Overview of Recent Results from the STAR Experiment

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(for the STAR Collaboration)

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STAR Physics Program: **Study Emergent Properties of QCD**

**Cold QCD**
- Polarized p+p/A:
  - Study the partonic spin structure of protons
- Study proton and nuclear Parton Distribution Functions

**Hot QCD:**
- Top RHIC energy:
  - sQGP properties ($\eta/s$, $\hat{q}$, $D_{HQ}$, chirality, ...)

**Beam Energy Scan (BES):**
- Phase diagram
  - onset of QGP
  - phase transition
  - critical point
Outline (updates since last QM)

- Heavy Flavor:
  - Heavy Flavor Tracker (HFT)
    → First result of $D^0$ azimuthal anisotropy and nuclear modification factor
  - Muon Telescope Detector (MTD)
    → Quarkonia via di-muon channels

- Beam Energy Scan I (BES-I) completed with $\sqrt{s_{NN}} = 14.5$ GeV

- Chirality
  - Di-electrons
  - Chiral Magnetic Effects
  - Effects of E-field (Cu+Au)

- Jets
Excellent tracking coverage and PID capabilities for $2\pi$ and $-1<\eta<1$:

- Time Projection Chamber (TPC)
- Time of Flight (TOF)
- Electromagnetic Calorimeter (BEMC)
STAR - New Subsystems

Muon Telescope Detector (MTD): Results from 30% of collected Au+Au data are presented at this conference

Heavy Flavor Tracker (HFT): Results from 70% of collected Au+Au data are presented at this conference [G. Contin (254)]
Particle Identification

Excellent long-lived hadron and electron identification
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Secondary vertex reconstruction with HFT $\rightarrow$ Full kinematics reconstruction of charmed hadron
Muon/Quarkonia identification using MTD
Topological Reconstruction of $D^0$

<table>
<thead>
<tr>
<th></th>
<th>w/o HFT</th>
<th>w HFT</th>
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<tbody>
<tr>
<td>significance/</td>
<td>13</td>
<td>51</td>
</tr>
<tr>
<td>billion events</td>
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- ~4 orders of magnitude reduction of combinatorial background
  → Highly enhanced S/B

- Total significance ~ 39 (MinBias – $p_T$ inclusive)
D^0 Nuclear Modification Factor (R_{AA})

- Significant improvement in central Au+Au D^0 measurement using HFT
- Enhanced D mesons for p_T < 2 GeV/c
  → Manifestation of charm coalescence with a flowing medium

STAR, PRL 113 (2014) 142301
D\textsuperscript{0} Nuclear Modification Factor (R_{AA})

- Significant improvement in central Au+Au D\textsuperscript{0} measurement using HFT
- Enhanced D mesons for p_{T} < 2 GeV/c → Manifestation of charm coalescence with a flowing medium
- D mesons are suppressed at high p_{T} → R_{AA} (h) ∼ R_{AA} (D) → Charm energy loss is an interplay of elastic and radiative energy loss
**D⁰ Nuclear Modification Factor (R_{AA})**

- Significant improvement in central Au+Au D⁰ measurement using HFT
- Enhanced D mesons for p_T < 2 GeV/c
  → Manifestation of charm coalescence with a flowing medium
- D mesons are suppressed at high p_T
  → R_{AA} (h) ~ R_{AA} (D)
  → Charm energy loss is an interplay of elastic and radiative energy loss
  → R_{AA} @ RHIC ~ R_{AA} @ LHC

STAR, PRL 113 (2014) 142301
ALICE, arXiv: 1509.06888
D⁰ Azimuthal Anisotropy ($v_2$)

- Finite D⁰ $v_2$ observed ($p_T > 2 \text{ GeV/c}$) at top RHIC energy
D⁰ Azimuthal Anisotropy (v₂)

- Finite D⁰ v₂ observed (p_T > 2 GeV/c) at top RHIC energy
- D⁰ v₂ is lower than those of light hadrons for p_T < 4.0

→ What can we learn about charm thermalization with the medium?

STAR, PRC 77 (2008) 54901
Comparison to Theory

- Data favors models with charm diffusion
  \[\text{→ charm exhibits collectivity with the medium}\]

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<td>Duke</td>
<td>7</td>
<td>Free parameter</td>
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Comparison to Theory II – Charm Diffusion Coefficient

- Models with charm diffusion coefficient of 2 - ~10 describe STAR $R_{AA}$ and $v_2$ data
- Lattice calculations are consistent with values inferred from data
Quarkonia in p+p highlights

- Correlation between relative J/ψ yields and relative charged particles multiplicity (event activity), and for higher multiplicities stronger than linear growth at $p_T > 4$ GeV/c observed.

- PYTHIA 8 and Percolation Model describe the observed increase.  
  
