Introduction
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory (BNL), New York

• 2 concentric rings of 1740 superconducting magnets
• 3.8 km circumference
**The Solenoidal Tracker At RHIC**

- **Tracking and PID (full 2π)**
  - TPC: \(|\eta| < 1\)
  - TOF: \(|\eta| < 1\)
  - BEMC: \(|\eta| < 1\)
  - EEMC: \(1 < \eta < 2\)
  - HFT (2014-2016): \(|\eta| < 1\)
  - MTD (2014+): \(|\eta| < 0.5\)

- **MB trigger and event plane reconstruction**
  - BBC: \(3.3 < |\eta| < 5\)
  - EPD (2018+): \(2.1 < |\eta| < 5.1\)
  - FMS: \(2.5 < \eta < 4\)
  - VPD: \(4.2 < |\eta| < 5.1\)
  - ZDC: \(6.5 < |\eta| < 7.5\)

- **On-going/future upgrades**
  - iTPC (2019+): \(|\eta| < 1.5\)
  - eTOF (2019+): \(-1.6 < \eta < -1\)
  - FCS (2021+): \(2.5 < \eta < 4\)
  - FTS (2021+): \(2.5 < \eta < 4\)
Introduction

RHIC Top Energy
p+p, p+Al, p+Au, d+Au, $^3$He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U
QCD at high energy density/temperature
Properties of QGP, EoS

Beam Energy Scan
Au+Au 7.7-62 GeV
QCD phase transition
Search for critical point
Turn-off of QGP signatures

Fixed-Target Program
Au+Au =3.0-7.7 GeV
High baryon density regime with 420-720 MeV
1. Open heavy flavor - $D^0 \nu_1$, $D^0 R_{AA}$ and $R_{CP}$, $\Lambda_C$

2. Quarkonium – $\Upsilon R_{AA}$

3. Jet modification and high-$p_T$ hadrons - di-jet imbalance, di-hadron correlation

4. Chirality, vorticity and polarization effects - $\Lambda$ polarization, $\Phi$ polarization, CME, CMW

5. Initial state physics and approach to equilibrium - $v_2$ and $v_3$ fluctuations

6. Collectivity in small systems - $v_2$ in p+Au and d+Au

7. Collective dynamics - longitudinal decorrelation, identified particle $v_1$

8. High baryon density and astrophysics - $v_1$ from fixed target

9. Correlations and fluctuations – femtoscopy

10. Phase diagram and search for the critical point - net $\Lambda$ and off-diagonal cumulants

11. Thermodynamics and hadron chemistry - triton, hypertriton mass

12. Upgrades - BES-II and forward upgrades
1. Open heavy flavor - $D^0 \nu_1$, $D^0 R_{AA}$ and $R_{CP}$, $\Lambda_c$ 

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7. Upgrades - BES-II and forward upgrades (as summary)
Results
First evidence of non-zero $D^0 v_1$ is measured.
Probe the initial tilt of the source and the initial EM field
2) Initial state physics

Q-cumulant method (traditional)

\[ \langle 2 \rangle_n = \langle e^{in(\phi_1 - \phi_2)} \rangle \]

\[ v_n^4\{4\} = \langle 4 \rangle_{nn} - 2 \langle 2 \rangle_n \langle 2 \rangle_n \]

Two-subevent method

\[ \langle 2 \rangle_{n}^{Sub} = \langle e^{in(\phi_A - \phi_B)} \rangle \]

\[ v_n^2\{2\} = c_n\{2\} = \langle 2 \rangle_n^{Sub} \]

\[ v_n^4\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \]

\[ \langle 4 \rangle_{nm} = \langle e^{in(\phi_1 - \phi_2)} + im(\phi_3 - \phi_4) \rangle \]

\[ NSC(n, m) = \frac{\langle 4 \rangle_{nm} - \langle 2 \rangle_n \langle 2 \rangle_m}{\langle 2 \rangle_n^{Sub} \langle 2 \rangle_m^{Sub} } \]

Φ - azimuthal angle

\[ |\Delta \eta| > 0.7 \]

\[ A \quad B \]

\[ \eta \]

\[ \frac{v_n^4\{4\}}{v_n^2\{2\}} = 2 - \frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2} \]

Sensitive to flow fluctuations
2) Initial state physics

**Strong** dependence of \( v_2 \{k\} \) on collision energy.

Weak dependence of \( v_2 \{4\}/v_2 \{2\} \) on collision centrality
2) Initial state physics

