STAR Beam Use Request for the Continuation of Run 25

STAR Collaboration

October 2025

Executive Summary

In this addendum to the original 2025 Beam Use Requests [1], the STAR Collaboration outlines highly compelling physics programs proposed for data taking after the completion of the Au+Au program at top energy, before the RHIC shutdown. **Our plans leverage recent detector investments, address fundamental questions in QCD, and can serve as a vital bridge to the EIC era.** The STAR Collaboration reiterates that its plans secure a maximum scientific return from the facility's final operational years, directly addressing both the structure of matter and the nature of the QCD phase diagram.

As of October 3, 2025, in 200 GeV Au+Au collisions, we have collected 4.7 B minimum-bias events and sampled 13.0 nb^{-1} of luminosity for high-transverse-momentum (p_T) triggers, corresponding to 52% and 45% of our goals, respectively. Based on the two-week average before the 69 kV power issue, and assuming we resume physics on October 7, we project reaching the minimum-bias goal on December 31 and the high-p_T goal on December 25.

STAR's **highest scientific priority** is to complete the *must-do* Cold QCD physics program enabled by the newly installed suite of forward detectors, through the collection of **transversely polarized p+Au data at 200 GeV**. We request at least 5 weeks of physics running to achieve a sampled luminosity of 0.22 pb^{-1}, assuming a proton beam polarization of 53%. This dataset will enable the first exploration of the gluon GPD, provide sensitivity to the nuclear dependence of PDFs, FFs, and TMDs, allow studies of non-linear QCD effects, and potentially reveal novel vortical configurations.

STAR's **next priority** is a substantially large **fixed-target dataset for the QCD critical point search** at 4.5 GeV and 4.2 GeV. In a 3-week scenario, STAR expects to collect 2 billion events at each energy. In the 2-week scenario, STAR will collect 2 billion events at 4.5 GeV and 0.5 billion events at 4.2 GeV. In a 1-week scenario, STAR will focus on 1 billion events at 4.5 GeV.

In addition, STAR requests 250 million **isobar events (Zr+Zr and Ru+Ru combined)** each at two energy points (27 GeV and 62 GeV) to measure charge transport. We estimate this requires approximately one week of running (including setup). These measurements will represent a significant and unique advance in our understanding of quark and gluon transport in relativistic heavy-ion collisions.

Contents

1 Cold QCD & Spin: The Structure of Matter

Proton-nucleus collisions at RHIC provide a unique environment to study QCD in nuclear matter, with the additional advantage of a **transversely polarized proton beam**. The proposed measurements are essential to constrain initial-state effects and understand how parton distributions, fragmentation, and transverse-momentum dynamics are modified in nuclei. They are also critical for universality tests with the EIC: a 2.5-week dataset would not provide statistics comparable to the EIC projections, making such tests impossible.

The STAR forward upgrade enables full jet reconstruction at $2.5 < \eta < 4$, charged-hadron PID down to 0.2 GeV$/c$, and extended kinematic coverage to both high-x (for TMD physics) and low-x (for saturation physics). To fully exploit these capabilities, we **propose at least five additional weeks of p+Au physics running**. Without this data, the upgrades would be underutilized, and RHIC would miss critical opportunities to deliver high-impact results in Cold QCD and Spin physics.

STAR has requested 10.5 weeks of p+Au data-taking since BUR23 [1–3]. A 5-week scenario was investigated per PAC request, but it would only allow a limited set of physics goals to be achieved, and the reduced beam polarization (53% as in Run-24, lower than the 60% achieved in Run-15 p+Au) would further diminish sensitivity to spin observables. **The 2.5-week p+Au scenario does not satisfy the statistical requirements for any of the measurements.** Table 1 summarizes the projected luminosity provided by CAD, the luminosity for 5- and 2.5-week PAC requests calculated from CAD projections, and the feasibility of our physics measurements.

