RHIC Heavy Ion Program (in the Next Decade)

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Introduction

• **Critical** point search
  – Beam energies 7.7-39 (Starting next year)
  – Lower beam energies after low-E electron cooling ($\geq 2014$)

• **Luminous** beams with stochastic cooling
  – Stochastic cooling ramp-up 2010-2014 (mostly by 2012)

• **Charming** physics with vertex upgrades
  – PHENIX: 2011
  – STAR: prototypes beginning 2011, full installation 2013

**Key Physics Questions:**

What are the landmarks on the QCD phase diagram?
What is the mechanism for QCD energy loss?
What are the quantitative properties of the QCD matter produced at RHIC?
RHIC: A flexible accelerator

- Flexibility is key to understanding complicated systems
  - Polarized protons, $\sqrt{s} = 10-500$ GeV
  - Nuclei from d to Au, $\sqrt{s_{NN}} = 5-200$ GeV
- Physics runs to date
  - Au+Au @ 9.2, 20, 62, 130, 200 GeV
  - Cu+Cu @ 20, 62, 200 GeV
  - Polarized p+p @ 200, 500 GeV
  - d+Au @ 200 GeV
- Future reach
  - Increase A to Uranium
  - Scan in $\sqrt{s}$ to 5 GeV
  - Increase Luminosity x10
Precision ID in a selected range of phase space
STAR: A Correlation Machine

**Tracking: TPC**

**Particle ID: TOF**

**Electromagnetic Calorimetry: BEMC+EEMC+FMS**

\((-1 \leq \eta \leq 4)\)

**Heavy Flavor Tracker (2013)**

**Forward Gem Tracker (2011)**

Full azimuthal particle identification over a broad range in pseudorapidity
• 1\textsuperscript{st} order phase transition: bracket location of the Critical Point
  – Hydrodynamics: $\nu_1$, $\nu_2$, azimuthally sensitive HBT for EOS softest point
• Direct signatures of Critical Point via enhanced fluctuations
  – Large-acceptance identified particle fluctuations and correlations
Non-monotonic behavior would indicate a softest point: 1st order
Identified particle fluctuations

- Example: $K/\pi$ fluctuations
  - Rise in NA49 data not explained by models
- STAR: Full PID, large acceptance uniform over $\sqrt{s_{NN}}$
- Unprecedently accurate and differential measurements possible
Turn-off of QGP Signatures

- Search for onset of signatures of new phenomena discovered at highest RHIC energy
  - Number of constituent quark scaling in $v_2$: partonic collectivity
  - Hadron suppression: opacity
  - “Ridge”: pair correlations extended in pseudorapidity
  - Local parity violation
Local Parity Violation

- Signature consistent with local parity violation at 200, 62 GeV
  - Measure Parity Even so potential contamination
    - No background found to date that can mimic effect
    - Background (and magnetic field) expected to change with energy
- Program: vary energy, vary species (isobars?) to test behavior

Requirements:
- Large Magnetic Field from initial L
- Chiral symmetry restoration
- Deconfinement

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Luminosity progression to the fb\(^{-1}\) era

26 nb\(^{-1}\) * 197 * 197 = 1 fb\(^{-1}\) pp equivalent

Stochastic cooling: order of magnitude increase in luminosity for rare probes
Mechanisms for Energy Loss

• QED: different momenta, different mechanisms
• Just beginning the exploration of this space in QCD

Bremsstrahlung
Radiative dE/dx
\( \gamma \)-Jet: Golden Probe of QCD Energy Loss

- \( \gamma \) emerges unscathed from the medium
  - Probes deeply into the medium: different surface bias from hadron, dihadron
  - Fully reconstructed kinematics: measure real fragmentation function \( D(z) \)
γ-Jet: RHIC is clean

RHIC: Clean separation of γ from π⁰ for \( p_T > \sim 10 \) GeV

Fragmentation contribution also expected to be small

\[ \pi^0 \text{ suppression at RHIC & LHC} \]

W. Vogelsang NLO
RHIC II \( \mathcal{L} = 20 \) nb⁻¹
LHC: 1 month run
γ-Hadron Correlations: First Peek

Both STAR and PHENIX have made first measurements in both Au+Au and p+p


\( \gamma \)-Hadron Correlations: need for precision


\( \gamma \) triggers \( 8 < E_{\text{trig}}^{\gamma} < 16 \text{ GeV/c} \)

- First measurements made
  - Agree with theory within uncertainties
  - Higher precision needed
- Major progress possible in coming years with RHIC II

\( E_{\text{jet}} = E_{\gamma} \)

Projection for \( E_{\gamma} > 15 \text{ GeV}, 4 < p_{T}^{\text{assoc}} < 6 \text{ GeV} \)

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Jet reconstruction: another way to constrain hard kinematics

Positive: large cross-section, so large $p_T$ reach

Negative: large backgrounds, limited $E$ resolution
Jets in Au+Au: Results so Far

Beginning results from 2007 indicative, but in no way final word.

