Energy Correlators as a probe of the hard process in Run 24 $p-p$ collisions at $\sqrt{s} = 200\ GeV$ with the sPHENIX detector at RHIC

by

Skadi Kurt Grossberndt

A dissertation submitted to the Graduate Faculty in Physics in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

2025

This manuscript has been read and accepted by the Graduate Faculty in Physics in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

Professor Stefan Bathe

Date	Chair of Examining Committee

Professor Daniel Kabat

Date	Executive Officer

Professor Adrian Dimitru

Professor Raghav Kunnawalkam Elayavalli

Professor Jamal Jallian-Marian

Professor Miguel Castro Nunes Fiolhais

Supervisory Committee

THE CITY UNIVERSITY OF NEW YORK

Abstract

Energy Correlators as a probe of the hard process in Run 24 $p-p$ collisions at $\sqrt{s} = 200\ GeV$ with the sPHENIX detector at RHIC

by

Skadi K Grossberndt

Adviser: Professor Stefan Bathe

This dissertation consists of three parts in addition to a literature review establishing the state of the art of jet physics and the Energy-Energy correlator at high energies…

Part 1: Hardware This part discusses the physical hardware used to make the measurements of the energy in the jets created by the proton-proton collisions. This part contains a discussion of the sPHENIX detector and an in-depth look at the relevant susbsystems for the meausements in this analysis. In addition, the Monte Carlo methods and models to discern the expected respnse and calibrate the detector are discussed in detail, with both subparts coming together in a disucssion of backgrounds and error calculation in general and for the observables at hand.

Part 2: Technicalities This part builds from first principles up to the jet measurement in a theoretical light, and then discusses the additional computational techniques on display that will provide the bridge between the theory of these observables and the practical application to sPHENIX. This part continains a chapter that is a pared down discussion of a midstream paper proposed as part of the thesis process that establishes the safety of this observable against jet finding choices.

Part 3: Experimental Output This part is the meet and potatoes of the dissertation, discussing results from the experiment and the analysis in light of the previous parts and comparing to the world results from related systems.

Contents

1 Literature Review **1**

1.1 Jets Definitions 2

1.1.1 Jet Reconstruction Algorithims 2

1.1.2 Quark and Gluon Jets 2

1.2 Jet Substucure Measurements 3

1.3 N-Point Energy Correlator 3

I Hardware: The Detector and Simulations **4**

2 The sPHENIX detector **5**

2.1 Calorimetery 6

2.1.1 Hadronic Calorimeters 6

2.1.2 Electromagnetic Calorimeter 8

2.1.3 Zero Degree Calorimeter 8

2.2 Tracking 9

2.2.1 INTT 9

2.2.2 Micromegas Vertex Detector 9

2.2.3 Time Projection Chamber 9

2.2.4 TPC Outer Tracker 9

2.3 Event Characterization 10
2.3.1 sPhenix Event Plane Detector 10
2.3.2 Minimum Bias Detector 10
2.4 Triggers 10

3 Monte Carlo Simulations **11**

4 Determining Backgrounds and Errors **12**

II Technicalities: The finer points of theory and computing **13**

5 The Energy Correlator and the primary vertex **14**

6 Jets in Vacuum and the PDF **15**
6.1 Jet Identification Algorithms 15

7 So exactly how intelligent is AI **16**

8 Proof Solving and Validation as Quality Control Mechanisms **17**

III Experimental Output: The Main Event **18**

9 So is sPHENIX actually working? **19**

10 Measuring the Energy Correlator **20**

11 The Power of the ENC: α_s at the few GeV scale **21**

12 Event-by-Event distinguishing **22**

13 Comparison is the Theft of Joy: What does the LHC say, and how about STAR? 23

14 Entanglement and other Lofty Goals 24

IV Wrapping it all up 25

15 Observable prospects for Run 25 and the EIC 26

16 Remaining Questions 27

17 Implementation and application for the remaining sPHENIX data 28

List of Tables

List of Figures

2.1 The sPHENIX detector. The Zero Degree Calorimeter is not picutred but is located further along the beam pipe. 6
2.2 Top: Presistence Waveform. Bottom: Energy distribution averaged across 10^5 events 7

Chapter 1

Literature Review

1.1 Jets Definitions

The study of Quantum Chromodynamics in high energy collisions, such as those at the Relativistic Heavy Ion Collider or the Large Hadron Collider, is often carried out through investigation of the kineatics of jets. Jets, as objects, sit in the boundary between experiment and theory, being an experimental signature corresponding to final states of quarks and gluons produced in collisions. Jets are a cluster of final state particles that result from the showering and hadronization of the inital parton, that are identified in experiment through use of one of the multiple jet reconstruction algorithims.