**Strong** dependence of $v_2(2)$ and $v_2(4)$ on collision centrality.

**Weak** dependence of $v_2(2)/v_2(4)$ on collision centrality.
2) Initial state physics

Weak dependence of $v_2\{2\}/v_2\{4\}$ on transverse momentum
2) Initial state physics

Significant dependence of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{2\}/v_2\{4\}$ on $\langle N_{ch} \rangle$ among different systems.
Anisotropic flow magnitude is sensitive to:
- initial-state spatial anisotropy
- flow fluctuations and correlations
- viscous attenuation ($\propto \eta/s (T)$)

**Weak** dependence of $v_2 \{2\}/\varepsilon_2 \{2\}$
on collision centrality among different systems.

Are dynamical final-state fluctuations significantly lessthan the initial-state fluctuations?
2) Initial state physics

**Strong** dependence of $v_2\{2\}$, $v_2\{4\}$ on collision centrality, collision energy, transverse momentum

**Weak** dependence of $v_2\{4\}/v_2\{2\}$ and $v_2\{2\}/\varepsilon_2\{2\}$ (elliptic flow fluctuations) on the size of colliding system and: collision centrality, collision energy, transverse momentum

Flow fluctuations are dominated by the fluctuations of the **initial state eccentricity**

**Similar** viscous coefficient for different colliding systems
3) Small systems

Near-side ridge observed in High Multiplicity (HM) of d+Au collisions

$$dN/d\Delta\phi \sim 1 + \sum_{n=1}^{4} 2V_{n,n} \times \cos(n\Delta\phi)$$

Integral \( v_n = \sqrt{V_{n,n}} \); \( v_n(p_T) = V_{n,n}(p_T)/v_n \)
3) Small systems

Low multiplicity subtraction scaled by short-range near-side ($|\Delta \eta|<0.5$) jet yield

$$V_{n,n}^{HM} \text{ (subtracted)} = V_{n,n}^{HM} - V_{n,n}^{LM} \times \frac{N_{asso.}^{LM}}{N_{asso.}^{HM}} \times \frac{Y_{jet, near-side}^{HM}}{Y_{jet, near-side}^{LM}}$$

Short-range near-side jet modification = long-range away-side jet modification

Template fit

$$Y_{templ.}(\Delta \phi) = F \times Y_{LM}(\Delta \phi) + Y_{ridge}(\Delta \phi)$$

where

$$Y_{ridge}(\Delta \phi) = G \times (1 + 2 \times \sum_{n=2}^{4} V_{n,n} \times \cos(n \Delta \phi))$$

A new method by ATLAS Collaboration away-side jet shape can be measured in Low Multiplicity (LM) events scaled by "F" parameter (due to jet modification)
3) Small systems

$v_2$ without subtraction is **larger** than that with subtraction for both methods.

The subtraction of non-flow contributions are very **important** for STAR results are comparable with PHENIX results.

At lowet $p_T$ $v_2$ from Low Multiplicity subtraction is **35% lower** than from template fit

At intermediate $p_T$ they **agree** with each other

STAR results are **comparable** with PHENIX ones.
v$_2$ in p+Au collisions without subtraction is **larger** than v$_2$ in d+Au collisions that with subtraction for both methods.

v$_2$ in p+Au collisions from Low Multiplicity subtraction is **lower** than from template fit.

STAR results are **comparable** with PHENIX results, except at high pT. The STAR data is clearly lower than PHENIX for p$_T$ > 1.5 GeV/c
3) Small systems

Large **difference** between subtraction method and template fit

$v_2$ from subtraction method is **negative** at lower collision energies (different kinematics between near-side and away-side jet-like correlations?)

$v_2$ from template fit **increases** with collision centrality
v<sub>2</sub> becomes **negative** at high transverse momentum in d+Au collisions at low collision energy.

The correlation from away-side jet is **stronger** at high transverse momentum.
3) Small systems

Large **difference** between $v_2$ from two methods has been observed at low energy → large uncertainties in the non-flow subtraction in small systems.

We do see **similar** $v_2$ between p+Au and d+Au collisions for same multiplicity → $v_2$ is not only driven by initial geometry.

