Highlights from the heavy-ion program in STAR

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2nd International Conference on Particle Physics and Astrophysics, Moscow, 10-14th October

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**Relativistic Heavy-Ion Collider**

- Extremely versatile: has collected data colliding a large array of different heavy ions
  - Luminosity: Au+Au: $2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$; p+p: $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Only polarized proton collider in the world
  - Beam polarizations P=70%
STAR experiment

- EEMC
- Magnet
- MTD
- BEMC
- TPC
- TOF
- BBC

- FMS
- FPS

- DAQ Trigger
- ZDC

TPC/TOF/BEMC: |\(\eta\)|<1
HFT: |\(\eta\)|<1
MTD: |\(\eta\)|<0.5

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Heavy Flavor Tracker (HFT)

- Took data in 2014-2016
- First application of Monolithic Active Pixel Sensor technology in collider experiments.
- DCA resolution <50 µm for $p_T=750$ MeV/c Kaon

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Beam Energy Scan

Key physics questions:

• Where is the onset of sQGP formation
  – Can we “turn it on/off”?

• Where starts the 1\textsuperscript{st} order phase transition
  – Is there a critical point?

• What are the symmetries (degree of freedom) of the sQGP
  – Chiral symmetry restoration
  – Quark and gluon degree of freedom
  – Response to external field

• What is Equation of State (soft)
Beam Energy Scan I

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_b$ (MeV)</th>
<th>#Events</th>
<th>#Weeks</th>
<th>Year</th>
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</thead>
<tbody>
<tr>
<td>200</td>
<td>20</td>
<td>350 M</td>
<td>11</td>
<td>2010</td>
</tr>
<tr>
<td>62.4</td>
<td>70</td>
<td>67 M</td>
<td>1.5</td>
<td>2010</td>
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<tr>
<td>39.0</td>
<td>115</td>
<td>130 M</td>
<td>2</td>
<td>2010</td>
</tr>
<tr>
<td>27.0</td>
<td>155</td>
<td>70 M</td>
<td>1</td>
<td>2011</td>
</tr>
<tr>
<td>19.6</td>
<td>205</td>
<td>36 M</td>
<td>1.5</td>
<td>2011</td>
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<tr>
<td>14.5</td>
<td>260</td>
<td>20 M</td>
<td>3</td>
<td>2014</td>
</tr>
<tr>
<td>11.5</td>
<td>315</td>
<td>12 M</td>
<td>2</td>
<td>2010</td>
</tr>
<tr>
<td>7.7</td>
<td>420</td>
<td>4 M</td>
<td>4</td>
<td>2010</td>
</tr>
</tbody>
</table>

- Large, Uniform Acceptance at Mid-rapidity
- Ideal detector for BES
- Eight energies scanned
Search for onset of QGP signatures

Evolution of $R_{CP}$ suppression

- $R_{CP}$ Exhibits suppression down to 39 GeV
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision show indicate a balance of enhancement and suppression effects at $\sqrt{s_{NN}} = 14.5$ GeV.

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Search for onset of QGP formation

Triangular flow $v_3$ – a third harmonics in the fourier decomposition of the two-particle azimuthal correlations
– is a sensitive indicator for the presence of a low viscosity QGP phase
– higher energy collisions produces more particles and higher pressure should be more effective to convert geometry fluctuations to $v_3$


- Sizable $v_3$ at lower energies in central to mid-central centralities
- While the $v_3$ grows as $\sim \log(\sqrt{s})$ at higher energy, it is nearly independent of energy below 20 GeV.
- Peripheral collisions consistent with zero for $\sqrt{s}_{NN}$ less than 14.5 GeV (absence of low viscose QGP phase)

$v_3$ scaled by $n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2) \sim$ energy density

- Local minimum around 20 GeV
- Softening of EoS?
Search for 1\textsuperscript{st} order phase transition: $v_1$

Directed flow $v_1$
- Sensitive to the pressure
- Sensitive to EoS
- Dip in $dv_1/dy$ – softening of EOS

• Minimum in $dv1/dy|_{y=0}$ – hydro and baryon transport interplay
• (Anti)-Lambdas follow those of (anti)-protons
• Net-$K$ and net-$p$ are consistent with each other down to $\sim 14.5$ GeV
  - net-$K$ stays negative for $\sqrt{s_{NN}} < 14.5$ GeV
• The non-monotonic variation for slope of net-proton directed flow could be related to the softening of equation-of-state due to the first order phase transition

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Search for critical point

Critical point
• susceptibilities and correlation length diverge
• large fluctuation

Observables
• Higher moments of conserved quantum numbers (Q, S, B)
  – Direct link between theory and moments of distributions (cumulant ratios)

\[ \frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i} \]
\[ \frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i} \]
\[ \frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i} \]

\[ \chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial (\mu_q)^n}, q = B, Q, S \]

A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

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The values of net-Kaon’s and net-Charge’s $\kappa \sigma^2$ and $S_\sigma$/Skellam are consistent with Poisson distributions within errors.