- **Nuclear Parton Distribution Functions (nPDFs)**

  Compared to the well-constrained free proton PDFs, nPDFs are still subject to large uncertainties, especially for sea quarks and gluons at low to intermediate momentum fractions x. RHIC offers a unique kinematic window at moderate Q^2 and low-to-intermediate x, where nuclear modifications are expected to be significant. Future p+Au data will enable precision measurements that are highly complementary to both LHC and future EIC studies. Drell-Yan production at forward rapidity provides sensitivity to sea quark modifications, while direct photon production offers direct constraints on the gluon distribution. Existing STAR results from Run-15 already demon-

Table 1: Luminosity of p+Au collected during Run-15 and its 5-week projection provided by CAD

Time	CAD $\frac{Lumi.}{week}$	*Lumi.* per PAC Req. (calc. from CAD number)	nPDF	Saturation	GPD	TMD
Run-15	0.233 pb^{-1}	0.45 pb^{-1} (5w, collected)	✓	di-π^0 (✓)	✓	✓
June 2023	0.233 pb^{-1}	0.52 pb^{-1} (5w)	✓	di-π^0 (✓) di-$h^\pm$ (✓)	✓	✓
BUR23-24	0.120 pb^{-1}	0.27 pb^{-1} (5w)	Limited	di-π^0 (×) di-$h^\pm$ (✓)	Limited	Limited
BUR25	0.095 pb^{-1}	0.22 pb^{-1} (5w)	Limited	di-π^0 (×) di-$h^\pm$ (✓)	Limited	Limited
BUR25 Ext.	0.095 pb^{-1}	0.07 pb^{-1} (2.5w)	×	×	×	×

strate the feasibility of such measurements, and additional data will substantially improve precision.

- **Non-linear QCD and Saturation Physics**

  A second area of opportunity is the study of non-linear QCD effects. Theoretical frameworks such as the Color Glass Condensate predict that, at sufficiently small x, gluon densities in nuclei become so large that non-linear recombination effects counterbalance gluon splitting, leading to the emergence of a saturation scale Q_s. This phenomenon is expected to be enhanced in heavy nuclei due to the scaling $Q_s^2 \propto A^{1/3}$. STAR, with its forward rapidity coverage, is uniquely positioned to access the semi-hard kinematic regime where Q_s reaches values of a few GeV, making saturation effects experimentally testable. Previous measurements at STAR [4] have already shown suppression of back-to-back π^0 correlations in p+Au relative to $p+p$, which is qualitatively consistent with saturation expectations. With upgraded forward detectors, future runs will extend these studies to di-charged hadron (see projection in Fig.1), photon-jet, photon-hadron, and di-jet correlations. These channels reduce background contributions and provide a cleaner probe of the underlying gluon dynamics. These measurements represent the most stringent opportunity to test the universality of the saturation picture in hadronic collisions before the EIC era.

- **Ultra-peripheral Collisions**

  In addition to hard scattering, p+Au collisions at RHIC also provide unique opportunities through ultra-peripheral collisions (UPCs), in which the proton interacts with the intense electromagnetic field of the nucleus. In this configuration, the nucleus acts as a source of quasi-real photons, giving access to photon-proton and photon-nucleus interactions. Exclusive vector meson production in UPCs, such as J/ψ and Υ, provides direct sensitivity to the gluon generalized parton distributions (GPDs) and to the transverse spatial distribution of gluons in nuclei. RHIC is particularly well suited to measure such processes at intermediate photon-proton center-of-mass energies, complementary to the higher-energy reach of the LHC. The kinematic regime accessible at

