Highlights from the heavy-ion program in STAR

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Outline

sQGP at top RHIC energy
- Recent heavy flavor results with new detectors
  (parallel talk by M. Lomnitz)

Beam Energy Scan (BES)
- Onset of sQGP
- Phase boundary and critical point
- Chiral effects and global polarization

Beam Energy Scan - Phase II (BES)
STAR experiment

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

- Installed for year 2014
- First application of Monolithic Active Pixel Sensor technology in collider experiments.
- DCA resolution <50 µm for p_T = 750 MeV/c Kaon
D_0 results from the HFT – R_{AA}, \text{v}_2

- Greatly enhanced D_0 significance w HFT
- Low p_T R_{AA}
  - for p_T \sim 1.5 \text{ GeV}/c \quad R_{AA} > 1
  - Charm coalescence with a radially flowing bulk medium
- High p_T R_{AA}
  - significant suppression in central Au+Au collisions.
  - Similar suppression as for light partons
  - Suggests charm-medium interaction

\[
R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}
\]
Greatly enhanced $D_0$ significance w HFT

- Low $p_T$ $R_{AA}$
  - for $p_T \sim 1.5$ GeV/c $R_{AA} > 1$
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- Non-zero $v_2$ for $p_T > 2$ GeV/c
  - Favors charm quark diffusion

- Lower than light hadron $v_2$
  - charm quarks not fully thermalized?

- Better statistics and narrower centrality bins are needed
Comparison to models

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

<table>
<thead>
<tr>
<th>Model</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 2-11 describe STAR $D_0 R_{AA}$ and $v_2$ results.

Lattice calculations are consistent with these values inferred from data.
Quarkonia measurements with MTD

- Based on the same proven MRPC technology as TOF
- Precise timing info (~100ps) for $p_T > 1.2 \text{GeV}/c$
  - 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**

- **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

- 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 dielectron channel
\( \text{J}/\psi \ R_{AA} \) – comparison to LHC and models

- \( \text{J}/\psi \ R_{AA} \) for \( p_T > 0 \text{ GeV/c} \): RHIC is smaller than LHC -> more recombination at LHC
- \( \text{J}/\psi \ R_{AA} \) for \( p_T > 5 \text{ GeV/c} \): 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
- Combined signal of $Y(2S+3S)$ from the di-muon channel
  - Challenging for di-electron channel due to Bremsstrahlung

- Less melting of $Y(2S+3S)$ at RHIC than at LHC?
Beam Energy Scan

Key physics questions:

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

- Where starts the 1st 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 the Equation of State?
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 indicate a balance of enhancement and suppression effects at $\sqrt{s_{NN}} = 14.5$ GeV.
Search for onset of QGP formation

Triangular flow $v_3$ – is a sensitive indicator for the presence of a low viscosity QGP phase

- 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

$v_3$ scaled by $n_{ch,PP} = \frac{2}{N_{part}} dN_{ch}/d\eta$
- Local minima $\sqrt{s_{NN}} = 7.7 – 20$ GeV
- Softening of EoS?
Search for 1\textsuperscript{st} order phase transition: $dv_1/dy$

- Minimum in $dv_1/dy|_{y=0}$ – 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

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

STAR Preliminary

Subhash Singha SQM 2016
Search for 1st order phase transition: HBT

- High precision azimuthally sensitive HBT
- Significant non-monotonic behavior of \((R_{out}^2 - R_{side}^2)\)
  - \((R_{out}^2 - R_{side}^2) \sim \) emission duration
  - Peaking around 20 GeV – increased emission duration, lower pressure?
Search for critical point

- Susceptibilities and correlation length diverge
- Large fluctuation

\[ \chi_{q}^{(n)} = \frac{1}{VT_{q}} \times C_{n,q} = \frac{\partial^{n}(p/T^{4})}{\partial(\mu_{q})^{n}}, q = B, Q, S \]

Observables

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

\[ \frac{\chi_{2}^{i}}{\chi_{1}^{i}} = \frac{(\sigma^{2}/M)^{i}}{c_{1}^{i}} \]
\[ \frac{\chi_{3}^{i}}{\chi_{2}^{i}} = \frac{(S\sigma)^{i}}{c_{2}^{i}} \]
\[ \frac{\chi_{4}^{i}}{\chi_{2}^{i}} = \frac{(\kappa\sigma^{2})^{i}}{c_{2}^{i}} \]

\[ i = B, Q, S \]

HotQCD, PRL109, 192302 (2012)
WB Group, PRL111, 062005 (2013)
Non-monotonic behavior of net-proton $\kappa \sigma^2$ seen in top 5% 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
Search for chiral effects

Chiral Magnetic Effect
Chirality Imbalance ($\mu_A$)
Magnetic Field ($\omega \mu_e$)
$\downarrow$
Electric Charge ($j_e$)

Electric charge separation

vs

Chiral Vortical Effect
Chirality Imbalance ($\mu_A$)

Fluid Vorticity ($\omega \mu_B$)

$\downarrow$
Baryon Number ($j_B$)

Baryonic charge separation

D. Kharzeev, D. T. Son, PRL 106 (2011) 062301
Charge separation wrt. Event plane

CME signal (ΔH) drops to 0 from 19.6 to 7.7 GeV
Probable domination of hadronic interactions over partonic ones

\[ \gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\text{RP}}) \rangle = \kappa v_2 F - H \]
\[ \delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H, \]

\( H \) and \( F \) are the CME and background contributions.

