Overview of Open Heavy Flavor Results at RHIC and LHC

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Quantitative Measure of QGP

What is the microscopic picture of “perfect fluid”?
Uniqueness of Heavy Flavor Quarks

$\begin{align*}
  m_u \quad m_d \\
  1 \quad 10 \\
  m_s \quad \Lambda_{QCD} \\
  10^2 \quad 10^3 \\
  m_c \quad m_b \\
  10^4 \quad MeV
\end{align*}$

$T_c \quad T_{QGP}$

$m_{c,b} >> \Lambda_{QCD}$ amenable to perturbative QCD

$m_{c,b} >> T_{QGP}$ predominately created from initial hard scatterings

“Brownian” motion

$D_s(2\pi T) \sim \eta/s$

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096

$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_p E_p}{p}$

gauge to disentangle collisional vs. radiative energy loss

Heavy quark transport – to probe QGP with comprehensive $p_T$ coverage
- unique insights to both perturbative and non-perturbative regimes
# Key Instruments - Pixel Detector

<table>
<thead>
<tr>
<th></th>
<th>ALICE</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
<th>PHENIX</th>
<th>STAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor tech.</td>
<td>Hybrid</td>
<td>Hybrid</td>
<td>Hybrid</td>
<td>Hybrid</td>
<td>Hybrid</td>
<td><strong>MAPS</strong></td>
</tr>
<tr>
<td>Pitch size ((\mu m^2))</td>
<td>50x425</td>
<td>50x400</td>
<td>100x150</td>
<td>200x200</td>
<td>50x425</td>
<td><strong>20x20</strong></td>
</tr>
<tr>
<td>Radius of first layer (cm)</td>
<td>3.9</td>
<td>5.1</td>
<td>4.4</td>
<td>N/A</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Thickness of first layer</td>
<td>1%(X_0)</td>
<td>(~1%X_0)</td>
<td>(~1%X_0)</td>
<td>(~1%X_0)</td>
<td>1%(X_0)</td>
<td><strong>0.4%(X_0)</strong></td>
</tr>
</tbody>
</table>

**STAR Pixel** – first application of **MAPS** technology in collider experiments

**MAPS** - *Monolithic Active Pixel Sensor*

Next generation **MAPS** planned for future experiments:

- ALICE ITS upgrade, sPHENIX MVTX
  - to address the QGP medium properties
- Also for CBM, EIC detector R&D
Exclusive reconstruction of HF hadrons in heavy-ion collisions

\[ D^0 \rightarrow K\pi \]
\[ D_s \rightarrow \phi\pi \]

\[ \Lambda_c \rightarrow pK\pi \]
\[ B^+ \rightarrow J/\psi K \]

**σ_{XY} (μm)**

- **STAR**: 30 μm @ 1 GeV/c (p)
- **ALICE**: 70 μm @ 1 GeV/c (p_{T})
- **ATLAS/CMS**: 100 μm @ 1 GeV/c (p_{T})

**Total Momentum p (GeV/c)**

**Invariant mass**

\[ M_{KK'^{\pm}} (GeV/c^2) \]

\[ M_{pK} (GeV/c^2) \]

**Au+Au @ 200 GeV, 0-80%**

1. \[ \frac{dN}{dM} \] vs. \[ M_{KK'^{\pm}} \] for 2.5 < p_{T} < 8.0 GeV/c
2. \[ \frac{dN}{dM} \] vs. \[ M_{KK'^{\pm}} \] for 1 < p_{T} < 8 GeV/c

**STAR Preliminary**

**CMS Preliminary**

\[ B^+ \rightarrow J/\psi K \]

**Significance**: 10.8
D⁰ Meson $R_{AA}$ in Central A+A Collisions

**RHIC**

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

$R_{AA}$ vs $p_T$ (GeV/c)

- D⁰ 0-10%
- $\pi^\pm$ 0-12% STAR

**LHC**

27.4 pb⁻¹ (5.02 TeV pp) + 530 μb⁻¹ (5.02 TeV PbPb)

CMS

CMS, PLB 782 (2018) 474

- $R_{AA}(D) \sim R_{AA}(h)$ at $p_T > \sim 4$ GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

STAR, PRC 99 (2019) 034908
**D⁰ Total Cross Section and Radial Flow**

- **D⁰ p_T-integrated X-sec. suppressed in central Au+Au collisions at RHIC**
- **Blast-Wave thermal model fit => D⁰ mesons kinetically freeze out earlier than light flavor hadrons**

