Experimental Approach to the QCD Phase Diagram & Search for the Critical Point

Grazyna Odyniec / LBNL, Berkeley

The John Cramer Symposium
University of Washington, Seattle, September 10-11, 2009

Outline:
QCD phase diagram
Heavy Ion Collisions – the only experimental tool
BES @ RHIC: Physics goals and observables:

• search for the CP and 1st order phase transition
• demonstrate the onset of deconfinement (QGP)
Theory at the “edges” is believed to be well understood:

1. Lattice QCD finds a rapid, but smooth, crossover at large $T$ and $m_B \sim 0$
2. Various models find a strong 1st order transition at large $m_B$

So, there must be a critical point, but where?

Lattice at $m_B = 0$: serious problems, several methods on lattice, no agreement so far:

$\rightarrow$ CP range: $160 < m_B < 500$ MeV

Given the significant theoretical difficulties, data may lead the study of QCD phase diagram

$\rightarrow$ **Beam Energy Scan** Program at RHIC will cover this range

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Beam Energy Scan at RHIC: $S_{NN} \sim 5-50$ GeV

experimental window to QCD phenomenology
at finite temperature and baryon number density

at RHIC: indications of sQGP
but remain unknown:
- boundary between hadronic and partonic phases
- critical point

HOW to investigate it? BES @ RHIC
also: SPS, FAIR (fixed target)

INT Program “The QCD Critical Point”
Univ. of Washington, Seattle, 2008

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Why RHIC is such an excellent choice? - Collider

1. Variation of particle density with beam energy slower. Occupancy in detectors reasonable compared to fixed target experiments at similar collision energy.

2. Uniform acceptance for different particle species and for different beam energies in the same experimental setup.

Excellent control of systematics!

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Luminosity is the key issue

Rate can be increased by:

- factor 2 by adding more bunches, only 56 used for tests (max 120).
- factor 3-6 by operating with higher charge in bunches.
- factor few by running in continuous injection mode
- electron cooling in RHIC (in 2012)

Expect to reach $\gamma^3$ rate even at lowest energies

Determined collision rate for 2008 9.2 GeV Au+Au test to be $\sim 1\text{Hz}$.
Search for:

(1) indications of the existence of Critical Point & phase transition
   • fluctuation measures
     • higher moments of net proton distribution (kurtosis)
   • azimuthally-sensitive femtoscopy
   • elliptic & directed flow
   • …

(2) disappearance of signals of partonic activities seen at 200 GeV
   • disappearance of constituent-quark-number scaling of $v_2$
   • disappearance of hadron suppression in central collisions
   • disappearance of ridge
   • local parity violation
   • …

Search for the QCD Critical Point: Higher Moments

Thermodynamics: Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point.

Lattice QCD: Spikes for both $\chi_B$ and $\chi_S$

Berdnikov, Rajagopal, PRD61, 105017 (00)
Stephanov, Rajagopal, Shuryak, PRD 60, 114028 (99)
Hatta, Stephanov, PRL. 91, 102003 (03)

Observable:
Kurtosis of net-proton & net-C
- connect to lattice calculations!
- sensitive to long range fluctuations

Caveats: dynamical effects in collisions
- finite time and size
- critical slowing
Centrality dependence of net-proton Kurtosis

STAR Preliminary:

200 GeV Au+Au \((m_B \leq 25 \text{ MeV})\)

First Kurtosis measurement for net-protons in high-energy nuclear collisions

Monotonic behavior observed at relatively small \(m_B\) region \(\rightarrow\) baseline

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Disappearance of partonic activities (I)
(Onset of sQGP)

disappearance of $n_q$ scaling, disappearance of hadron suppression at high $pt$, … (a long list)

$n_q$ scaling observed at RHIC:

(1) Mass separation at low $p_T$

(2) Light and heavy quarks have similar magnitude of flow

(3) In intermediate $p_T$: separation between baryon and meson band
Disappearance of partonic activities (II)

Scaling flow parameters by quark content $n_q$ (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons.

With lowering energy, disappearance of $n_q$ scaling would suggest that we exit partonic dof world.

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Local Parity Violations in Deconfined Medium

(1) Under strong magnetic field, when the system is in the state of deconfinement and chiral symmetry restoration is reached, local fluctuation may lead to parity violation.

(2) Experimentally one would observe the separation of the charges in high-energy nuclear collisions.

