

# The Physics of sPHENIX

**Anne M. Sickles, for the PHENIX Collaboration**

Physics Department, Brookhaven National Laboratory, Upton, NY 11973

E-mail: [anne@bnl.gov](mailto:anne@bnl.gov)

**Abstract.** Jet related observables have been some of the most powerful and exciting probes for understanding the matter produced in ultra-relativistic heavy ion collisions. Full jet reconstruction was begun at RHIC, and the LHC experiments have shown the power and kinematic reach of these observables. Here we discuss the sPHENIX detector and physics program which aims to bring full calorimetric based jet reconstruction to RHIC in order to explore the temperature dependence of the strongly interacting Quark Gluon Plasma.

## 1. Introduction

In 2010 the RHIC collaborations were charged to set out their plans for the next decade of RHIC running. After much discussion the PHENIX Collaboration decided that the most exciting heavy ion physics over the coming years was hard probe physics (jets, quarkonia and heavy flavor), but that quality measurements of these observables over the next decade were incompatible with the existing PHENIX central detectors which have small acceptance and lack hadronic calorimetry. What emerged from these considerations was a more radical plan of replacing the current central arms of PHENIX with a compact calorimeter and solenoid. This idea generated a lot of interest and the PHENIX Collaboration has recently written a proposal laying out the physics case and a planned design [1].

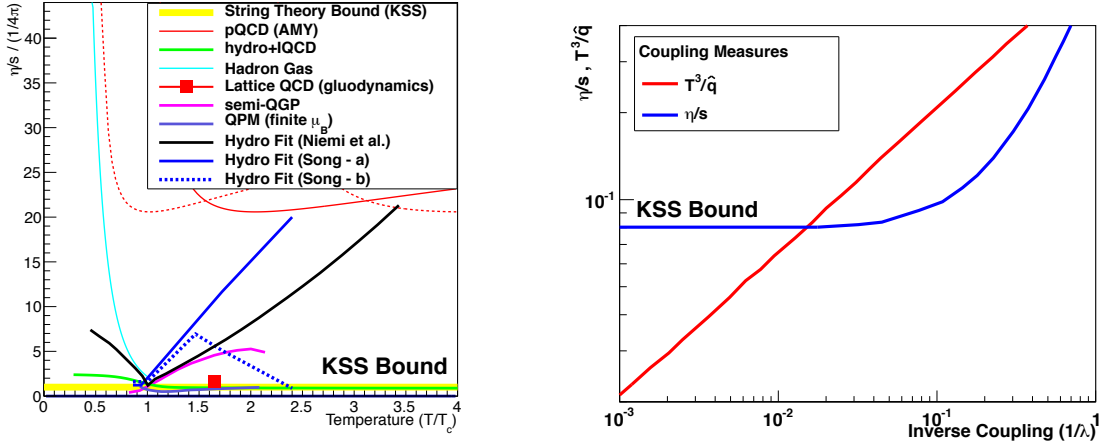
## 2. Physics of sPHENIX

The goal of the sPHENIX Upgrade to the PHENIX experiment is to make calorimetric jet measurements at RHIC in order to study the Quark Gluon Plasma in the temperature region near the critical temperature.

The discovery of the extremely low shear viscosity to entropy density ratio,  $\eta/s$ , established that RHIC created the QGP in a regime that was characterized by strong coupling rather than a weakly coupled gas of quarks and gluons. The  $\eta/s$  values required to reproduce the experimental flow measurements are small [2] and within a factor of a few of the conjectured lower quantum bound [3]. The left panel of Figure 1 shows the lower quantum bound and the perturbative calculation for  $\eta/s(T)$ . It is not known how  $\eta/s$  evolves from the near minimum value near  $T_c$  to the perturbative value at very high temperatures. Flow data are not able to constrain the temperature dependence adequately.

