STAR Heavy-Ion Results

**David Tlusty**
For the STAR Collaboration
Creighton University, Physics Department
**Outline**

- **QCD Phase Diagram of Nuclear Matter**
  - Heavy-Ion Collisions - main tool to explore QCD
  - Relativistic Heavy Ion Collider
  - Introduction to STAR Experiment

- **Physics Observables Measured by STAR and Highlight Results**
  - Bulk Properties of "hot" Matter
  - Anisotropic Flow
  - Production Suppression and Enhancement
  - Hypertriton
  - Electromagnetic Processes
  - Global Hyperon Polarization

- **Detector Upgrades and Future Programs**

- **Summary**
Beam Energy Scan – Phase I Results:

- Seen the turn-off of QGP signatures.
- Seen suggestions of the first order phase transition.
- Not seen conclusive evidence of a critical point.

The most promising region for refining the search is in the lower energies $19.6, 15, 11.5, 7.7, \text{ and lower.}$

The iTPC Upgrades strengthen the BES II physics program, and enable new key measurements:

- Rapidity dependence of proton kurtosis
- Dilepton program (sys. errors and intermediate mass region)
- Enables the internal fixed target program to cover 7.7 to 3.0 GeV

The Phases of QCD

- Critical Point?
- Vacuum
- Hadron Gas
- Nuclear Matter
- Color Superconductor

The Phases of QCD
The temperature, $T$, measures the average excitation energy per degree of freedom:
- early universe after the Big Bang
  - ($T \gg 10^{10}$ K & negligibly small baryon surplus)

The baryon chemical potential, $\mu_B$, is a measure of the excess of baryons over antibaryons:
- atomic nuclei and collapsed stars
  - ($\mu_B > 1$ GeV)
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Experimentally, one can access different regions of the phase diagram by varying centre-of-mass energy $\sqrt{s_{NN}}$ of ion collisions.
QCD Phase Diagram and RHIC

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QCD Phase Diagram and RHIC

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QCD Phase Diagram and RHIC

★ Relativistic Heavy Ion Collider
- $\sqrt{s_{NN}}$ from 200 GeV down to 3 GeV
- p+p, p+Al,Au, d+Au, $^3$He+Au, Cu+Cu, Cu+Au, Au+Au, U+U

★ Experimentally, one can access different regions of the phase diagram by varying centre-of-mass energy $\sqrt{s_{NN}}$ of ion collisions

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The Solenoidal Tracker At RHIC
The Solenoidal Tracker At RHIC

- Tracking of charged particles covered in full $2\pi$ azimuth
- New subsystems
  - Inner Time Projection Chamber (iTPC) upgrade
    - Increased acceptance in pseudorapidity
  - Event Plane Detector (EPD)
  - Endcap Time-Of-Flight (eTOF)
    - Particle identification in forward direction

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ICNFP 2019
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Freeze-out Temperatures from STAR BES-I

\(T_{ch}\) - chemical freeze-out temperature

- THERMUS model fit using \(\pi, K, p, p^-, \Lambda, \) and \(\Xi\)
Freeze-out Temperatures from STAR BES-I

- **$T_{ch}$** - chemical freeze-out temperature
  - THERMUS model fit using $\pi$, $K$, $p$, $p^-$, $\Lambda$, and $\Xi$
- **$T$** - kinetic freeze-out temperature
  - the separation between $T_{ch}$ and $T$ grows with increasing energy
  - might suggest the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
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★ $T_{ch}$ - chemical freeze-out temperature
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★ $T$ - kinetic freeze-out temperature
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★ $\langle \beta \rangle$ - radial flow velocity

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Anisotropic Flow
Anisotropic Flow

Asymmetry in initial geometry $\Rightarrow$ final-state momentum anisotropy

The flow harmonic coefficients $(h_n)$ are influenced by eccentricities $\eta$, fluctuations, system size, speed of sound $(\gamma, \beta, \rho)$, and transport coefficients $\ldots$.
Anisotropic Flow

★ Asymmetry in initial geometry $\implies$ final-state momentum anisotropy

$$dN/d\Phi \propto \left( 1 + 2 \sum n \nu_n \cos(n(\Phi - \Psi_R)) \right)$$

- $\nu_1 \approx$ directed ($v_1$);
- $\nu_2 \approx$ elliptical ($v_2$);
- $\nu_3 \approx$ triangular ($v_3$) flow

