High T QCD at RHIC II

Introduction
- High T QCD and RHIC
- Fundamental open questions

Experimental quest for answers
- Hard probes: jet tomography and heavy flavor
- Expected progress with upgrades of RHIC

Ongoing and planed improvements to RHIC
- Time line, detector and accelerator upgrades (RHIC II)

Summary
Study high $T$ and $\rho$ QCD in the Laboratory

Exploring the Phase Diagram of QCD

- Quark Matter: Many new phases of matter
  - Asymptotically free quarks & gluons
  - Strongly coupled plasma
  - Superconductors, CFL ....

- Mostly uncharted territory

- Experimental access to “high” $T$ and moderate $\rho$ region: heavy ion collisions
  - Pioneered at AGS and SPS
  - Ongoing program at RHIC

Overwhelming evidence: Strongly coupled quark matter or nearly perfect liquid produced at RHIC
Quark Matter Produced at RHIC

I. Transverse Energy

Bjorken estimate:
\[ \tau_0 \sim 0.3 \text{ fm} \]

Quark Matter Produced at RHIC
\[ \varepsilon_{\text{initial}} \sim 10-20 \text{ GeV/fm}^3 \]

II. Flow → Hydrodynamics

Initial conditions:
\[ \tau_{\text{therm}} \sim 0.6 -1.0 \text{ fm/c} \]
\[ \varepsilon \sim 15-25 \text{ GeV/fm}^3 \]

Heavy ion collisions provide the laboratory to study high T QCD!
Fundamental Questions
that can now be addressed at RHIC

What are the properties of new state of matter?
- Temperature, density, viscosity, speed of sound, diffusion coefficient, transport coefficients, color screening length
- Is it a perfect liquid?
  - If it’s a fluid: What is the nature a relativistic quantum fluid?
  - If not: What is it and what are the relevant degrees of freedom?
- Is chiral symmetry restored?
- What is the mechanism of rapid thermalization?
- How does the deconfined matter transform into hadrons?

Is there a critical point in the QCD phase diagram and where is it located?

Key are precision measurements with hard probes and collective behavior currently not accessible at RHIC

→ RHIC upgrades: improved detectors and increased luminosity
**Key Experimental Probes of Quark Matter**

- Rutherford experiment: \( \alpha \rightarrow \) atom discovery of nucleus
- SLAC electron scattering: \( e \rightarrow \) proton discovery of quarks

**Nature provides penetrating beams or “hard probes” and the QGP in A-A collisions**

- Penetrating beams created by parton scattering before QGP is formed
  - High transverse momentum particles \( \rightarrow \) jets
  - Heavy particles \( \rightarrow \) open and hidden charm or bottom
  - Calibrated probes calculable in pQCD
- Probe QGP created in A-A collisions as transient state after \( \sim 1 \) fm

Penetrating beam (jets or heavy particles)

absorption or scattering pattern
Hard Probes: Light quark/gluon jets

**Status**
- Calibrated probe
- Strongly modified in opaque medium
  - Jet quenching
  - Reaction of medium to probe
    - (2 particle corr. → Mach cones, etc)
- Open issues:
  - Which observables are sensitive to details of energy loss mechanism?
  - What is the energy loss mechanism?
  - What phenomena relate to reaction of media to probe?

Answers will come from jet tomography (γ-jet):
- single, two and three particle analysis

Will be possible at RHIC II:
- statistics ($p_T$ reach) → increased luminosity and/or rate capability
- kinematic coverage → increased acceptance & added PID

Axel Drees
Jet Tomography at RHIC II

medium reacting hadron < 4 GeV

γ: jet energy

recoil jet: energy loss

RHIC II will give jets up to 50 GeV
→ separation of medium reaction and energy loss
→ sufficient statistics for 3 particle correlations $p_T > 5$ GeV
→ 2-3 particle correlations with identified particles

W. Vogelsang NLO
RHIC II $\mathcal{L} = 20$ nb$^{-1}$
LHC: 1 month run

π$^0$ suppression at RHIC & LHC

PHENIX Central Arms

0
10
20
30
40
50
60
70
80
90
100
10
9
8
7
6
5
4
3
2
1
0

$|n|<1.0$

$\gamma_\text{jet}$

$\gamma_\text{dir}$

$\gamma_\text{had}$

$\gamma_\text{jet}$
Hard Probes: Open Heavy Flavor

Electrons from c/b hadron decays

Status

- Calibrated probe?
  - pQCD under predicts cross section by factor 2-5
  - Factor 2 experimental differences in pp must be resolved
  - Charm follows binary scaling
- Strong medium effects
  - Significant charm suppression and $v_2$
  - Upper bound on viscosity?
- Open issues:
  - Limited agreement with energy loss calculations
  - What is the energy loss mechanism?
  - Are there medium effects on b-quarks?

