STAR Heavy Flavor Tracker (HFT) and HFT+ Upgrade Plan

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for the STAR Collaboration
STAR Physics Program

Hot QCD

Cold QCD

Study QCD Emergent Properties

August 3-7th, 2015 Hadron Physics in China, Kunshan X. Dong
Heavy Quarks for Measuring sQGP Properties

Heavy quarks are conserved

![Diagram showing Higgs quark mass versus total quark mass](image)

Heavy quarks are conserved

Heavy quarks are tractable

\[
\frac{dp^i}{dt} = -\eta Dp^i + \xi^i(t)
\]

- Drag
- Fluctuations

Diffusion coefficient \( D_{HQ} \)


- Heavy quarks created at early stage of HIC, and sensitive to the partonic re-scatterings
- Heavy quark collectivity/flow – more sensitive to thermalization and medium transport properties
**Experimental Challenges**

**Direct**
- through exclusive hadronic channels
- full charmed hadron kinematics
- hard to trigger
- smaller branching ratios
- need precision vertex detector to reduce combinatorial background

- \(dN_{ch}/d\eta \sim 700\) in central Au+Au collisions

<table>
<thead>
<tr>
<th>Hadron</th>
<th>Abundance</th>
<th>c(\tau) ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0)</td>
<td>56%</td>
<td>123</td>
</tr>
<tr>
<td>(D^+)</td>
<td>24%</td>
<td>312</td>
</tr>
<tr>
<td>(D_s)</td>
<td>10%</td>
<td>150</td>
</tr>
<tr>
<td>(\Lambda_c)</td>
<td>10%</td>
<td>60</td>
</tr>
<tr>
<td>(B^+)</td>
<td>40%</td>
<td>491</td>
</tr>
<tr>
<td>(B^0)</td>
<td>40%</td>
<td>456</td>
</tr>
</tbody>
</table>

\(c\tau \sim 123\) \(\mu\)m
Heavy Flavor Tracker for STAR

Magnet Return Iron

Inner Field Cage

Outer Field Cage

20 cm

TPC Volume

HFT

SSD

IST

PXL

Heavy Flavor Tracker for STAR
HFT Design

- HFT consists of 3 sub-detector systems inside the STAR Inner Field Cage

<table>
<thead>
<tr>
<th>Detector</th>
<th>Radius (cm)</th>
<th>Hit Resolution R/ϕ - Z (µm - µm)</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD</td>
<td>22</td>
<td>30 / 860</td>
<td>1% X₀</td>
</tr>
<tr>
<td>IST</td>
<td>14</td>
<td>170 / 1800</td>
<td>1.32 %X₀</td>
</tr>
<tr>
<td>PIXEL</td>
<td>8</td>
<td>6.2 / 6.2</td>
<td>~0.52 %X₀</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>6.2 / 6.2</td>
<td>~0.39% X₀</td>
</tr>
</tbody>
</table>

- **SSD** existing single layer detector, double side strips (electronic upgrade)
- **IST** one layer of silicon strips along beam direction, guiding tracks from the SSD through PIXEL detector - **proven pad technology**
- **PIXEL** double layers, 20.7x20.7 mm pixel pitch, 2 cm x 20 cm each ladder, 10 ladders, delivering ultimate pointing resolution. - **new active pixel technology**

TPC $\rightarrow$ SSD $\rightarrow$ IST $\rightarrow$ PXL $\rightarrow$ vertex

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Monolithic Active Pixel Sensors (MAPS) - PXL

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 Sensors</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>
### Some pixel features and specifications