One interesting theoretical development is the identification of a connection between  $\eta/s$  and  $\hat{q}$ , the transverse momentum broadening per unit length of a fast parton as it traverses the QGP [4]. At weak coupling:

$$\frac{\eta}{s} = 1.25 \frac{T^3}{\hat{q}} \quad (1)$$



**Figure 1.** (left)  $\eta/s$  as a function of temperature. The red curves show the perturbative result from AMY [5]. The blue and black curves show parameterizations of  $\eta/s$  which have been used in hydrodynamical models to reproduce existing RHIC and LHC results [6, 7]. (right)  $\frac{T^3}{\hat{q}}$  (red) and  $\eta/s$  (blue) as a function of the inverse 't Hooft coupling,  $\lambda$  [4].

while at strong coupling:

$$\frac{\eta}{s} \gg \frac{T^3}{\hat{q}}. \quad (2)$$

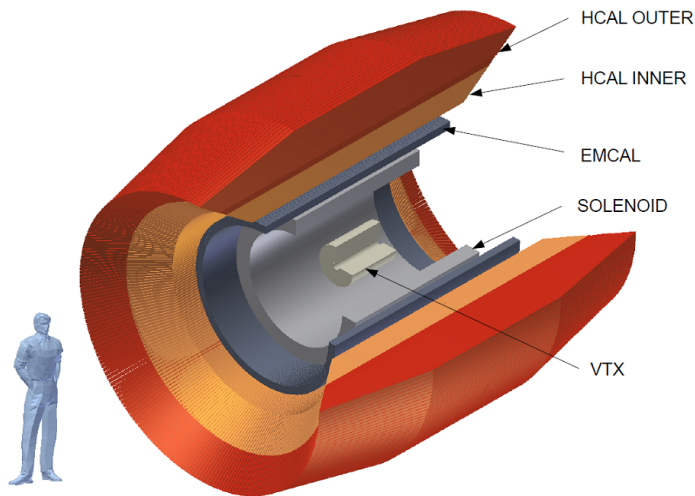
The authors of Ref. [4] state that  $T^3/\hat{q}$  “is a more broadly valid measure of the coupling strength of the medium than  $\eta/s$ .” This is illustrated in the right panel of Figure 1 which shows both  $T^3/\hat{q}$  and  $\eta/s$  as a function of the inverse coupling. As the coupling becomes large  $\eta/s$  saturates at the quantum bound,  $1/4\pi$ , while  $T^3/\hat{q}$  retains its sensitivity to further increases in the coupling strength.

The key to understanding the coupling in the QGP is to measure both  $\eta/s$  and  $\hat{q}$ , and their temperature dependences, independently. This requires high quality jet measurements at RHIC collision energies. Each collision evolves from its maximum initial temperature down as the system expands and cools. Since  $\hat{q}$  depends on  $T^3$  in pQCD the quenching is dominated by the highest temperatures in the collision. Thus, the way to study the temperature dependence is to vary the maximum initial temperature by varying the collision energy. Measurements at the LHC alone cannot do this.

### 3. sPHENIX Design

The jet performance desired for sPHENIX drives the design considerations. Full calorimeter coverage, both electromagnetic and hadronic is required. The detector needs to have full azimuthal coverage over  $|\eta| < 1$ . The currently existing Silicon Vertex Detector (VTX) is to remain for tracking, with possible additional silicon layers added at larger radii to improve the momentum resolution and improve the track finding ability.

A cut-away view of the detector is shown in Figure 2. The design is for a thin superconducting solenoid with a 2T field at a radius of 70 cm. Behind this is a silicon tungsten electromagnetic calorimeter followed by an iron scintillator hadronic calorimeter. Using tungsten as the absorber allows the electromagnetic calorimeter to be very compact; the calorimeter is about 10 cm thick. Geant 4 single particle simulations give an energy resolution of  $14.2\%/\sqrt{E} + 0.7\%$ .