Answers expected from direct charm/beauty measurements

Will be possible at RHIC II:
- b-c separation → decay vertex with silicon vertex detectors
- statistics ($B \rightarrow J/\Psi$) → increased luminosity and/or rate capability
Direct Observation of Charm and Beauty

Detection options with vertex detectors:
- Beauty and low $p_T$ charm through displaced $e$ and/or $\mu$
- Beauty via displaced $J/\psi$
- High $p_T$ charm through $D \rightarrow \pi K$

<table>
<thead>
<tr>
<th></th>
<th>$m$</th>
<th>$c\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$^0$</td>
<td>1865</td>
<td>125</td>
</tr>
<tr>
<td>D$^\pm$</td>
<td>1869</td>
<td>317</td>
</tr>
</tbody>
</table>

PHENIX VXT $\sim$2 nb$^{-1}$

STAR HFT $\sim$20 nb$^{-1}$

RHIC II increases statistics by factor $>$10
Hard Probes: Quarkonium

**Status**
- **J/ψ production is suppressed**
  - Similar at RHIC and SPS
  - Consistent with consecutive melting of χ and ψ'
  - Consistent with melting J/ψ followed by regeneration

**Open issues:**
- Recent Lattice QCD developments
  - Quarkonium states do not melt at T_C
- Is the J/ψ screened or not?
- Can we really extract screening length from data?

Answers require “quarkonium” spectroscopy including p_T and reaction plan dependence

Will be possible at RHIC II:
- statistics (ψ', Y) → increased luminosity and/or rate capability
# Quarkonium and Open Heavy Flavor

## Signal

<table>
<thead>
<tr>
<th>Signal</th>
<th>PHENIX</th>
<th>STAR</th>
<th>ALICE</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>\text{ or } \eta$</td>
<td>$&lt;0.35, 1.2-2.4$</td>
<td>$&lt;1$</td>
<td>$&lt;0.9, 2.5-4$</td>
</tr>
<tr>
<td>$J/\Psi \rightarrow \mu \mu \text{ or ee}$</td>
<td>440,000</td>
<td>220,000</td>
<td>800,000</td>
<td>180,000</td>
<td>8000-100,000</td>
</tr>
<tr>
<td>$\Psi' \rightarrow \mu \mu \text{ or ee}$</td>
<td>8000</td>
<td>4000</td>
<td>19,000</td>
<td>-</td>
<td>1400-1800</td>
</tr>
<tr>
<td>$\chi_c \rightarrow \mu \gamma \text{ or eeg}$</td>
<td>120,000 *</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$Y \rightarrow \mu \mu \text{ or ee}$</td>
<td>1400</td>
<td>11,000**</td>
<td>11,000</td>
<td>37,000</td>
<td>15,000</td>
</tr>
<tr>
<td>$B \rightarrow J/\Psi \rightarrow \mu \mu \text{ (ee)}$</td>
<td>6500</td>
<td>2500</td>
<td>12,900</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$D \rightarrow K\pi$</td>
<td>8000****</td>
<td>30,000***</td>
<td>8,000</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

* large background  
** states maybe not resolved  
*** min. bias trigger  
**** $pt > 3 \text{ GeV}$  

Heavy flavor in heavy ion collisions at RHIC and RHIC II  
A.D.Frawley, T.Ullrich and R.Vogt  

LHC relative to RHIC  
Luminosity $\sim 10\%$  
Running time $\sim 25\%$  
Cross section $\sim 10-50\times$  

~ similar yields!  

