The STAR experiment at Relativistic Heavy Ion Collider (RHIC) is designed to study the QCD at extreme high temperature and density regions through heavy ion collisions. In the first few years of STAR running early this century, many key evidences have been discovered that demonstrate the creation of a new form of matter, namely the Quark-Gluon Plasma (QGP) in central Au+Au collisions at center-of-mass energy of 200 GeV per nucleon pair. Ever since, the heavy ion program at STAR have been focused on (1) Precision characterization of emergent properties of the QGP medium utilizing high luminosity Au+Au 200 GeV collisions (2) Investigate the QCD phase structure at high baryon density region through Beam Energy Scan (BES).

Heavy flavor quarks offer unique sensitivity in quantifying the QGP medium properties due to their large masses. The RNC group has led the design, construction, operation and physics analyses of the STAR Heavy Flavor Tracker (HFT) upgrade that is aimed for precision measurements of charm hadron production and anisotropic flows. The HFT finished data taken in year 2016. And the group has published several key findings on the open charm hadron production using the HFT data. Charm hadron D0 yields suffer significant suppression in central Au+Au collisions and these hadrons exhibit strong collective flows. Charm baryon Lc yield is also significantly enhanced compared to the fragmentation baseline. These demonstrate that charm quarks interact with the medium strongly and for the first time one can quantify the QGP medium transport parameter, the charm quark spatial diffusion coefficient 2pTDs to be 2-5 at near Tc region. The next important step in the heavy flavor program is to further determine the bottom quark transport parameter through precision open bottom measurements and to investigate the temperature dependence of these parameters as well as to test the universality. We plan to carry out these measurements utilizing the MVTX detector at the sPHENIX experiment (see the sPHENIX section for details).

Lattice QCD calculations demonstrate that the phase transition from hadronic matter to the QGP phase at vanishing baryonic chemical potential (mB) is a cross-over. However, there is no available first principal calculation regarding the Equation-of-State (EoS) for the QCD matter at finite mB. QCD inspired models indicate the phase transition at sufficient high mB is first-order which indicates a critical point could exist at the end of the first-order phase transition boundary. In order to experimentally study the QCD phase structure at finite mB region, RHIC initiated the first phase Beam Energy Scan (BES-I) program in 2010 which covered the collision energy down to 7.7 GeV. Several important findings including the disappearance of apparent Number-of-Constituent-Quark scaling, non-monotonic energy dependence of net-proton kurtosis. These findings point to the interested energy region between 7.7 – 20 GeV which requires much more statistics for further investigation. The RHIC BES-II program was prioritized in the 2015 Long Range Plan and conducted in 2019-2021. To maximize the physics output, STAR detector has added several key subsystem upgrades: the inner TPC (iTPC), the Event Plane Detector (EPD) and the endcap Time-of-Flight (eTOF) Detector. These detectors significantly improve the STAR detector tracking and particle identification capabilities, especially at high eta and low transverse momentum regions.

To fully utilize the versatility of the RHIC machine and to reach the highest baryon density, STAR added a fixed-target (FXT) program by installing inside the beampipe a gold target with a thickness of ~1% interaction length and collecting data from collisions that happens with incoming gold ion beam hitting on the gold target. In total, STAR has collected a serious of FXT datasets covering the energy range from 3.0 to 13.1 GeV with 12 energy points, and datasets with collider mode covering the energy range from 7.7 to 19.6 GeV with 6 energy points. The collider mode datasets collected in BES-II are roughly a factor of 20-40 larger compared to those from BES-I at the corresponding collision energy.

The first set of BES-II data, the FXT data at 3.0 GeV collected in 2018 (without iTPC and eTOF) were recently analyzed. Several key observations/publications have demonstrated the dominance of hadronic matter at Au+Au collisions at 3 GeV, anchoring the expectations for the search for a possible critical point. In the following years, the group focus within the STAR program will be analyzing these high statistics BES-II datasets including both FXT and collider data. Our physics interests include