The integral $v_2$ extracted by a template fit shows an **universal** trend as a function of $<dN/d\eta>$ for different small systems at different energies → multiplicity plays an important role in small systems.
4) Fixed target mode

**BES goals:**
- Search for 1st order phase transition
- Search for existence of the Critical Point
- Search for turn-off QGP signatures

**Collider mode** is unusable for $\sqrt{s_{NN}} < 7.7$ GeV

**Fix target mode** is able to cover $\sqrt{s_{NN}}$ from 3.0 GeV to 7.7 GeV
4) Fixed target mode

Detector’s scheme

Spectra corrections:
- Detector efficiency
- Detector acceptance (each rapidity window)
- Energy loss
\(4)\) Fixed target mode

\[\pi^-\text{ spectra are consistent with AGS results.}\]
4) Fixed target mode

Directed flow for pions and protons with fit describing mid-rapidity region.

Directed flow of protons agrees with AGS results.
Directed flow for $\Lambda$ and $K^0_S$ particles and their fits describing mid-rapidity region.
4) Fixed target mode

Directed flow for identified particles agrees with AGS results.
4) Fixed target mode

HBT radii for pions are consistent with AGS results.
4) Fixed target mode

- **STAR is ready** to operate with the Fixed Target mode

- **Spectra** and **particle yields** agree with AGS results

- **Proton directed flow** and **elliptic flow** \((v_1 \text{ and } v_2)\) agree with AGS results

- **HBT radii** agree with AGS results

High-baryon density regime will be accessible with the Fix Target mode in STAR!
5) Femtoscopy

Single- and two- particle distributions

\[ P_1(p) = E \frac{dN}{d^3p} = \int d^4x \, S(x, p) \]

\[ P_2(p_1, p_2) = E_1 E_2 \frac{dN}{d^3p_1 d^3p_2} = \int d^4x_1 S(x_1, p_1) d^4x_2 S(x_2, p_2) \Phi(x_2, p_2 | x_1, p_1) \]

\[ \mathbf{S}(\mathbf{x}, \mathbf{p}) \] – emission function: the distribution of source density probability of finding particle with \( \mathbf{x} \) and \( \mathbf{p} \)

The correlation function

\[ C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1) P_1(p_2)} \]

Pair Rest Frame reference
5) Femtoscopy

**Identical baryon- baryon**
- Quantum Statistics - QS
- Final State Interactions - FSI
  - Coulomb
  - Strong

**Non-identical baryon-(anti)baryon**
- Final State Interactions - FSI
  - Coulomb
  - Strong
5) Femtoscopy

No significant difference between proton-proton and antiproton-antiproton correlation functions

| centrality | \( R_{inv} \ p - p \ [fm] \) | \( R_{inv} \ \bar{p} - \bar{p} \ [fm] \) | \( R_{inv} \ p - \bar{p} \ [fm] \) |
|------------|-------------------------------|-------------------------------|-------------------------------|
| 0-10%      | 4.00 ± 0.15 ± 0.02           | 3.83 ± 0.20 ± 0.03           | 3.39 ± 0.12 ± 0.14           |
| 10-30%     | 3.61 ± 0.13 ± 0.17           | 3.68 ± 0.15 ± 0.11           | 2.69 ± 0.10 ± 0.12           |
| 30-70%     | 2.72 ± 0.07 ± 0.07           | 2.95 ± 0.11 ± 0.08           | 2.56 ± 0.09 ± 0.12           |
5) Femtoscopy

Radii from proton-proton and antiproton-antiproton systems differ from those from proton-antiproton system → Residual Correlations. Residual feed-down correction needs to be applied.

proton-proton @39 GeV

proton-antiproton @39 GeV

STAR Preliminary
QM 2018
5) Femtoscopy

Energy dependence more significant for proton-proton than for proton-antiproton system.

| Energy   | $R_{inv} \ p - \ p$ [fm] | $R_{inv} \ p - \ \bar{p}$ [fm] |
|----------|--------------------------|-------------------------------|
| 7.7 GeV  | 3.59 ± 0.16 ± 0.19       |                               |
| 11.5 GeV | 3.66 ± 0.08 ± 0.05       | 3.30 ± 0.42 ± 0.28            |
| 19.6 GeV | 3.82 ± 0.15 ± 0.06       | 3.32 ± 0.25 ± 0.13            |
| 27 GeV   | 3.80 ± 0.12 ± 0.08       | 3.49 ± 0.25 ± 0.16            |
| 39 GeV   | 4.00 ± 0.15 ± 0.02       | 3.39 ± 0.12 ± 0.14            |
Feed-down correction may decrease significance of centrality dependence.

