The Heavy Flavor Tracker (HFT)
The Silicon Vertex Upgrade of STAR @ RHIC

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Outline

- The Heavy Flavor physics opportunities in Heavy Ion Collisions
- The Challenges of the ultra-high multiplicity environment
- The HFT concept and realization
The Bottom Line

- Hot and dense (partonic) matter with strong collectivity has been formed in Au+Au collisions at RHIC. Study of the properties of the new form of matter requires more penetrating probes like heavy quarks.
  - Mechanism for parton energy loss.
  - Thermalization.

- New micro-vertex detector is needed for STAR experiment.

- DOE milestone 2016: “Measure production rates, high pT spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}} = 200$ GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.”
STAR Detector

MRPC ToF barrel
100% ready for run 10 (now!)

BBC

FPD

PMD

DAQ1000

HLT

HFT

FGT

MTD

EMC barrel

EMC End Cap

FMS

FHC

Completed

Ongoing

R&D
The QCD Phase Diagram and High-Energy Nuclear Collisions

The nature of thermalization at the top energy:

- Heavy quarks
- Di-lepton

The QCD Phase Diagram:

1. Initial thermalization
   - $T_{\text{init}}$, $T_C$
   - LHC, RHIC

2. Critical point
   - $T_E$
   - RHIC

3. Hadron gas

Baryon Chemical Potential

Early Universe

RHIC, FAIR

RHIC, LHC

Critical Point?
STAR Physics Program

1) At 200 GeV top energy
- Study *medium properties, EoS*
- pQCD in hot and dense medium

2) RHIC beam energy scan
- Search for the *QCD critical point*
- Chiral symmetry restoration

Spin program
- Study *proton intrinsic properties*

Forward program
- Study low-x properties, search for *CGC*
- Study elastic (inelastic) processes (pp2pp)
- Investigate *gluonic exchanges*
Central Au+Au collisions: light quark hadrons and the away-side jet in back-to-back ‘jets’ are suppressed. Different for p+p and d+Au collisions.

Energy density at RHIC: $\varepsilon > 5$ GeV/fm$^3 \sim 30\varepsilon_0$

Explore pQCD in hot/dense medium $R_{AA}(c,b)$ measurements are needed!
Heavy Quark Energy Loss

Surprising results -
- challenge our understanding of the energy loss mechanism
- force us to RE-think about the elastic-collisions energy loss, <L> etc
- Requires direct measurements of c- and b-hadrons.

1) Non-photonic electrons decayed from - charm and beauty hadrons

2) At $p_T \geq 6$ GeV/c,

$R_{AA}(n.p.e.) \sim R_{AA}(h^\pm)!$

Contradicts naïve pQCD predictions

Decay $e$ $p_T$ vs. B- and C-hadron $p_T$

Key: Directly reconstructed heavy quark hadrons!

Pythia calculation   Xin Dong, USTC October 2005
Challenge: e.g. $D^0$ decay length

- $D^0 \rightarrow K + \pi$

- Decay Length in X-Y plane $\sim 1 \text{ cm} \tau$

- Used $<pt> \sim 1 \text{GeV}$
- $1 \text{ GeV/ } \eta=0 \ D^0$ has $\beta_\gamma \sim 0.5$
  - Un-boost in Collider!
- Mean R-$\phi$ value $\sim 70 \ \mu\text{m}$
HFT Strategy

- Replace Drift Silicon with small/square Pixels

- Move as close to beam as possible
  - New beam pipe (Radius 4cm -> 2cm)

- Keep it as thin as possible
  - Si (300->50 microns)
  - Air-cool
  - ~0.4% $X_0$ thickness per layer

- Remove/install with ~20 micron overall envelope
  - Need special engineering
Detector resolutions differ by a factor of two but pointing by a factor of ten.
HFT Technology

- Low mass
- Near the event vertex
- Active pixels

New beam pipe

Pixel 1-2 \( R=2.5, 8 \text{cm} \)

IST \( R=14 \text{cm} \)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Hit resolution ( R-\phi )</th>
<th>Radiation Length</th>
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</thead>
<tbody>
<tr>
<td>SSD+</td>
<td>double sided strips</td>
<td>30 - 857</td>
</tr>
<tr>
<td>IST</td>
<td>Silicon Strip Pad sensors</td>
<td>170 - 1700</td>
</tr>
<tr>
<td>ACTIVE PIXELS</td>
<td>Active Pixels</td>
<td>8.6 - 8.6</td>
</tr>
</tbody>
</table>
Projection error is a strong function of first-layer distance and thickness.