Will be statistics limited at RHIC II (and LHC!)
Examples of Quarkonium Spectroscopy at RHIC II

J/ψ measurements will reach high precision

![Graph showing J/ψ measurements at RHIC II](image)
Axel Drees

Long Term Timeline of Heavy Ion Facilities

2006  2009  2012  2015

RHIC

Vertex tracking, large acceptance, rate capabilities

PHENIX & STAR upgrades

electron cooling “RHIC II”
electron injector/ring “e RHIC”

LHC

FAIR

Phase III: Heavy ion physics
RHIC Upgrades

On going effort with projects in different stages

Detector upgrades

forward meson spectrometer
DAQ & TPC electronics
full ToF barrel
heavy flavor tracker (HFT)
intermediate silicon tracker (IST)
forward GEM tracker (FGT)

Accelerator upgrades

EBIS ion source (started)
Electron cooling (x10 luminosity) by 2010
- at 200 GeV extra x10
- Au+Au ~40 KHz event rate

Electron cooling at <20 GeV
- Additional factor of 10
- Au+Au 20 GeV ~15 KHz event rate
- Au+Au 2 GeV ~150 Hz event rate

Completed, on going, expect funding in FY08, in preparation
Which Measurements are Unique at RHIC?

- **General comparison to LHC**
  - LHC and RHIC (and FAIR) are complementary
  - They address different regimes (CGC vs sQGP vs hadronic matter)
  - RHIC is a dedicated machine with broad program, LHC may run 4-5 weeks/year
  - Experimental issues: “Signals” at RHIC overwhelmed by “backgrounds” at LHC

- **Measurement specific (compared to LHC)**
  - **Jet tomography:** measurements and capabilities complementary
    - RHIC: large calorimeter and tracking coverage with PID in few GeV range
    - Extended $p_T$ range at LHC
  - **Charm measurements:** favorable at RHIC
    - Abundant thermal production of charm at LHC, no longer a penetrating probe
    - Charm is a “light quark” at LHC, signal from jet fragmentation and bottom decay
    - Bottom may assume role of charm at LHC
  - **Quarkonium spectroscopy:** $J/\psi$, $\psi'$, $\chi_c$ easier to interpret at RHIC
    - Large background from bottom decays and thermal production at LHC
    - Rates about equal; LHC 10-50 $\sigma$, 10% luminosity, 25% running timer
RHIC II Perspectives

RHIC II has potential to provide key measurements and many precision measurements unavailable at RHIC today!

Progress from:

- Improved detectors (STAR and PHENIX)
  vertex tracking, large acceptance, rate capability

- Luminosity upgrade (RHIC II)
  electron cooling for all energies

- Improved theoretical guidance
  phenomenological tools (e.g. 3-D viscous hydro)
  lattice QCD (e.g. finite density)
  new approaches (e.g. gauge/gravity correspondence)

RHIC II will continue to spearhead research in high T QCD through the LHC area.
Backup
Comparison of Heavy Ion Facilities

**Initial conditions**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Temperature</th>
<th>Energy</th>
<th>Intensity</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCB</td>
<td>$3 \rightarrow 4 , T_C$</td>
<td>$\sqrt{s_{NN}} \sim 5 \rightarrow 200 , \text{GeV} , \text{U+U}$</td>
<td>$L \sim 8 \times 10^{27} , \text{cm}^{-2} \cdot \text{s}^{-1}$</td>
<td>$\sim 5 , \text{kHz}$</td>
</tr>
<tr>
<td>RHIC</td>
<td>$2 , T_C$</td>
<td>$\sqrt{s_{NN}} \sim 1 \rightarrow 8 , \text{GeV} , \text{U+U}$</td>
<td>$L \sim 2 \times 10^9 , \text{s}^{-1}$</td>
<td>$\sim 20 , \text{MHz}$</td>
</tr>
<tr>
<td>FAIR</td>
<td>$T_C \leq T_C$</td>
<td>$\sqrt{s_{NN}} \sim 1 \rightarrow 8 , \text{GeV} , \text{U+U}$</td>
<td>$I \sim 2 \times 10^9 , \text{s}^{-1}$</td>
<td>$\sim 20 , \text{MHz}$</td>
</tr>
</tbody>
</table>

**Complementary programs with large overlap:**

- **High T: LHC**
  - Adds new high energy probes
  - Test prediction based on RHIC data
  - $\sim 4 \, \text{week/year}$

- **High $\rho$: FAIR**
  - Adds probes with ultra low cross section

**FAIR: cold but dense baryon rich matter**
- Fixed target $p$ to $U$
- $\sqrt{s_{NN}} \sim 1 \rightarrow 8 \, \text{GeV} \, \text{U+U}$
- Intensity $\sim 2 \times 10^9 / \text{s} \rightarrow \sim 10 \, \text{MHz}$
- $\sim 20 \, \text{weeks/year}$