No significant difference between $p - p$ and $\bar{p} - \bar{p}$ correlation functions at $\sqrt{s_{NN}} = 39$ GeV

QM 2018

STAR Preliminary

Significant centrality dependence weak for all centralities.
- Clear centrality dependence of source size at BES energies
- Visible energy dependence of source size at BES energies
- No visible difference between proton-proton and antiproton-antiproton correlation functions at $\sqrt{s_{NN}} = 39 \text{ GeV}$
- Correlation functions contaminated by residual correlations – residual correction required
6) Hypertriton

**Hyperon-Nucleon:**
- play an important role in neutron star and QCD theory

- measurements of masses of hypertriton and anti-hypertriton provide insight into H-N interactions and the CPT symmetry

- measurements sensitive to the temperature and nucleon phase-space of the system freeze-out.

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[1] R. O. Gomes, V. Dexheimer, S. Schramm, and C. A. Z. Vasconsellos, The Astrophys. J. 808, 8 (2015).
[2] L. L. Lopes and D. P. Menezes, Phys. Rev. C 89, 025805 (2014).
[3] J. Antoniadis et al., Science 340, 448 (2013).
[4] László P. Csernai, Joseph I. Kapusta, Phys. Reps. 131, 223 (1986).
[5] A. Z. Mekjian, Phys. Rev. C 17, 1051 (1978).
[6] Kaijia Sun et al., Phys. Lett. B 774, 103 (2017).
6) Hypertriton

\[ ^3\Lambda H \rightarrow ^3He + \pi^- \]
\[ \vec{P}_0 = \vec{P}_1 + \vec{P}_2 \]

\[ ^3\Lambda H \rightarrow p + \pi^- + d \]

\begin{itemize}
  \item \( ^3\Lambda H \) has many decay channels:
    \begin{itemize}
      \item Non-meson decay channels:
        \[ ^3\Lambda H \rightarrow d + n \]
        \[ ^3\Lambda H \rightarrow p + n + n \]
      \item Meson decay channels:
        \[ ^3\Lambda H \rightarrow ^3He (^3H) + \pi^- (\pi^0) \]
        \[ ^3\Lambda H \rightarrow d + p (n) + \pi^- (\pi^0) \]
        \[ ^3\Lambda H \rightarrow p + n + p (n) + \pi^- (\pi^0) \]
    \end{itemize}
\end{itemize}

Good PID of charged particles in STAR detector.

Reconstructing \( ^3\Lambda H (\overline{\Lambda H}) \) through:
\[ ^3\Lambda H \rightarrow ^3He + \pi^- \]
\[ ^3\Lambda H \rightarrow d + p + \pi^- \]
6) Hypertriton

(A) 

$^3\Lambda$H Counts: 121 ± 11

STAR Preliminary

 Counts / (2MeV/c^2)

$^3$He + $\pi^-$ Invariant mass (GeV/c^2)

(B) 

$^3\Lambda$H Counts: 36 ± 6

STAR Preliminary

 Counts / (2MeV/c^2)

d + p + $\pi^-$ Invariant mass (GeV/c^2)

(C) 

$^3\Lambda\bar{\Lambda}$ Counts: 34 ± 6

STAR Preliminary

 Counts / (2MeV/c^2)

$^3$He + $\pi^+$ Invariant mass (GeV/c^2)

(D) 

$^3\Lambda\bar{\Lambda}$ Counts: 24 ± 5

STAR Preliminary

 Counts / (2MeV/c^2)

$\bar{d} + \bar{p} + \pi^+$ Invariant mass (GeV/c^2)
6) Hypertriton

Worldwide binding energy of $^3_\Lambda$H of experimental measurements.

Measurements of the mass-over-charge ratio differences between light nuclei and anti-nuclei.
Conclusions & Summary
Summary

1. Open heavy flavor - $D^0 \nu_1$, $D^0 R_{AA}$, and $R_{CP}$, $\Lambda_c$

2. Quarkonium – $\Upsilon R_{AA}$

3. Jet modification and high-$p_T$ hadrons - di-jet imbalance, di-hadron correlation

4. Chirality, vorticity and polarization effects - $\Lambda$ polarization, $\Phi$ polarization, CME, CMW

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12. Upgrades - BES-II and forward upgrades
**Upgrades**

**STAR**

**iTPC Upgrade:**
- Improves tracking and acceptance at low pT and extra y acceptance
- Ready in 2019

**eTOF Upgrade:**
- Improves PID and acceptance
- Ready in 2019

**EPD Upgrade:**
- Improves event plane resolution and centrality definition
- Taking data in 2018 run

STAR Note 0644: Technical Design Report for the iTPC Upgrade

arXiv:1609.05102v1 [nucl-ex]