<table>
<thead>
<tr>
<th><strong>Pointing resolution</strong></th>
<th>$(12 \oplus 19\text{GeV/p\cdot c})\ \mu\text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Layers</strong></td>
<td>Layer 1 at 2.8* cm radius</td>
</tr>
<tr>
<td></td>
<td>Layer 2 at 8 cm radius</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>$20.7\ \mu\text{m} \times 20.7\ \mu\text{m}$</td>
</tr>
<tr>
<td><strong>Hit resolution</strong></td>
<td>$6.2\ \mu\text{m} \ \text{rms}$</td>
</tr>
<tr>
<td><strong>Position stability</strong></td>
<td>$8\ \mu\text{m} \ (30\ \mu\text{m} \ \text{envelope})$</td>
</tr>
<tr>
<td><strong>Radiation thickness per layer</strong></td>
<td>$X/X_0 = 0.39% \ \text{Al-cable}$</td>
</tr>
<tr>
<td><strong>Number of pixels</strong></td>
<td>$360\ \text{M}$</td>
</tr>
<tr>
<td><strong>Integration time</strong></td>
<td>$186\ \mu\text{s}$</td>
</tr>
<tr>
<td><strong>Radiation requirement</strong></td>
<td>$20-90\ \text{kRad}$</td>
</tr>
<tr>
<td><strong>Rapid detector replacement</strong></td>
<td>$&lt; 12\ \text{Hours}$</td>
</tr>
</tbody>
</table>

**Additional Notes**
- Radiation thickness per layer: critical and difficult
- Radiation thickness per layer: more than a factor of 3 better than hybrid vertex detectors
HFT Commission and Operation in STAR

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 May</td>
<td>PXL prototype engineering run with 3 sectors (out of 10 in total)</td>
</tr>
<tr>
<td>2013 Sept</td>
<td>IST, SSD fully installed into STAR</td>
</tr>
<tr>
<td>2014 Jan</td>
<td>PXL fully installed into STAR (within 12 hours)</td>
</tr>
<tr>
<td>2014 Jan-Feb</td>
<td>Cosmic runs for detector commissioning, data for alignment calibration</td>
</tr>
<tr>
<td>2014 March</td>
<td>Commissioning in Au+Au 200 GeV collisions. Physics mode since then</td>
</tr>
<tr>
<td>2014 Sept</td>
<td>HFT project closeout. Project finished on time and under budget</td>
</tr>
</tbody>
</table>

STAR HFT – first application of MAPS pixel detector at a collider
Operating point: noise rate $\sim 2 \times 10^{-6}$ with $>99\%$ efficiency

Goal: $> 98\%$ at $10^{-4}$ noise rate

Efficiency measured with cosmic ray data - $\sim 97.2\%$ average efficiency over all sensors
Pointing Resolution and $D^0$ from Au+Au Collisions

Physics datasets collected with STAR-HFT

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam Species</th>
<th>Data sets</th>
<th>Physics goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Au+Au 200 GeV</td>
<td>1.2B minbias</td>
<td>D-meson $v_2$, $R_{cp}$</td>
</tr>
<tr>
<td>2015 Al-cable</td>
<td>p+p 200 GeV</td>
<td>1.1B minbias, 12 pb$^{-1}$</td>
<td>D-meson $R_{AA}$ baseline</td>
</tr>
<tr>
<td></td>
<td>p+Au 200 GeV</td>
<td>0.5B minbias, 42 nb$^{-1}$</td>
<td>D-meson $R_{pA}$</td>
</tr>
<tr>
<td>2016* Al-cable</td>
<td>Au+Au 200 GeV</td>
<td>2B minbias, 1 nb$^{-1}$</td>
<td>$\Lambda_c$, bottom, D-meson $v_2$, $R_{AA}$</td>
</tr>
<tr>
<td></td>
<td>Au+Au 62.4 GeV</td>
<td>1B minbias</td>
<td>$\sqrt{s}$ dependent D-meson $v_2$, $R_{cp}$</td>
</tr>
</tbody>
</table>

* 2016 requests accommodated by the STAR Beam-Use-Request

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Physics Goals with HFT

Assuming $D^0 v_2$ distribution from quark coalescence.

1 billion Au+Au m.b. events at 200 GeV.