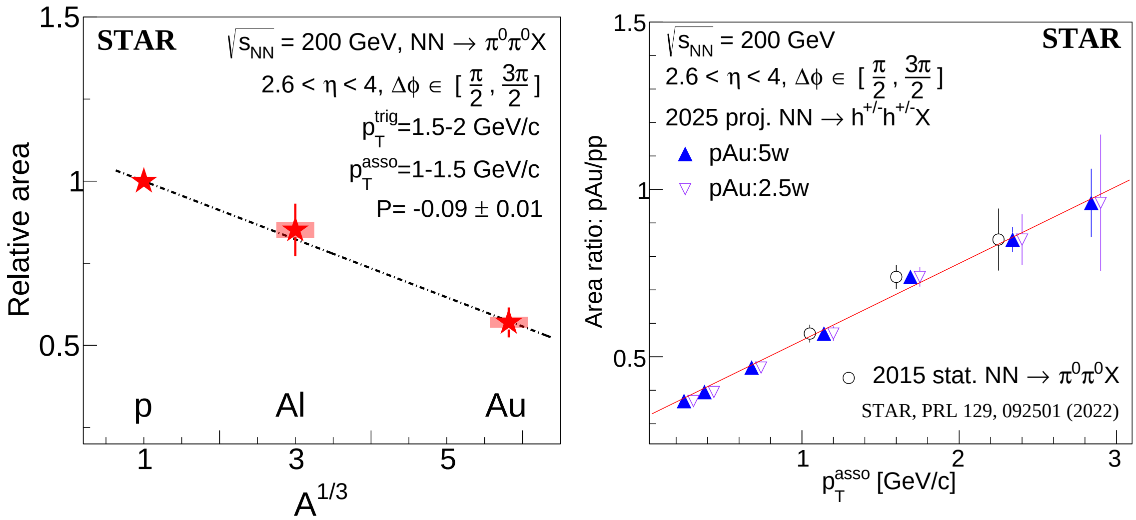

Figure 1: Left: Relative area of back-to-back di-π^0 correlations at forward pseudorapidities ($2.6 < \eta < 4.0$) in p+Au and p+Al relative to p+p collisions for $p_T^{\rm trig} = 1.5{-}2$ GeV$/c$ and $p_T^{\rm asso} = 1{-}1.5$ GeV$/c$. **Right:** Relative area of back-to-back di-$h^{\pm}$ correlations at forward pseudorapidities ($2.6 < \eta < 4.0$) in Run-25 p+Au with respect to Run-24 p+p collisions, in comparison with the published Run-15 di-π^0 results. The black open circles represent the published Run-15 di-π^0 data points with statistical errors only. The rest of the data points come from the projected statistical errors under five weeks and two and half weeks of p+Au data-taking assumptions for Run-25.

RHIC is also of direct relevance to the EIC, enabling cross-checks of universality and providing baseline data for future precision studies. With additional 5 weeks of p+Au runs, STAR can significantly improve the statistics of UPC measurements (see Fig. 2 left panel) and further constrain the coherent and incoherent vector meson production mechanisms.

- **Nuclear modification of single spin asymmetries**

  STAR has pioneered the use of jets and their substructure as a powerful tool to study both initial- and final-state TMD effects with a polarized proton beam. An additional five weeks of polarized p+Au running would enable high-precision measurements of hadron-in-jet Collins asymmetries in a nuclear environment. Such measurements will provide a unique test of the universality of the Collins fragmentation function in the presence of cold nuclear matter and probe potential nuclear modifications to the spin-dependent hadronization process. The STAR Forward Upgrade offers excellent forward-rapidity jet reconstruction, enabling access to high-x quark transversity in p+Au collisions and direct comparison with existing p+p results. The 2015 proof-of-principle dataset demonstrated the feasibility of this program but lacked the statistical precision to draw definitive conclusions. The proposed run would deliver the first precise benchmark of medium-induced effects on Collins asymmetries (see projection in Fig. 2 right panel), providing critical input for TMD factorization studies and future

