PROCEEDINGS OF SCIENCE

The sPHENIX experiment at RHIC

Gunther Roland for the sPHENIX Collaboration*
Massachusetts Institute of Technology, Cambridge, USA
National Central University, Zhongli, Taiwan
E-mail: `rolandg@mit.edu`

sPHENIX is a state-of-the-art jet, upsilon and open heavy flavor experiment currently under construction at the BNL Relativistic Heavy Ion Collider, RHIC. sPHENIX will take first physics data in 2023, performing measurements of hard-probe obervables of the Quark-Gluon Plasma complementary to those from the LHC experiments. In this article we describe the science mission, detector layout and key performance parameters of sPHENIX, and give illustrative examples of planned measurements in heavy-ion collisions.

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*Speaker.

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1. Science Mission

Over the last decades, experiments have shown that collisions of heavy nuclei produce a novel hot and dense state of matter, called Quark-Gluon Plasma (QGP). Studies at RHIC and LHC have demonstrated that the QGP has properties that are unique among all forms of matter - in particular it is the most perfect liquid known. The QGP is a key example of a class of strongly coupled systems found recently in wide range of areas of physics, from string theory to condensed matter and ultra-cold atom systems.

While measurements have provided detailed knowledge of the QGP's macroscopic (long wavelength) properties, we do not yet understand how these properties arise from the fundamental interactions of its constituents, i.e., quarks and gluons governed by the laws of Quantum Chromodynamics (QCD). In the 2015 Hot QCD Whitepaper and the US Nuclear Physics Long Range Plan (LRP) [1], one of two highest priority goals in the field of Hot QCD was described as "Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities [RHIC and LHC] is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX" [1].

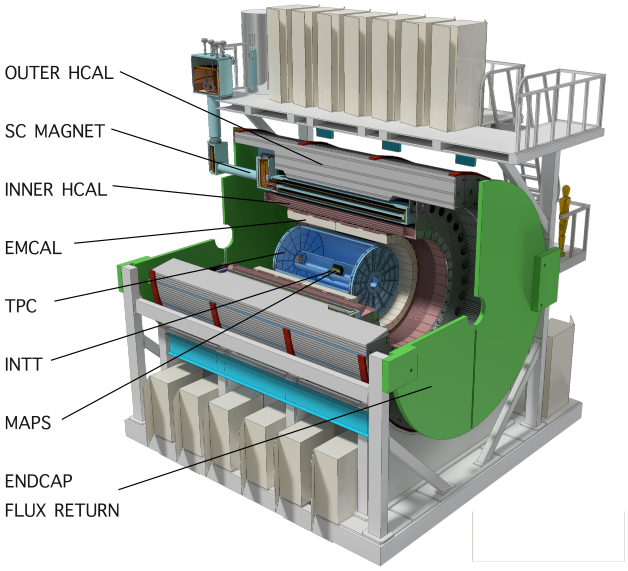

Figure 1: Engineering drawing (cutaway) of the sPHENIX detector. From the inside out the drawing shows tracking system, electromagnetic calorimeter and inner hadronic calorimeter, superconducting magnet and outer hadronic calorimeter. A detailed discussion of the sPHENIX detector subsytems can be found in [4]

The sPHENIX physics program rests on a broad set of measurements using hard probes that are sensitive to the QGP microscopic structure over a range of length or momentum scales. These measurements include in particular studies of jet production and substructure, quarkonia suppression and open heavy flavor production and correlations. sPHENIX was proposed by the PHENIX collaboration in their 2010 decadal plan as an upgrade (or replacement) of the PHENIX experiment at RHIC. The physics case and detector case were further developed in the years leading up to the 2015 Nuclear Physics LRP. A detailed design proposal was completed in 2015 [2], and in early 2016 the current sPHENIX collaboration was formed. As of early 2019, sPHENIX has more than

250 members from 77 institutions in 13 countries. The project received DOE CD-0 approval in late 2016 and CD-1/3A approval in 2018, entering its peak construction phase in 2019. The current schedule foresees commissioning of the detector in 2022 and start of physics data taking in early 2023.