**Figure 2.** A cut-way view of the sPHENIX detector.

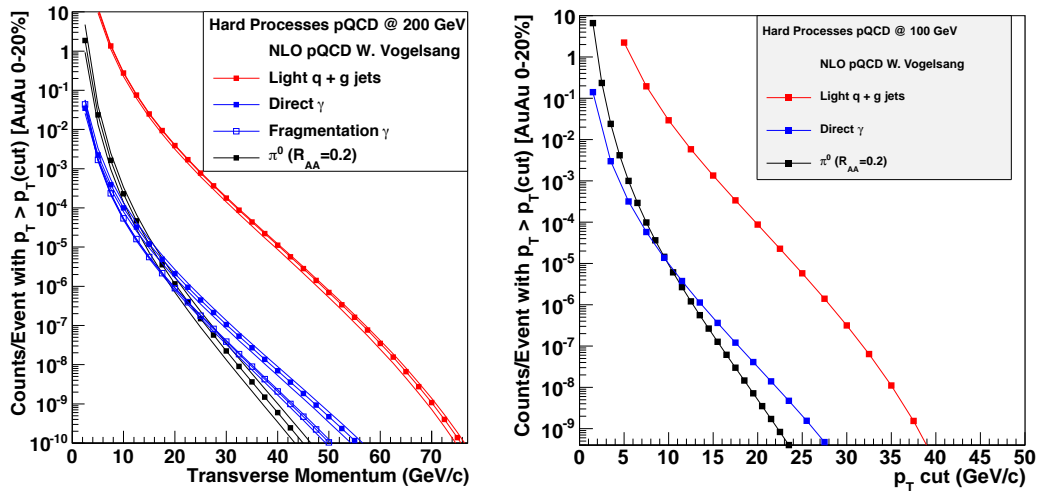
#### 4. Jet Reconstruction Performance at RHIC

The rates for jet production at RHIC given the expected machine luminosity and expected 20 week/year runs are such that sPHENIX would have access to huge numbers of jets up to approximately 60 GeV/c for  $\sqrt{s_{NN}} = 200$  GeV. Figure 3 (left) shows the pQCD rates for jet, photon and  $\pi^0$  production in central Au+Au events. sPHENIX would be able to sample approximately 50B Au+Au events in a year. The numbers of jets and photons above various  $p_T$  cuts are shown in Table 1. Over 80% of the single jets that sPHENIX detects also have the opposing jet within the sPHENIX acceptance. Jet rates at  $\sqrt{s_{NN}} = 100$  GeV [8] are shown in Figure 3 (right) and one 20 week run would yield  $10^5$  jets with  $p_T > 20$  GeV/c.

For  $p_T > 20$  GeV/c the yield of direct photons surpasses that of photons from  $\pi^0$  decay in Au+Au collisions. As can be seen in Table 1 there are abundant direct photons at RHIC in this region. Because the photon does not interact via the strong force, it decouples from the medium after it is created. sPHENIX will be able to make measurements of both photon-jet and photon-hadron correlations to probe energy loss in this region.

	Au+Au (central 20%)	$p+p$	$d+Au$
$> 20$ GeV	$10^7$ jets $10^4$ photons	$10^6$ jets $10^3$ photons	$10^7$ jets $10^4$ photons
$> 30$ GeV	$10^6$ jets $10^3$ photons	$10^5$ jets $10^2$ photons	$10^6$ jets $10^3$ photons
$> 40$ GeV	$10^5$ jets	$10^4$ jets	$10^5$ jets
$> 50$ GeV	$10^4$ jets	$10^3$ jets	$10^4$ jets

**Table 1.** Table of jet rates at  $\sqrt{s_{NN}} = 200$  GeV for different systems. Each column shows the number of jets or direct photons that would be measured within  $|\eta| < 1$  in one 20 week running period.



**Figure 3.** NLO jet,  $\pi^0$  and photon rates [8] at  $\sqrt{s_{NN}}=200$  GeV (left) and  $\sqrt{s_{NN}}=100$  GeV (right) as a function of the  $p_T$  cut.

