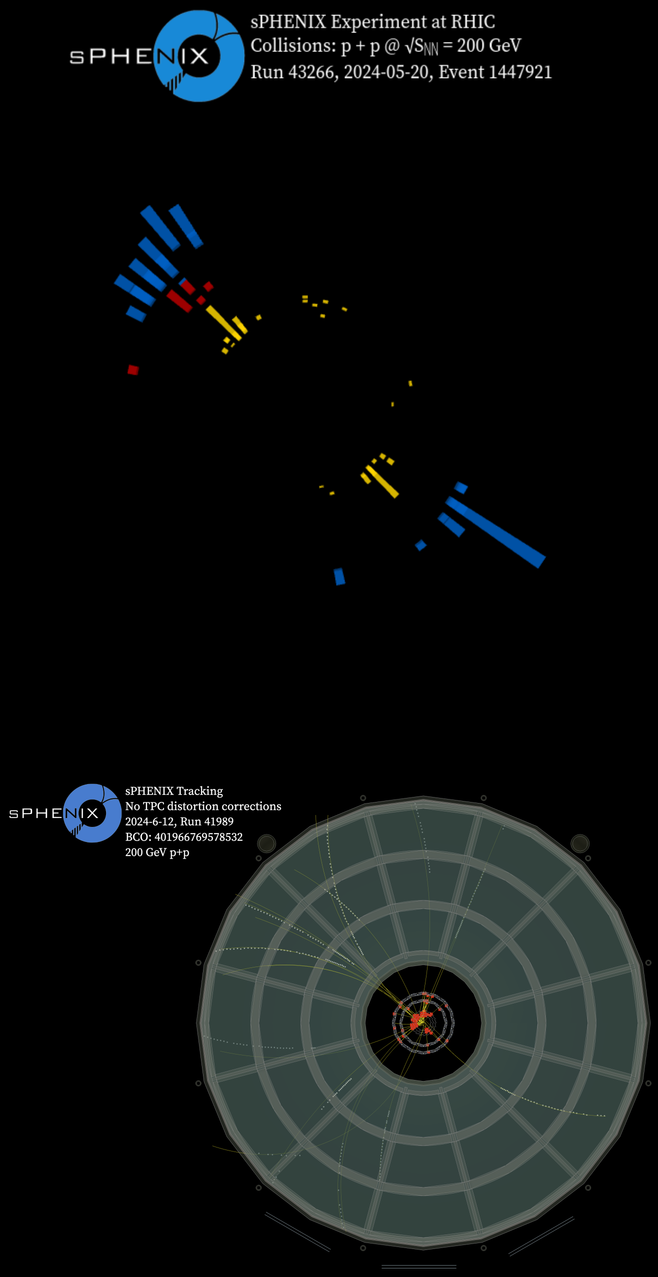
sPH-TRG-2024-01



sPHENIX proton-proton collision data showing a dijet event in the calorimeter system (top) and an example event in the combined tracking system (bottom)

sPHENIX Beam Use Proposal

November 1, 2024

Contents

Chapter 1

Introduction

sPHENIX is the first new collider detector at the Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC) in over twenty years, with the goal of bringing qualitatively new measurement capabilities for the exploration of the Quark-Gluon Plasma (QGP) not previously available in this energy range. The experiment is a specific priority of the DOE/NSF NSAC 2015 Long Range Plan (LRP) for Nuclear Science [1] and is consistently noted in the 2023 LRP [2] and associated community white papers [3, 4] as being essential to completing the scientific mission of RHIC. The significance of the expected results from sPHENIX, complementing those coming from the Large Hadron Collider (LHC), is additionally highlighted in venues such as the "Working Group 5: Heavy-Ion" input to the European Strategy for Particle Physics. For the many junior scientists who have spent the beginning of their careers in experimental nuclear physics working to realize this new collider detector, it is an exciting time as sPHENIX has just finished its first physics data-taking and looks forward to the long-anticipated Au+Au running in 2025.

This document responds to a charge from the BNL Nuclear and Particle Physics (NPP) Associate Laboratory Director (ALD) to prepare a Beam Use Proposal (BUP) by sPHENIX for 20- and 28-cryoweek funding scenarios in Run-25, including for any extended running beyond this in Fiscal Year 2026. We note that the BUP is due in advance of a meeting of the NPP PAC less than two weeks after the end of Run-25. Nevertheless, the sPHENIX Collaboration has worked quickly under these circumstances to evaluate the updated luminosity guidance from the Collider-Accelerator Department (C-AD) and assess possible data-taking strategies in Run-25.

sPHENIX finished construction in early 2023, and the process of commissioning the experiment with Au+Au beams began in May of that year. Run-23 ended after approximately eleven weeks on August 1, 2023 due to the unexpected shutdown of the RHIC machine. While sPHENIX made great progress in commissioning with beam, this early termination date did not allow for the full commissioning of several key sub-systems, most notably the MAPS Vertex Tracker (MVTX) and Time Projection Chamber (TPC). In the shutdown period after the end of Run-23, there was major work performed on these and other sPHENIX detector sub-systems to make them ready for Run-24 p+p data-taking.

Chapter 2 of this document summarizes the sPHENIX Run-24 experience. After the start of Run-24 in April 2024, sPHENIX required a dedicated period with beam to finish the commissioning process and establish that all sub-detectors were ready for full-luminosity physics data taking. Furthermore, in the beginning of Run-24, the luminosity production in the envisioned RHIC mode fell below C-AD projections. Thus, to fulfill the luminosity target for some parts of the program while simultaneously performing the last detector development work needed to enable full-system data-taking, sPHENIX ran in multiple detector+beam configurations throughout Run-24. Therefore, the final accounting of whether sPHENIX achieved its Run-24 p+p luminosity targets is measurement-dependent, with a major success in triggered calorimetric observables and qualified but significant partial successes in triggered full-subsystem running and the tracker-only streaming dataset. RHIC then switched to Au+Au running for the last three cryoweeks of Run-24, which provided important input for sPHENIX on beam conditions and data-taking capability as the Collaboration plans for Run-25.

In addition to preparations for first physics data-taking in Run-24, the scientific Collaboration has spent the time after Run-23 preparing for first physics measurements via a number of activities. While the Au+Au data taken in Run-23 was of commissioning quality, attempting to analyze it as physics data allowed an opportunity for major advancements in the Collaboration's offline reconstruction, calibration, and simulation pipelines. A small number of Paper Preparation Groups (PPGs) were formed, which produced the first sPHENIX Preliminary measurements of bulk particle production in Au+Au collisions, namely the azimuthal modulation of neutral pions [5] and the transverse energy pseudorapidity density [6], the latter performed for the first time with a hadronic calorimeter at RHIC. Other major sPHENIX-associated activities by collaborators included the development of Artificial Intelligence / Machine Learning (AI/ML) methods for simulations, data compression, and analysis [7, 8, 9], the organization of sPHENIX-focused physics workshops [10], and the preparation of technical papers on sub-system performance [11].

Given the experience of Run-23 and Run-24, the sPHENIX Collaboration maintains a significant concern about the performance of the RHIC in upcoming data-taking. We stress that the science program as envisioned a decade ago, and as consistently endorsed by the heavyion physics community, relies on very high delivered luminosities. It is the large luminosity together with a high DAQ rate and large acceptance that enables some of the key flagship measurements such as photon-tagged jet structure, b-tagged jets, and excited Upsilon states. For Au+Au data-taking, the original expectation of delivered luminosities was as high as 25 nb^{-1} for triggered observables, which are now significantly lower based on the observed RHIC performance. sPHENIX is grateful to the many hard-working members of C-AD, Lab and DOE leadership, and the PAC for their support and for making many resources available to try to raise the luminosity production to meet the sPHENIX luminosity targets.

Chapter 3 of this document details the luminosity projections for Run-25 Au+Au running scenarios, which are summarized in Table 1.1. For sPHENIX, collecting a high-statistics Au+Au dataset for its envisioned physics program of rare QGP probes is the absolutely highest priority. Based on a number of considerations, sPHENIX believes that the minimum luminosity target needed to execute this program is 7 nb^{-1} or just under 50 billion minimum-bias events. Given C-AD's latest luminosity projections, this target could be reached with an aggressive 28 cryoweek scenario or with additional running beyond this in Run-25.

The ALD has additionally asked sPHENIX for input on further running opportunities should they arise. If and only if the Au+Au minimum luminosity target is expected to be met, and there is sufficient time remaining for impactful physics data-taking, the sPHENIX Collaboration proposes a priority-ordered list of additional beam use. This ordered list comprises a supplementary eight

sPHENIX Physics Target in Run-25: **7 nb^{-1} (50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\lvert z \rvert < 10$ cm
Au+Au 200 GeV	20	2.4 – 4.2 nb^{-1} recorded
Au+Au 200 GeV	28	3.6 – 6.4 nb^{-1} recorded

If Au+Au luminosity target is met, ordered priority list for additional running:		
Collision Species	Physics weeks	Projected luminosity, $\lvert z \rvert < 10$ cm
1. p+p 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. p+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming

Table 1.1: Summary of the sPHENIX Beam Use Proposal for 2025 for 20- and 28-cryoweek scenarios, and a priority-ordered list for further data-taking should additional cryoweeks become available in FY26.

weeks of p+p running to double the statistics for the channels in which the luminosity target was only partially met in Run-24, followed by five weeks of p+Au running and a short two week oxygen-oxygen (O+O) run, either of which would expand the sPHENIX physics program to a new collision system. Some of this additional running could be obtained in a long Run-25 scenario in Fiscal Year 2026. Alternatively, all of the impactful datasets on the priority-ordered list could be obtained in a separate 20-cryoweek Run-26, or in a combination of the two.

Chapter 4 presents selected statistical projections of physics measurements corresponding to the proposed luminosity targets and running scenarios above. For this Beam Use Proposal, we show a considered selection of quantitative projections updated to match the current best estimate of RHIC performance which best illustrate the particular impact of different scenarios. Previous BUPs [12] have discussed the full breadth of the science case in more detail.

Finally, Chapter 5 provides a summary of the sPHENIX Beam Use Proposal 2024.

Chapter 2

Run-24 Summary

The 4K cooldown of the RHIC rings began on April 15th, 2024. The available funding for RHIC operations was for 19 cryoweeks plus 6 cryoweeks carried over from the unexpected early end of Run-23, giving a nominal ending date for Run-24 of October 7th. The first running mode for Run-24 operation was p+p collisions at $\sqrt{s} = 200$ GeV, with initial injection of each beam and first collisions usable for commissioning completed before the end of April.

RHIC initially ran with a beam-beam crossing angle of $\theta = -2$ mrad in the sPHENIX Interaction Region (IR), as part of a deliberate strategy to decrease the luminosity for collisions outside the narrow vertex range of $|z| < 10$ cm. Such collisions are not within the acceptance of the inner silicon trackers, which are the MVTX and the Intermediate Silicon Tracker (INTT), while still contributing to the charge load of the TPC. The luminosity in this running mode was significantly lower than predicted, causing sPHENIX to collect luminosity at a rate too low to meet its luminosity targets for the year. Furthermore, sPHENIX was still in the process of commissioning its tracking system, with the Time Projection Chamber (TPC) in particular having not yet found a voltage and gas mixture working point where it could take physics-quality data without damage to the detector.

Thus, the decision was made to switch to running in a “head-on” configuration (0 mrad crossing angle) in sPHENIX, starting on June 25th. In this configuration, the luminosity was substantially higher but with a much wider vertex distribution ($\sigma_z \approx 55$ cm) than what would have been desired if the full tracking system was physics-operational. During this running period, sPHENIX focused on collecting a high-luminosity data sample in which essentially only the calorimeters and global detectors were providing physics-quality data. Figure 2.1 (top) shows an example of a dijet event recorded with the calorimeters.