STAR Note 0666: An Event Plane Detector for STAR
Upgrades

STAR Note 0696: STAR Collaboration Beam Use Request for Run 19+ (Scenario 1)

| Single Beam Energy (GeV/nucleon) | $\sqrt{s_{\text{NN}}}$ (GeV) | Run Year | Run Time | Species | Min-Bias Events Number |
|----------------------------------|-------------------------------|----------|----------|---------|------------------------|
| 5.75                             | 3.5 (FXT)                     | 2020     | 2 days   | Au+Au   | 100M                   |
| 7.3                              | 3.9 (FXT)                     | 2019     | 2 days   | Au+Au   | 100M                   |
| 9.8                              | 4.5 (FXT)                     | 2019     | 2 days   | Au+Au   | 100M                   |
| 13.5                             | 5.2 (FXT)                     | 2020     | 2 days   | Au+Au   | 100M                   |
| 19.5                             | 6.2 (FXT)                     | 2020     | 2 days   | Au+Au   | 100M                   |
| 31.2                             | 7.7 (FXT)                     | 2019     | 2 days   | Au+Au   | 100M                   |

- iTPC & eTOF upgrades will be available
- Need 100M events at each energy to match sensitivity of BES-II: 2 days per energy (3.5 GeV – 7.7 GeV)
- Data rate is DAQ limited
- Data at 7.7 GeV will provide an overlap energy with collider mode

FXT in Run 18

Trigger commissioning occurring now
1 Billion events at 7.2 GeV
100 Million events at 3.0 GeV
EPD ready and available for flow analyses
Can obtain fluctuation measurement at energies below BES-I
Thank you!
6) Hipertriton

Energy loss in the material in front of and in the TPC.

\[ ^3H \text{ (2-body + 3-body)} \]
\[ 2990.90 \pm 0.11 \text{ (stat.)} \pm 0.15 \text{ (syst.) MeV/c}^2 \]

\[ ^3\bar{H} \text{ (2-body + 3-body)} \]
\[ 2990.59 \pm 0.25 \text{ (stat.)} \pm 0.15 \text{ (syst.) MeV/c}^2 \]

\[ ^3H \text{ and } ^3\bar{H} \text{ combined} \]
\[ 2990.85 \pm 0.10 \text{ (stat.)} \pm 0.15 \text{ (syst.) MeV/c}^2 \]

Systematical uncertainty source:

- Energy loss correction.
- Different cuts impact.

Fit Function:

\[ N_{\text{sig}} \left( \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-p)^2}{2\sigma^2}} \right) + N_{\text{bkg}} (ax + b) \]
Hipertriton $B_A$ definition:
$$m_A + m_d - m_{3H}$$

1. Early measurements of $B_A$ have large statistical uncertainty due to the limited statistics.

2. The difference between the STAR measurement and the previous measurement is $0.31 \pm 0.11$ (stat. only) MeV.

Figure 8. A summary of worldwide binding energy of $^3_H$ experimental measurements. The vertical lines are the statistical uncertainty, the brackets are the systematical uncertainty. The gray band is the mean value with its statistical uncertainty measured in 1973.
6) Hipertriton

1. $^{3}\Lambda H$ was discovered in 1952.

2. $^{3}\Lambda H$ was discovered in 2010 by STAR collaboration [7].

3. Mass difference between $^{3}\Lambda H$ and $^{3}\Lambda \bar{H}$ was measured for the first time.

4. The mass difference consistent with CPT prediction.

5. Test of CPT symmetry in the light hypernuclei sector.

\[
\frac{\Delta (m/|z|)}{m/|z|} \bigg| _{d} = (0.9 \pm 0.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)}) \times 10^{-4}
\]

\[
\frac{\Delta (m/|z|)}{m/|z|} \bigg| _{^{3}\text{He}} = (-1.2 \pm 0.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-3}
\]

\[
\frac{\Delta m}{m} \bigg| _{^{3}\Lambda H} = (1.0 \pm 0.9 \text{ (stat.)} \pm 0.7 \text{ (syst.)}) \times 10^{-4}
\]

[7] B. I. Abelev et al. (STAR Collaboration), Science 328, 58 (2010).
6) Hipertriton

Triton from Au+Au Collision

\[ \frac{d^2N}{2\pi p_T dy dp_T} \text{ (GeV/c)}^2 \]

Transverse Momentum \( p_T \) (GeV/c)

STAR Preliminary

- 0-10% \times 4
- 10-20% \times 2
- 20-40% \times 1
- 40-80% \times 1
- Blast-wave