Numerous studies have been done to establish the feasibility of reconstructing jets at  $\sqrt{s_{NN}}=200$  GeV in sPHENIX. A large HIJING study was done in order to evaluate the separation of true jets from fake jets (background fluctuations) [9] in an ideal calorimeter. Results for anti- $k_T$   $R=0.2$  jets are shown in Figure 4 (left). For jets with  $E_T > 20$  GeV true jets dominate over fake jets. For larger jet radii the crossing point is at higher  $E_T$ , but still within the range that sPHENIX expects to have statistics for.

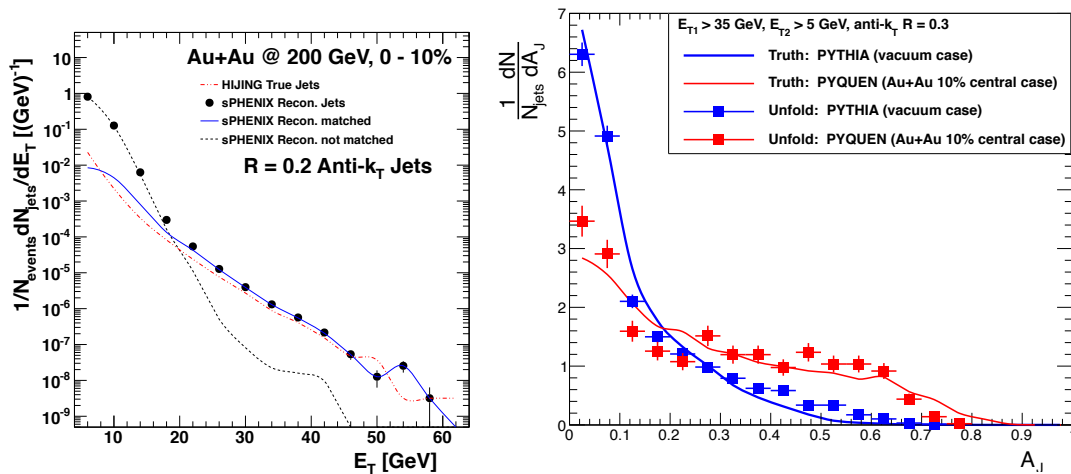
Dijet asymmetry measurements have been used extensively at the LHC. In heavy ion collisions, the large jet quenching decreases the fraction of symmetric (balanced) dijets and increases the fraction of unbalanced dijets. In order to estimate how well sPHENIX would be able to distinguish these scenarios we embedded PYTHIA p+p events into central HIJING events and reconstructed the jet asymmetry,  $A_J$ . We also did the same with PYQUEN events, where jet quenching is applied to PYTHIA events. The results are shown in the right panel of Figure 4. The unfolded results for both the PYTHIA and PYQUEN samples are in agreement with the initial truth asymmetry distributions.

## 5. sPHENIX Upgrades

As discussed above, the sPHENIX proposal in Ref. [1] includes a solenoid and electromagnetic and hadronic calorimetry. This is appropriate for jet and direct photon measurements. However, other very interesting probes, such as separated upsilon states and heavy flavor jets will require additional detectors. There are plans for additional tracking layers beyond the existing VTX and a preshower detector that will be needed for electron identification.

The physics made available by these upgrades is extremely important and the goal is to have these in place at the same time as the rest of sPHENIX. Here we highlight one example, heavy flavor jets. Heavy quarks, especially bottom, were expected to lose much less energy than light quarks due to the dead cone effect [13] suppressing gluon radiation. However, results from both RHIC and the LHC have shown evidence for substantial energy loss of both charm and bottom quarks [14, 15, 16].