2. sPHENIX detector

The need for state-of-the-art measurement capabilities for jets, quarkonia and open heavy flavor, as well as the capability to utilize the full delivered RHIC luminosity, puts stringent requirements on the performance of the sPHENIX detector and its subsystems. A comprehensive assessment of these requirements has led to the development of the reference design shown in Fig. 1. In its overall layout, sPHENIX folllows the typical geometry of collider detectors, with a tracking system consisting of a MAPS microvertex detector (MVTX), a silicon strip intermediate tracker (INTT) and a time projection chamber (TPC). The calorimeter stack includes a tungsten/scintillating fiber electromagnetic calorimeter (EMCAL) and a steel/scintillator tile hadronic calorimeter (HCAL), divided into inner and outer parts. The inner HCAL sits inside a 1.5 T superconducting solenoid, which was obtained from the decommissioned BaBar detector, and has been delivered to BNL and tested at full field in early 2018. Prototypes of the calorimeter system have been successfully tested in test beam data taking periods at FNAL, with the results of the 2016 test described in [3].

Below is a description of key components of the sPHENIX detector:

Magnetic Solenoid Built for the BaBar experiment at SLAC, the magnet became available after the termination of the BaBar program. The superconducting magnet, with a cryostat of 140 cm inner radius and 33 cm thickness, can produce a central field of 1.5 T.

Tracking system The tracking system consists of three components:

Time Projection Chamber A continuous readout TPC utilizing the SAMPA chip, with an outer radius of about 80 cm measures space points on charged tracks, providing sufficient momentum resolution to identify the three Υ(nS) states through their decays to e^+e^-.

Intermediate Tracking The Intermediate Tracker is a silicon strip detector consisting of two layers which can measure space points on charged tracks inside the inner radius of the TPC for robust tracking even in a high multiplicity heavy ion collision with time resolution that can separate pileup in the TPC. This detector is based on commercial silicon sensors read out with the FPHX ASIC developed for the PHENIX FVTX detector.

MAPS Vertex Detector A Monolithic Active Pixel (MAPS) vertex detector in close proximity to the beam pipe designed to provide high precision tracking for the identification of displaced vertices from decays of particles containing b and c quarks, and to provide additional precisely measured space points for charged particle tracking. This detector is based on duplicating as much as possible the ALICE Inner Tracking System (ITS) inner barrel detector.

Calorimeter stack The calorimeter stack consists of three separate subdetectors, with a common readout chain using silicon photo multipliers.

Electromagnetic Calorimeter Tungsten-scintillating fiber sampling calorimeter inside the magnet bore. The calorimeter has a small Molière radius and short radiation length, allowing for a compact design.

Inner Hadronic Calorimeter Sampling calorimeter of non-magnetic metal and scintillator located inside the magnet bore, instrumented with scintillating tiles.

Outer Hadronic Calorimeter Sampling calorimeter of magnet steel located outside the cryostat which doubles as the flux return for the solenoid and is instrumented with scintillating tiles.

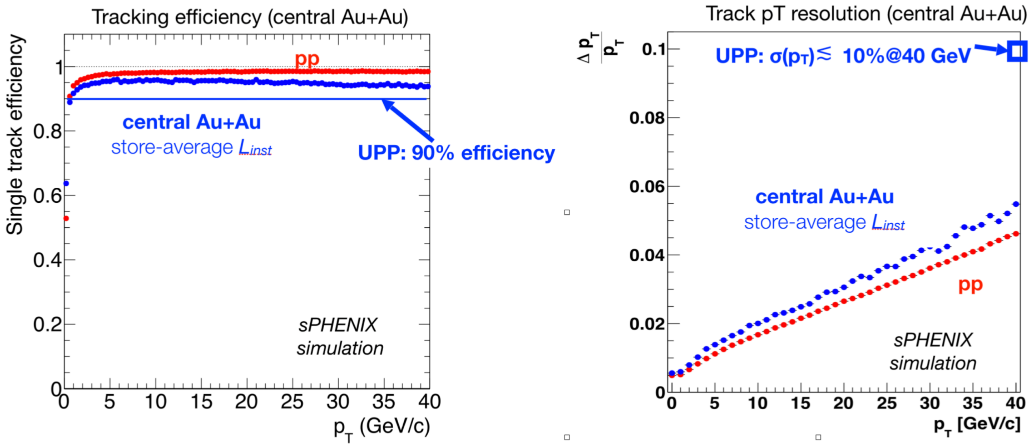

Figure 2: Performance of the tracking system determined from GEANT simulations, using a Kalman-filter based iterative tracking algorithm. The observed performance is compared to physics-driven performance requirements (UPP). (Left) Tracking efficiency as a function of particle momentum. (Right) Relative momentum resolution as a function of momentum.