On July 27th, sPHENIX received safety approval to operate with a 5% admixture of isobutane ($HC(CH_3)_3$) in the TPC. It was soon determined that this gas mixture allowed the TPC to operate in a stable manner with full physics capability (for example, in terms of the efficiency for MIPs along track trajectories). Thus, starting on August 13th, the RHIC running mode returned to that envisioned for full-subsystem running, with a crossing angle of $\theta = +1.5$ mrad in sPHENIX. This crossing angle change greatly decreased the width of the vertex distribution, resulting in a large fraction of the luminosity within the $|z| < 10$ cm acceptance needed for the tracking system while simultaneously decreasing the charge load on the TPC. sPHENIX ran under this machine configuration for seven cryoweeks with a hybrid triggered plus extended streaming mode, in which

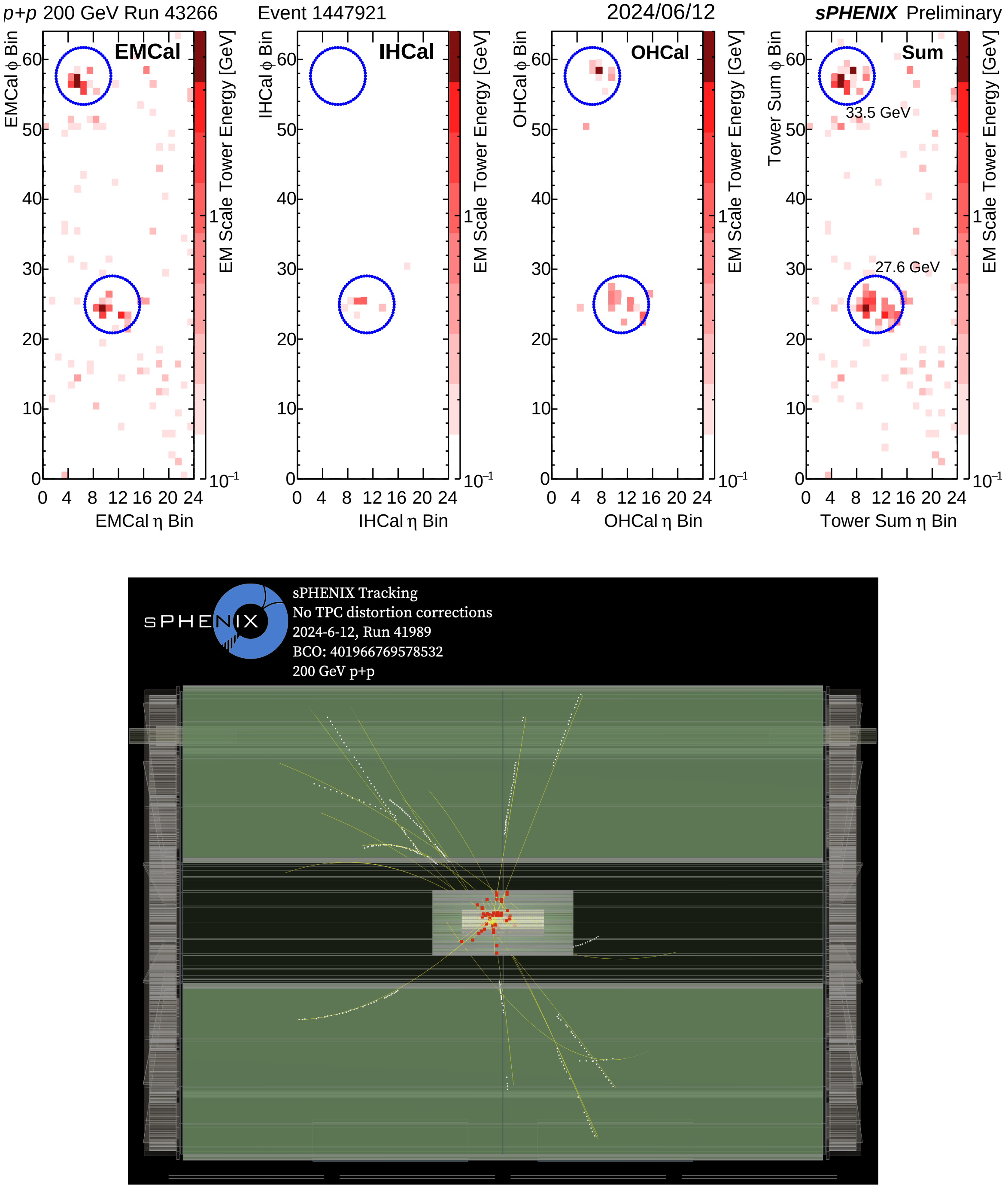


Figure 2.1: Top: Event display of a dijet in Run-24 p+p running, measured with the calorimeter system. From left to right, the panels show the energy deposited in the EMCal, IHCal, OHCal, and combined calorimeter system. The blue circles show the position and measured kinematics of reconstructed jets. Bottom: Reconstructed tracks matched through the full tracking system, including hits in the TPC (white) and the MVTX and INTT (red), with initial estimates of trajectories as dashed yellow lines.

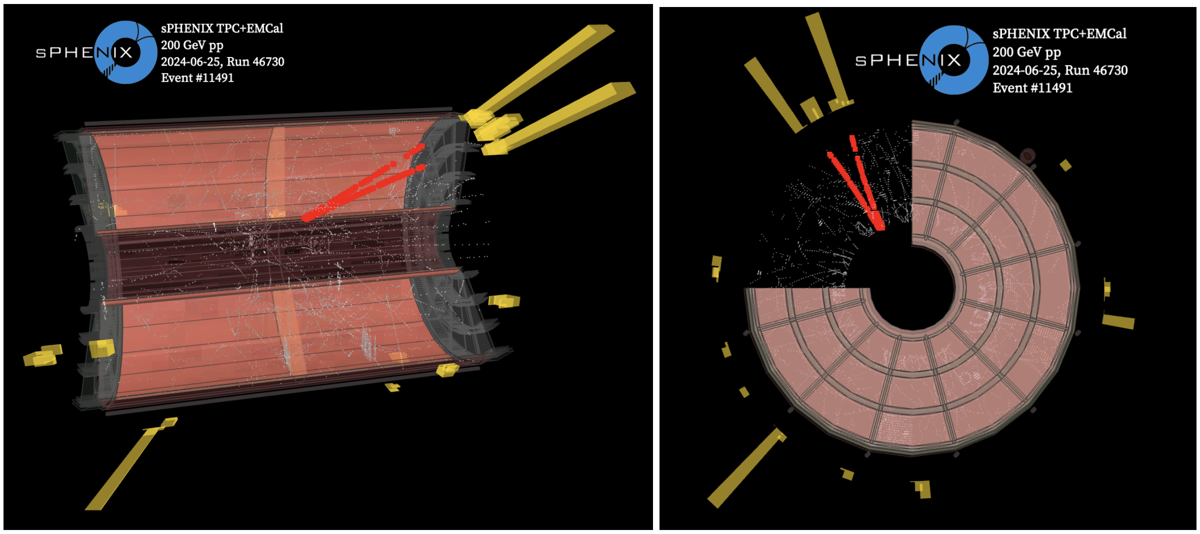


Figure 2.2: Event display of a photon conversion event, showing the TPC track-hits (red) originating from a secondary vertex near the inner radius of the detector, along with the magnitude of energy deposits in the EMCal towers (yellow). A side view (left) and beam view (right) are shown.

all subsystems were read out for events selected via minimum-bias or rare calorimeter triggers, and the trackers (only) were read out for a continuous length of time in streaming mode after a trigger. Figure 2.1 (bottom) shows an example of an event recorded with the full tracking system, albeit from earlier running. Figure 2.2 shows a candidate photon conversion event, demonstrating the event synchronization of calorimeter and tracking detector information. Section 2.2 gives a summary of the history and performance of each subsystem in Run-24 p+p data taking.

Given that sPHENIX was now successfully taking data with all subsystems, the ALD decided to move forward two cryoweeks from Run-25 to Run-24, extending the p+p part of the running by this amount of time and bringing sPHENIX significantly closer to its BUP'23 goals. Section 2.1 discusses the collected p+p datasets in Run-24 and their mapping onto elements of the sPHENIX science program. Polarized proton physics operation ended on September 30th, 2024. Throughout p+p running in Run-24, preliminary estimates of proton beam transverse polarizations by C-AD range between 55–60% depending on the ring and the method used.

After p+p running concluded, RHIC switched to three weeks of Au+Au operation at $\sqrt{s_{\mathrm{NN}}} =$ 200 GeV. The motivation for Au+Au running is for C-AD to prepare for high-luminosity Run-25 Au+Au running and to test the readiness of sPHENIX sub-systems, including data throughput rates, stability of the TPC under the different machine conditions, and mitigation of beam background impact on the MVTX (as first observed in Run-23 Au+Au commissioning running). A summary of the commissioning activities and lessons learned is given in Section 2.3.

2.1 Collected p+p datasets

Table 2.1 summarizes the p+p data collected in Run-24, and how it maps onto the core components of the sPHENIX physics program. Figure 2.3 shows a history of the integrated luminosity

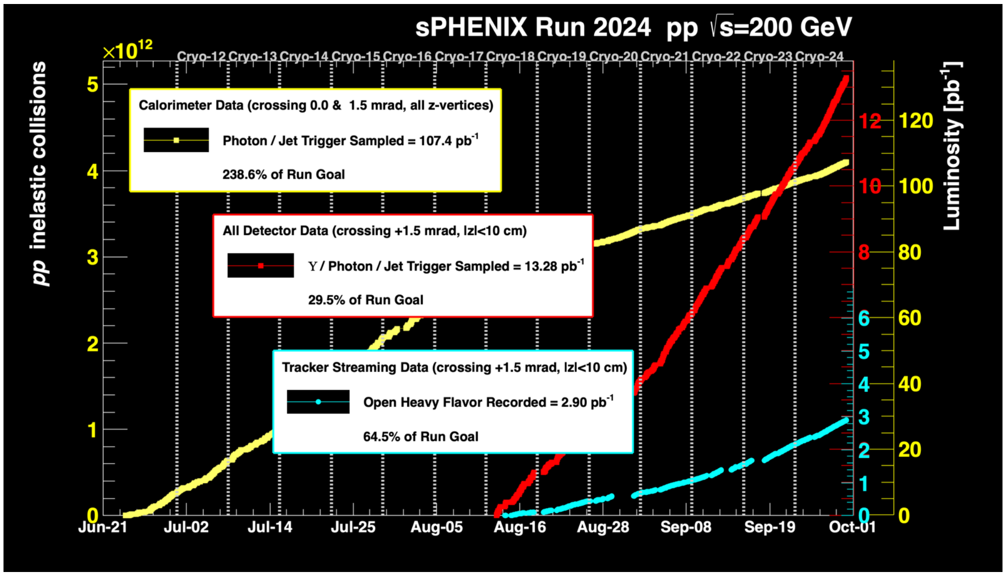


Figure 2.3: Summary of Run-24 p+p data taking, showing the integrated luminosity as a function of time for three main data-taking configurations, including triggered calorimeter data (yellow), triggered full-system data (red), and tracking only streaming data (blue), along with the final luminosity values.

accumulated with different data-taking configurations over the course of the run.

A major success of Run-24 data-taking is the very large luminosity (107 pb^{-1}) sampled via rare photon and jet triggers, with mainly the calorimeters and global detector systems active. Approximately two-thirds (one-third) of this data was collected in the 1.5 mrad, wide-vertex (0 mrad, narrow-vertex) running periods. This dataset enables an unprecedented kinematic reach for high-p_T observables at RHIC such as isolated photons and photon+jet correlations, jets of varying size parameters, and di-jet correlations. Additionally, some but not all aspects of the jet (sub-)structure program can be accomplished in this dataset using the fine segmentation of the EMCal, for example via jet$\rightarrow \pi^0$ fragmentation functions. The collected luminosity represents 240% of the PAC-endorsed goal from the sPHENIX Beam Use Proposal 2023 of 45 pb^{-1}.