Non-monotonic behavior of net-proton $\kappa \sigma^2$ seen in top 0-5%, 5-10% central collisions
- Largest deviation from Poisson and uRQMD around 19.6 GeV

Need more precise measurements below 20 GeV
- Finer steps in $\mu_B$
- Increase accepted rapidity window
Probing Quark Gluon Plasma with charm quark

- Charm quark: $m_c \gg T_{QGP}, \Lambda_{QCD}$
  - Produced in the hard scatterings at the early stage of nuclear collisions $\rightarrow$ experience the entire evolution of medium
  - Charm cross section scales with $N_{coll}$ in Au+Au collisions $\rightarrow$ important input for models to calculate regeneration contribution to charmonium
    - Currently, 16% uncertainty in 0-10% Au+Au events*
  - Clean probe at RHIC as contributions from gluon splitting and bottom quark are small.
  - Its production rate is well described by pQCD in elementary collisions

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*PRL 113 (2014) 142301
**D⁰ R⁰ AA in central Au+Au collisions**

- \( R_{AA} > 1 \) for \( p_T \sim 1.5 \text{ GeV/c} \)
  - Charm coalescence with the flowing medium

- \( R_{AA} < < 1 \) for \( p_T > 2.5 \text{ GeV/c} \)
  - Strong charm-medium interaction leading to sizable energy loss

- Similar suppression as pions at high \( p_T \)
  - Collisional energy loss is important
  - Shapes of parton spectrum & fragmentation function need to be taken into account.

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**STAR**

STAR Preliminary

**STAR: PRL 113 (2014) 142301**
First $D^0 v_2$ measurement at RHIC

- Finite $D^0 v_2$ observed above 2 GeV/c
- Data favor a model with charm diffusion

Charm quark flows in the medium

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\( v_2: D^0 \text{ vs light hadrons} \)

- \( v_2 \) for \( D^0 \) is systematically lower than those of light hadrons
  - Hints that charm quarks might not be fully thermalized with medium

STAR: Preliminary
Comparison to models

Values for the diffusion coeff. extracted from models and compared to STAR data

<table>
<thead>
<tr>
<th></th>
<th>$D \times 2\pi T$</th>
<th>Diff. Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAMU</td>
<td>2-11</td>
<td>T-Matrix</td>
</tr>
<tr>
<td>SUBATECH</td>
<td>2-4</td>
<td>pQCD+HTL</td>
</tr>
<tr>
<td>Duke</td>
<td>7</td>
<td>Free parameter</td>
</tr>
</tbody>
</table>

STAR $D_0$ 2010/11: PRL 113 (2014) 142301
Theory curves private communications
DUKE: PRC 92 (2015) 024907
Comparison to models

Values for the diffusion coeff. extracted from models and compared to STAR data

Models with charm diffusion coefficient of \(2 - \sim 12\) describe STAR \(D_0\) \(R_{AA}\) and \(v_2\) results.

Lattice calculations are consistent with these values inferred from data.
$D_s$ reconstruction

- $D_s^\pm \rightarrow \pi^\pm \phi(1020) \rightarrow \pi^\pm K^\pm$
- $c\tau = 150 \, \mu m$
- B.R. 2.32 %
- Mass 1968.47 MeV/$c^2$
- First measurement of $D_s$ at RHIC
**Ds yield and Ds/D0 ratio**

\[ \text{Au+Au} \ \sqrt{s_{NN}} = 200 \text{ GeV, 10-40}\% ]

- **Hint of Ds enhancement compared to D0**

$R_{AA}$ compared to a model calculation

- $p+p$ reference obtained from the charm cross-section measured by STAR scaled by $c \rightarrow D_s$ fragmentation factor
  

- Consistent with the He-Rapp model calculations within uncertainties

- Hint of $D_s$ enhancement

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Probe QGP with quarkonium

• **Color-screening**: quarkonium dissociates in the medium

   ![Illustration: A. Rothkopf]

   

   **J/ψ** suppression was proposed as a direct proof of QGP formation

   T. Matsui and H. Satz PLB 178 (1986) 416

• However, interpreting J/ψ suppression is no easy job!
  
  – **Hot nuclear matter effects**
    
    • Dissociation
    • Regeneration from uncorrelated quarks
    • Medium-induced energy loss
    • Formation time effects
  
  – **Cold nuclear matter effects**

  – **Feed-down of excited charmonium states and B-hadrons**

   

   |y|<0.35
   0-20%

   T. Matsui and H. Satz PLB 178 (1986) 416
Quarkonia measurements with MTD

• Based on the same proven MRPC technology as TOF

• Precise timing info (~100 ps) for $p_T > 1.2$ GeV/c
  — muon online triggering and offline identification

• Recorded 28 pb$^{-1}$, 120 pb$^{-1}$, 400 nb$^{-1}$ and 22 nb$^{-1}$ dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au

• data for J/ψ and Υ studies
J/ψ $R_{AA}$ in Au+Au at 200 GeV

- First J/ψ results from the dimuon channel at mid-rapidity in Au+Au collisions at RHIC
- Full statistics from 2014 Au+Au 200 GeV run
- Consistent with di-electron channel

Suppression at low-$p_T$
- Dissociation
- Regeneration
- Cold nuclear matter effect