- Beginning application of FastJet... to handle large background.
- Orders of magnitude more luminosity available by Run 14.

- Issue: effective triggers to sample luminosity w/o physics bias.

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Quarkonium: Upsilon

Proof of principle: STAR p+p 2006
Upsilon(1S+2S+3S)→e^+e^-

Sequential dissociation of quarkonia to measure energy density of plasma
Both STAR and PHENIX have made first measurements
PHENIX: (1S+2S+3S) \( R_{AA} < 0.64 \) at 90% CL; need to separate states
Quarkonium in the fb\(^{-1}\) era: Upsilon

Proof of principle: STAR p+p 2006
Upsilon(1S+2S+3S)→e^+e^-

Sequential dissociation of quarkonia to measure energy density of plasma
Good start, but needs full luminosity of RHIC II to be definitive
Heavy Quark Motivation: Grey Probes

- Problem: interaction with the medium so strong that information lost: “Black”
- Significant differences between predicted $R_{AA}$, depending on the probe
- Experimental possibility: recover sensitivity to properties of the medium by varying probe

\[ Wicks \text{ et al, Nucl. Phys. A784 (2007) 426} \]
Charm/Beauty: No shade of gray

- Strong suppression and flow of non-photonic electrons
- Study mechanism of energy loss (especially B)
- Study thermalization and transport properties (esp. low $p_T$ D)
Measurement: a wealth of decay

- 4 pages $D^0$, 10 pages of $B^+$ decay modes in PDB
- Most promising modes:
  - Leptons: B.R. $\sim 10\%$ per lepton species of B and D
    - Electrons: triggerable in calorimeters
    - Muons: no Bremsstrahlung, photonic background
    - Neither have full kinematic reconstruction
  - Pure hadronic: full kinematics
    - $D \rightarrow K\pi$, $D^* \rightarrow K\pi\pi$
    - Not easily triggerable
  - $B \rightarrow J/\Psi + \chi$
    - Clean from D contamination
    - B.R. $\sim 1\%$, triggerable
Outlook: Precision Vertexing

Entering prime years for heavy flavor with precision vertexing
Complementary capabilities and systems

**ALICE**: LHC, where c becomes a “light” quark

**PHENIX**: Focus on electrons and muons

**STAR**: Focus on fully reconstructed kinematics
Separating Charm from Beauty

ALICE Projections

\[ \tilde{q} = 4 (\text{dot-dash}), 25 (\text{dash}), 100 (\text{solid}) \text{ GeV}^2/\text{fm} \]

- No E loss
- E loss, \( m_c = m_b = 0 \)
- E loss, \( m_c = 1.2 \text{ GeV}, m_b = 4.8 \text{ GeV} \)

PHENIX Projection

Expected with VTX (0.4/nb)

- \( c+b \to e \)
- \( b \to e \)
- \( c \to e \)

- At ALICE, c a “light quark”, \( e_B/e_C \) sensitive to B energy loss
- PHENIX VTX: built to isolate \( e_B \) from \( e_D \)
- Clean measurements of beauty quenching will be possible
Open Charm with the STAR HFT

• Direct reconstruction with full kinematic information
• Only possible for charm:
  – $D^+$, $D^0$, $\Lambda_c$
• No ambiguities
Conclusion

Key Physics Questions:
What are the landmarks on the QCD phase diagram?
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RHIC is well-positioned to provide answers to these questions over the next decade with
Critical point search
Luminous beams (Jets, γ-jet, Quarkonia)
Charming and beautiful suppression and flow
Quarkonia: High Pt J/ψ

Test mechanism of J/ψ production

J/ψ only hadron with $R_{AA} = 1$?

Start of high precision with Run 10 – expect $\sim 2\, \text{nb}^{-1}$

Precision measurements later in the decade after full stochastic cooling