- Charm $v_2$

*Thermalization of light-quarks!*

*Drag/diffusion coefficients!*

Assuming $D^0 R_{AA}$ as charged hadron

1 billion Au+Au m.b. events at 200 GeV + 8pb$^{-1}$ sampled L in p+p 200 GeV

- Charm $R_{AA} \Rightarrow$

*Energy loss mechanism!*

*Interaction with QCD matter!*
Open bottom production over a wide range of momentum

Flavor dependence of parton energy loss – medium properties at small scale

Cleanest probe to quantify medium transport properties – e.g. $D_{HQ}$
- medium properties at large scale

Total bottom yield
- verify CNM for precision interpretation of Upsilon suppression

Is charm heavy enough?
Sizable correction to the Langevin approach for charm
- may limit the precision in determining $D_{HQ}$

**PRL 108 (2012) 022301**

**PRC 90 (2014) 044901**
**HFT+ Upgrade for Bottom Production Measurements**

Next generation fast MAPS sensors – integration time reduced from 186µs to <20µs

*R&D projects under development for ALICE ITS upgrade*

Detector capable of being operated at high luminosity with good efficiency

*CAD projected L at 2020+ is 100x10^{26} cm^{-2}s^{-1}(ZDCx rate ~ 100kHz)*

Preserve high detection efficiency in high luminosity environment

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**Graph**

![Graph showing single pion efficiency vs. transverse momentum (p_T) for Au+Au at 200 GeV at 2020.](image)

- **HFT(10µs)**
- **HFT(40µs)**
- **HFT(200µs)**

**Legend**

- **Au+Au 200 GeV @ 2020**
- **ZDCx = 100 kHz**

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August 3-7th, 2015 Hadron Physics in China, Kunshan X. Dong
Physics Projection with STAR-HFT+

HFT+: aimed for precision open bottom measurements at RHIC
- flavor dependent energy loss
- cleaner extraction of medium transport properties $D_{HQ}$

Curves – average of calculations from TAMU, Duke and CUJET

RHIC 200 GeV @ 2021+
  w/ STAR HFT+
  10B MB + 10 nb$^{-1}$ Au+Au
  40 pb$^{-1}$ p+p
Summary

STAR Heavy Flavor Tracker (HFT)
- first application of MAPS pixel detector at a collider
- fully in operation and meet all performance goals
- physics results anticipated - precision charm measurements

STAR HFT+
- next generation fast MAPS pixel detector
- aim for open bottom measurements at 2020+ period

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<tr>
<td>RHIC</td>
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<td></td>
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<tr>
<td></td>
<td>STAR HFT</td>
<td>PHENIX (F)VTX</td>
<td>Precision charm</td>
<td>Spin</td>
<td></td>
<td>BES-II</td>
<td></td>
<td></td>
<td>STAR HFT+</td>
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<td>sPHENIX</td>
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<td></td>
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<td>Open bottom</td>
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<tr>
<td>LHC</td>
<td>LS1</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>ALICE ITS upgrade</td>
</tr>
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<td></td>
<td></td>
<td>Run 2 (x10 statistics)</td>
<td></td>
<td></td>
<td>LS2</td>
<td></td>
<td></td>
<td>CMS/ATLAS upgrades</td>
<td></td>
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<td></td>
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<td></td>
<td>Run 3 (x100 statistics)</td>
</tr>
</tbody>
</table>
Backups
Heavy Quarks to Probe Medium Thermalization

- Heavy quarks created at early stage of HIC, and sensitive to the partonic re-scatterings.
- Heavy quark collectivity/flow to experimentally quantify medium thermalization.

HQ propagation in QCD medium – Brownian Motion, described by Langevin Equation

\[ \frac{dp_i}{dt} = \xi_i(t) - \eta_D p_i \]

\( \eta_D / \xi \) – drag/diffusion coefficients related to the medium transport properties

G. Moore & D. Teaney, PRC 71 (2005) 064904
Heavy Quark Production in p+p Collisions

Charm/bottom hadron spectra well described by pQCD calculations (FONLL, MC@NLO etc.)
- Similar for data at Tevatron, HERA etc.