  Percolation: Ferreiro et. al., PRC 86 (2012) 034903
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- PYTHIA 8 and Percolation Model describe the observed increase

- J/ψ polarization ($\lambda_{\psi}$): common trend towards strong negative values with $x_T$ (in the helicity frame)
Quarkonia in Au+Au

- $p_T < 5$ GeV/c: suppression in all centralities. Rising trend with $p_T$
- Consistent $R_{AA}$ using di-muon and di-electron channels

Quarkonia in Au+Au

- $p_T < 5$ GeV/c: suppression in all centralities. Rising trend with $p_T$
- Consistent $R_{AA}$ using di-muon and di-electron channels
- $\Upsilon$ signal observed in di-muon channel, full data production on the way.

Semi-Inclusive Charged Jets in Au+Au

\[ \frac{1}{N_{trig}^h} \frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{AA\rightarrow h+jet+X}} \frac{d\sigma^{AA\rightarrow h+jet+X}}{dp_{T,jet}} \]

Trigger-normalized yield of jets recoiling from a high \( p_T \) hadron trigger.
Semi-Inclusive Charged Jets in Au+Au

- Direct comparison to similar measurements at LHC
- Out-of-cone energy transport: hint of reduction for larger R; smaller vs. LHC
- Molière scattering of low energy jets in QGP: proof of principle

\[
\Delta p_T = -6.3 \pm 0.6 \pm 0.8 \text{ GeV} \\
\Delta p_T = -3.8 \pm 0.5 \pm 1.8 \text{ GeV}
\]

Trigger-normalized yield of jets recoiling from a high \( p_T \) hadron trigger.
Quantifying the effect of Chiral Symmetry Restoration: Di-electrons

- Acceptance-corrected di-electron excess mass in 27, 39, 62.4 GeV Au+Au, and 193 U+U collisions

- In-medium $\rho$ broadening calculations describe data across all collision energies, centralities and $p_T$

Theory:
R. Rapp, PRC 63 (2001) 054907
STAR, PLB 750 (2015) 64
STAR, PRC 92 (2015) 024912
Acceptance-corrected low-mass dielectron excess production, normalized by \( dN_{\text{ch}}/dy \), is proportional to the lifetime of the medium from 17.3 to 200 GeV.

Given that the total baryon density is nearly a constant and that the emission rate is dominant in the near-\( T_c \) region.

*R. Rapp, H. van Hees, arXiv:1411.4612*
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R. Rapp, H. van Hees, arXiv:1411.4612
Study of Chiral Effects via PID Correlations

Chiral Magnetic Effect (CME): local chirality imbalance + magnetic field → electric charge separation
Chiral Vortical Effect (CVE): local chirality imbalance + fluid vorticity → baryonic charge separation

Separation w.r.t reaction plane was studied via a three-point correlator

\[ \gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle \]

Here \( \alpha \) and \( \beta \) denote particle charge, \( \gamma_{0s} - \gamma_{ss} \) quantifies the strength of charge separation

Correlation of different particle species → different sensitivity to CME/CVE
Study of Chiral Effects via PID Correlations

Chiral Magnetic Effect (CME): local chirality imbalance + magnetic field $\rightarrow$ electric charge separation

Chiral Vortical Effect (CVE): local chirality imbalance + fluid vorticity $\rightarrow$ baryonic charge separation

- A clear hierarchical structure was observed, which meets the expectation of chiral effects
- On-going background studies to decouple B-field, $v_2$ and charge separation
  - Select events with $v_2 = 0$ in non-central collisions [STAR, PRC, 89 (2014) 044908], much smaller effects observed
  - Collide nuclei with special configurations $(^{238}\text{U}+^{238}\text{U}, ^{96}\text{Ru}+^{96}\text{Ru}, ^{96}\text{Zr}+^{96}\text{Zr})$
  - Measure impact of initial E-field independently (Cu+Au)
Study of initial E-field via $v_1$ in Cu+Au

Sizable E-field pointing from Au to Cu
→ Expect charge dependent $v_1$ relevant to CME/CMW quark/anti-quark creation time

- $\Delta v_1 = v_1 (h^+) - v_1 (h^-)$ shows the right sign as expected by the model with initial E-field
- E-field does leave an imprint. So should the B-field? (CME/CMW)
- Help constrain the initial quark/anti-quark production
Beam Energy Scan I (BES-I)

- BES-I: $20 < \mu_B \text{ (MeV)} < 420$.
- A suite of observables are studied for rapid changes and non-monotonicity
  - Directed, elliptic and triangular flow
  - Spectra, and nuclear modification factors
  - Femtoscopy
  - Higher moments

\[ \sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27, 39 \text{GeV} \]
New measurements at $\sqrt{s_{NN}} = 14.5$ GeV

Fills the $205 < \mu_B < 315$ gap

All measurements follow the trends of BES-I

Jochen Thaeder (153)
Prashanth Shanmuganathan (398)
Liao Song (258)
Vipul Bairathi (492)
Daniel Brandenburg (606)
Chris Flores (320)
Stephen Horvat (323)
• Smooth transition from a strong suppression at high energies to enhancement at lower beam energies.
• Cronin effects play a bigger role at lower energies.
Search for the Onset of QGP Formation: Charged Hadrons $R_{cp}$