$\nu_n$ influenced by eccentricities, $\varepsilon_n$, fluctuations, system size, speed of sound, $c_s(\mu_B, T)$, and transport coefficient, $\eta/s(\mu_B, T)$
Anisotropic Flow

★ Asymmetry in initial geometry $\implies$ final-state momentum anisotropy

$\star\star$ $dN/d\phi \propto \left(1 + 2 \sum n v_n \cos(n(\phi - \Psi_R))\right)$

- $v_1$≈directed ($v_1$);
- $v_2$≈elliptical ($v_2$);
- $v_3$≈triangular ($v_3$) flow

$\star\star$ $v_n$ influenced by eccentricities, $\varepsilon_n$, fluctuations, system size, speed of sound, $c_s(\mu_B, T)$, and transport coefficient, $\eta/s(\mu_B, T)$

★ STAR presented

- Number of constituent quark scaling behavior of $v_2$
- The scaling breakdown for $\phi$ meson at 11.5 and 7.7GeV
  - $\phi$ significantly lower collision x-section in hadron gas than other hadrons

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Anisotropic Flow

★ asymmetry in initial geometry $\Rightarrow$ final state momentum anisotropy

$$dN/d\phi \propto \left(1 + 2 \sum_n \nu_n \cos(n(\Phi_a - \Phi_b)) \right)$$

- $\nu_1 \approx$ directed ($v_1$); $\nu_2 \approx$ elliptical ($v_2$); $\nu_3 \approx$ triangular ($v_3$) flow, $\nu_n(ab) = \nu_n(a)\nu_n(b) + \delta_{NF}$
- $\nu_n$ influenced by eccentricities, $\varepsilon_n$, fluctuations, system size, speed of sound, $c_s(\mu_B, T)$, and transport coefficient, $\eta/s(\mu_B, T)$
Anisotropic Flow

- Asymmetry in initial geometry → final state momentum anisotropy

\[ \frac{dN}{d\phi} \propto (1 + 2 \sum n \mathbf{v}_n \cos(n(\Phi_a - \Phi_b))) \]

\( \mathbf{v}_1 \approx \text{directed } (v_1); \mathbf{v}_2 \approx \text{elliptical } (v_2); \mathbf{v}_3 \approx \text{triangular } (v_3) \) flow, \( \mathbf{v}_{n(ab)} = v_n(a)v_n(b) + \delta_{NF} \)

- \( \mathbf{v}_n \) influenced by eccentricities, \( \varepsilon_n \), fluctuations, system size, speed of sound, \( c_s(\mu_B, T) \), and transport coefficient, \( \eta/s(\mu_B, T) \)

- \( v_2 \propto \varepsilon_2 \) & \( v_3 \propto \varepsilon_3 \) & \( \eta/s[T] \) reduces \( v_n/\varepsilon_n \)

- Acoustic scaling

\[ \ln \left( \frac{v_n}{\varepsilon_n} \right) \propto -n^2 \left( \frac{\eta}{s(T)} \right) \left( N_{ch} \right)^{-1/3} \]

\( N_{ch} \) ... charged particle multiplicity
Anisotropic Flow

★ asymmetry in initial geometry → final state momentum anisotropy

\[ dN/d\phi \propto (1 + 2 \sum_n \mathbf{v}_n \cos(n(\Phi_0 - \Phi_D))) \]

- \( \mathbf{v}_1 \approx \) directed (v1);
- \( \mathbf{v}_2 \approx \) elliptical (v2);
- \( \mathbf{v}_3 \approx \) triangular (v3) flow,
- \( \mathbf{v}_n(ab) = \mathbf{v}_n(a) + \mathbf{v}_n(b) + \delta_n \)
- \( \mathbf{v}_n \) influenced by eccentricities, \( \varepsilon_n \), fluctuations, system size, speed of sound, \( c_s(\mu_B, T) \), and transport coefficient, \( \eta/s(\mu_B, T) \)

★ \( v_2 \propto \varepsilon_2 \) & \( v_3 \propto \varepsilon_3 \) & \( \eta/s[T] \) reduces \( v_n/\varepsilon_n \)
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\[ \ln \left( \frac{\langle v_n \rangle}{\varepsilon_n} \right) \propto -n^2 \langle \frac{\eta}{s}(T) \rangle \langle N_{ch} \rangle^{-1/3} \]

\( N_{ch} \) ... charged particle multiplicity

d+Au & p+Au follows the trend (\( N_{ch} \sim 21 \))