A further highlight is the collection of 2.9 pb^{-1} of minimum-bias data recorded in streaming readout mode, including just the tracking sub-systems, and accounting for the fraction of events within the narrow-z acceptance of the MVTX+INTT. While this luminosity is approximately two-thirds (65%) of the sPHENIX BUP'23 goal, nevertheless it represents a major qualitative improvement by *multiple* orders of magnitude over previous minimum-bias p+p datasets for open heavy flavor measurements at RHIC. Notably, this dataset was collected in only seven cryoweeks, using a streaming fraction that varied over the course of individual RHIC fills, reaching a high of 30% towards the end of some fills (compared to the 10% projected in the sPHENIX BUP'23).

The third major dataset includes all sPHENIX sub-systems reading out in triggered mode, again counting only the fraction of the luminosity within the $|z| < 10$ cm vertex range. This is the only dataset with both calorimeter and full tracking coverage, and is thus the one appropriate for jet+track structure or correlation measurements, and for the b-jet and quarkonia physics programs. The luminosity corresponds to 13 pb^{-1}, which is only 30% of the BUP'23 targeted luminosity of

Physics program	Luminosity	% BUP23 Goal	Detector and Beam Conditions
Photons, jets, neutral mesons (HCal unique at RHIC)	107 pb^{-1} Sampled	240%	Calo+Global, Triggered, 0mrad + 1.5mrad, wide vertex
Jet+track structure, quarkonia, *b*-jets	13 pb^{-1} Sampled	30%	All sub-systems, Triggered, 1.5mrad, $\lvert z\rvert < 10$ cm
Open heavy flavor (RHIC-unique dataset)	2.9 pb^{-1} Recorded	65%	Trackers, Streaming, 1.5mrad, $\lvert z\rvert < 10$ cm

Table 2.1: Summary of data collected by sPHENIX during RHIC Run-24 p+p operation, separated into the major datasets corresponding to different components of the physics program.

45 pb^{-1} for these measurements. While the size of this dataset still allows for detailed measurements of the properties of inclusive jets, it does have a negative effect on some aspects of the flagship sPHENIX physics program, including as examples photon-tagged jet (sub-)structure and Upsilon measurements. Below, in this year's BUP, we explore the quantitative impact that supplementary full-system triggered p+p running could have in FY26.

Other datasets include samples collected with minimum-bias or other supporting triggers (e.g. based on the Zero Degree Calorimeter, ZDC), and may have additional analysis-specific uses or are intended to be used for calibration, trigger efficiency, etc., purposes.

2.2 Subsystem performance highlights

The calorimeter systems, composed of the electromagnetic calorimeter (EMCal) and the inner and outer hadronic calorimeters (IHCal and OHCal), were available for physics-quality data-taking as soon as RHIC began providing first collisions. Over the course of Run-24, the EMCal and I/OHCals typically had 99% and 100% of their channels active, respectively. One particular point of attention was monitoring the effects of accumulating radiation damage to the EMCal silicon photo-multipliers (SiPM's), which are attached to the front (i.e. collision-facing) face of the EMCal. For the EMCal, data-driven tower-by-tower calibrations were derived based on the observed π^0 peak position. Fig 2.4 (left) shows an example of the π^0 and η meson peaks in early p+p data after application of a preliminary calibration. Calorimeter data-taking was supported throughout the run with special pedestal and cosmics running.

An important usage of the calorimeters in p+p data-taking was to provide rare Level-1 photon and jet trigger signals to ensure that sPHENIX would record all such processes in the high-luminosity running. The main triggers used were based on square sliding windows of energy sums, with Photon triggers based on requiring different energy sum thresholds in non-overlapping 8x8 tower EMCal windows, and Jet triggers based on energy sums in partially-overlapping $\Delta\phi \times \Delta\phi = 0.8 \times 0.8$ patches in the EMCal and HCals summed together. Fig 2.4 (right) shows an example of an early evaluation of the performance of the Jet trigger.

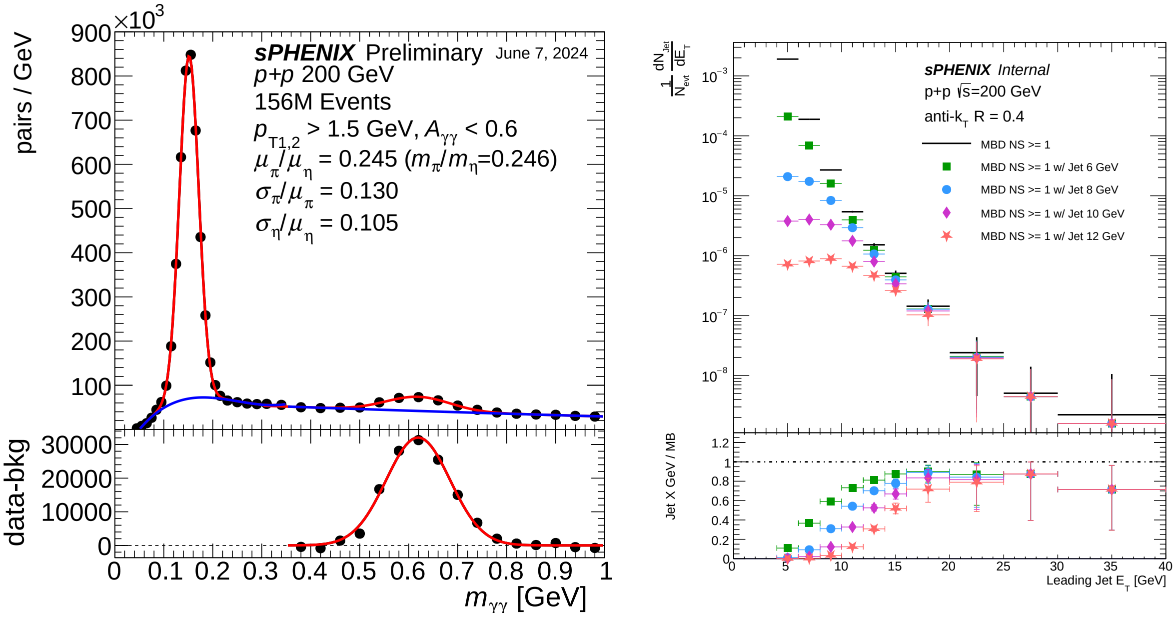


Figure 2.4: Left: Two-photon invariant mass distribution, measured in Run-24 p+p collision data, showing Gaussian fits to the π^0 and η meson peaks. The bottom panel shows the shape of the background-subtracted distribution in the region of the η meson. Right: Per-event jet yield compared between minimum-bias p+p events (black) and in MB events in association with Jet triggers of different thresholds (colors). The bottom panel shows the ratio of Jet triggered distributions to the minimum-bias one.

A highlight of Run-24 was completing the commissioning of the full set of tracking sub-systems and bringing them all into routine physics operation. The two innermost tracking sub-systems are silicon detectors, the MVTX and the INTT. The MVTX was commissioned in p+p data which, benefiting from the cleaner beam conditions compared to Run-23 Au+Au, did not induce beam background-related chip lockup. The MVTX read out in streaming mode and a thorough set of offline checks established the integrity of the data by the time of full-subsystem running at 1.5 mrad. The noise threshold per channel was set to 100 electrons and the resulting noise level was at the level of 10^{-8} to 10^{-9}. Further offline evaluation confirmed a high track hit efficiency and layer efficiency given a track. Figure 2.5 (left) shows an example performance plot studying the MVTX pixel cluster sizes. The INTT had been successfully commissioned in Run-23 and ran without issue in Run-24, with almost 99% active chip area. Streaming readout for the INTT was implemented this run and this subsystem contributed successfully to the open heavy flavor dataset collection in p+p, before switching back to triggered mode for Run-24 Au+Au running and looking ahead to Run-25.

The two outermost tracking subsystems are gas detectors, the TPC and the TPC Outer Tracker (TPOT). Significant technical work was performed on the TPC before Run-24, including replacing the high voltage (HV) distribution to the gas electron multiplier (GEM) foils, which also enabled granular gain balancing. This was sufficient to take cosmics data before the run. During Run-24 beam conditions, there was an exhaustive search for a stable operating point in terms of GEM and central membrane voltages, both with the nominal gas mixture and with a nitrogen-admixture, which was not successful in finding a physics-capable configuration that would not systematically damage the readout chambers over time. With the 5% isobutane admixture, the TPC was able

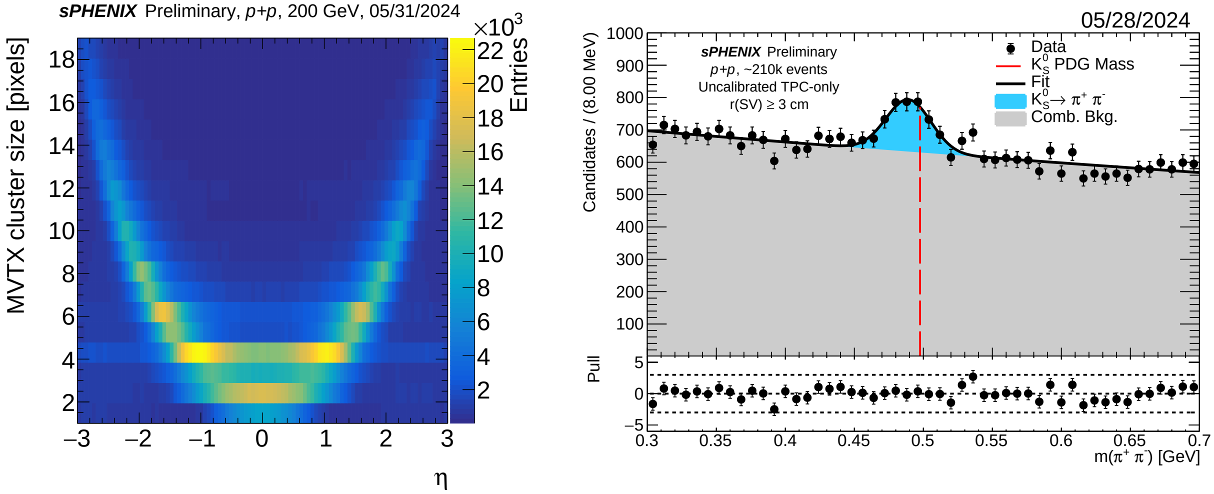


Figure 2.5: Left: Distribution of MVTX pixel cluster sizes (y-axis) for different pseudorapidity values relative to the primary vertex (x-axis). Right: Invariant mass distribution of track pairs reconstructed in the TPC, showing an early K_s^0 peak. The used tracks do not have any corrections, including those to account for static distortions, applied.

to establish a working point with 3.3 kV nominal HV in full-luminosity 111×111 bunch running. In this configuration the TPC was stable (no discharges) and had full efficiency for minimum-ionizing particles (MIPs). After finishing gain balancing and confirming the data integrity of the online zero suppression, the TPC started taking physics data-taking in the 1.5 mrad configuration. Figure 2.5 (right) shows an example two-track mass distribution in early TPC data. TPOT had been successfully commissioned in Run-23 [11]. It operated with high efficiency in Run-24 and continued to develop readout capabilities such as zero suppression (i.e. the online removal of hits with charge below a predefined threshold), the ability to run at high trigger rates, and running in streaming readout mode.