1. Net-proton high order cumulants. Model calculations expect an oscillation behavior for the net-baryon high order cumulant ratios vs. collision energy. And the cumulant ratios can be related to the susceptibility ratios of conserved quantities in Lattice QCD calculations. It is one of the main goals of the BES-II program to experimentally establish the evidence for the oscillation dependence of net-proton high order cumulant ratios vs. collision energy as well as the returning to reference/baseline at higher and lower collision energies. The group is planning to take the leading role in this measurement. The extended acceptance and particle identification enabled by the new detector upgrades will allow us to investigate systematically and more differentially, therefore to consolidate the experimental evidence.
2. Strange and multi-strange particle production and collective flows. Strange quark dynamics has been long proposed to be sensitive to the QCD phase transition. Their collective behavior is expected to shed insights on the early collision dynamics which may offer deep understanding on the phase transition nature at high baryon density region. The group is planning to take the leading role in the measurement of strange and multi-strange hadrons (Ks, phi, La, Xi, Omega etc.) production yields and directed/elliptic flows.
3. Light hypernuclei production. Hypernuclei offer a great tool to study the hyperon-nucleon (Y-N) interaction which is expected to play an important role in determining the EoS of the nuclear matter at high baryon density region. It also has great implications to the inner structure of compact starts. Light hypernuclei are expected to be copiously produced at low energies, which leaves the BES-II program an opportunity to study Y-N interactions, possibly at high baryon density region. The group is planning to lead the measurements of light hypernuclei yield, collective flow and their intrinsic properties, e.g. lifetime, binding energy etc. We also aims to search for the onset of the double-Lambda hypernuclei which offer insights into the little-known hyperon-hyperon (Y-Y) interaction.
4. Dielectron production. Dilepton invariant mass spectrum provide direct (blue-shift free) measure of the medium temperature, offering unique insights into the EoS of the medium in the finite temperature and density regime. A recent theoretical study has shown that a softening of the EoS due to first-order phase transition can result in an increase of the low-mass dilepton yield relative to a cross-over scenario. The group is planning to take the leading role in the measurement of dielectron invariant mass spectra including their pT dependence in BES-II energies from both collider and FXT datasets.

The sPHENIX experiment is the next-generation fast detector at RHIC focusing on the high statistics measurements of rare probes to characterize the microscopic structure of the QGP medium properties. The sPHENIX detector is currently under construction and is aimed to start data taken in year 2023 RHIC run.

The RNC group joined the sPHENIX collaboration in December 2016 with the interest to further develop the heavy flavor physics program at RHIC. We led the proposal of the Micro-VerTeX (MVTX) detector based on the next-generation MAPS pixel sensor for sPHENIX. We initiated and led the heavy flavor physics program which became the third pillar of physics programs at sPHENIX. The group is now working on the construction of the MVTX detector which is expected to be delivered later this year.

In the near future, we will participate and lead the commissioning, calibration of the MVTX detector in the sPHENIX first year run. The goal is to establish the automatic real-time calibration while taking data. And for the alignment calibration, we will combine the survey measurement which is currently being conducted using the CMM machine at LBL together with the cosmic ray data after installation.

The physics measurements we plan to carry out at sPHENIX focus on the open heavy flavor probes. Our physics interests include

1. Open bottom hadron (through their decay daughters) and charm hadron RAA and v2 measurements. These measurements are aimed to provide critical inputs to the understanding of heavy quark (HQ) energy loss, hadronization and collectivity at the RHIC energy, offering stringent constraints to various phenological models. The goal is to extract the QGP transport parameter, the heavy quark diffusion coefficient, especially for the bottom quark for the first time and its temperature/momentum dependence. Their relation with respect to the shear-viscosity-to-entropy ratio may shed light on the understanding of the strong/weak coupling nature of the QGP medium created in these collisions.
2. Heavy quark hadrochemistry. Heavy quarks offer a unique sensitivity to probe hadronization as they are mostly created in the initial hard scatterings in high energy collisions. Recent RHIC and LHC measurements show charm quark hadronization in the hot QGP medium receive significant contribution from coalescence mechanism. Deep understanding on the hadronization scheme in vacuum and hot QCD matter may shed light into the nature of color confinement. We plan to carry out measurements of various charm/bottom hadrons including baryons in both pp and heavy-ion collisions.
3. Heavy quark (HQ) and anti-HQ directed flow (v1). Heavy quark directed flow in heavy-ion collisions is particularly unique in constraining the HQ diffusion coefficient in high temperature region since v1 is developed earlier in these collisions. Furthermore, the difference between HQ and anti-HQ v1 can offer a clean access to the initial strong magnetic field. Recent STAR measurement of D0/D0bar v1 show a much larger slope vs. rapidity compared to light flavor, offering new insight into the charm-medium interaction, however, the data precision between D0 and D0bar v1 is limited to draw a conclusion. We plan to carry out the similar measurement with greatly improved precision for D0 and D0bar with the sPHENIX MVTX detector. Given the predicted signal from the model, the sPHENIX data projection shows a precision of 5sigma separation power between D0 and D0bar v1.