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Elliptical Flow in Small Systems

★ Small Systems - low multiplicity p+Au, d+Au
- $v_2$ extracted from two particle correlation
  - pseudorapidity $|\eta| < 0.9$, $|\Delta \eta| > 1.0$: reduces short range nonflow
- Long range nonflow contribution (near side ridge) significant
  - subtracted using new method developed by ATLAS [ATLAS: PRL 116 (2016) 172301]

Collectivity plays an important role for the flow in small systems
Strong collective behavior of charm quarks

Elliptic Flow of D⁰ Mesons

![Graph showing anisotropy parameter v_2 vs (m_T - m_0) / n_q (GeV/c^2)]

- D⁰
- Λ
- Ξ⁻
- K_S

STAR Au+Au \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

10-40%

STAR: PRL 118 (2017) 212301

J. Bielcik, Tuesday 1pm, Room 2

L. Kramarik, Poster #7

David Tlusty (Creighton)
Directed flow, $v_1$, is sensitive to the EoS in the early stage of HIC.

- Net baryons show hints of a minimum and double-sign change $\Rightarrow$ indicating the softening EoS.
Directed Flow

- Directed flow, $v_1$, is sensitive to the EoS in the early stage of HIC
  - Net baryons show hints of a minimum and double-sign change ⇒ indicating the softening EoS

- First $v_1$ measurement of $D^0$ mesons
  - The tilt of bulk $x$ longitudinal density profile of heavy quarks
  - Rapidity dependent slope is much steeper for both $D^0 + \bar{D}^0$ than for kaons
  - More in J. Bielcik talk (Tuesday 1pm, Room 2)
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   • Global Hyperon Polarization

★ Detector Upgrades and Future Programs
★ Summary
**Strong enhancement compared to**

- HERA
- Pythia

**Comparable with baryon-to-meson ratios of light flavor hadrons**
(Anti-)Hypertriton Binding Energy and Mass

- **Providing insight on Hyperon-Nucleon interaction - probe of a neutron star structure**
- **Mass difference is the first test of the CPT symmetry in the light hyper-nuclei sector**
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Detector Upgrades and Future Programs
Summary
Coherent $\gamma + \gamma$ and $\gamma + \text{Nuclear Processes}$

Colliding ions generate strong electromagnetic fields
Coherent interactions: $\gamma + \text{whole nucleus}$

\[ \text{photon-photon interaction } \propto Z^4 \]

\[ \text{photonuclear interaction } \propto Z^2 \]


$V = \rho, \omega, \phi, /\psi$
Low-\(p_T\) J/\(\psi\) And Di-electron Enhancement

- Significant di-lepton enhancement at low-\(p_T\)

- Model calculation has successfully explained the SPS and RHIC data with broadened QGP radiation.

- The model calculations are for Au+Au collisions and U+U collisions compared to cocktails.

- The systematic uncertainties are shown as gray boxes. The hadronic cocktail, also shown in the figure, can describe the data for yields from U collisions for pair invariant mass \(\approx 2\) GeV/c.

- The observed excess is found to concentrate below the enhancement factors are the largest.

- Interestingly, the different behaviors in the enhancement factors for all three centrality bins in both collision systems can describe the data for yields from U collisions for pair invariant mass.

- The hadronic cocktail, also shown in the figure, can describe the data for yields from U collisions for pair invariant mass.

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Low-\(p_T\) J/\(\psi\) And Di-electron Enhancement

- Significant di-lepton enhancement at low-\(p_T\)
- The invariant mass \(M_{ee}\) shape of the low \(p_T\) region described well by two models [Zha et al.: PLB 781 (2018) 182, STARlight: PRC 97 (2018) 054903]
Low-\( p_T \) J/\( \psi \) And Di-electron Enhancement

- **Significant di-lepton enhancement at low-\( p_T \)**
- **The invariant mass \( M_{ee} \) shape of the low \( p_T \) region described well by two models**
  - No effect of hadronic interactions on virtual photon production
**Low-p_T J/ψ And Di-electron Enhancement**

- Significant di-lepton enhancement at low-p_T
- The invariant mass $M_{ee}$ shape of the low p_T region described well by two models

*No effect of hadronic interactions on virtual photon production*  
*The excess is dominated by photon-photon interactions*

![Graph showing di-electron enhancement](image)