The full set of sPHENIX sub-systems also included a trio of global/forward detectors which were active during p+p data-taking. The Minimum-Bias Detector (MBD) provided the Level-1 minimum-bias trigger signal and initial z-position of the collision primary vertex. The sPHENIX Event Plane Detector (sEPD) was fully commissioned in Run-24. It had approximately 99% active live area, and a channel-by-channel calibration to the MIP peak was performed using collision data. Fig 2.6 (left) shows an example of the correlation between the total signal in the MBD and that in the acceptance-matched rings of the sEPD in p+p running. The Zero-Degree Calorimeter (ZDC) was calibrated (in lieu of a mono-energetic single neutron peak as in Au+Au data) using the known position of the peak in the summed energy spectrum from PHENIX p+p data. The ZDC, including particularly information from the Shower-Max Detector (SMD), played a key role in polarized p+p running by providing local polarimetry information, for example as monitored by the forward neutron A_N. Fig 2.6 (right) shows an example of the raw cosine modulation from the Left-Right asymmetry in one of the ZDC sides.

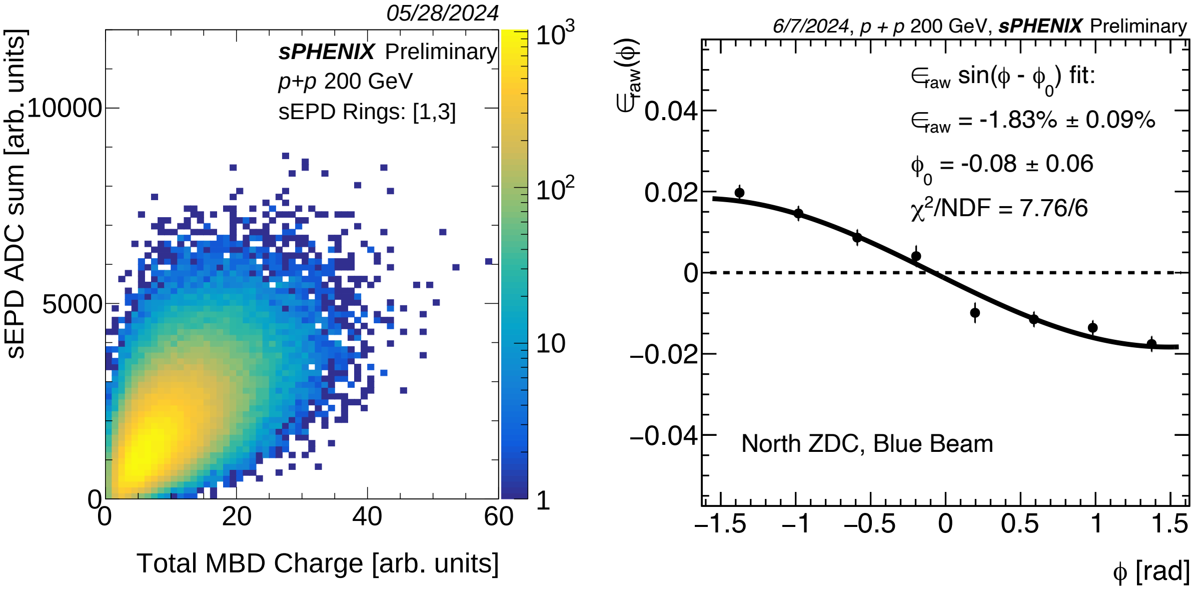


Figure 2.6: Left: Correlation between the sum signal in the MBD (x-axis) and in the pseudorapidity rings of the sEPD approximately matching the MBD acceptance (y-axis) in p+p running. Right: Raw asymmetry of forward neutron production as a function of ϕ for the blue beam going into the North ZDC, uncorrected for the beam polarization.

2.3 Run-24 Au+Au highlights

For sPHENIX, the final three-week period of Run-24 was for completing the commissioning of the detector with Au+Au collisions, necessary due to the early termination of Run-23. The switch from proton to Au beams started on Monday, September 30, 2024 and first collisions were available to sPHENIX on the following Monday, October 7, 2024.

Within one day, the minimum bias MBD and ZDC triggers were timed in and working. Within a couple of days, sPHENIX was taking data with all detector subsystems together. The calorimeter systems performed very well and zero suppression levels matched expectations for full 15 kHz minimum bias trigger capabilities. A summary of data taking is shown in Fig. 2.7, highlighted by over 1.5 billion Au+Au events recorded for the photon/jet calorimeter analyses. A majority of the data taking for the tracking detectors was for commissioning and included over 100 specific accelerator tests and sPHENIX detector tests.

The TPC high voltage operation with isobutane gas mixture was extremely stable, including in controlled tests of running at different crossing angles ($\theta = 2.0, 1.5, 1.0, 0.5, 0.0$) that corresponded to ZDC coincidence rates from 6–40 kHz. In fact, it was found that a substantial portion of the charge load on the TPC GEMs is from beam backgrounds and not from collisions, as independently determined by steering the beams vertically out of collision. Thus, the optimal running condition was with a crossing angle of +1.0 mrad, which is important information for Run-25 planning.

The resistor chains to re-balance the GEM high voltage, discussed earlier in Section 2.2, will be replaced by the CAEN HV system in Run-25 (as is used in ALICE). Two sectors of the TPC were connected to the newly arrived CAEN modules during an extended access, and were operated

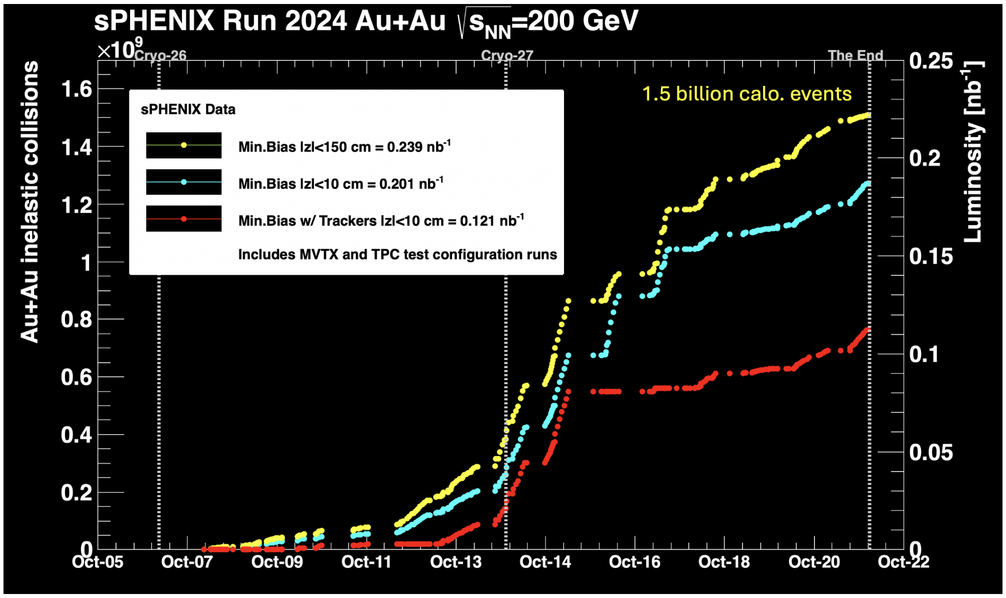


Figure 2.7: Summary of Run-24 Au+Au data taking, showing the integrated luminosity as a function of time for different data-taking configurations.

over the last week of collisions. Valuable experience was gained in terms of their required wiring, installation, and operation ahead of Run-25.

During the Au+Au data taking, the TPC displayed a substantially lower efficiency for tracks passing through the gas volume near the central membrane as compared to near the GEM readout plane. This pattern was not evident during the p+p running, and multiple tests were performed with beam and then with cosmic rays just after beam ended. The issue is still being investigated and may be related to a problematic CF_4 bottle. Improved monitoring and real-time feedback must be implemented for next run to maintain high efficiency at all times.

In Run-23 Au+Au commissioning, the MVTX saw significant beam related backgrounds, so-called "splash events" that locked up the MVTX readout rendering a large fraction of the staves unusable. In preparation for this year, an auto-recovery (AR) was deployed where after such a splash event, the individual chip resets and can return to data taking (which takes of order 15 seconds). Additionally, a set of stainless steel absorbers were constructed to potentially range out some backgrounds with trajectories outside the beam pipe, but inside the inner radius of the magnet end doors. Lastly, a monitoring system was developed to quickly analyze the rate of AR events and their distribution for real-time diagnostics by both sPHENIX and C-AD.

These splash events were again observed in Run-24 with Au beam, noting that such events were completely absent with proton beam. The distribution of these events, and hence AR rates, is shown in Fig. 2.8 (left). The background is present even in single beam running and is focused along the horizontal plane with a larger rate of ARs on the outside (relative to the ring). C-AD, led by their Run Coordinator Kiel Hock, carried out innumerable tests to isolate the issue and work to mitigate the problem. As one example test, the background was observed to shift from the outer to the inner side when changing the crossing angle.

The sPHENIX data acquisition specification was for a 4 microsecond trigger latency, and running

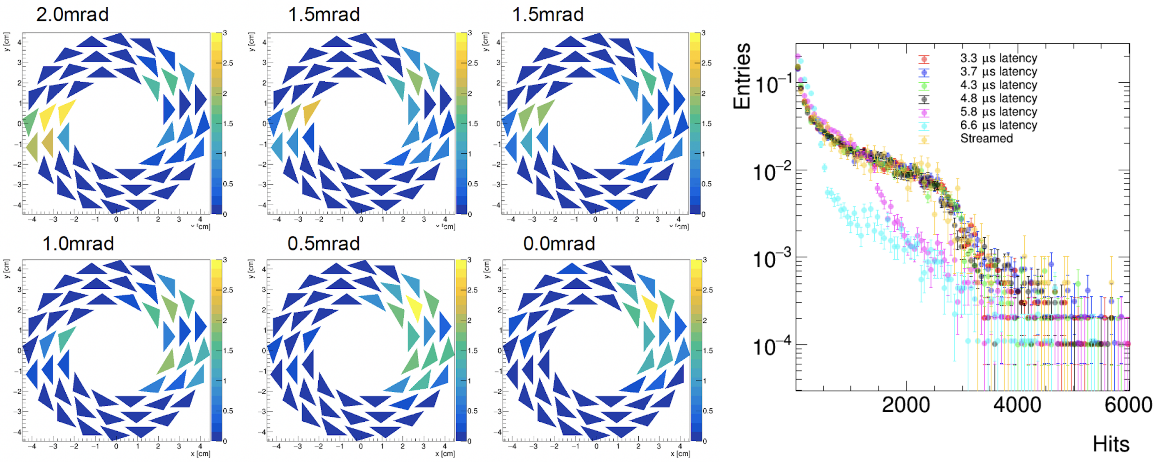


Figure 2.8: (left) MVTX auto-recovery rate during 1x1 bunch test at different beam crossing angles. Yellow indicates an AR rate at the maximum. (right) Number of pixel hits from minimum bias Au+Au collisions in the MVTX layer-2 running in triggered mode with different latencies.

of the MVTX in (non-triggered) streaming mode. In this streaming mode, 100% of splash events result in ARs. However, the MVTX can also run in triggered mode in which case only splash events within approximately 5 μs of the trigger cause an AR. The rate of AR is then reduced by an order of magnitude even at the highest DAQ trigger rates. The ALPIDE chip, designed for ALICE, generally requires a 2.6-3.0 μs trigger latency, and thus there is the possibility of missing high-charge deposit hits with a longer trigger latency. A trigger latency scan was performed with the results shown in Fig. 2.8 (right). The distribution follows the expected Au+Au minimum bias distribution and appears mostly unchanged until the latency is greater than 4.3 μs. This initial study indicates that the majority of the particles (mostly pions) have hits captured with good efficiency in the triggered configuration. Further examination connecting TPC, INTT, and MVTX tracks is needed to determine if low momentum kaons and protons might have lower efficiency and the potential physics impact, if any. Running in this triggered mode yields a reduction in AR that is multiplicative with any reduction in the splash events from accelerator improvements. Given the detailed studies by C-AD this running period and the MVTX triggered mode option, we are confident that the MVTX will be fully operational for Au+Au running next year.