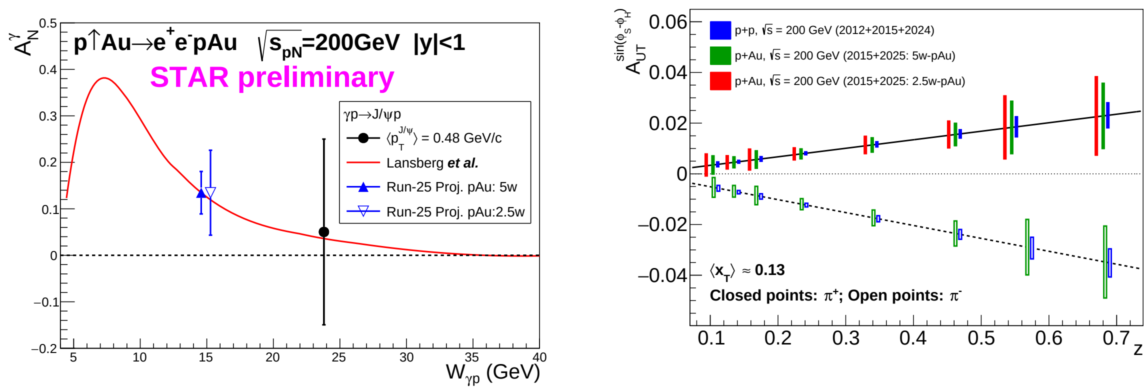

Figure 2: Left: The measured J/ψ transverse asymmetry A_N^{γ} and a prediction based on a parameterization of E_g. **Right:** Projected statistical uncertainties for Collins asymmetry measurements. Both plots assume five weeks and two and half weeks of p+Au data-taking for Run-25.

EIC measurements in e+A collisions.

2 Fixed Target: The Search for the Critical Point

In order to take the advantages of the current STAR fixed targer (FXT) mode setup and fully explore the high baryon density region for the QCD critical point, we propose to take additional Au+Au collision data at the center of mass energy of $\sqrt{s_{NN}} = 4.2$ and 4.5 GeV, 2B good events per energy during the last heavy-ion run of RHIC. These data will allow a systematic analysis of proton multiplicity distributions and enhance chance of discovery the onset of the predicted QCD critical point at the high baryon density region.

Recent results from the FXT datasets indicate a reasonable agreement between experimental data and UrQMD baseline at 3.0, 3.2, 3.5, 3.9 GeV as presented in Quark Matter 2025, while it seems to show an enhanced trend from the baseline of below 2 σ at 4.5 GeV as seen in Fig. 3. The proposed plan is to achieve 5 σ signal above the baseline.

The endcap Time-of-Flight (eTOF) plays an important role for proton identification in the FXT setup as seen in Fig. 4, where the front-end electronics of the eTOF would need to be repaired, as a large fraction of them have been damaged after previous FXT runs. The eTOF detector modules are currently taken out from the detector setup and being repaired in the clean room. The repaired eTOF modules will be re-installed and will be ready before we resume physics run on October 7. The following tests are currently being pursued and/or requested in order to study the feasibility of the FXT run without using the eTOF and/or without removing additional detector materials, especially the FST detector and its service materials, that are located just behind the FXT and before the primary tracks entering into the TPC.

A: Experimental data analysis test just with TPC and bTOF without eTOF information for particle identification; The fraction of eTOF acceptance for proton with dynamical