**Figure 1:**  
- Data vs. Cocktail  
- Au+Au 200 GeV  
- U+U 193 GeV  
- $p_T > 0.2$ GeV/c, $|y| < 1$, $|y_{ee}| < 1$

**Figure 2:**  
- Data-Cocktail  
- Au+Au 200 GeV  
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*Data - Cocktails*  
- Au+Au 200 GeV  
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*Significant di-lepton enhancement at low-p_T*

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**Figure 3:**  
- Data vs. Cocktails  
- Au+Au 200 GeV  
- U+U 193 GeV  
- $p_T > 0.2$ GeV/c, $|y| < 1$, $|y_{ee}| < 1$

**Significant di-lepton enhancement at low-p_T**

**The invariant mass $M_{ee}$ shape of the low p_T region described well by two models**

- No effect of hadronic interactions on virtual photon production
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Low-pT $J/\psi$ Enhancement
Low-pT J/ψ Enhancement

- Significant J/ψ enhancement at low $p_T$ relative to extrapolation

![Graph showing the J/ψ invariant yield for different centralities and pt ranges.](image)
Low-pT J/ψ Enhancement

★ Significant J/ψ enhancement at low p_T relative to extrapolation
★ Low-p_T yield enhancement most consistent with the Nucleus+Spectator scenario in the coherent photoproduction model

[ W. Zha et al., PRC 97 (2018) 044910]

- There may exist a partial disruption by hadronic interactions in the overlapping region
Global Hyperon Polarization

dependencies, our analysis assumes that averaged over all phase space, symmetry demands that depend on the momentum of the emitted hyperons. However, when \( \Lambda \) in a heavy ion collision. However, the fluid can be used to determine local fluid cell, which, when averaged alignment, or polarization, along the direction of the vorticity in the symmetry restoration and the production of false quantum chromoent in theories that predict observable effects associated with chiral...

The subscript H denotes \( \alpha \). Because our limited sample sizes prohibit exploration of these...
Global Hyperon Polarization

\[
\frac{dN}{d \cos \theta^*} = \frac{1}{2} (1 + \alpha_H |P_H| \cos \theta^*)
\]

\[
\omega = k_B T \left( \frac{P_N + \bar{P}_{\Lambda}}{\hbar} \right)
\]

Beam–beam counter

Quark–gluon plasma

Forward-going beam fragment

Beam–beam counter

\[\text{Quark–gluon plasma}\]

\[\text{Beam–beam counter}\]

\[\text{Forward-going beam fragment}\]

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Global Hyperon Polarization

**Measurement of vorticity $\omega$ of the QGP (perfect liquid)**

- With the new 200 GeV results, the polarization is found to decrease at higher collision energies.
- May provide important information on the chiral dynamics of the system.
  - Axial charge separation due to the Chiral Vortical Effect [PRC 97 (2018) 041902]
- Difference between $P_H$ and $P_{\bar{H}}$ provide constraints on the magnitude and the lifetime of the magnetic field in heavy-ion collisions [PRC 95 (2017) 054902]

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Outlook: Forward Upgrade

Positive internal review in November 2018 - will be ready for 2022

Cold QCD and heavy-ion physics
Collectivity plays an important role for the flow in small systems

- Small droplets of QGP?
Summary

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- Strong collective behavior of charm quarks
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★ Stay tuned - many more exciting results are coming
Thank you
Backup Slides
Freeze-out Temperatures from STAR BES-I

![Graph showing freeze-out temperatures](image)

- **Tch** - chemical freeze-out temperature
  - particles included in the THERMUS model fit were $\pi$, $K$, $p$, $p^-$, $\Lambda$, and $\Xi$
  - $T_{ch}$ appears to be lower when strange particles were excluded from the fit
- **T** - kinetic freeze-out temperature
  - the separation between between $T_{ch}$ and $T$ grows with increasing energy
    - might suggest the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
- **$\langle \beta \rangle$** - radial flow velocity
  - rapid $\times$ slow increase at lower $\times$ higher energies

David Tlusty (Creighton)   ICNFP 2019
STAR Au+Au \( \sqrt{s_{NN}} = 200 \) GeV 20%-60%

\[ |\eta|<1, 0.5<p_T<6 \text{ GeV/c} \]

slope \( \pm \) stat.uncert. \( \pm \) syst.uncert.

\( \Lambda: \ 0.097 \pm 0.041 \pm 0.043 \% \]

\( \bar{\Lambda}: \ -0.112 \pm 0.045 \pm 0.102 \% \]