STAR COLLABORATION OVERVIEW
7TH INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS IN THE LHC ERA
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WHY RELATIVISTIC HEAVY ION COLLISIONS?

A way to explore QCD matter at extreme conditions of temperature and/or baryonic density

An important tool to investigate the QCD phase diagram
- Search for different phases of QCD matter
- Understand phase transitions
- Look for critical phenomena
DIFFERENT OBSERVABLES, DIFFERENT EVOLUTION STAGES

A nucleus-nucleus (A-A) collision is a very complex dynamic system

- Different observables permit the investigation of different evolution stages and their properties.

To better understand what is happening in A-A collisions, it is often necessary to compare to p-p and p(d)-A collisions
OVERVIEW OF THIS TALK

The STAR experiment

Bulk observables
- Spatial anisotropies – flow harmonics
- Hyperon polarization and vorticity
- Exploration of QCD phase diagram

Heavy flavor measurements in STAR
- Heavy flavor meson production and flow
- $J/\psi$ and $\Upsilon$ production

Future measurements and perspectives
THE STAR EXPERIMENT

Large acceptance:
- $|\eta| < 1; \ 0 < \phi < 2\pi$

Time Projection Chamber
- tracking, particle identification, momentum

Time of Flight detector
- particle identification

Electromagnetic Calorimeters
- electron identification, triggering

Muon Telescope detector
- muon identification, triggering

Heavy Flavor Tracker
- track pointing resolution $\sim 50 \ \mu m$ at $p_T \sim 0.8 \ GeV/c$
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FLOW HARMONICS

Non-zero impact parameter and quantum fluctuations of initial state generates anisotropies in the spatial distribution of partons.

Different pressure gradients transfer these anisotropies to the momentum space in the final distribution.

Flow harmonics $v_n$ are used to study these anisotropies.

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \psi_n)) \right)$$
CENTRALITY DEPENDENCE OF FLOW HARMONICS

$v_2$, $v_3$ and $v_4$ of $\phi$, $K$ and $\Lambda$ in Au+Au and U+U collisions

- Similar $p_T$ dependence in both collision systems

Au+Au data PRC 77, 054901 (2008)
NCQ SCALING IN U+U

Flow coefficients in U+U follows number of constituent quarks (NCQ) scaling
FLOW HARMONICS IN U+U: COMPARISON WITH MODELS

AMPT (string melting) describes data at low-\(p_T\) region

Dashed line – Ideal hydro with LQCD+HGR EOS

- Over predicts data.
  Viscous hydro is needed

AMPT: Z. W. Lin et al. PRC 72, 64901 (2005)
Hydro calculations done by V. Roy, NISER, India
Very large initial angular momentum ($L \sim 1000\hbar$) in non-central A+A collisions

Baryon stopping may transfer this angular momentum to the QGP

Spin-orbit coupling may align spin of the particles with angular momentum

Magnetic field coupling may align (anti-align) $\Lambda$ ($\Lambda$) spin with B field

Vorticity of the fluid may generate larger in-plane than out of plane $\Lambda$ polarization
MEASURING $\Lambda$ POLARIZATION

Global polarization can be measured from the angular distribution of $\Lambda$ decay products relative to the system angular momentum:

$$\frac{dN}{d\cos \theta^*} = \frac{1}{2} \left( 1 + \alpha_H |\vec{P}_H| \cos \theta^* \right)$$

$\rho_H = \langle \vec{P}_H \cdot \hat{j}_{\text{syst}} \rangle = \frac{1}{\text{Res}(\Psi) \pi \alpha_H} \frac{8}{R_e(s)} \langle \sin(\Psi - \phi^*_p) \rangle$
\( \Lambda \) AND \( \bar{\Lambda} \) POLARIZATION

Significant non-zero polarization for energies below 40 GeV

Both \( \bar{\Lambda} \) and \( \Lambda \) show positive polarization implying that spin-orbit coupling and vorticity in the QGP are present

Systematic lower values of polarization for \( \Lambda \) than for \( \bar{\Lambda} \) indicates magnetic coupling with the medium B field

\[ \bar{\rho}_H (\%) \]

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

Nature 548 (2017) 62
EXPLORING THE QCD PHASE DIAGRAM

Our understand of the QCD phase diagram
- Smooth crossover at large $T$ and $\mu_B \sim 0$
- 1st-order phase transition at large $\mu_B$

Location of critical point is a theoretical challenge

The STAR beam energy scan (BES) program
- Explore the phase diagram to discover the possible critical point

Evolution of system focuses near the critical point causing change of behavior in many observables

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<th>Events ($10^9$)</th>
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FREEZE-OUT PARAMETERS

From particle ratios in the final state it is possible to infer chemical freeze-out parameters $T_{\text{ch}}$ and $\mu_{\text{B}}$
- Smooth evolution
- Well described by empirical models

From particle momentum distribution it is possible to extract kinetic freeze-out parameters $T_{\text{kin}}$ and $\langle \beta \rangle$
- Explosive collective expansion
- More radial flow for higher energies

SOURCE SIZE

Increase of source radii with collision energy for kaons and pions

- Increase of $R_{\text{long}}$ – increase on emission duration
- Increase in $R_{\text{out}}$ and $R_{\text{side}}$ – large system at particle emission
EVOLUTION OF JET QUENCHING

One of the most striking results from RHIC is jet quenching
- The suppression of high-$p_T$ particles being one of the characteristic observable

The BES-I data allow to investigate the evolution of particle suppression with energy
- Suppression turns off around 17 GeV

arXiv:1707.01988v1
IN FACT...