Finally, in term of data acquisition bandwidth, the sPHENIX specification is 15 kHz and thus in Au+Au data taking essentially every collision can be recorded. The calorimeter systems (EMCal, I/O HCal) and the MBD, ZDC, sEPD, MVTX, INTT were run at 14.5 kHz during extended tests, and further improvement via ENDAT time adjustment and zero suppression optimization should enable the full 15 kHz rate. The TPC readout is limited by the total data volume and the I/O bandwidth for a farm of buffer box machines. Tests yielded a 5.5 kHz rate and purchases for doubling the number of buffer boxes for Run-25, along with HPSS upgrades, will double that value to 11 kHz. We are confident that further optimization of the zero suppression and data compression can provide the additional rates.

Overall, the 3-week running period of Au+Au was very successful and has yielded the required information for C-AD and sPHENIX to be ready for data taking in Run-25. Additionally, a modest Au+Au physics sample was recorded.

Chapter 3

Beam Use Proposal for Run-25

3.1 Luminosity projections

This section documents the quantitative basis and assumptions for the projected luminosities presented in this chapter.

To start, we note that the projected luminosities for Au+Au running have evolved substantially over time, with significant decreases after the observed performance of the RHIC machine in Run-23. For example, in Beam Use Proposals from sPHENIX submitted to the ALD and endorsed by the PAC in 2020 through 2022 [12], the projections based on C-AD guidance were 15 nb^{-1} of recorded minimum-bias Au+Au events in a 28 cryoweek scenario in Run-25, corresponding to 0.1 trillion such collisions. In fact, the instantaneous luminosities were expected to be so high that the collision rate is larger than the highest-foreseeable sPHENIX data acquisition system (DAQ) rate of 15 kHz. Thus, with a modest triggering strategy for rare high-p_{T} probes such as photons, di-electrons from Upsilons, and potentially jets, sPHENIX could sample up to 25 nb^{-1} in a 28-cryoweek scenario. After the experience of Run-23, the expected performance for RHIC Au+Au operation was significantly lowered. The sPHENIX BUP delivered in 2023 [13] had projected 6.3 nb^{-1} of recorded Au+Au collisions in a 28 cryoweek scenario of Run-25. In that previous BUP, there was no longer a distinction between “recorded” and “sampled” luminosities, since the instantaneous collision rates would always be within the upper limit on the DAQ bandwidth, and thus all rare probes events could be collected with a straightforward minimum-bias trigger.

In preparation for this BUP, sPHENIX considered two ways to calculate projected luminosities. For the nominal values, we rely on the official projections of the luminosity production per week under different crossing angle scenarios provided in the C-AD “RHIC Projections” document [14], dated 28 October 2024. The C-AD calculation folds in factors such as the luminosity reduction under a $\theta = 1$ mrad crossing angle, the fraction of the collisions within the narrow vertex $|z| < 10$ cm, the expected RHIC uptime, etc. We use the “min” and “max” scenarios provided to determine the ranges of possible outcomes.

We note some additional factors that are not explicitly accounted for in these projections. First, the guidance from C-AD above does not include the potential impact of commissioning the 56 MHz cavities, which could slow the reduction of the luminosity in the $|z| < 10$ cm range over the course

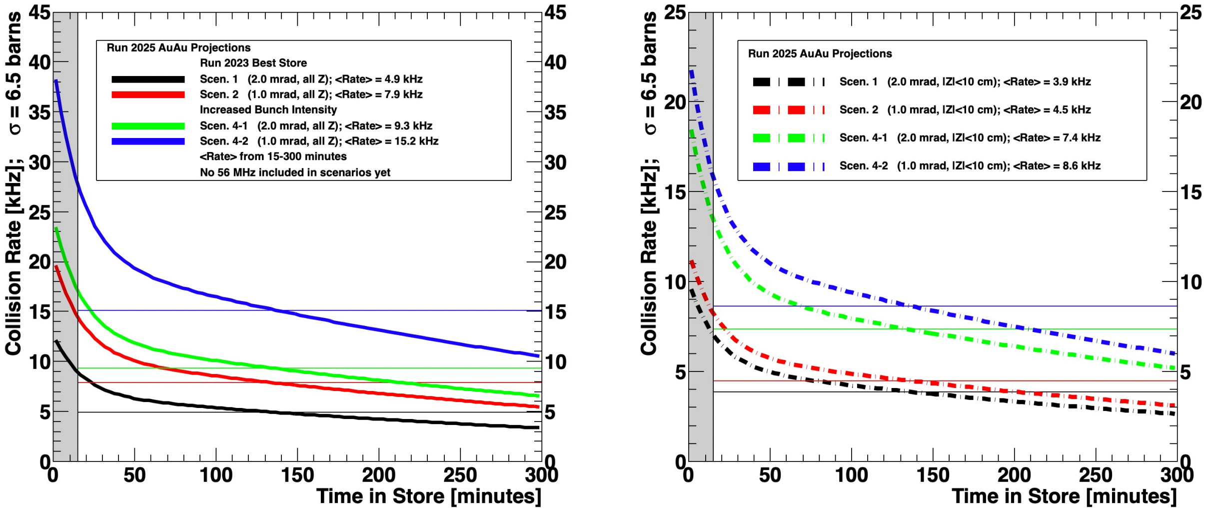


Figure 3.1: Projected Au+Au luminosity curves as a function of time in store, for a typical store under different running scenarios. These projections are based on the achieved Run-23 experience. The left and right plots show the luminosity over all z-vertices and only the subset of the luminosity within $|z| < 10$ cm. Note that the y-axis here corresponds to the ZDC coincidence rate with a given visible cross-section, which is close but not identical to the minimum-bias trigger rate.

of the fill. If achieved, this could result in as much as a +20% increase in the luminosity. Second, the calculations are based on an overall factor of 0.50 for the RHIC uptime. This factor is lower than the 0.60 value used in previous projections, accounting for the difficulty experienced in running top-energy Au+Au collisions during the summer months in Run-23. In principle RHIC may be able to sustain a higher uptime during Au+Au running in Spring and Fall, but that is not accounted for here, and the flat value of 0.50 is used in the official projections. Thus, both of these factors could help to modestly improve the integrated luminosity production per cryoweek and thus achieve the sPHENIX goal in Au+Au collisions, as discussed further below.

The second way of calculating projected luminosities is based on evaluating the "best achieved" store in Run-23, with modeling by Kiel Hock of C-AD to account for alternative crossing angles or potential improvements in the bunch intensities. Fig 3.1 shows the projected luminosity curves under different scenarios, which are based on the results of a two-component exponential fit to the achieved Run-23 experience. The curve in black (Scenario 1) represents most closely the actual luminosity curve for a best store near the end of Run-23 under crossing angle of $\theta = 2$ mrad, while the red curve (Scenario 2) shows the modeled luminosity with $\theta = 1$ mrad but otherwise the same beam conditions. These scenarios assume bunch intensities of approximately 1.45×10^9 in each ring as was achieved in Run-23 and in the Au+Au running at the end of Run-24. The curves in green (Scenario 4-1) and blue (Scenario 4-2) show the $\theta = 2$ mrad and $\theta = 1$ mrad configurations but under the assumption of an increase in the bunch intensities to 1.89×10^9 in each ring. Given that the lower bunch intensities were achieved early in the Au+Au running periods of their respective Runs, it is expected that they would increase given more time for luminosity development. Thus Au+Au Scenarios 2 and 4-2, with the $\theta = 1$ mrad crossing angle that sPHENIX demonstrated in Run-24 it could run with, can also be taken as plausible minimum/maximum ranges, with the latter considered aggressive but realistic for Run-25. When folded together with the RHIC uptime of 0.5 from C-AD guidance, these give compatible results to the official luminosity projections, which assume bunch intensities of 1.75×10^9 for the "max" performance.

For mapping out a specific run plan, we distinguish between cryoweeks and physics data-taking weeks, i.e. when Physics Running is declared by C-AD. The guidance from C-AD is that there is a 0.5 week "cool down from 50 K to 4 K", then a 2.0 week "set-up mode" for the specific collision species, and then a 0.5 week "ramp-up". If switching species, there is a combined 1.5 weeks for "set-up" and then the physics running begins "with further ramp-up" (not detailed). Lastly, at the end of the running period, there is a 0.5 "warm-up from 4 K to 50 K". In addition, we assume that in the first, second and third weeks of declared Physics Running, one achieves only 25%, 50%, and then 75% of the luminosity target, with subsequent weeks at 100%. These are standard assumptions following C-AD guidance. The luminosities are folded with an sPHENIX operational efficiency of 0.70 during this running period. This prescription leads to the specific luminosities calculated in Sec. 3.2 below.

3.2 Proposal for Run-25 and Beyond

For Run-25 Au+Au running, the sPHENIX integrated luminosity target is 7 nb^{-1} of recorded data, which corresponds to a little under 50 billion recorded minimum-bias events. With this integrated luminosity, the equivalent nucleon–nucleon luminosity in the most central 0–10% Au+Au matches the 107 pb^{-1} sampled via photon and jet triggers in calorimeter+global data in Run-24 p+p running (see Sec. 2.1). That is, the matched nucleon-nucleon luminosity ensures that comparisons of these measurements in 0–10% Au+Au and p+p collisions, such as in photon+jet events, are not statistically dominated by either the Au+Au or p+p dataset in particular. This goal corresponds to just over half of the 13 nb^{-1} of recorded Au+Au collisions proposed in 24-cryoweek scenarios in previous Beam Use Proposals 2020-2022 [12], and is considered by sPHENIX to be the minimum viable dataset to address the full breadth of the science program. While this luminosity is the target for Run-25, sPHENIX continues to seek opportunities to further increase the integrated luminosity of its Au+Au dataset.

Table 3.1 summarizes the projected luminosity ranges following C-AD guidance, all within the narrow z-vertex range $|z| < 10$ cm, which is the range for which the inner tracking subsystems have their nominal acceptance. For the Au+Au running in Run-25, the range of projections is given corresponding to the minimum–maximum range with $\theta = 1$ mrad in Sec. 3.1, which is a proven running configuration in the Run-24 Au+Au experience. We note that the luminosity target of 7 nb^{-1} is slightly above the maximum projected luminosity in a 28 cryoweek scenario of 6.4 nb^{-1}. However, it is possible that the sPHENIX luminosity target could be met in an aggressive 28 cryoweek scenario where additional targeted improvements (such as commissioning the 56 MHz cavities or increased RHIC uptime outside of the summer months, which are not assumed in the present calculations) were to become available.

The ALD has further charged sPHENIX to consider possible running scenarios in FY26, for which the Collaboration has prepared a list of priority-ordered goals for additional data-taking. This request is made if and only if the Au+Au luminosity goal of 7 nb^{-1} is expected to be met within the total number of cryoweeks, and there is sufficient time remaining for impactful physics data-taking for a given item. Such additional running could occur opportunistically in calendar year 2025,

sPHENIX Physics Target in Run-25: **7 nb^{-1} (50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\|z\| < 10$ cm
Au+Au 200 GeV	20	2.4 – 4.2 nb^{-1} recorded
Au+Au 200 GeV	28	3.6 – 6.4 nb^{-1} recorded

If Au+Au luminosity target is met, ordered priority list for additional running:		
Collision Species	Physics weeks	Projected luminosity, $\|z\| < 10$ cm
1. p+p 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. p+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming

Table 3.1: Summary of the sPHENIX Beam Use Proposal for 2025 for 20- and 28-cryoweek scenarios, and a priority-ordered list for further data-taking should additional cryoweeks become available in FY26.

after meeting the sPHENIX luminosity target in Au+Au running, in a separate Run-26 in the next calendar year, or a combination of both.

The priority-ordered list is as follows:

1. Eight weeks of supplementary p+p 200 GeV reference data taking, in a similar configuration to that at the end of the p+p period in Run-24.
2. Five weeks of p+Au running at 200 GeV.
3. Two weeks of O+O or alternative small, symmetric collision system running at 200 GeV.