\[
\sigma^2 = \frac{\sigma_1^2 r_2^2 + \sigma_2^2 r_1^2}{(r_2 - r_1)^2} + \frac{\theta_{mcs}^2 r_1^2}{\sin^2(\theta)}
\]

\[
\theta_{mcs} = \frac{13.6 \ (MeV/c)}{\beta \ p} \sqrt{\frac{X}{X_0}}
\]

- In the critical region for Kaons from D^0 decay, 750 MeV to 1 GeV, the PXL single track pointing resolution is predicted to be 20-30 \(\mu\)m ... which is sufficient to pick out a D^0 with \(cT = 125 \mu\)m
- The system (and especially the PXL detector) is operating at the MCS limit
Glimpses at 200 GeV DATA

• (Relatively) low significance peaks have been observed already in the DATA but of limited physics reach.
HFT Performance example on the $D^0 \rightarrow K\pi$ reconstruction

- Simulation of Au+Au@200GeV Hijing events with STAR tracking software including pixel pileup (RHIC-II luminosity) extrapolated to 500 M events (~one RHIC run).
- Identification done via topological cuts and PID using Time Of Flight
Heavy Quark Production

NLO pQCD predictions of charm and bottom for the total p+p hadro-production cross sections.

Renormalization scale and factorization scale were chosen to be equal.

**RHIC:** 200, 500 GeV
**LHC:** 900, 14000 GeV

Ideal energy range for studying pQCD predictions for heavy quark production.

Necessary reference for both, heavy ion and spin programs at RHIC.

Estimated error bars of measurement comparable to line thickness!

- 200 GeV Au+Au minimum bias collisions (500M events).
- Charm collectivity $\uparrow$ drag/diffusion constants $\uparrow$ medium properties!
- 200 GeV Au+Au minimum bias collisions (500M events).
- Charm collectivity $\uparrow$ drag/diffusion constants $\uparrow$ medium properties!
HFT - Charm Hadron $R_{CP}$

- Significant Bottom contributions in HQ decay electrons.
- 200 GeV Au+Au minimum bias collisions ($|y|<0.5$ 500M events).
- Charm $R_{AA}$ $\uparrow$ energy loss mechanism!

$$R_{CP} = \frac{\frac{dN}{dp_T}^{10\%}}{\langle N_{bin}^{10/(60-80)} \rangle} \frac{dN}{dp_T^{(60-80)\%}}$$

Simulation – D^0s, NOT decay electrons

200 GeV Au+Au Collisions at RHIC
($D^0$: 500M minimum bias events; $|y|<0.5$)

Transverse Momentum $p_T$ (GeV/c)
$\Lambda_c$ Measurements

$\Lambda_c \rightarrow p + K + \pi$:

1) Lowest mass charm baryon
2) Total yield and $\Lambda_c/D^0$ ratios can be measured.
$D_s$ Reconstruction

200 GeV Central Au+Au Collisions at RHIC

- $D_s \rightarrow K^+K^\mp\pi$ (BR 5.5%)
- $D_s \rightarrow \phi\pi \rightarrow K^+K^\mp\pi$ (BR 2.2%)
- mass = $1968.49 \pm 0.34$ MeV
- decay length $\sim 150 \mu m$

- Work in progress …
  - 200 GeV central Au+Au
  - Ideal PID
  - Power-law spectrum with:
    $$n = 11, \langle p_T \rangle = 1 \text{ GeV/c}$$

0.5B events will work!
Strategies for Bottom Measurement

(1) All Charm states
(D^0, D^+, D^-)

(1.a) Displaced vertex electrons (TOF+HFT)

(2) Charm decay electrons
(Charm)

(1.a) - (2)

Some Bottom states
(Statistics limited at RHIC)

Bottom decay electrons

Measure **Charm** and **Bottom** hadron:

**Cross sections, Spectra and v_2**
B-meson capabilities (in progress)

B->e+X approach
Rate limited, not resolution
**c- and b-decay Electrons**


\[
R_{CP} = \frac{dN / dp_T^{10\%}}{< N_{bin}^{10/(60-80)} > dN / dp_T^{(60-80)\%}}
\]