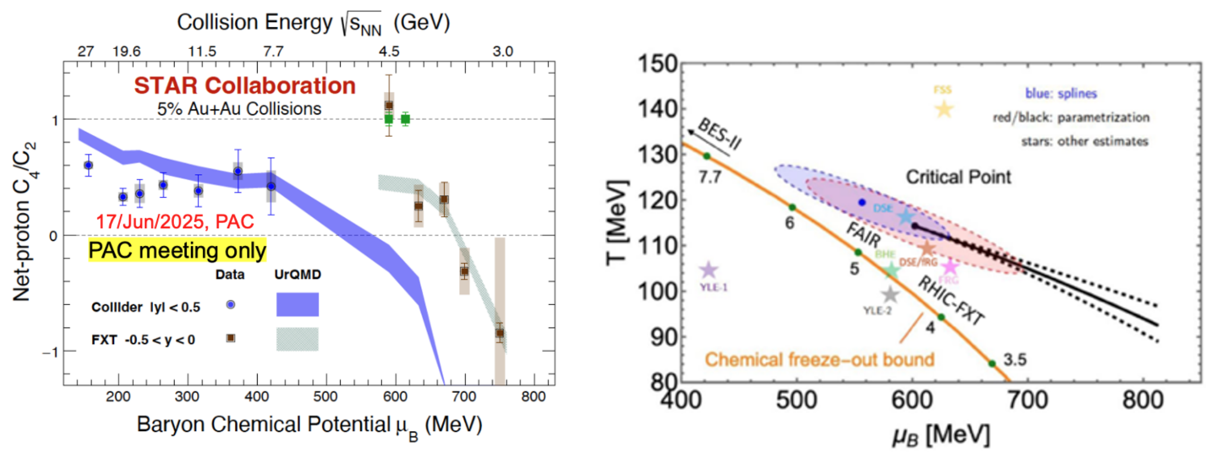

Figure 3: left: The measured net-proton cumulant ratio C4/C2 as a function of baryon chemical potential (collision energy on the upper axis). **right:** The expected locations of critical point in QCD phase diagram from different models.

PID methods, that minimizes the use of eTOF, is about 15% largely at lower p_T region. If we consider this as a loss of efficiency ϵ, (which we can not do in principle, though), we would loose the effective sensitivity of C4/C2 measurement of about 28 % $(1 - \epsilon^2)$.

B: Full Geant simulation test using UrQMD events with/without FST detector materials between FXT and TPC; The full event simulation shows that the efficiency of proton is reduced by about 5% for the same track selection, which is caused by the increase of the DCA distribution given by the additional materials, where no visible effect is seen in the higher order cumulant ratios with the current statistics of 5M events simulation, while we need to keep in mind that the only active material from FST is defined in this Geant model.

C: One hour actual beam time on the FXT is requested to investigate all other possible effects including active and passive materials of FST. This is to understand detection efficiency, backgrounds and other possible experimental effects in realistic environment, which are crucial for these higher order net-proton fluctuation measurements.

In summary, we propose to take 2B events for each energy at 4.2 and 4.5 GeV with fully repaired eTOF and with removing FST detector including support lines after p-Au experiment, in order to have comparable experimental setup as Run21. 2B events have been collected at 2 kHz DAQ rate in 3 weeks during Run21 at 3 GeV with FXT setup, with improved DAQ rate by factor of 2, it would take 3 weeks in total for 2 energies. The number of beam bunches will be increased by factor of 2 compared to the previous Run21 FXT runs in order to keep the in-bunch pile-up to the same level. The additional pile-up protection trigger information will be stored for more effective pile-up rejection. If we only have 2 (or 1) weeks of beam time, we would take 2B/0.5B (or 1B/0B) events at 4.5/4.2 GeV. Even if we don't have enough access time, we would still take data in FXT mode without removing

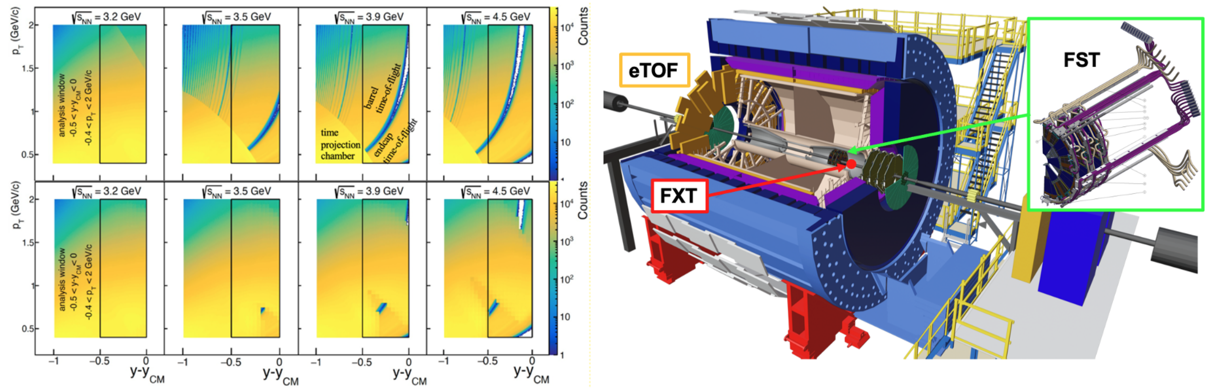

Figure 4: **left:** The proton pT-rapidity acceptances in upper/lower panels with two PID methods including TPC, bTOF and eTOF at FXT energies from 3.2 to 4.5 GeV. **right:** The STAR experimental setup with forward detector upgrades including FST, sTGC and FCS.