The weeks in the above requests are "physics weeks" and include the impact of the initially low luminosities available at the beginning of a given running period which then increase with time. Thus, we believe they represent a realistic estimate of the impact of these running periods in the middle of an ongoing RHIC run. We note that the total number of requested physics weeks (15), together with the needed cryoweeks for cooling and warming up the collider ring, machine development, and time needed to change collision species between running periods, could fit comfortably within a standalone 20-cryoweek Run-26 scenario. However, sPHENIX is ultimately flexible about the particular ordering of running species within a given Run or between Runs, if it is helpful in achieving the full program.

The motivation for supplementary p+p running is to double the p+p reference for the quarkonia, b-jet, and track-based jet (sub-)structure parts of the physics program since, as described above in Sec 2.1, this part of the program achieved the smallest fraction of its BUP23-quantified goal of 45 pb^{-1} and thus poses a serious challenge to these aspects of the program. The projected luminosity is estimated from that achieved at the end of Run-24 with $\theta = 1.5$ mrad running, corresponding to approximately 2 pb^{-1} per week sampled with rare triggers in the narrow $|z| < 10$ cm vertex range. An additional 30% of this luminosity would be recorded in streaming mode, more than doubling the open heavy flavor component of the physics program successfully and bringing it above its BUP23-quantified goal.

High-luminosity p+Au running was an exciting component of the original envisioned sPHENIX science program, which sPHENIX was forced to deprioritize only as a response to large decreases in the projected luminosities for large collision system and polarized proton running. Recovering this part of the program with a p+Au dataset would for the exploration of cold nuclear matter effects and collective phenomena in small systems with state-of-the art detector instrumentation, including the qualitatively new capabilities of sPHENIX at RHIC. The data would be collected in a high-luminosity mode, producing large datasets for studies of hard process rates, jet structure, and quarkonia production in the cold nuclear environment. A fraction of the data would be taken in partial streaming mode, enabling a large unbiased open heavy flavor sample. Finally, the protons would be transversely polarized, allowing for transverse single spin asymmetry and other cold QCD measurements over a wide kinematic range. The projected p+Au luminosity range given in Table 3.1 is estimated using C-AD guidance as input, but should be considered with a significant uncertainty given the ten years since the last time RHIC ran in this mode.

As a specific note about this collision system, since p+Au running uses the Yellow-ring Au beam and its associated beam backgrounds which induce MVTX ARs, a technical solution would need to be developed to have the MVTX read out in streaming (rather than triggered mode) for the open heavy flavor program in this system. Thus, if there were a scenario in which p+Au running preceded Au+Au, this would be a challenge for sPHENIX.

Finally, before the end of RHIC operations, running smaller, symmetric collision species, such as O+O or Ar+Ar would provide a major opportunity for key insights on some of the outstanding puzzles in the field of heavy-ion physics related to collective, high-density effects in small systems [15]. For illustrative purposes, we pick O+O as a nominal proposal, with additional discussion in Section 4.4. For the O+O running, we use the experience reported by C-AD in RHIC Run-21 with O+O collisions in STAR [14]. RHIC delivered approximately 16 nb^{-1} per week with $\theta = 1.65$ mrad crossing angle, resulting in a vertex width of 12 cm. Assuming similar running conditions and taking into account sPHENIX uptime and the $|z| < 10$ cm requirement, we estimate that even in a short two-week running period sPHENIX could sample 13 nb^{-1} with rare triggers and record a significant fraction of minimum-bias events in streaming mode. We note that the resulting O+O dataset would be a major increase in data over that recorded by STAR in Run-21, which corresponded to approximately 1 nb^{-1} of minimum-bias events and 250M high-multiplicity-triggered events, and would be timely given the upcoming O+O run at the LHC in 2025.

Chapter 4

Physics Projections

4.1 Projections for Run-25 Au+Au

The sPHENIX science mission is based on probing the QGP with jet, direct photon, and heavy-flavor measurements. The impact of this scientific program critically relies on the large acceptance, high data readout rate, and extensive RHIC luminosities for statistical precision and systematic control. Run-25 has long been planned to be the “golden” Au+Au dataset for sPHENIX, with the large luminosity to be collected enabling a suite of detailed jet structure, photon-tagged jet production, high-p_T hadron, jet-hadron correlation, heavy-flavor jet, open heavy flavor, Upsilon measurements, and other channels, for many years of physics analysis.

To illustrate how the integrated luminosity is a driver of the sPHENIX science case, the projections presented in this section highlight some of the flagship measurements which are the most sensitive to large statistical data samples. We evaluate the expected statistical uncertainties according to the minimal Au+Au luminosity of 2.4 nb^{-1}, which is the pessimistic scenario provided by C-AD for a shorter 20-cryoweek Run-25, and for the sPHENIX target luminosity of 7 nb^{-1} as described in Section 3.2. The projections are based on a variety of sources, including perturbative QCD (pQCD) calculations of cross-sections and/or simulations using Monte Carlo (MC) generators such as PYTHIA or JEWEL, and include some attempts to model realism such as the impact of reconstruction and selection efficiencies, or irreducible backgrounds which contribute to statistical uncertainties. In some cases, the Au+Au projections are centered at values approximately predicted by theoretical calculations to illustrate how the size of a possible physics signatures compares to the expected uncertainties in data. A more detailed description, including additional projections, can be found in previous sPHENIX BUP documents [12, 13].

An important category of measurements is related to the internal (sub-)structure of reconstructed jets. This broad category includes single-particle fragmentation functions and jet shapes, sophisticated de/re-clustering sub-structure observables, energy-energy correlators in jets, and more. These measurements rely on high luminosities to select a large population of jets whose properties can be precisely measured. As one specific example, the left panel of Figure 4.1 shows the expected uncertainties on the groomed jet radius R_g. For context, the magnitude of the modification in this quantity for jets in a similar kinematic range observed in A+A collisions at the LHC is also shown. It can be seen that the minimal luminosity scenario results in large uncertainties, making it

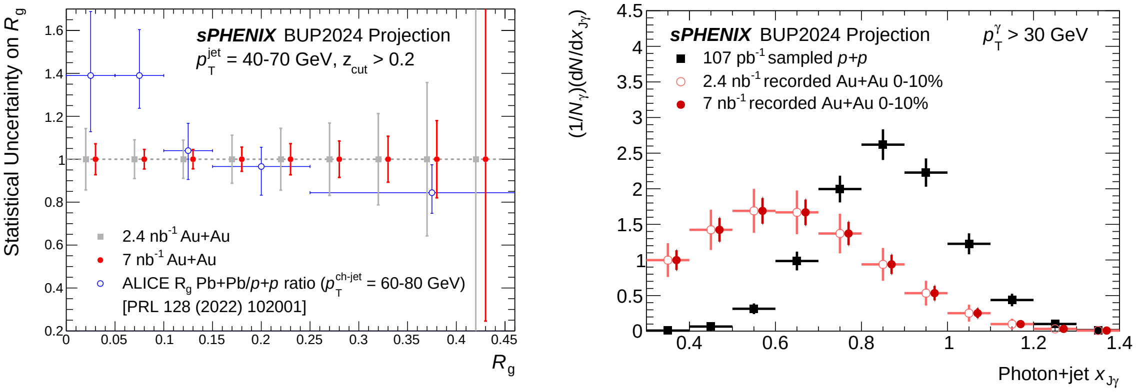


Figure 4.1: Left: Projection for the statistical uncertainty on measurements of the groomed jet radius R_g for $p_{\mathrm{T}}^{\mathrm{jet}} = 40\text{–}70$ GeV. The gray and red points represent the minimum 2.4 nb^{-1} luminosity scenario and the sPHENIX Au+Au target of 7 nb^{-1}, respectively. The projected uncertainties are compared to the magnitude of the modifications observed by ALICE for jets in a similar kinematic range. Right: Statistical projections for the distribution of photon+jet p_{T} ratio $x_{\mathrm{J}\gamma}$, for events with $p_{\mathrm{T}}^{\gamma} > 30$ GeV photons. The approximate shapes of the distributions are taken from the JEWEL MC generator to demonstrate the possible size of physics signals. The black points are a projection based on the collected calorimeter-only p+p reference dataset in Run-24. The open and filled red markers represent the projection of the minimum and target Au+Au luminosities in Run-25.

challenging to make a precise measurement of potential physics effects, while the sPHENIX luminosity target results in a significant reduction of these uncertainties. The right panel of Figure 4.1 shows a projection for the photon+jet p_{T} ratio measurement, another flagship for the experiment. The sPHENIX luminosity target results in a precise distribution which can be used to map out the QGP-induced modifications in detail, as well as provide a sample of photon-tagged jets for (sub-)structure or energy-flow studies.

Figure 4.2 shows two examples of the impact of the Au+Au luminosity on open and closed heavy flavor observables. The left panel shows projected measurements of the b-jet azimuthal anisotropy in central- and mid-central collisions. This measurement is highly dependent on acquiring a large luminosity, due to the small cross-section for high-p_{T} b-jets as well as the significant challenge in tagging such jets in a heavy-ion environment. In this case, the sPHENIX target luminosity is required for a definite measurement of the physics effect, with the uncertainties in a minimum luminosity scenario potentially similar in size to the magnitude of the signal. More generally, a large Au+Au luminosity is essential for measuring b-jet production rates and properties (a unique capability of sPHENIX at RHIC), and making a precision comparison to the analogous quantities for inclusive jets as a way of constraining the mass effect in parton-QGP interactions.

The right panel of Figure 4.2 shows the projected uncertainties on the ratio of the Upsilon 2S to 1S yields, in both central Au+Au events and p+p data. In the Au+Au case, in the minimal luminosity scenario the uncertainties on the ratio are comparable to the expected difference with respect to the measured p+p baseline. The sPHENIX luminosity target would result in a significant improvement in the ability to constrain the modification of the 2S/1S ratio in QGP, and to do so differentially in p_{T} and centrality.

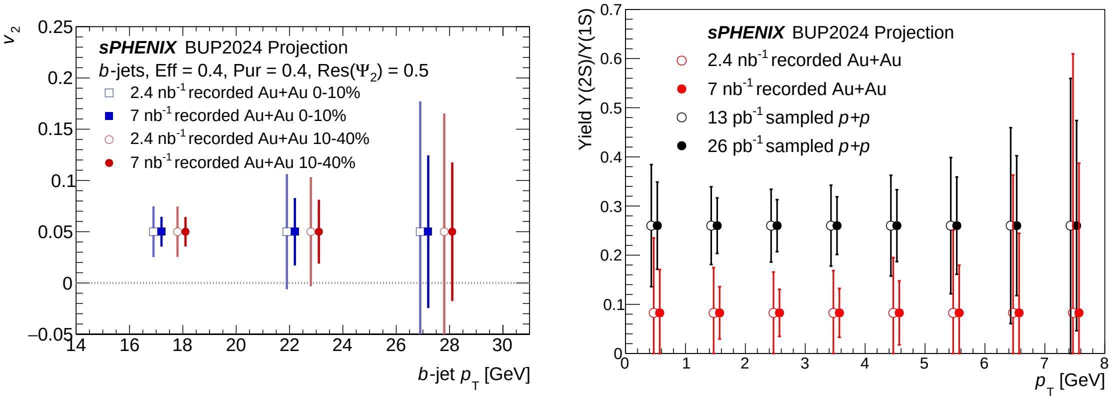


Figure 4.2: Left: Statistical projection for the b-jet azimuthal anisotropy v_2 for two different centrality selections, including quantified assumptions about the tagging efficiency and purity. The open and filled points correspond to the minimal Au+Au Run-25 luminosity and the sPHENIX 7 nb^{-1} luminosity target. Right: Statistical projections for the Upsilon 2S/1S yield ratio as a function of p_T in Au+Au (red) and p+p (black). The open points correspond to the minimal luminosity scenario for Au+Au and the triggered full-subsystem data recorded in Run-24 for p+p, respectively. The filled points correspond to the improved luminosity scenarios of the sPHENIX 7 nb^{-1} Au+Au target and from an additional eight physics weeks of supplementary p+p data, respectively.