**RHIC: dense quark matter to hot quark matter**
- Collider $p+p$, $d+A$ and $A+A$
- $\sqrt{s_{NN}} \sim 5 \rightarrow 200 \, \text{GeV} \, \text{U+U}$
- Luminosity $\sim 8 \times 10^{27} / \text{cm}^2 \cdot \text{s} \rightarrow \sim 50 \, \text{kHz}$
- $\sim 15 \, \text{weeks/year}$

**LHC: hot quark matter**
- Collider $p+p$ and $A+A$
- Energy $\sim 5500 \, \text{GeV} \, \text{Pb+Pb}$
- Luminosity $\sim 10^{27} / \text{cm}^2 \cdot \text{s} \rightarrow \sim 5 \, \text{kHz}$
- $\sim 4 \, \text{week/year}$

**RHIC is unique and at “sweet spot”**
Low Energy Running at RHIC

Physics goals:
- Search for critical point $\rightarrow$ bulk hadron production and fluctuations
  Requires moderate luminosity
can maybe be done in next years
- Chiral symmetry restoration $\rightarrow$ dilepton production
  Requires highest possible luminosity, i.e.
electron cooling

Luminosity estimate with electron cooling
- Assume 4 weeks of physics each, 25%
recorded luminosity and sufficient triggers

- 20 GeV $\rightarrow$ $10^9$ events
- 2 GeV $\rightarrow$ $10^7$ events

CERES best run $\sim 4\times10^7$ events
NA60 In+In $\sim 10^{10}$ sampled events

Very strong low energy program possible at RHIC
Fundamental Questions (III)

- How are colliding nuclei converted into thermal quark-gluon plasma so rapidly?
  - Initial state and entropy generation.
  - What is the low x cold nuclear matter phase?

Status:
- Intriguing hints for CGC (color glass condensate) at RHIC
  Bulk particle multiplicities “mono jets” at forward rapidity

Answers at RHIC from hard probes at forward rapidity, ultimately EIC needed

Progress at RHIC limited by:
  detection capabilities → forward detector upgrades
Compelling Physics of RHIC II

Provide key measurements so far inaccessible at RHIC in three broad areas:

- **High T QCD (A+A, d+A, and p+p):**
  - Electromagnetic radiation ($e^+e^-$ pair continuum)
  - Heavy flavor (c- and b-production)
  - Jet tomography (jet-jet and $\gamma$-jet)
  - Quarkonium ($J/\psi$, $\psi'$, $\chi_c$ and $\Upsilon(1s),\Upsilon(2s),\Upsilon(3s)$)

- **Spin structure of the nucleon:**
  - Quark spin structure $\Delta q/q$ (W-production)
  - Gluon spin structure $\Delta g/g$ (heavy flavor and $\gamma$-jet correlations)

- **Low $x$ phenomena**
  - "Low $x" \Leftrightarrow "forward measurements"
  - gluon saturation in nuclei
    (particle production at forward rapidity)

All measurements require upgrades of detectors and/or RHIC luminosity
# RHIC Upgrades Overview

<table>
<thead>
<tr>
<th>Upgrades</th>
<th>High T QCD</th>
<th>Spin</th>
<th>Low x</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e+e- heavy jet quarkonia flavor tomography W ΔG/G</td>
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<tr>
<td><strong>PHENIX</strong></td>
<td></td>
<td></td>
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<tr>
<td>hadron blind detector (HBD)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertex tracker (VTX and FVTX)</td>
<td>X X O O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>μ trigger</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>forward calorimeter (NCC)</td>
<td></td>
<td>O X</td>
<td>O</td>
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<tr>
<td><strong>STAR</strong></td>
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<tr>
<td>time of flight (TOF)</td>
<td></td>
<td>O X</td>
<td>O</td>
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<tr>
<td>Heavy flavor tracker (HFT)</td>
<td></td>
<td>X</td>
<td>O</td>
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<tr>
<td>tracking upgrade</td>
<td></td>
<td>O</td>
<td>O</td>
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<tr>
<td>Forward calorimeter (FMS)</td>
<td></td>
<td>O X</td>
<td>O</td>
</tr>
<tr>
<td>DAQ</td>
<td></td>
<td>O X</td>
<td>O</td>
</tr>
<tr>
<td><strong>RHIC luminosity</strong></td>
<td></td>
<td>O</td>
<td>O</td>
</tr>
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</table>