(3) In RHIC Beam Energy Scan program:
- test the model prediction
- the energy when the charge separation disappear => phase boundary

## Collision Energies (GeV)

<table>
<thead>
<tr>
<th>Observables</th>
<th>5</th>
<th>7.7</th>
<th>11.5</th>
<th>17.3</th>
<th>27</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_2$ (up to ~1.5 GeV/c)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$v_1$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Azimuthally sensitive HBT</td>
<td>4</td>
<td>4</td>
<td>3.5</td>
<td>3.5</td>
<td>3</td>
<td>3</td>
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<tr>
<td>PID fluctuations (K/p)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>net-proton kurtosis</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>differential corr &amp; fluct vs. centrality</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$n_q$ scaling p/K/p/L ($m_T-m_0$)/n&lt;2GeV</td>
<td>8.5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>$f/W$ up to $p_T/n_q=2$ GeV/c</td>
<td>56</td>
<td>25</td>
<td>18</td>
<td>13</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>$R_{CP}$ up to $p_T$ ~4.5 GeV/c (at 17.3)</td>
<td>5.5</td>
<td>(at 27) &amp; 6 GeV/c (at 39)</td>
<td>15</td>
<td>33</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>untriggered ridge correlations</td>
<td>27</td>
<td>13</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>parity violation</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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</table>
# Requested Beam Energies and # of Days Running (from STAR BUR)

<table>
<thead>
<tr>
<th>Beam Energy sqrt(s) (GeV)</th>
<th>$m_B$ (MeV)</th>
<th>Event Rate (Hz)</th>
<th>Days/1M Events</th>
<th>Events proposed</th>
<th>8-hr days proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>550</td>
<td>0.8</td>
<td>45</td>
<td>200 k</td>
<td>9</td>
</tr>
<tr>
<td>7.7</td>
<td>410</td>
<td>3</td>
<td>11</td>
<td>5M</td>
<td>56</td>
</tr>
<tr>
<td>11.5</td>
<td>300</td>
<td>10</td>
<td>3.7</td>
<td>5M</td>
<td>19</td>
</tr>
<tr>
<td>17.3</td>
<td>230</td>
<td>33</td>
<td>1.1</td>
<td>15M</td>
<td>16</td>
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<tr>
<td>27</td>
<td>150</td>
<td>92</td>
<td>0.4</td>
<td>33M</td>
<td>12</td>
</tr>
<tr>
<td>39</td>
<td>110</td>
<td>190</td>
<td>0.2</td>
<td>24M</td>
<td>5</td>
</tr>
</tbody>
</table>

Sufficient rates for the initial physics program at all energies

“binary” experiment: YES/NO (no “maybe’s” & more statistics needed)
BES @ RHIC:
run 10 and 11

PAC recommendations, May 2008:
“The search for the QCD Critical Point is a “must do” experiment”

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STAR has experience with low energy running

9.2 GeV Au+Au
March 2008

for comparison 200 GeV Au+Au
STAR experiment demonstrated capabilities

9.2 GeV results consistent with the published data

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Elliptic Flow

STAR and NA49 results are consistent
STAR 9.2GeV $v_2$ fits with the observed trends

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Pion Interferometry

error bars for Au+Au 9.2 GeV are statistical systematic errors < 10 % for all radii

CERES : NPA 714 (2003) 124
E895 : PRL 84 (2000 ) 2798
WA97 : JPG 27 (2001) 2325

9.2 GeV Au+Au paper in preparation (PRC)

Results from the 9.2 GeV run demonstrate STAR readiness to take up the proposed Beam Energy Scan Program
Summary – part I (BES@RHIC)

Main directions of Beam Energy Scan program at RHIC are established:
• Search for turn-off of sQGP signatures
• Search for the evidence of CP and/or 1\textsuperscript{st} order phase transition
• + many other measurements

We propose to first scan available phase space with 6 equally spaced points between 5 and 39 GeV (we already have 62, 130, 200 data), and return to “interesting” regions for more detailed studies in the next year

STAR is ready:
• STAR BES program will be definite
• Demonstrated capabilities to complete program
• Perfect time: low interior mass, PID due to TOF, DAQ with DAQ1000

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CERN Beam Energy Scan Program – NA61/ SHINE

What is the difference vs. NA49?

- New spectator calorimeter for centrality selection
- Forward Time-Of-Flight
- Beam pipe
- TPC readout

**Physics program:**
- Studying QCD Critical Point and Onset of various observations with varying colliding ion size, collision centrality and having a proper p+p baseline

**Outline of setup:**
- BEAM
- TARGET
- TRACKER
- VTX-1
- VTX-2
- VERTEX MAGNETS
- MTPC-L
- MTPC-R
- ToF-L
- PSD
- Forward-ToF
- TPC readout

Detector upgrades are necessary.

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NA61/Shine search for the critical point

Look for the hill of fluctuations

In+In
S+S
C+C
p+p

energy (A GeV)

T (MeV)

158A
10A GeV

p+p
In+In

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BES at RHIC *(STAR, PHENIX, collider exp.)*
starting date December 2009 (run 10) to continue in 2011 (run 11)

BES at CERN *(NA61/Shine, fixed targ.exp.)*
starting date with ion data 2011 (A~30) to continue in 2012 and 2013 (with lighter and heavier ions)

No turning back, John!
It is not enough to watch from a distance …
That’s right!
CP search is waiting ....
Happy Birthday, John!
And many happy returns of this special day...
Thank you!