4.2 Projections for supplementary p+p running

While some measurements of rare probes of the Quark-Gluon Plasma can be carried out solely in the Au+Au system, the majority of the sPHENIX scientific program crucially relies on a comparable p+p dataset, both to benchmark the vacuum QCD reference directly in data and for calibration purposes. Without an appropriate p+p reference in data, the modification of rare probes in Au+Au becomes difficult to interpret as one must rely on a vacuum baseline with large uncertainties or with a theoretical expectation, and the scientific impact is reduced.

In the Beam Use Proposal 2023 [13] process, after it was found that the projected luminosities from RHIC during sPHENIX running would be significantly lower than planned, the PAC endorsed a minimum p+p luminosity target of 45 pb^{-1} sampled with rare probes triggers, and 4.5 pb^{-1} of minimum-bias tracking-only data taken in streaming readout mode. For purely calorimetric observables, the collected p+p reference data of 107 pb^{-1} is a good match to the Au+Au luminosity target. However, the triggered plus all-subsystem dataset to be used for the jet-track, b-jet, and Upsilon baseline contains 13 pb^{-1}, representing only 30% of the BUP'23-defined luminosity target. This low integrated luminosity is a serious challenge to those aspects of the science program, and a major motivation for supplementary p+p running. The streaming dataset in Run-24 achieved 2.9 pb^{-1} which, while representing a major technical and scientific advance, is still only approximately 65% of the BUP'23 defined goal, affecting the open heavy-flavor charm and bottom baselines.

sPHENIX proposes, as the highest priority given sufficient available beam time, eight weeks of supplementary p+p data-taking. Based on the RHIC performanced achieved at the end of Run-24, this is expected to double the jet-track, b-jet, and Upsilon p+p baselines, bringing the luminosity of the sample to more than 50% of the 45 pb^{-1} target, and to successfully meet the luminosity target for the streaming dataset of 4.5 pb^{-1}. Thus, after this, RHIC would have successfully delivered the

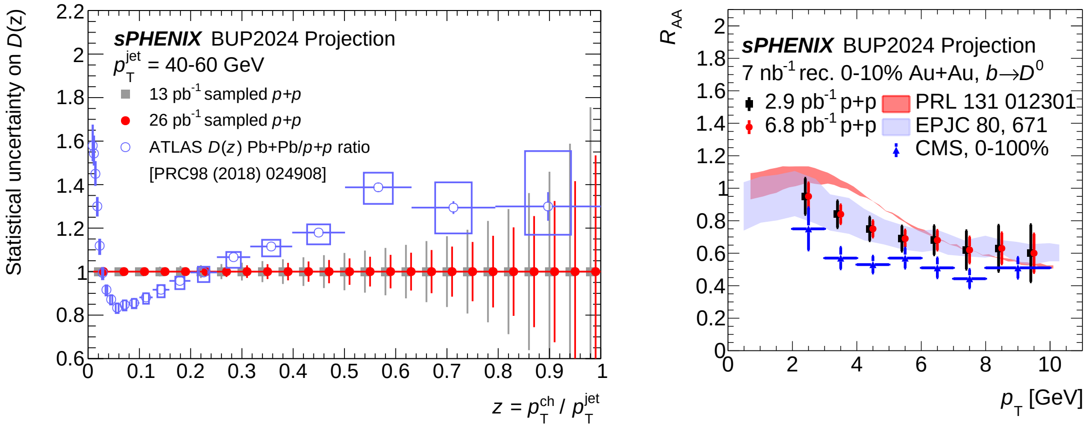


Figure 4.3: Left: Projection for the statistical uncertainty on the jet to charged hadron fragmentation function $D(z)$ for $p_T = 40$–60 GeV jets in p+p data. The gray and red points represent the statistics in the triggered full-subsystem dataset recorded in Run-24 and the impact of an additional eight weeks of supplementary p+p running. The uncertainties are compared to the magnitude of the fragmentation function modification found at the LHC by ATLAS. Right: Statistical projections for the R_{AA} of non-prompt $b \to D^0$'s as a function of p_T in central events, under different p+p streaming dataset scenarios. The CMS measurement of $b \to D^0$ is shown for comparison. While there are $b \to e$ measurements at RHIC in Au+Au events, the sPHENIX measurement in this channel would be unique.

luminosity targets for two out of three p+p dataset types, and would achieve more than halfway on the third, representing a major overall success for the p+p part of the program. sPHENIX believes that the luminosity provided by eight weeks of running is the minimum needed to have an impact on the p+p baseline. Thus, the supplementary p+p running is considered the highest priority only if this amount of additional beam-time is available.

The left panel of Figure 4.3 demonstrates the impact of the supplementary p+p running on “jet-track” observables, a broad category which includes charged-hadron fragmentation functions, sophisticated sub-structure observables with tracking+calorimeter “particle flow”-style jet reconstruction, energy-energy correlators with tracks in the jet cone, and wide angle jet-hadron correlations. In the figure, the statistical uncertainties on the fragmentation function $D(z)$ for a sample of high-p_T jets is used as an example, with additional p+p running significantly reducing the statistical uncertainties in the high-z region, especially compared to the potential magnitude of the modifications as observed at the LHC. We emphasize that this is just one example, with all observables relying on full-subsystem calorimeter and tracking information being similarly affected. The right panel of Figure 4.3 shows the impact for the open heavy flavor baseline. For the nuclear modification factors of charm and bottom, measured in this example through prompt and non-prompt D^0's, the p+p reference is the statistically-limiting one. Thus the supplementary p+p running translates into reduced uncertainties in, for the example in Figure 4.4, the non-prompt D^0 R_{AA}. Reducing these uncertainties is important for distinguishing between overall models, constraining specific model parameters, and for complementarity with such measurements at the LHC.

Furthermore, Figure 4.1 in Section 4.1 also shows the impact of supplementary p+p running on the Upsilon baseline at RHIC. The proposed doubling of the Upsilon statistics would significantly

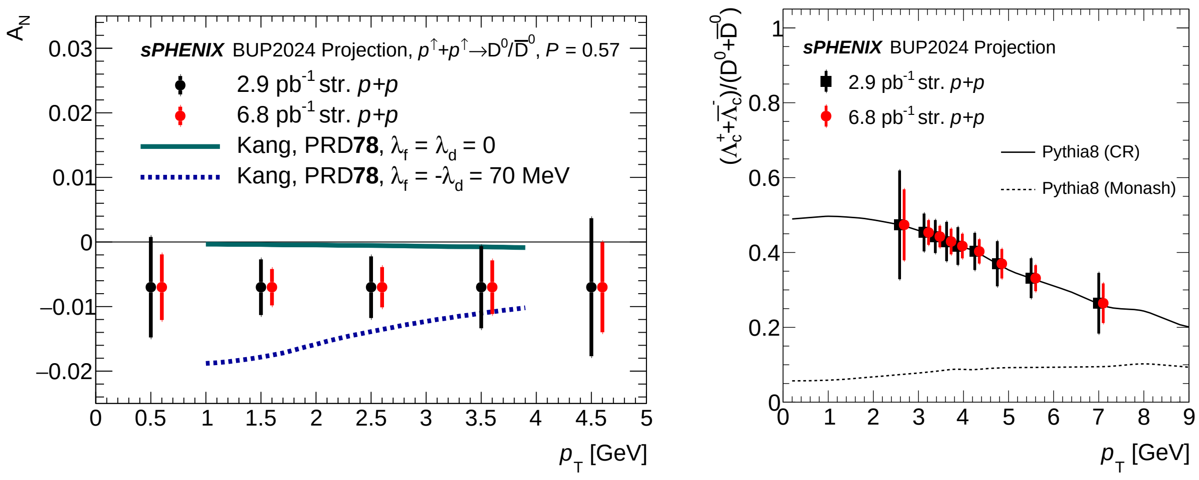


Figure 4.4: Impact of additional streaming-readout p+p data on unique sPHENIX measurements. Left: Statistical projections for the D^0 single spin asymmetry A_{N} as a function of p_{T} in polarized $\vec{p}+\vec{p}$, under different luminosity scenarios. Theoretical calculations for two different physics scenarios are shown for comparison. Right: Statistical projection for the Λ_c/D^0 ratio as a function of p_{T} in p+p data, under different luminosity scenarios. The predictions of PYTHIA8 with different tunes are shown as curves.

decrease the uncertainties in the 2S/1S ratio, which is crucial in establishing the significance of any observed modification in Au+Au. Thus for the sPHENIX Upsilon program, it is both the Au+Au and p+p luminosities which are drivers.

In addition to greatly improving the statistical sample of the p+p reference for key Au+Au measurements, supplemental p+p running would have a major impact on RHIC-unique measurements just in the p+p system, capitalizing on the capabilities of sPHENIX. The left panel of Figure 4.4 shows the projected uncertainties for a measurement of $D^0/\overline{D^0}$ transverse single spin asymmetry. This measurement would probe a unique quantum phenomenon in the gluon Sivers effect, with a clear connection to the EIC. The right panel of Figure 4.4 shows the projected uncertainties for a measurement of the baryon-to-meson ratio in the charm sector, Λ_c/D^0. This quantity has not been previously measured in p+p collisions at RHIC, with major differences predicted by the models. The lack of a p+p reference thus translates into a significant uncertainty in the interpretation of its value in Au+Au collisions (for which sPHENIX is also expected to bring an order-of-magnitude or larger improvement). Furthermore, other ratios of identified heavy flavor hadrons can be studied differentially as a function of p_{T}, event multiplicity, etc.

4.3 Projections for p+Au running

The sPHENIX Collaboration maintains a long-standing and major interest in finding an opportunity for high-luminosity, polarized p+Au running before the end of the RHIC program. p+A style collision systems have led to major paradigmatic shifts in the field of heavy ion physics with key experimental input, for example the small systems "geometry scan" [16], originating from unique

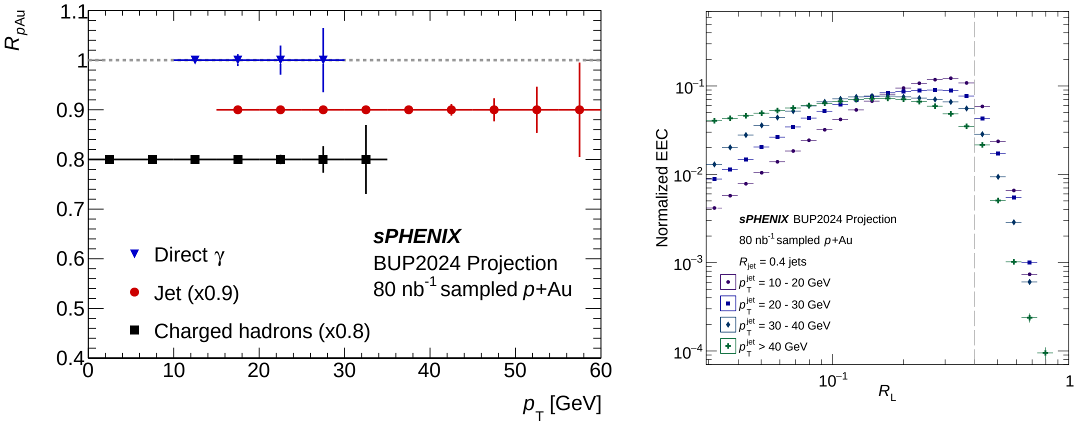


Figure 4.5: Statistical projections for light flavor measurements in five weeks of p+Au running in sPHENIX. Left: Projected nuclear modification factor in centrality-integrated collisions for jets, charged hadrons, and direct photons. The different point series are vertically offset for visibility. Right: Projected uncertainties on two-point energy-energy correlators in differential selections on jet p_T.

