233 \pm 22\)
Significance = 10.8
\( \Lambda_c/D^0 : p_T \) Dependence

- Significant enhancement of \( \Lambda_c/D^0 \) compared to PYTHIA/fragmentation baseline
- The \( \Lambda_c/D^0 \) ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
  -- higher than model predictions, particularly at higher \( p_T \)
$\Lambda_c/D^0$: Centrality Dependence

- $\Lambda_c/D^0$ ratio increases from peripheral to central collisions, indicative of hot medium effects
- Ratio for peripheral $Au+Au$ comparable with $p+p$ value at 7 TeV
D$_s$/D$^0$ Enhancement

- Strong D$_s$/D$^0$ enhancement observed in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than model predictions, particularly at higher p$_T$

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**Total Charm Cross-section**

- Total charm cross-section is estimated from the various charm hadron measurements.

-- $D^0$ yields are measured down to zero $p_T$.
-- For $D^{+/−}$ and $D_s$, Levy fits to measured spectra are used for extrapolation.
-- For $Λ_c$, three model fits to data are used and differences are included in systematics.

<table>
<thead>
<tr>
<th>Charm Hadron</th>
<th>Cross Section $dσ/dy$ (μb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$41 \pm 1 \pm 5$</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$18 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$15 \pm 1 \pm 5$</td>
</tr>
<tr>
<td>$Λ_c^+$</td>
<td>$78 \pm 13 \pm 28^*$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>152 \pm 13 \pm 29</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>130 \pm 30 \pm 26</strong></td>
</tr>
</tbody>
</table>

* derived using $Λ_c^+ / D^0$ ratio in 10-80%

- Total charm cross-section is consistent with $p+p$ value within uncertainties, but redistributed among different charm hadron species.
D*+ Production in Au+Au Collisions

- D*+ feeds down to D^0 yields $D^{*+} \rightarrow D^0 + \pi^+_\text{soft}$
- Possible hot medium effects:
  - D*+ life time could become shorter in hot medium
  - Re-scattering can lead to loss of yield

D*+/D0 Ratio in Au+Au Collisions

- D*+/D0 ratio in Au+Au collisions at 200 GeV is consistent with PYTHIA and with ALICE data at higher pT.
- Ratio of the integrated yields shows no strong centrality dependence

\[ \text{STAR Preliminary} \]

\[ \text{Guannan Xie} \]

\[ K^*/K, \text{ Phys. Rev. C (2011) 84. 034909.} \]

\[ ALICE \text{ Collaboration, arXiv:1804.09083.} \]
• Strong modification of charm hadron spectra in A+A collisions. \((D^0 R_{AA} \& R_{CP}, D_s/D^0, \Lambda_c/D^0)\).
  -- total charm quark cross-section consistent with that in p+p, but redistributed
  -- substantial energy loss
  -- coalescence hadronization
• Next, measurement of bottom hadrons via various decay channels to test mass hierarchy of parton energy loss

Bottom production: Xiaolong Chen on 2\(^{nd}\) Oct
Back up
**D^0 in AuAu (2010/2011 TPC Analysis) - I**

**Erratum: PRL 113 (2014) 142301**

1. Two mistakes were discovered in calculating TOF related efficiency corrections
   - Hybrid PID: algorithm inconsistently implemented in data analysis vs. efficiency calculation
   - a DCA_{xy} cut efficiency was included in the correction two times
2. p+p measurement: no issue discovered, but the p+p D^0 baseline used for R_{AA} is updated with latest knowledge of charm frag. ratios
   - considering the p_T dependence of D*/D^0 frag. ratio
   - latest world average of c->D^0 and c->D* frag. ratios

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Hard Probes 2018 (Aix-Les-Bains, France)
Topological Reconstruction

- Direct topological reconstruction through hadronic channels

\[ D^0 (\bar{D}^0) \rightarrow K^\mp \pi^\pm \]
\[ \Lambda_c^+ \rightarrow pK^- \pi^+ \]
\[ D_s^+ \rightarrow \phi(1020)\pi^+ \rightarrow K^+K^-\pi^+ \]

- With HFT: greatly reduced combinatorial background

- Topological cuts optimized by TMVA (Toolkit for Multi Variate Analysis)
• Similar suppression for $D^0$ and $D^{+/−}$

• Spectra measurement was important for the total charm cross-section

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

Centrality 0-10%

D$^\pm$ 2016
D$^0$ 2014
D$^\pm$ 2016 Glob. Sys.
Glob. p+p uncert.
p+p uncert.
B Study from Non-prompt J/ψ & D⁰ & e

- Strong interaction of charm with the medium. How about bottom?
- Strong suppression for $B \to J/\psi$ and $D^0$ at high $p_T$.
- Indication of less suppression for $B \to e$ than $D \to e$ ($\sim 2 \sigma$): consistent with $\Delta E_c > \Delta e_b$. Measurements with improved precision on the way.

$R_{AA}$ references (data vs. theory) are different for comparisons. The decay kinematics needs to be unfolded for different channels.