- DCA cuts \(\uparrow\) c- and b-decay electron distributions and \(R_{CP}\)
- 200 GeV Au+Au minimum biased collisions (\(|y|<0.5\) 500M events)
Summary

• Detailed spectra of heavy flavor (c, b) is an invaluable piece of information

• First generation of detectors needs smart replacements

• The **Heavy Flavor Tracker** in STAR is the most advanced answer to this need
Spares
Low $p_T$ ($\leq 2$ GeV/c): hydrodynamic mass ordering
High $p_T$ ($> 2$ GeV/c): number of quarks ordering
  s-quark hadron: smaller interaction strength in hadronic medium
  light- and s-quark hadrons: similar $v_2$ pattern

$\Rightarrow$ Collectivity developed at partonic stage!
The di-Lepton Program at STAR

TOF + TPC + HFT

(1) $\sigma$
(2) $V_2$
(3) $R_{AA}$

- Direct radiation from the Hot/Dense Medium
- Chiral symmetry Restoration

$\uparrow$ A robust di-lepton physics program extending STAR scientific reach
- Higgs mass: electro-weak symmetry breaking (current quark mass).
- QCD mass: Chiral symmetry breaking (constituent quark mass).

↑ Strong interactions do not affect heavy-quark mass.

↑ New scale compare to the excitation of the system.

↑ Study properties of the hot and dense medium at the *foremost early stage* of heavy-ion collisions.

↑ Explore pQCD at RHIC.

# Requirement for the HFT

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<th>Measurements</th>
<th>Requirements</th>
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<tr>
<td><strong>Heavy Ion</strong></td>
<td>heavy-quark hadron $v_2$ - the heavy-quark collectivity</td>
<td>- Low material budget for high reconstruction efficiency</td>
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<tr>
<td></td>
<td></td>
<td>- $p_T$ coverage $\geq 0.5$ GeV/c</td>
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<tr>
<td></td>
<td></td>
<td>- mid-rapidity</td>
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<td></td>
<td></td>
<td>- High counting rate</td>
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<tr>
<td></td>
<td>heavy-quark hadron $R_{AA}$ - the heavy-quark energy loss</td>
<td>- High $p_T$ coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- $p_T$ coverage $\approx 10$ GeV/c</td>
</tr>
<tr>
<td><strong>p+p</strong></td>
<td>energy and spin dependence of the heavy-quark production</td>
<td>- $p_T$ coverage $\geq 0.5$ GeV/c</td>
</tr>
<tr>
<td></td>
<td>gluon distribution with heavy quarks</td>
<td>- wide rapidity and $p_T$ coverage</td>
</tr>
</tbody>
</table>
"$\phi$-mesons (and other hadrons) are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies hot and dense matter with partonic collectivity has been formed at RHIC."

In order to test early thermalization: $v_2(p_T)$ of $c$- and $b$-hadrons data are needed!
Charm Cross Sections at RHIC

1) Large systematic uncertainties in the measurements
2) New displaced, topologically reconstructed measurements for c- and b-hadrons are needed ⇔ Upgrade
• Left: correlation between reconstructed path length and MC
• Right: Decay length resolution
  – There is no systematic shift (red crosses = mean) in reconstructed quantities.
  – The standard deviation (blue crosses) of the distribution ($\text{reco-MC}$) is flat at 
    $\sim 250 \, \mu m$, which is of the order of the resolution of (SSD+SVT).
Charm Baryon/Meson Ratios

\( \Lambda_c / D^0 \) yield ratios

- Case 2. Most deeply binding \( (m_{ud} = 450 \text{ MeV}) \)
  - 2-body collisions by \( c \) and \( ud \)
  - 3-body collisions by \( c, u \) and \( d \)

- Case 1. Threshold \( (m_{ud} = 600 \text{ MeV}) \)
  - 2-body collisions by \( c \) and \( ud \)

QGP medium

\( \Lambda_c \rightarrow pK^-\pi^+ \)

\( D^0 \rightarrow K^+\pi^- \)

Λc Measurements

Λc( → p + K + π):

1) Lowest mass charm baryon
2) Total yield and Λc/D0 ratios can be measured.

![Graphs showing results of measurements](image-url)