**STAR, PRC 99 (2019) 034908**

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**Graph**

- **Au+Au √s_{NN} = 200 GeV**
  - **p+p**
  - **• 2014**
  - **○ 2010/11**

**Graph Details**

- **p_T > 0 GeV/c**
- **p_T > 4 GeV/c**

**Axes**

- **N_{part}**
- **dσ^{NN}/dy**
- **T_{kin}**
- **⟨β⟩**

**Legend**

- **D⁰**
- **φ, Ξ^-**
- **π, K, p**

**Data Points**

- **60-80%**
- **0-10%**
- **70-80%**
- **0-5%**
Strange-Charm Meson Enhancement

STAR, QM17; ALICE, JHEP 1810 (2018) 174; CMS-PAS-HIN-17-008

• Enhancement in $D_s/D^0$ ratio in A+A w.r.t to PYTHIA/pp baseline
  - Coalescence hadronization
  - Strangeness enhancement
Reconstruction in Heavy-Ion Collisions

\[ \Lambda_c \rightarrow pK^+\pi^+ \]

\[ \Lambda_c^+ \rightarrow pK_S^0 \rightarrow p\pi^+\pi^- \]

Great experimental achievement in reconstructing charm baryon in heavy-ion collisions!
Charm Baryon Enhancement

- Significant enhancement in $\Lambda_c / D^0$ ratio in A+A collisions w.r.t PYTHIA/p+p baselines
  - Coalescence hadronization

STAR, QM18; ALICE, arXiv:1809.10922
## Total Charm Production Cross Section

<table>
<thead>
<tr>
<th>Charm Hadron</th>
<th>Cross Section $d\sigma/dy$ ($\mu$b)</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>$\Lambda^+_c$</td>
<td>$78 \pm 13 \pm 28^*$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$152 \pm 13 \pm 29$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$130 \pm 30 \pm 26$</td>
</tr>
</tbody>
</table>

- Total charm cross section follows $\sim N_{\text{bin}}$ scaling from $p+p$ to $Au+Au$
- However, charm hadro-chemistry changes considerably!
Charm Hadron $v_2$ at RHIC

- Mass ordering at $p_T < 2$ GeV/c (hydrodynamic behavior)
- $v_2(D)$ follows the same $(m_T-m_0)$ scaling as light hadrons below 1 GeV/c$^2$
- Transport models including $c$ diffusion in medium consistent with data

STAR, PRL 118 (2017) 212301; QM18
Charm Hadron $v_2$ at LHC

- Significant $D$-meson $v_2$ at 5.02 TeV Pb+Pb collisions
- $D^0 v_2$ follows the same trend as light hadrons at LHC
Charm Hadron $v_2$ and $R_{AA}$

**PbPb 5.02 TeV, Cent. 30-50%**
- ALICE $D^0$, $D^0$, $D^+$ lyl < 0.8
- CMS $D^+$ lyl < 1

**AuAu 200 GeV, Cent. 10-40%**
- STAR $D^+$ lyl < 1

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$v_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**$27.4 \text{ pb}^{-1} (5.02 \text{ TeV pp}) + 530 \mu\text{b}^{-1} (5.02 \text{ TeV PbPb})$**

**$D^0 + \bar{D}^0$**
- CMS lyl < 1
- ALICE lyl < 0.5
- STAR 2014

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$R_{AA}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**5.02 TeV PbPb, Centrality 30-50%**
- LBT
- PHSD
- SUBATECH
- TAMU

**Average $D^0$, $D^+$, $D^{*}$, lyl < 0.8**
- BAMPs el.+rad.
- POWLANG HTL
- LBT

**5.02 TeV PbPb, Centrality 0-10%**
- Dijndjevic et al.
- Vitev et al. (g=1.9-2.0)
- PHSD w/ shadowing
- PHSD w/o shadowing

**Average $D^0$, $D^+$, $D^{*}$, lyl < 0.5**
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**5.02 TeV PbPb, Centrality 0-10%**
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**Average $D^0$, $D^+$, $D^{*}$, lyl < 0.5**
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- POWLANG HTL
- LBT

**$R_{AA}$**
- CMS lyl < 1
- ALICE lyl < 0.5
- STAR 2014

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Current Knowledge of HQ Diffusion Coefficient

\[ 2\pi T D_s \sim 2-5 \text{ at } T_c \]

Next: temperature dependence? charm vs. bottom universality?
Towards Precision Determination of $D_s$

Rapid developments among theorists to resolve/understand trivial/non-trivial differences between different models

EMMI Rapid Reaction Task Force - R. Rapp et al., 1803.03824
Jet-HQ Working Group - S.S. Can et al., 1809.07894

**Figure:**
- Effects and consequence in various systems
- Core ingredients:
  - HQ – (local) Coupling to hot matter
  - Transport of HQ in medium
  - Hadronization process at FO
  - Effective lagrangian, Effective potential, Effective DOF
  - Transport equation, Path integrals,...
- Theoretical understanding of other QGP aspects

**Source:**
- Courtesy of P.B. Gossiaux – QM18
$D^0 v_1$ - New Insight to QGP Properties

**Data**

$D$-meson $v_1$ sensitive to
- $T$ dependence of HQ diffusion coefficient
- geometry tilt of the QGP source
- Initial magnetic field ($D/\bar{D} v_1$ difference)

**Hydro Model**

$\gamma \propto T$ vs $\propto T^{1.5}$

STAR, QM18

Chatterjee & Bozek, 1804.04893
Bottom Quark: Cleaner Measure of HQ Diffusion

Is charm quark heavy enough?