- Smooth transition from a strong suppression at high energies to enhancement at lower beam energies.
- Cronin effects play a bigger role at lower energies.
- Yields per binary collision show indicates a balance of enhancement and suppression effects at $\sqrt{s_{NN}} = 14.5$ GeV.
Search for the Onset of QGP Formation: $v_3$

- Sizable $v_3$ at lower energies in central to mid-central centralities
- Peripheral collisions $v_3$ consistent with zero for $\sqrt{s_{NN}}$ less than 14.5 GeV

Triangular flow is argued to be almost directly proportional to the duration of the low-viscosity ($\eta/s$) phase

[J. Aunvine, H. Petersen PRC 88, 064908]
Search for the Onset of QGP Formation: $v_3$

$\nu^2_3(2)$ - Au+Au
- 0-5%
- 10-20%
- 30-40%
- 50-60%

$\nu^2_3(2)/n_{ch,PP}$ - Au+Au
- 0-5%
- 10-20%
- 30-40%

$n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$ is the multiplicity per participant pair, proportional to the system energy density

- Scaling out the increase in the system energy density reveals a flat trend $\sqrt{s_{NN}} = 7.7 - 20$ GeV
- Signature of softening of EoS?
Search for Phase Transition: Directed Flow

- The dip in $\frac{dN_1}{dy}|_{y=0}$ is argued to indicate an interplay between hydro and baryon transport dynamics (and baryon/anti-baryon annihilation)
- (Anti)-Lambdas $\frac{dN_1}{dy}$ closely follow those of (anti)-protons
Search for Phase Transition: Directed Flow

- The dip in $dv_1/dy|_{y=0}$ is argued to indicate an interplay between hydro and baryon transport dynamics (and baryon/anti-baryon annihilation)
- (Anti)-Lambdas $dv_1/dy$ closely follow those of (anti)-protons
- $dv_1/dy$ for net-K and net-p are consistent with each other down to $\sim$14.5 GeV, and deviate at lower energies
Search for the Critical Point: Higher Moments Fluctuations (Net-Protons)

- Higher moments of conserved quantum numbers (Q, S, B) are expected to be sensitive to the proximity to a critical point

Higher order moments → higher sensitivity to criticality

- New: extended phase space volume of net-proton higher moments measurement
  \[0.4 < p_T (\text{GeV/c}) < 0.8 \rightarrow 0.4 < p_T (\text{GeV/c}) < 2.0\]

- Non-monotonic change of \(\kappa \sigma^2\) for in central \(Au+Au\) collisions

\[\sigma^2\text{Poisson} \quad \text{0-5%} \quad \text{70-80%} \quad \text{0-5% UrQMD} \]

\[\kappa \sigma^2 \text{STAR Preliminary}\]
Beam Energy Scan II (2019-2020)

Planned hardware upgrades:
- inner Time Projection Chamber:
  Larger acceptance: $|\eta| < 1 \rightarrow |\eta| < 1.5$
  higher $dE/dx$ resolution
- Event Plane Detector
- Endcap Time of Flight

Higher luminosity with electron cooling.
Scan of $205 < \mu_b < 420$ MeV with high events statistics

Physics focus:
- Search for critical point
- Search for onset of QGP
- Quantify the effect of Chiral Symmetry Restoration via total baryon density on vector meson in-medium modifications.
Summary

- Heavy Flavor Tracker (HFT) delivers its first results → Charm flows at RHIC top energy

- First result of quarkonia suppression from the Muon Telescope Detector (MTD)

- Beam Energy Scan I (BES-I) completed with $\sqrt{s_{NN}} = 14.5$ GeV
  → Net-protons $\kappa \sigma^2$, baryons $dv_1/dy|_{y=0}$, and charged hadron scaled-$v_3^2$ exhibit non-monotonicity at similar energies
### STAR Future Plans

|------|------|------|------|------|------|------|------|------|------|

#### HF-I, \((e, \mu), spin\)
- charm
- dilepton
- sQGP properties

#### BES-II
- QCD phase structure
- Critical Point

#### HF-II, \(p_+ + p/A\)
- Any: \(B, \Lambda_c, \text{jet, } \gamma\text{-jet, 3D correl.}\)
- \(p_+ A\): CNM, proton structure

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- **e-Cooling, iTPC, EPD**
- **Forward tracking/calorimetry, HFT+, TPC speed-up**

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**physics upgrade**

- **iTPC proposal:** [drupal.star.bnl.gov/STAR/starnotes/public/sn0619](drupal.star.bnl.gov/STAR/starnotes/public/sn0619)
- **BES-II whitepaper:** [drupal.star.bnl.gov/STAR/starnotes/public/sn0598](drupal.star.bnl.gov/STAR/starnotes/public/sn0598)
- **Polarized p+p and p+A:** [drupal.star.bnl.gov/STAR/starnotes/public/sn0605](drupal.star.bnl.gov/STAR/starnotes/public/sn0605)