Data precision provides inputs to constrain pQCD calculations
- R.E. Nelson et al, PRC 87(2013)014908
**A Comparative Look on RHIC vs. LHC**

**Comparable suppression at high $p_T$**
- collisional and radiative $\Delta E$

**Possibly different physics at low $p_T$**
- Initial parton distributions
  $x_T$ at 2 GeV/c $\sim 10^{-2}$ (RHIC)
  $\sim 10^{-3}$ (LHC)
- “Cronin” effect
- Charm quark flow

**Precision charm $v_2$ data, particularly to low-intermediate $p_T$ are critical for the extraction of sQGP $D_{HQ}$.**

*STAR, PRL 113(2014)142301*
*ALICE, PRL111 (2013) 102301, PRC 90 (2014) 034904*
Pixel Geometry

End view

8 cm radius

2.6 cm radius

Inner layer

Outer layer

total 40 ladders

20 cm

One of two half cylinders

\( \eta \) coverage \pm 1
Intermediate Silicon Tracker (IST)

24 ladders, liquid cooling.

S:N > 20:1, >99.9% live and functioning channels
Silicon Strip Detector (SSD)

New/Faster Readout
“Old” Ladders, refurbished
New, direct mounting on support

“Old” SSD

Ladder Cards

~1 Meter

44 cm

20 Ladders
Uniqueness

Uniqueness of HFT:

- Fine pixel granularity provides ultimate hit resolution
- Thin detector design allows precision measurements down to low $p_T$
- State-of-art mechanical design retains detector stability
- Full azimuthal acceptance allows high statistics correlation measurements

HF measurements at RHIC – not just complementary to those at LHC

Uniqueness of HF measurements at RHIC

- Heavy quarks are calibrated probes at RHIC - predominately created via initial gluon-gluon hard scatterings.
- Heavy quarks are mostly created through the leading order 2->2 process at RHIC – clean physics interpretation of results, particularly correlation measurements.
Unique Measurements with HFT+TPC+MTD

B → J/ψ + X

- HFT to separate B decay J/ψ from prompt J/ψ
- MTD to reconstruct J/ψ from di-muon decays

Lepton pairs from correlated charm

- MTD - unique measurement of e-μ correlation
- HFT+MTD – systematic measurement of e-e, e-μ, μ-μ with controlled charm contributions
Charm to Probe Nucleon/Nucleus Structure

Charm production

- Sensitive to gluon distribution functions.

K. Kurek, Spin Workshop @LBL 2009
Heavy Flavor to Probe Gluon Spin Structure

Riedl et al, PRD 80 (2009) 114020

PHENIX, PRD 87 (2012) 012011

STAR Preliminary

Run 5
Heavy Flavor Probes for Broad QCD Studies

\[ W^+ \rightarrow c + \bar{s} \quad \text{higher decay B.R. than semi-leptonic decays} \]

- W reconstruction via full di-jets (one charm jet)
  - explored by UA1

Heavy flavor jet – intrinsic HF PDF in nucleon/nucleus

\[ pp \rightarrow \gamma + c(b)\text{-jet} + X. \]

- Heavy flavor jet – good probe to study the hot QCD medium properties
## Key Instruments

### Pixel Silicon Detector at LHC/RHIC experiments

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

* physics results from PHENIX/STAR discussed here don’t include data from silicon pixel detectors
What we have learned?

A) How do energetic heavy quarks lose energy in sQGP medium?

\[ R_{AA}(h) \sim R_{AA}(e) \sim R_{AA}(D) < R_{AA}(J/\psi^B) \]  
   at high \( p_T \)

- described by pQCD calculations including collisional and radiative energy loss
- only revealed with heavy quark measurements

B) How do charm quark flow?

low-intermediate \( p_T \):

“bump” structure in \( R_{AA}(D) \) at RHIC  – hint of charm flow + coalescence

\( v_2(D) \sim v_2(\pi) \) at LHC  – indication of large charm flow

C) Can we extract the medium transport properties (e.g. \( D_{HQ} \))?

Theory: Need to unify different models – diff. in initial cond., medium evolution etc.
Experiments: Precision data

Future Measurements:

- Precision charmed hadron data (particularly \( v_2 \)) over a broad momentum range
- Open bottom production over a broad momentum range
- Heavy quark correlations

Calibration of charm/bottom total cross section
Cold nuclear matter effects
Next generation MAPS sensors with much shorter integration time (< 20 µs)

**Goals:**
- precision charmed hadron ($D^0$, $\Lambda_c$) measurements down to low $p_T$
- open bottom measurements