$2\pi T D_s \sim 2 - 5 \quad @ \quad T_c$

scattering rate: $\Gamma_{\text{coll}} \sim 3 / D_s \sim 1 \text{ GeV}$

- comparable to charm quark mass

Sizable correction to Langevin approach for charm quarks

Das et al., PRC 90 (2014) 044901
$b$-jet and $B^+$ Hadron at High $p_T$

- $R_{AA}(b$-jet) $\sim R_{AA}(\text{incl. jet})$ at $p_T > 70$ GeV/c
- $R_{AA}(B^+) \sim R_{AA}(D) \sim R_{AA}(h)$ at $p_T > 10$ GeV/c

**mass hierarchy**? -> going to lower $p_T$
Bottom Suppression at Low $p_T$

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530/404/368 $\mu$b$^{-1}$)

CMS Supplementary

**Light**
- $h^+$

**Charm**
- $D^0 + \overline{D}^0$
- (b $\rightarrow$) $D^0$
- (b $\rightarrow$) J/$\psi$
- $1.8 < y_l < 2.4$
- $y_l < 2.4$

$T_{AA}$ and lumi. uncertainty

CMS, arXiv:1810.11102; STAR/PHENIX QM17

$R_{AA}(J/\psi_B) \sim R_{AA}(D_B) > R_{AA}(D)$ at $p_T < 10$ GeV/c

$R_{AA}(e_B) < R_{AA}(e_D)$ at 3–8 GeV/c (2$\sigma$)

Mass hierarchy of parton energy loss
Summary

Significant charm hadron flow
- \(2\pi T D_s \sim 2-5@T_c\)

- \(T\)-dependence, \(c\) vs. \(b\) universality, relation to \(\eta/s\) etc.

Large \(D_s/D^0\) and \(\Lambda_c/D^0\) enhancement
- coalescence hadronization

- precise heavy baryon, relation to color confinement

\(R_{AA}(B) > R_{AA}(D)\) at low \(p_T\); \(\sim R_{AA}(D)\) at high \(p_T\)
- mass hierarchy of energy loss

- transition between collisional vs. elastic energy loss
# Prospective Heavy Flavor Program in Future

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</thead>
<tbody>
<tr>
<td>RHIC</td>
<td>HF Phase-I</td>
<td>pp</td>
<td>CME</td>
<td>BES-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HF Phase-II</td>
</tr>
<tr>
<td>LHC</td>
<td>LS1</td>
<td>Run-2</td>
<td></td>
<td>LS2</td>
<td></td>
<td>Run-3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Next generation MAPS pixel detectors: **ITS2@ALICE, MVTX@sPHENIX**

**Precision open bottom**

**Heavy flavor baryons and correlations**

![Graph showing CMS Projection](image1.png)

![Graph showing sPHENIX Simulation](image2.png)
Monolithic Active Pixel Sensor (MAPS)

MAPS pixel cross-section (not to scale)

Properties:
- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 μm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective boundaries at p-well and substrate

<table>
<thead>
<tr>
<th>MAPS and competition</th>
<th>MAPS</th>
<th>Hybrid Pixel</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granularity</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Small material budget</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Readout speed</td>
<td>+</td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td>Radiation tolerance</td>
<td>+</td>
<td>++</td>
<td>-</td>
</tr>
</tbody>
</table>

MAPS - particularly chosen for measuring HF hadron decays in heavy ion collisions

See Xiangming Sun’s talk (Sun.) for more applications
D⁰ v₂ Compared with Models

- D⁰ v₂
  <-> Charm quark diffusion in QGP
- Provide strong constraints to model calculations

<table>
<thead>
<tr>
<th>Compared Models</th>
<th>x²/NDF</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBATECH [1]</td>
<td>17.3/8</td>
<td>0.026</td>
</tr>
<tr>
<td>TAMU c quark diff. [2]</td>
<td>12.0/8</td>
<td>0.15</td>
</tr>
<tr>
<td>TAMU no c quark diff. [2]</td>
<td>33.7/8</td>
<td>4.5 x 10⁻⁵</td>
</tr>
<tr>
<td>Duke (Bayesian) [3]</td>
<td>8.5/8</td>
<td>0.39</td>
</tr>
<tr>
<td>3D viscous hydro [4]</td>
<td>3.7/6</td>
<td>0.71</td>
</tr>
<tr>
<td>LBT [5]</td>
<td>13.3/8</td>
<td>0.10</td>
</tr>
<tr>
<td>PHSD [6]</td>
<td>8.7/7</td>
<td>0.27</td>
</tr>
<tr>
<td>Catania [7]</td>
<td>9.7/8</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Bayesian Analysis to Extract HQ Diffusion Coefficient

Bayesian analysis based on Duke model: Langevin + Hydro

Y. Xu et al, PRC 97 (2018) 014907
What is the p- and T- dependence of HQ diffusion coefficient?

How will bottom measurement help determine HQ diffusion coefficient?
\[ \Lambda_c \text{ Baryon} \]

Does \( \Lambda_c \) yield go beyond SHM limit?

He and Rapp, 1902.08889