To map the requirements for the broad physics program outlined above onto the necessary performance characteristics of the detector subsystems, a set of Ultimate Performance Parameters (UPPs) was developed, and detailed simulations of the proposed detector layout were performed. Experience from the LHC experiments shows that also for measurements of jet suppression and jet structure, a high performance tracking system is essential, using measurements of charged jet-constituents for improving the determination of the total jet energy and for detailed measurements of the jet's internal structure. The sPHENIX tracking system has been shown to provide excellent tracking efficiency (Fig. 2, left) and momentum resolution (Fig. 2, right) even in central Au+Au collisions including the expected out-of-time event pileup in the TPC.

Equally important is the performance of the calorimeter system. The full calorimeter stack has been tested in several test beam campaigns [3], and the observed performance has been used to confirm the results of GEANT simulations. An example of such simulations is shown in Fig. 3, left, presenting the jet momentum resolution in central Au+Au collisions compared to the corresponding performance benchmark. Both tracking and calorimeter system are employed in measurements

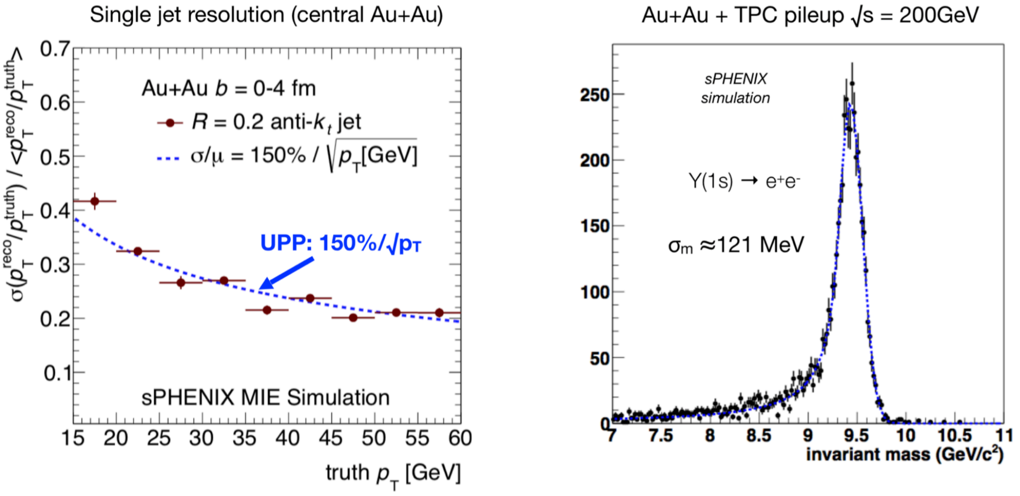

Figure 3: (Left) Performance of the calorimeter system determined from GEANT simulations. The observed performance is compared to physics-driven performance requirements (UPP). Shown is the relative jet momentum resolution as a function of true jet momentum. (Right) Observed mass resolution in GEANT simulations for single Υ(1s) $\rightarrow e^+e^-$ decays, embedded in central Au+Au events including TPC pileup.

of Υ(nS) decays to e^+e^-, with an expected resolution (Fig. 3, right) that allows a clean separation of the three states.

3. sPHENIX data collection and run plan

The goal of sPHENIX is to sample the key physics from the delivered RHIC luminosity in p+p, p+A and Au+Au collisions with as high statistics as possible, with a sustained design event rate of 15 kHz to mass storage. For Au+Au, sPHENIX will predominately focus on recording minimum bias collisions, with additional events sampled using rare event triggers, like, e.g. high p_T direct photons. For p+p and p+Au collisions, PHENIX will predominantly record events from Level-1 triggered events utilizing photon, electron (e.g. from Upsilon decays), hadron, and jet triggers. Consequently, some observables such as lower p_T hadrons (from D, B decays) will likely not sample the full luminosity.

sPHENIX has developed a tentative scenario for a five-year run plan, based on RHIC luminosity projections [5], estimated experimental commissioning time and ramp up, and statistics requirements for key physics observables. Details of this plan can be found in [6], with a summary given in Tables 1 and 2 below. We foresee that sPHENIX data taking will proceed in a sequence of multi-year "campaigns", with each campaign including p+p, p+A and Au+Au data taking periods, with increased luminosities in later campaigns expected in the RHIC performance projections. A key figure is the expected total of 240 billion recorded minimum bias Au+Au collisions in the first two campaigns.