Significantly enhanced understanding of jet modifications at RHIC

High $p_T$ hadron suppression at BES
($arXiv:1707.01988$)

pp in very good agreement with theory
($PRD 95 (2017) 71103 (R)$)

Unbiased recoil jets highly suppressed due to medium induced broadening

Total $E_{\text{loss}}$ less than at LHC ($PRC 96 (2017) 24905$)

Lost energy re-emerges at low $p_T$ not $z_T$ ($PLB 760 (2016) 689$)

Di-jet energy imbalance largely recovered within $R=0.4$ when low $p_T$ hadrons included
($PRL 119 (2017) 062301$ - Editor’s suggestion)

$z_g$ unmodified for hard core jets (preliminary release)

$\gamma$-jet, jet in small systems, flavor jet ... (soon available)
OPEN HEAVY FLAVOR HADRONS

The STAR Heavy Flavor Tracker was installed for data taking during 2014-2016

- Excellent track pointing resolution
- Topological reconstruction of heavy flavor hadrons
- Significantly improved signal to background ratio

\[ \text{Counts per 10 MeV/c}^2 \]

\[ \frac{s}{\sqrt{s} + b} \approx 210 \]

\[ \approx 900 \text{M events} \]

\[ \text{Invariant mass } M_{K\pi} \text{ GeV/c}^2 \]

\[ 1.7 \text{ to } 2.1 \]

\[ 0 \text{ to } 45 \times 10^3 \]

\[ 1 < p_T < 8 \text{ GeV/c} \]

\[ \text{Au+Au 0-80\%} \]

\[ \bullet \text{ unlike-sign} \]

STAR PRL 118, 212301 (2017)
**D⁰ ELLIPTIC FLOW**

D⁰ mesons exhibit large $v_2$, comparable to what is seen for light hadrons

- Mass ordering is seen for $p_T < 2$ GeV/c

Number of constituent quark (NCQ) scaling is seen for D⁰ mesons

- Same behavior as for light hadrons
- Suggests that charm quarks flow with the medium
**D^0 ELLIPTIC FLOW**

3D hydrodynamic simulation describes the data at low-\(p_T\) region, below \(\sim 4\) GeV/c.

Indication that charm quarks are thermalized with the medium created in 200 GeV Au+Au collisions.

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*STAR PRL 118, 212301 (2017)*
Non-zero $v_3$ values are observed for $D^0$ mesons in minimum-bias Au+Au collisions at 200 GeV

- Compatible to what is observed for light flavor hadrons

Consistent with NCQ scaling (be aware of large uncertainties)

- Strong interactions of heavy quarks with the QGP
$\Lambda_c$ PRODUCTION

Large baryon to meson ratio in heavy flavor sector
- Similar to the ratio observed for light hadrons

Consistent with model calculations including coalescence hadronization and thermalized heavy quarks in the medium
B MESON PRODUCTION

Suppression of B mesons is observed in three different decay channels

B is less suppressed than D mesons (2 sigma effect in electron channel)
J/ψ AND ψ(2S) PRODUCTION

Consistent with CGC + NRQCD and NLO NRQCD

ψ(2s)/ψ(1s) ratio consistent with world data
$R_{pAu}$ consistent with unity at high-$p_T$ (large uncertainties)

Production of $J/\psi$ in $p+Au$ collisions favors models with an extra nuclear absorption on top of PDF modification.

EPS09+NLO: Ma & Vogt, Private Comm
nCTEQ, EPS09+NLO: Lansberg Shao,
Comp. Phys. Comm. 198 (2016) 238-259
Ferreiro et al., Few Body Syst. 53 (2012) 27
**J/ψ IN A+Α**

Measurements of J/ψ v_2 in U+U collisions are consistent with the previous Au+Au results:

- Consistent with zero v_2 above 2 GeV/c disfavoring a dominating regeneration contribution in this kinematics range.

R_{AA} measurements indicate a strong suppression for p_T > 5 GeV/c in central collisions, a strong evidence of J/ψ dissociation in the medium.
**γ PRODUCTION IN p+p AND p+Au**

Production in p+p collisions consistent with world data trend

Measurements in p+Au collisions can be used to quantify CNM effects

- \( R_{pAu} = 0.82 \pm 0.10(\text{stat}) \pm 0.08(\text{syst}) \pm 0.10(\text{global}) \)
**Υ** PRODUCTION IN Au+Au

Indication of increasing suppression with centrality
- Similar suppression to that at the LHC for Υ(1S)

Υ(2S+3S) is more suppressed than Υ(1S) → sequential melting
FUTURE PERSPECTIVES

STAR has a striking physics and upgrade program for the upcoming years

2018 data taking
- Isobaric run (Ruthenium-96 (Ru+Ru) and Zirconium-96 (Zr+Zr)) to address chiral magnetic effect
- Au+Au collisions at 27 GeV to improve statistics on $\Lambda$ polarization
- Fixed target run at 3 GeV

BES – II (Beam Energy Scan phase II) (2019-2020)
- Several measurements at different energies in collider mode and fixed target mode to explore the QCD phase diagram
  - $\sqrt{s} = 9.1, 11.5, 14.5$ and 19.6 GeV in collider mode
  - $\sqrt{s} = 3.0, 3.5, 3.9, 4.5, 5.2, 6.2$ and 7.7 GeV in fixed target mode
- Several upgrades to improve STAR capabilities for the BES-II data taking
FUTURE UPGRADES

iTPC
- Continuous pad rows
- Replace all inner TPC sectors
- $|\eta| < 1.0 \rightarrow |\eta| < 1.5$
- Improved $dE/dx$ and momentum resolution

EPD
- Replace beam-beam counter
- Better trigger and EP resolution
- $2.1 < |\eta| < 5.1$

eTOF
- $-1.6 < \eta < -1.1$
- Extend PID capability (FXT)

From RHIC
- Low energy electron cooling
- Improved luminosity by a factor of 3 for BES-II