If sPHENIX were to be capable of identifying heavy quark jets this would extend the  $p_T$  range of heavy quark measurements at RHIC significantly. Figure 5 shows that there are accessible rates for heavy quark production for  $p_T > 30$  GeV/c. The constraints from such



**Figure 4.** (left) Reconstructed single jet spectra for anti- $k_T$   $R=0.2$  jets in central HIJING [10] events. The reconstructed jets are shown as points. Those reconstructed jets matched with a true jet from the HIJING event are shown with the blue curve and jets not matched with a true jet (i.e. fake jets) are shown with the black dashed curve. For jet  $E_T > 20$  GeV the matched jets dominate over the unmatched jets. Figure is from Ref [9]. (right) Asymmetry,  $A_J$ , for PYTHIA [11] (blue) and PYQUEN [12] (red) for dijets embedded in central HIJING events. The truth information is shown as curves and the reconstructed and unfolded results are shown as points. Figure is from Ref. [1].

measurements would also be greatly improved due to the ability to constrain the kinematics from jet measurements which is not possible with electron or heavy meson measurements. Heavy quark jet measurements are a crucial part of understanding hard physics and measurements are necessary both at RHIC and the LHC.

## 6. Conclusions

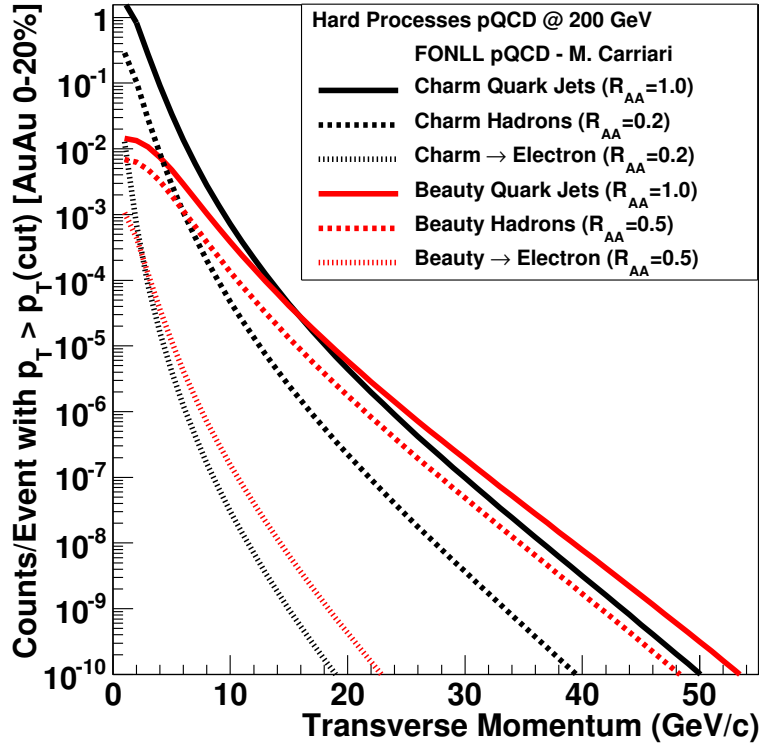
The sPHENIX detector will provide the first fully calorimetric jet measurements at RHIC. These measurements are crucial to understanding the behavior of fast partons in the QGP and the properties of the plasma in a region where the coupling might be the strongest.

We have done simulations that show that anti- $k_T$   $R = 0.2$  jets can be cleanly measured for  $E_T > 20$  GeV with no additional fake jet rejection. Applying fake jet rejection techniques, already being used at the LHC [19] will decrease the jet energies and increase the jet sizes which are accessible.

The sPHENIX design exploits technological advances in the years since PHENIX was constructed. The sPHENIX design also offers the ability to add additional detectors in the central region which will enable new key physics, such as heavy quark jets and separated upsilon states. Plans are also underway to instrument the forward region with emphasis on spin, asymmetric collisions and future eRHIC running.

## 7. References

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**Figure 5.** Fixed order next-to-leading log (FONLL) [17] results for heavy quark jet (solid curves), heavy hadron (thick dashed curves) and electron from semileptonic heavy meson decay (thin dashed curves) [18] as a function of the minimum  $p_T$  cut. Charm (black) and bottom (red) results are shown. Hadron and electron rates have been reduced by the assumed  $R_{AA}$  values shown in the figure.

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