4. sPHENIX physics measurements

sPHENIX has been designed to allow high-statistics, high-resolution measurements for a

Table 1: Five-year run plan scenario for sPHENIX. The recorded luminosity (Rec. Lum.) and first sampled luminosity (Samp. Lum.) values are for collisions with z-vertex $|z| < 10$ cm. The final column shows the sampled luminosity for all z-vertex values, relevant for calorimeter only measurements.

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Table 2: Summary of integrated samples summed for the entire five-year scenario.

Species	Energy [GeV]	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Au+Au	200	35 nb^{-1} (239 billion)	80 nb^{-1} (550 billion)	214 nb^{-1} (1.5 trillion)
p+p	200	—	197 pb^{-1} (8.3 trillion)	1.0 fb^{-1} (44 trillion)
p+Au	200	—	0.33 pb^{-1} (0.6 trillion)	1.46 pb^{-1} (2.6 trillion)

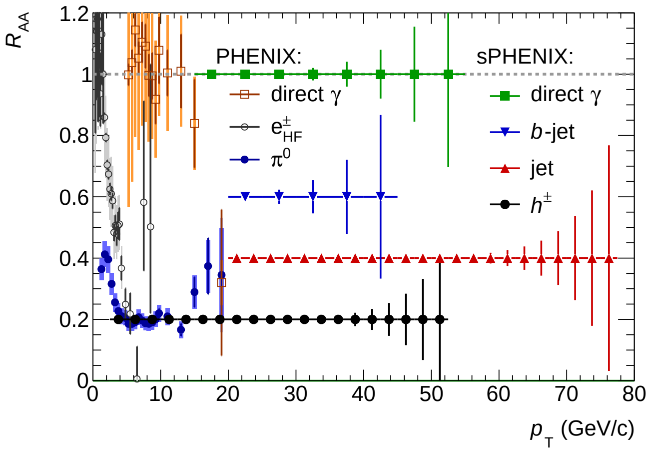

Figure 4: Statistical projections for the R_{AA} of various hard probes vs p_T in 0–20% Au+Au events with the sPHENIX detector after two years of data-taking, compared with a selection of current hard probes data from PHENIX.

broad range of observables related to jet production and modification, quarkonia production at high mass (or high p_T) and yields and correlations of heavy quark (charm *and* bottom) hadrons and heavy flavor tagged jets. Various benchmark plots for planned physics measurements are shown below, based on the expected statistics in the run plan described above, and the detector performance and acceptance seen in GEANT simulations.

An important result of the rate capability and resolution provided by the sPHENIX design is a significantly increased kinematic range for single particle observables, relative to prior measurements at RHIC. Figure 4 compares statistical projections for sPHENIX for various observables after the first sPHENIX data taking campaign to the corresponding current R_{AA} measurements in central Au+Au events by the PHENIX Collaboration. While the existing measurements have greatly contributed to our understanding of the QGP created at RHIC, the overall kinematic reach is constrained to < 20 GeV even for the highest statistics measurements. In contrast, the projected sPHENIX measurements reach sufficiently high p_T to provide a large overlap with both low and and high p_T measurements at the LHC.

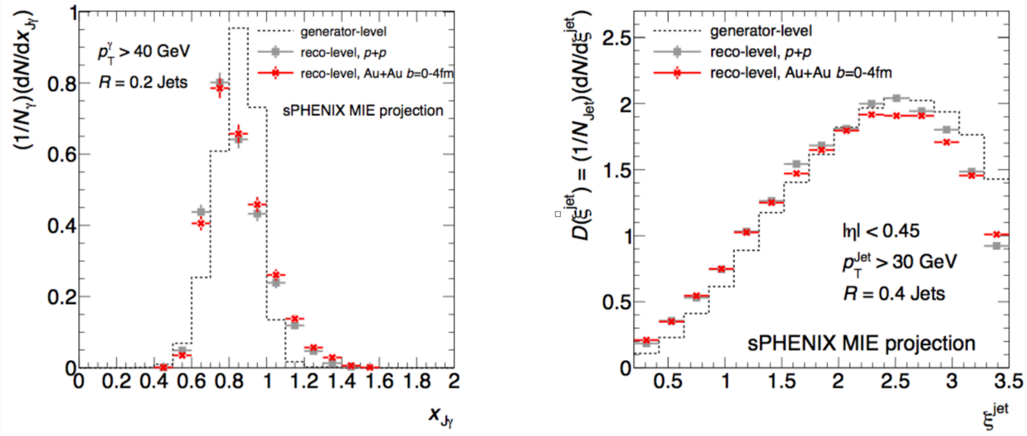

Figure 5: Simulations of measurements using photon-tagged jets in reconstructed p+p and Au+Au events, compared to generator level. No corrections or unfolding procedure have been applied to the reconstructed signals. (Left) Distribution of photon to jet momentum ratio, $x_{j\gamma}$. (Right) Jet fragmentation function relative to the jet energy, for photon-tagged jets.