High-$p_T$
- Strong suppression in 0-20%
- Rising trend in 20-60%
  - Dissociation
  - Formation time effect; B feed down

Takahito Todoroki, SQM 2016

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Takahito Todoroki, SQM 2016
**J/ψ R_{AA} – comparison to LHC and models**

- **J/ψ R_{AA}** for $p_T > 0$ GeV/c: RHIC is smaller than LHC -> more recombination at LHC
- **J/ψ R_{AA}** for $p_T > 5$ GeV/c: LHC is smaller than RHIC -> stronger dissociation at LHC
- Transport models with dissociation and recombination qualitatively describe data

Data:
ALICE: PLB 734 (2014) 314
CMS: JHEP 05 (2012) 063
PHENIX: PRL 98 (2007) 232301

Transport models:
Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114

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STAR preliminary

STAR: Au+Au, $|s_{NN}| = 200$ GeV $|y| < 0.5$
PHENIX: Au+Au, $|s_{NN}| = 200$ GeV $|y| < 0.35$
ALICE: Pb+Pb, $|s_{NN}| = 2.76$ TeV $|y| < 0.8$

Transport Model I
- RHIC
- LHC

Transport Model II
- RHIC
- LHC

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STAR preliminary

STAR: Au+Au, $|s_{NN}| = 200$ GeV, $|y| < 0.5$, $p_T > 5$ GeV/c
CMS: Pb+Pb, $|s_{NN}| = 2.76$ TeV, $|y| < 2.4$, $p_T > 6.5$ GeV/c

Transport Model I
- RHIC
- LHC

Transport Model II
- RHIC
- LHC

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STAR N_{coll} uncertainty
Does J/ψ flow?

- Measure elliptic flow $v_2$
  - **Primordial** J/ψ: little or zero $v_2$
  - **Regenerated** J/ψ: inherit $v_2$ from the constituent charm quarks

- Updated J/ψ $v_2$ in di-electron channel combining Run10 and Run11 data favors small contribution from regeneration above 2 GeV/c
- **Consistent results from di-muon channel**

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Upsilon measurements

ϒ -cleaner probe compared to J/ψ

• co-mover absorption → negligible
  – \( \Upsilon(1S) \): tightly bound, larger kinematic threshold.
    • Expect \( \sigma \sim 0.2 \text{ mb} \), 5-10 times smaller than for J/ψ
      Lin & Ko, PLB 503 (2001) 104

• recombination → negligible
  – at RHIC: \( \sigma_{cc} \sim 800 \mu\text{b} \) >> \( \sigma_{bb} \sim (1-2) \mu\text{b} \)

• Excited states: expect sequential suppression of \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) states

• Challenge: low rate, rare probe
  – Need large acceptance, efficient trigger
  – STAR upgrades
$\Upsilon(2S+3S)/\Upsilon(1S)$ ratio

- Combined signal of $\Upsilon(2S+3S)$ from the di-muon channel  
  – Challenging for di-electron channel due to Bremsstrahlung

- Less melting of $\Upsilon(2S+3S)$ at RHIC than at LHC?

N$_{\Upsilon(1S)}$ $\sim$ 157 ± 24

World-wide PRC 88(2013) 067901  
CMS : PRL 109(2012) 222301  
CMS : JHEP 04 (2014) 103
Direct photon-hadron/$\pi^0$ – hadron correlations

\[ \gamma \left( E_{\text{initial}} \right) \approx \text{recoil parton energy} \]

mostly quark jets

mostly gluon jets

surface biased

more medium

\[ I_{AA}(x) = \frac{Y_{\text{Au+Au}}(x)}{Y_{p+p}(x)} \]

\[ z_T = \frac{p_T^{\text{assoc}}}{p_T^{\text{trig}}} \]

\[ 12 < p_T^{\text{trig}} < 20 \text{ GeV/c} \otimes p_T^{\text{assoc}} > 1.2 \text{ GeV/c} \]

\[ Z_T = \frac{p_T}{E_\gamma} \]

- Suppression: hadron triggers $\approx$ photon triggers

No clear path length and color factor effect observed

STAR PLB 760 (2016) 689 arXiv:1604.01117
Summary of results

Beam Energy Scan

• Spanning a range of $\mu_B$ that could contain features of the QCD phase diagram.
• Observed signatures consistent with disappearance of parton dominated regime
• Indicators pointing towards a softening of the equation of state which
  – possible evidence for a first order phase transition.
• Critical phenomena – signal from higher moment fluctuations
  – Statistically demanding

Heavy flavor

• Successful data taking with MTD and HFT
• $D^0$ $R_{AA}$ and $v_2$ in Au+Au collisions:
  – favors models calculation with charm quark diffusion
  – Diffusion coefficient compatible with lattice calculations
• $J/\psi$ $R_{AA}$ in Au+Au collisions: larger (smaller) $R_{AA}$ at low (high) $p_T$ than LHC
  – Effect of recombination
• Upsilon in Au+Au collisions:
  – hint for less Upsilon(2S+2S) suppression at RHIC than LHC

Jets

• No clear path length and color factor effect observed in gama/$\pi^0$ hadron correlations
Thank you for your attention