FST. The 1st priority is to take data in FXT mode around 4-4.5 GeV, the 2nd is to remove FST.

3 Isobars: Quark & Gluon Transport in Heavy-Ion Collisions

Baryon number conservation, a principle stating that the total number of baryons (protons and neutrons) remains constant in particle interactions and since the birth of the Universe, is related to a U(1) vector current. In QCD, the vector current cannot connect between quarks, but can connect between quark and antiquark (mesons with zero baryon number). The vector currents connected to the three quarks inside a baryon have to join at one point (junction) to maintain gauge invariance. This is where the junction appears. There is no such topology in QED. The vector current can connect between junction and anti-junction (glueball with zero baryon number). It is difficult to separate quarks and gluons since quarks and gluons do not exist individually in the vacuum. However, experiments have demonstrated separately that quarks carry electric charge while gluons do not. The reason that this could be done relatively easily is because the scattering/production cross section is proportional to the electric charge squared. The difficulty with baryon number is that there is not a reaction with a cross section that is directly related to the baryon number in an obvious way. The proposal by theorists in the last few decades is to use the baryon transport over large unity of rapidity to achieve a similar goal as using the scattering/production cross section to measure the electric charge of quarks and gluons. Our three measurements are those baryon transports proposed by theorists in the last few decades [5,6] (references in the paper).

Figure 5 left panel shows the baryon transport (net-proton yield) as a function of beam rapidity. The exponential fit results in a slope of $\alpha_B = 0.61 \pm 0.02$. Charge transport is much harder to measure. To date, only measurements in isobar collisions at 200 GeV were performed with meaningful uncertainty. We propose to take two more data points at A+A energies of 62 and 27 GeV [7] to investigate if it exhibits the same exponential behavior and to extract the charge transport slope (α_Q). We would like to emphasize that charge transport measurements do not require particle identification and therefore detectors such as sPHENIX would have an advantage in terms of taking high-statistic dataset to perform this important measurement. Figure 5 right panel shows the $B/\Delta Q * \Delta Z/A$ as a function of beam rapidity for different beam energies from UrQMD simulation (green filled square) and the only data available as red open square. The dotted-dash line is an exponential fit with $-(\alpha_B - \alpha_Q) = -0.12$, that is more charge stopping than baryon stopping. PYTHIA-8 results with (black filled triangle) and without (orange filled circle) final-state color reconnection to form baryon junctions appear to increase the overall baryon yields. However, PYTHIA-8 does not have baryon junction in the initial nucleons and nor does it provide mechanism for junction interactions. Both PYTHIA-8 settings remain with negative slopes. On the contrary, the red line is an estimate of what a positive slope it should be ($\simeq 0.36$) if more baryon stopping happens consistently across all beam energies (≥ 20 GeV).