This overlap is particularly relevant for photon-jet related observables, where a photon tag at a given p_T will select nearly identical initial hard scattering processes at RHIC and LHC. One can then directly compare the resulting modifications of the jet's momentum and its fragmentation pattern in the QGP for two different QGP initial conditions and expansion scenarios. Such measurements will be crucial for characterizing the temperature dependence of QGP properties and its possible quasi-particle structure. Examples are shown in Fig. 5 for the photon-jet momentum ratio (left) and jet fragmentation functions for photon-tagged jets (right).

A final example of the projected sPHENIX physics capabilities is given in Fig. 6 for two measurements related to open heavy-flavor observables. The plots show a measurement of heavy-flavor elliptic flow as a function of p_T based on fully reconstructed D^0 mesons (left) and a measurement of charm and bottom suppression, based on R_{cp} for primary and secondary reconstructed D^0 mesons. A detailed description of the sPHENIX performance for open heavy flavor measurements can be found in [7].

5. sPHENIX cold QCD program

In addition to the QGP related program, sPHENIX has also developed several initiatives related to cold QCD physics, ranging from measurements with the reference detector configuration discussed above [8] to the possibilities afforded by a modest forward upgrade of the detector described in [9] and finally a detailed study of an EIC detector based on sPHENIX [10] that provides

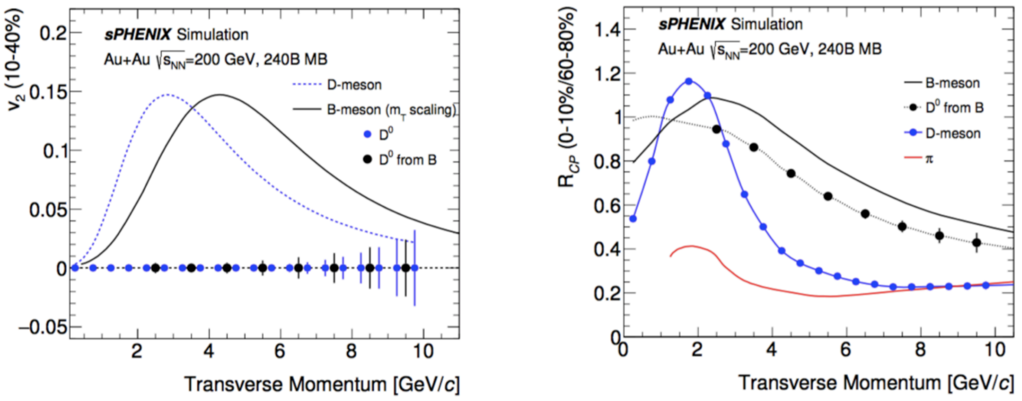

Figure 6: (Left) Projected statistical uncertainties of v_2 measurements of non-prompt/prompt D^0 mesons as a function of p_T in 10–40% central Au+Au collisions. (Right) Projected statistical uncertainties of nuclear modification factor R_{CP} of non-prompt/prompt D^0 mesons as a function of p_T in 0–10% central Au+Au collisions. Both projections are based on an expected data set of 240 billion minimum bias Au+Au collisions.

comprehensive capabilities to cover the physics program described in the EIC White Paper [11]. These initiatives both provide an important second physics program for sPHENIX, addressing fundamental questions in QCD, but also providing information on the initial state of heavy-ion collision processes that is essential for further improving our understanding of QGP formation.

6. Summary

The key goal for studies of the QGP over the next decade is to gain insights into the microscopic structure that underpins its intriguing long-wavelength properties. sPHENIX is a new state-of-the-art detector entering its constructing phase at RHIC, with a planned start of data taking in 2023. The sPHENIX capabilities for jet and heavy-flavor measurements will complement those of the upgraded LHC detectors, and provide input for a greatly enhanced understanding of the microscopic dynamics of the QGP.

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