Significant baryonic charge separation signal is observed.

The magnitude is larger than electric charge separation signal of h-h correlations. CVE predicts qualitatively the same order of hierarchy.

Ongoing background studies to decouple B-field, \( v_2 \) and charge separation

- Study impact of initial E-field independently (Cu+Au)
- Collide nuclei with special configurations (238 U+ 238 U, 96 Ru+ 96 Ru, 96 Zr+ 96 Zr)
- Proposed isobar experimental program for 2018
- Measuring the B-field and vorticity of the system
Global \( \Lambda \) polarization

- Large initial angular momentum \(|L| \sim 10^5 \hbar\) in non-central collisions
- Fluid vorticity may generate global polarization

Using Lambdas
- “self-analyzing” decay - preferentially emitting daughter proton in spin direction
- For AntiLambdas spin is opposite to anti-proton direction
Global $\Lambda$ polarization

- First clear positive signal of global polarization in heavy ion collisions
- Both Lambdas and AntiLambdas show positive polarization
- Splitting
  - suggests additional magnetic effect
- Allows Model-dependent estimate of B-field and plasma vorticity

Acceptance integrated polarization:

$$\bar{P}_H = \frac{8}{\pi \alpha} \frac{\langle \sin(\phi^*_p - \Psi^{(1)}_{EP}) \rangle}{R^{(1)}_{EP}}$$
Summary of results

First results from the HFT and MTD

- Successful data taking with MTD and HTT

- $D^0$ $R_{AA}$ 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

- $Y$ in $Au+Au$ collisions:
  - hint for less $Y(2S+2S)$ suppression at RHIC than LHC

- More results to come from run 2016
Summary of results

**Beam Energy Scan**
- Spaning 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
- Observation of charge and baryon charge separation
  - Possible signal of chiral magnetic and vortical effects
- First results on global hyperon polarization

**Near future**
- Beam Energy Scan II with fixed target program
Beam Energy Scan – phase II

- Zoom to the energy range of interest 5 to 20 GeV
  - Finer steps in $\mu_B$
- Improve significance
  - Long runs
  - Higher luminosity (eCooling)
- Detector upgrades
- Extend Range - Fixed Target Program
**Upgrades for BES II**

**iTPC Upgrade:**
- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends $\eta$ coverage from 1.0 to 1.5
- Lowers $p_T$ cut-in from 125 MeV/c to 60 MeV/c

**EndCap TOF Upgrade:**
- Rapidity coverage is critical
- PID at $\eta = 0.9$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR

**EPD Upgrade:**
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics
- Extend energy reach down to 3GeV
- overlap/complementary AGS/FAIR/JPARC
- Upgrades (iTPC+eTOF+EPD) crucial
- Unprecedented coverage and PID for Critical Point search in BES-II
- Real collisions taken in run 2014
Thank you for your attention
Backup slides
## Planned data taking runs

<table>
<thead>
<tr>
<th>Year</th>
<th>System and Energy</th>
<th>Physics/Observables</th>
<th>Upgrade</th>
</tr>
</thead>
</table>
| 2017 | • p+p @ 500 GeV  
      • Au+Au @ 62.4 GeV | • Spin sign change diffractive  
      • Jets | FMS post-shower, EPD (1/8\(^{th}\)), eTOF prototype |
| 2018 | • Zr+Zr, Ru+Ru @ 200 GeV  
      • Au+Au @ 27 GeV | • CME, di-leptons  
      • Lambda polarization | Full EPD? eTOF prototype |
| 2019 | Au+Au @ 11-20 GeV + fixed target | • QCD critical point  
      • Phase transition  
      • CME,... | Full iTPC, eTOF, and EPD |
| 2020 | Au+Au @ 7-11 GeV + fixed target | • QCD critical point  
      • Phase transition  
      • CME,... | |

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Fluctuations in initial conditions – expectations of a finite $D_0 v_3$

- First measurement of $D_0 v_3$
- Large uncertainties
- Should improve.
  - Currently reprocessing year 2014 data - discovered decoder issue in PXL
  - Run 16:
    - Full aluminum cables for inner layer of PXL
    - Factor 2 - 3 further improvement for $D_0$ significance @ 1 GeV -> centrality dependence for $v_2$

First $D_S$ signal at RHIC

- $D_S$ - study of the mechanism of charm hadronization and QGP properties
- The $R_{AA}$ of $D_S$ is higher than $D_S$, but statistically not significant
- Hint of finite $D_S v_2$ at RHIC.
- Run $14+16$ - increased statistics