*X* upgrade critical for success

*O* upgrade significantly enhancements program
(i) $\pi^0$ and direct $\gamma$ with combination of all electromagnetic calorimeters
(ii) heavy flavor with precision vertex tracking with silicon detectors
combine (i)&(ii) for jet tomography with $\gamma$-jet

(iii) low mass dilepton measurements with HBD + PHENIX central arms
PHENIX Detector Upgrades at a Glance

- **Central arms:**
  - **Electron and Photon measurements**
    - Electromagnetic calorimeter
    - Precision momentum determination
  - Dalitz/conversion rejection (HBD)
  - Precision vertex tracking (VTX)
  - **Hadron identification**
    - PID \((k, \pi, p)\) to 10 GeV (Aerogel/TOF)

- **Muon arms:**
  - **Muon**
    - Identification
    - Momentum determination
  - High rate trigger (\(\mu\) trigger)
  - Precision vertex tracking (FVTX)
  - **Electron and photon measurements**
    - Muon arm acceptance (NCC)
    - Very forward (MPC)
STAR Upgrades

- Full Barrel Time-of-Flight system
- DAQ and TPC-FEE upgrade
- Forward Meson Spectrometer
- Forward triple-GEM EEMC tracker
- Integrated Tracking Upgrade
  - HFT pixel detector
  - Barrel silicon tracker
  - Forward silicon tracker
Jet Tomography with RHIC II

RHIC II will give jets up to 50 GeV
→ separation of medium reaction and energy loss
→ sufficient statistics for 3 particle correlations $p_T > 5$ GeV
→ 2-3 particle correlations with identified particles
Comments on High $p_T$ Capabilities

- **LHC**
  - Orders of magnitude larger cross sections
  - $\sim$3 times larger $p_T$ range

- **RHIC with current detectors (+ upgrades)**
  - Sufficient $p_T$ reach
  - Sufficient PID for associated particles
  - What is needed is integrated luminosity!

Region of interest for associated particles up to $p_T \sim 5$ GeV
Fundamental Questions (I & II)

Key probe: electromagnetic radiation:
- No strong final state interaction
- Carry information from time of emission to detectors
  - $\gamma$ and dileptons sensitive to highest temperature of plasma
  - Dileptons sensitive to medium modifications of mesons
    (only known potential handle on chiral symmetry restoration!)

Status
- First indication of thermal radiation at RHIC
- Strong modification of meson properties
  - Precision data from SPS, emerging data from RHIC
- Theoretical link to chiral symmetry restoration remains unclear

Can we measure the initial temperature?
Is there a quantitative link from dileptons to chiral symmetry restoration?

Answers will come with more precision data → upgrades and low energy running
Fundamental Questions (III)

How does the deconfined matter transform into hadrons?

Status:
- Elliptic flow ($v_2$)
  - $v_2$ of mesons and baryons scale with constituent quark number
- Evidence for deconfined quarks
  - Hadronisation via recombination of constituent quarks in QGP

Progress from $\sqrt{s}$ and flavor dependence of collective flow

Limited by:
- flavor detection capabilities $s$, $c$, $b$ mesons and baryons
  - vertex detectors and extended particle ID
Beyond PHENIX and STAR upgrades?

- Do we need (a) new heavy ion experiment(s) at RHIC?
  - Likely, if it makes sense to continue program beyond 2020
    - Aged mostly 20 year old detectors
    - Capabilities and room for upgrades exhausted
    - Delivered luminosity leaves room for improvement
  - Nature of new experiments unclear at this point!
    - Specialized experiments or $4\pi$ multipurpose detector ???

- Key to future planning:
  - First results from RHIC upgrades
    - Detailed jet tomography, jet-jet and $\gamma$-jet
    - Heavy flavor (c- and b-production)
    - Quarkonium measurements ($J/\psi$, $\psi'$, $\Upsilon$)
    - Electromagnetic radiation ($e^+e^-$ pair continuum)
    - Status of low energy program
  - Tests of models that describe RHIC data at LHC
    - Validity of saturation picture
    - Does ideal hydrodynamics really work
    - Scaling of parton energy loss
    - Color screening and recombination

New insights and short comings of RHIC detectors will guide planning on time scale 2010-12