RHIC capabilities.

The sPHENIX detector, primarily designed to study the QGP with jet, photon, and heavy-flavor probes with its trigger and high DAQ rate capabilities, would provide key opportunities for cold QCD and small system collectivity measurements. These comprise a broad range of physics measurements, including measurements of jet, hadron and heavy flavor collective motion, measurements with transversely polarized beams, and studies of transverse momentum dependent (TMD) effects and hadronization in p+p and p+A collisions.

In previous Beam Use Proposals, sPHENIX has laid out a detailed case for p+A running which describes multiple aspects of the potential physics program. In this proposal, we instead highlight some illustrative opportunities with quantitative projections updated to match the current best estimate of RHIC performance for five weeks of p+Au running in 2025 or 2026.

The p+Au data-taking is projected to result in large samples of hard probes which would allow a variety of detailed, p_T-differential measurements. The left panel shows the expected statistical uncertainties on measurements of the nuclear modification factor R_{pA} for photons, jets, and charged hadrons, as one indication of the physics impact of this luminosity. Such measurements could help constrain the nuclear gluon PDF modification in particular (x, Q^2) ranges [17]. In addition to the overall hard process rates, this dataset would also allow for the detailed study of reconstructed jet properties in the nuclear environment. For example, a Preliminary measurement at Hard Probes 2024 by ALICE showed a surprising modification of two-point energy-energy correlations for jets in p+Pb collisions. As shown in the right panel of Figure 4.5, the sPHENIX statistics and capabilities would allow for a highly detailed study of this particular signature, as well as others related to jet properties and modification, in an overlapping kinematic range.

The left panel of Figure 4.6 shows the expected statistical uncertainties for measurements of the azimuthal anisotropy in high-multiplicity p+Au events after five weeks of running. For the light sector, there is a broad coverage in kinematic range, including the high-p_T region where, in large systems, such signatures would be attributed to jet quenching. Crucially, the unique sPHENIX

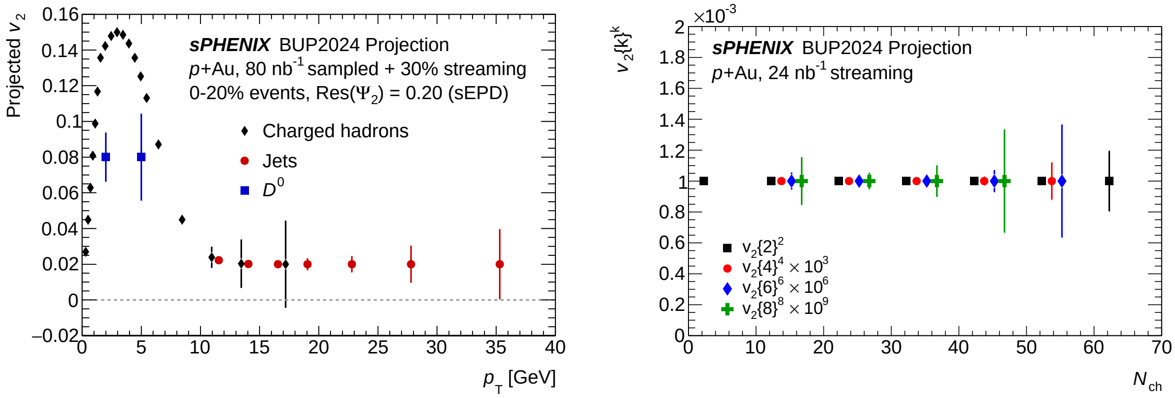


Figure 4.6: Statistical projections for flow and correlation measurements in five weeks of p+Au running in sPHENIX. Left: Projected v_2 vs. p_T for charged hadrons and jets (from triggered data) and open charm (from streaming dataset). Right: Statistical projections for charged hadron cumulants up to eighth order, leveraging the sPHENIX hybrid triggered + extended streaming readout.

streaming readout capability also allows for a study of heavy flavor modification in small systems at RHIC, for example with a measurement of the v_2 as shown here. Together with the measurements of hard process rates and jet properties noted above, an sPHENIX p+Au dataset could definitively map out the combined picture of high-p_T processes in high-multiplicity collisions. In addition, the large acceptance and high efficiency of the tracking system make sPHENIX an excellent tool to explore statistics-hungry multi-particle correlations, with an example projection of cumulant measurements as a function of multiplicity shown in the right panel of Figure 4.6.

We further stress that p+Au running enables a significant cold QCD program, with clear connections to the physics of the Electron Ion Collider. In transversely polarized p+Au running, there are unique opportunities, for example in measurements of charged-hadron transverse single spin asymmetries deeply differential in p_T and x_F, and in Collins and IFF asymmetries. Other measurements, such as studies of jet hadronization in a nuclear medium, non-perturbative transverse momentum effects in γ+hadron correlations, and quarkonia polarization, do not rely on the polarization of the proton beam.

4.4 Projections for small collision system running

Since the original design of sPHENIX for high-statistics probes of the Quark-Gluon Plasma in large collision systems and in collective QCD effects in small collision systems, there has been a significant interest in the heavy-ion physics field in so-called symmetric “light ion” systems [15], such as oxygen–oxygen (O+O), argon–argon (Ar+Ar), etc. These systems are thought to provide a unique way to reconcile the surprising lack of strong final-state jet quenching effects in p+A-type collisions, which otherwise show broad and durable signatures of collective phenomena well described by relativistic hydrodynamics. For example, centrality-integrated O+O collisions would not suffer from the multiplicity biases (vetoes) present in high-activity p+A (low-activity A+A) collisions, allowing for a focused search for the onset of final-state interactions for high-p_T probes.

This type of running would be very timely given the planned LHC operation of O+O collisions

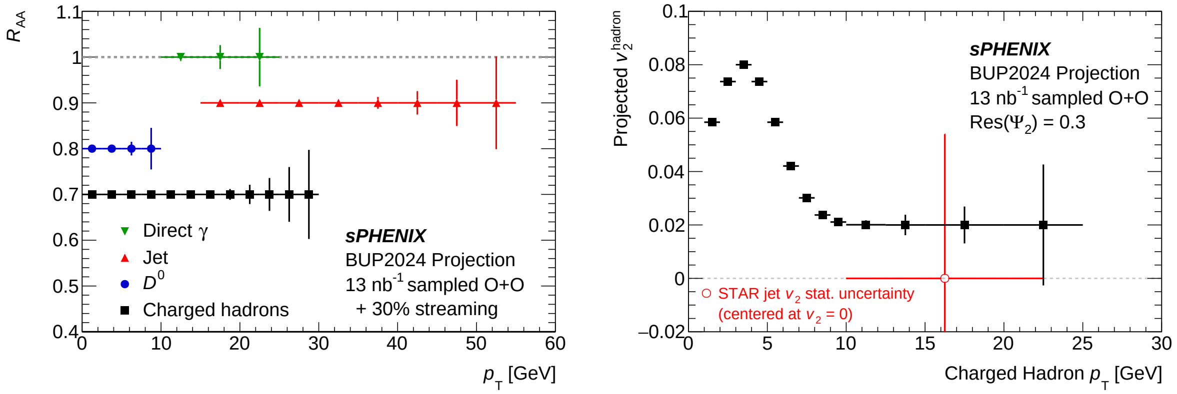


Figure 4.7: Statistical projections for key sPHENIX measurements in two weeks of O+O running. Left: Projected statistical uncertainties for R_{AA} measurements in centrality-integrated O+O collisions as a function of p_T for a variety of final states, including isolated photons, jets, unidentified charged hadrons, and open charm. The y-axis values are chosen arbitrarily to illustrate the possible magnitude of quenching effects. Right: Projected statistical uncertainties for a charged hadron azimuthal anisotropy v_2 measurement. The data are compared to a recent Preliminary measurement by STAR. Since that measurement has not been corrected for a potential event-plane bias, it is shown here centered at $v_2 = 0$ to compare the size of the statistical uncertainties.

in the summer of 2025, allowing for key RHIC-LHC comparisons in the identical system at very different energies. We note that, given the high sPHENIX DAQ bandwidth and efficient trigger capability for rare probes, even a short two week period of O+O data-taking would allow sPHENIX to sample a significant luminosity, which is an order of magnitude more data than that taken in the short Run-21 O+O by STAR.

As just one example of the potential physics output, the left panel of Fig 4.7 shows the expected kinematic reach for the nuclear modification factor R_{AA} of inclusive cross-sections, highlighting the separate capabilities for different colorless, light, and heavy flavor probes. We emphasize that a significant open heavy flavor sample can be collected using the streaming capability of the trackers. The statistics are also expected to be sufficient for a variety of correlation or (sub-)structure measurements. The right panel of Fig 4.7 shows the expected kinematic reach for azimuthal anisotropy measurements, with the potential to map out the transition from low-p_T collective flow to the high-p_T region traditionally associated with path-length dependent energy loss in detail. For comparison, the current uncertainties and p_T coverage from a Preliminary STAR measurement, presented at Quark Matter 2023 and made using the short RHIC O+O running in 2021, are shown.

Finally, we highlight that the RHIC program has an excellent track record of uncovering new physics and gaining insights from every novel nuclear species combinations put into collision. It is a testament to the facility and its constant improvements, including the Electron Beam Ion Source (EBIS), that have been the lifeblood of the machine. Thus, a last opportunity to run smaller symmetric collision species, such as O+O and Ar+Ar, before the conclusion of RHIC operations, is essentially guaranteed to provide fresh insights and resolve some key outstanding puzzles in the field. The proposal here uses O+O collisions since this is a proven capability of the machine in 2021, and to highlight the complementarity with the LHC, but we note that there is a similar physics case to be made with other light ions such as Al+Al, Ar+Ar, etc., which has been described in previous sPHENIX Beam Use Proposals.

Chapter 5

Summary

sPHENIX is the first new collider detector at RHIC in over twenty years, designed to perform high-precision studies of jet production, jet sub-structure, and open and hidden heavy flavor over an unprecedented kinematic range at RHIC. The experiment is a specific priority of the DOE/NSF NSAC 2015 Long Range Plan and will play a critical role in the completion of the RHIC science mission by enabling qualitatively new measurements of the microscopic nature of Quark-Gluon Plasma. sPHENIX is distinguished by its high data-recording rate and large geometric acceptance, combined with high precision tracking, hermetic electromagnetic and hadronic calorimetry, and unique streaming readout capabilities.

The sPHENIX detector was successfully commissioned in Run-24 and took a large amount of p+p physics data, achieving a major, but not full, portion of its luminosity targets in this system. After the three-week Au+Au running at the end of Run-24, the Collaboration is confident that the detector is in a good position to collect high-quality Au+Au data with all sub-systems operating with their full design capability in Run-25.

The remaining running periods play a critical role in fulfilling the sPHENIX science mission outlined in the U.S. Long Range Plan for Nuclear Science:

- The top priority is focused on collecting a very large statistics Au+Au dataset for measurements of jet and heavy flavor observables with unprecedented precision. The sPHENIX integrated luminosity target is 7 nb^{-1}, corresponding to 50 billion minimum-bias events.
- If and only if the sPHENIX luminosity target in Au+Au data is expected to be met and sufficient time is available, the Collaboration has constructed a priority-ordered list of additional running. At the top of the list is eight weeks of supplemental p+p data-taking to increase the reference statistics for key measurements. Following this, sPHENIX requests five weeks of p+Au and two weeks of O+O running, as qualitatively new collision systems which would apply the unique capabilities of sPHENIX to capitalize on the versatility of the RHIC machine.

The members of the sPHENIX Collaboration, comprising 350 scientists from 50 institutions in 11 countries, with a large workforce of junior scientists who have been working full-time for years towards the success of the experiment, are excited for the unique physics opportunities enabled by this run plan and to positively conclude the scientific mission of RHIC.

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