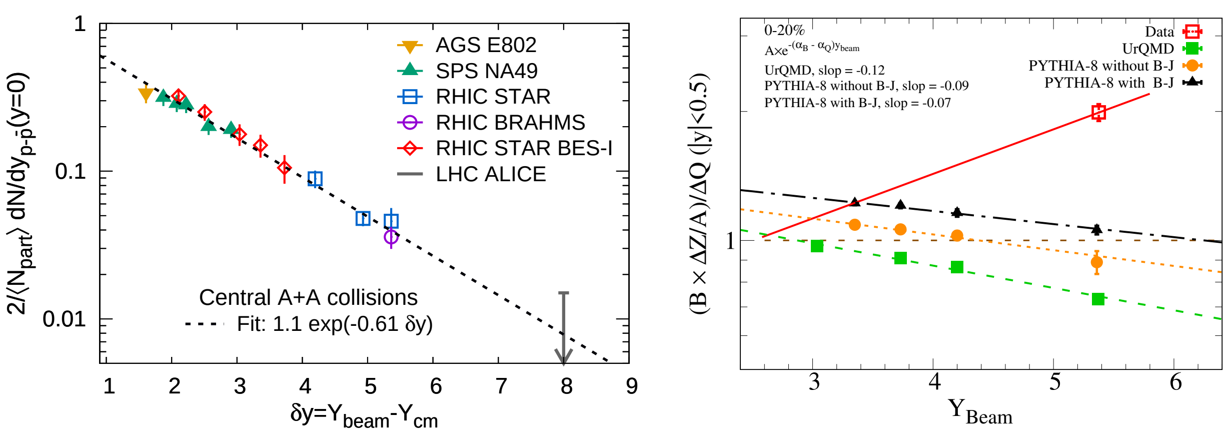

Figure 5: left panel: Exponential dependence of mid-rapidity ($y \approx 0$) net-proton density per participant pair in central heavy ion collisions with Y_{beam} which is equal to the rapidity difference between beam and detector mid-rapidity (δy) [[6]]. **right panel**: Slopes of $B/\Delta Q$ as a function of beam rapidity. Green filled circles are UrQMD simulation results at four different energies of isobar collisions. Red open square is the experimental data point from STAR [[5]]. The dotted-dash line is a fit to UrQMD simulation while the red line is a projection of what may be from future experimental data with baryon stopping more than charge stopping. PYTHIA-8 results with and without final-state color reconnection to form baryon junctions are shown to increase the total baryon yield but still produce negative slopes.

In order to estimate the number of events required and beam time needed, we performed the UrQMD simulation [8] and also extrapolate from the isobar data at 200 GeV. $B/\Delta Q * \Delta Z/A = 1.84 \pm 0.02 \pm 0.09$ is obtained from isobar collisions at 200 GeV and data was taken in 2018 with a total of 6.2 billion minbias events. This is a 1% statistical uncertainty. The

UrQMD predicts a slope difference of -0.12 while the data and baryon junction would suggest a positive slope as shown in Fig. 5. To achieve a positive slope with at least a 5σ significance away from the negative slope of -0.12, we would require a 5% statistical uncertainty each on $B/\Delta Q * \Delta Z/A$ at these two additional energies. If we further assume that the statistical uncertainty is directly related to event number ($\sqrt{N}$), we can conservatively project the minbias events necessary to achieve the required statistics. Table 2 lists the numbers, where the luminosity at 27 GeV may not saturate STAR DAQ bandwidth at 5 KHz all the time. All the minbias event numbers are 50/50 of the two isobar collisions (Zr+Zr and Ru+Ru). That is, a total of about 30 DAQ hours.

isobar beam energy	stat	raw minbias	good minbias	DAQ hours
200	1%	6.2B	3.2B	895
62	5%	250M	128M	14
27	5%	250M	128M	20

Table 2: comparisons of requested isobar collision events and DAQ hours at 62 and 27 GeV to the existing 200GeV. DAQ could take minbias isobar data at 5KHz. This will allow us to extract a slope (-($\alpha_B - \alpha_Q$)) with 2% stat uncertainty to distinguish between +0.00 and -0.12 at 5σ level.

In summary, we request roughly a week of isobar collisions (including setup time) at two different energies in total to measure charge transport and make a significant and unique step toward our understanding of quark and gluon transports in relativistic heavy-ion collisions. This textbook measurement will also further our understanding of what carries the baryon number, a conserved quantum number key to the existence of the Universe and fundamental physics.

References

[1] STAR BUR Run 25, STAR Note SN0850.

[2] The STAR Beam Use Request for Run-23-25, STAR Note SN0793.

[3] STAR BUR Runs 24 - 25, STAR Note SN0819.

[4] STAR, M. S. Abdallah *et al.*, Phys. Rev. Lett. **129**, 092501 (2022), 2111.10396.

[5] STAR, STAR, arXiv: 2408.15441 (2024), 2408.15441.

[6] N. Lewis *et al.*, Eur. Phys. J. C **84**, 590 (2024), arXiv: 2205.05685.

[7] Proposal for two more beam energies of isobar data at RHIC, STAR Note SN0873.

[8] W. Lv *et al.*, Chin. Phys. C **48**, 044001 (2024), 2309.06445.