1.1.1 Jet Reconstruction Algorithims

In Ryan Atkin's paper *Review of jet reconstruction algorithms* [1], Atkin provides an overview of the standard algorithms with a focus on pratical implementation for experimental usage. Atkin disucsses a number of algorithms that fall into two categories: Cone based and Sequential Clustering

Cone Methods

In Atkin's paper, Atkin discusses two itterative cone procedures–Iterative Cone with Progressive Removal and with Split Merge–and one more modern cone method, Seedless Infrared Safe Cone. These itterative cone procedures are described as simple to implement in an experimental context, however, they both suffer defficiencies from a theoretical perspective as they fail to be IRC safe [1] [**Salam2007**].

1.1.2 Quark and Gluon Jets

In their paper *An Operational Definition of Quark and Gluon Jets* Kimiske, Metodiev and Thaler present a theoretical definition of jet flavor with an eye towards application at collieders. They aim to present a precise and practical definition of jet flavor at the hadron level, thus allowing for direct measurement from collider experiments rather than a measurement by proxy. While the gluon or quark jet is well definied at the level of the hard scattering, corresponding to an intiating parton of the primary vertex [**Jones1989**] [**Fodor1990**]. Experimentally, there is signifigant intrest in being able to discriminate quark and gluon jets in searches for BSM physics, searchs for Dark Matter, in jet substructure analysis, in QGP physics and in understanding the processes of hadronization [**Gallicchio2011**][**Lima2017**][**Bhattecherjee2017**][]

1.2 Jet Substucure Measurements

1.3 N-Point Energy Correlator

Part I

Hardware: The Detector and Simulations

Chapter 2

The sPHENIX detector

The sPHENIX detector is part of the Relativistic Heavy Ion Collider (RHIC) complex at Brookhaven National Laboratories (BNL) in Upton, New York. RHIC is one of two major circular particle colliders in the world, the other of which is the Large Hadron Collider at CERN in Geneva, Switzerland. Over the course of the sPHENIX experiment which will run from run 23 until RHIC ceases operations after run 25, RHIC will be colliding gold nuclei and protons with run 23 having been dedicated to commissioning Au+Au running, run 24 dedicated to p+p with three weeks of Au+Au for further tracking commissioning and run 25 dedicated to physics running in Au+Au collisions. RHIC runs with a center of mass energy of $\sqrt{s} = 200GeV$ for both protons and gold, and additionally is the sole collider that collides polarized protons, which allows for more in depth studies of spin physics. At RHIC, sPHENIX's forerunner, the Pioneering High Energy Nuclear Interaction eXperiment (PHENIX), performed the first measurement of the Quark Gluon Plasma droplets [**QGP˙droplets**] in nuclei-nuclei collisions.

sPHENIX is designed to offer significant upgrades to PHENIX, specifically providing increased coverage with hadronic and electromagnetic calorimeters, increasing effectiveness in studies of jets and heavy flavor at mid-to-high Bjorken x [**sPHENIX˙TDR**][2][3] Broadly,

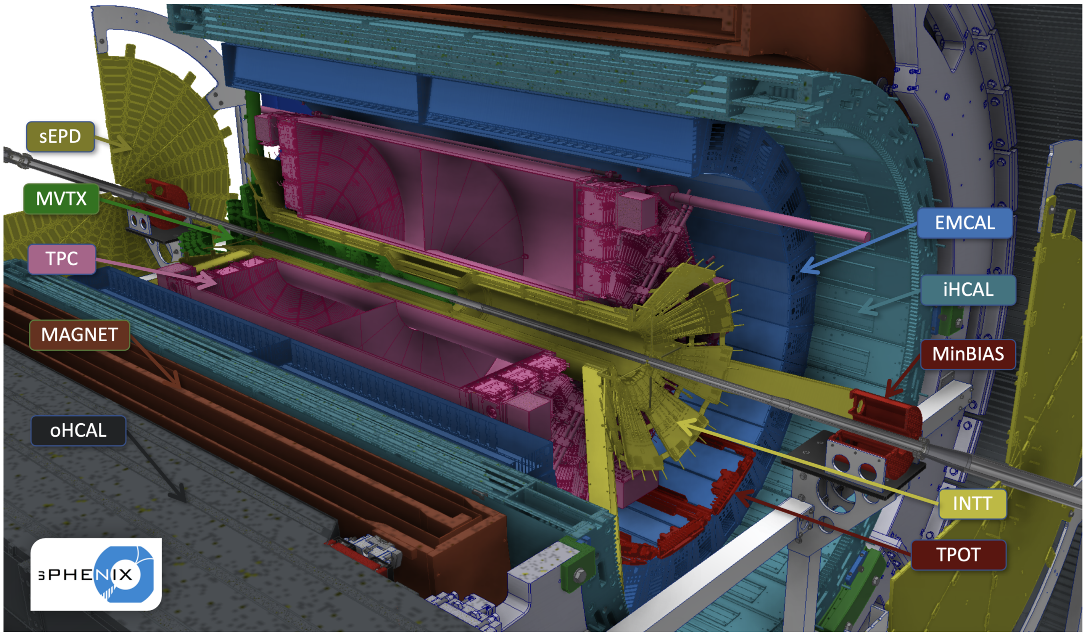


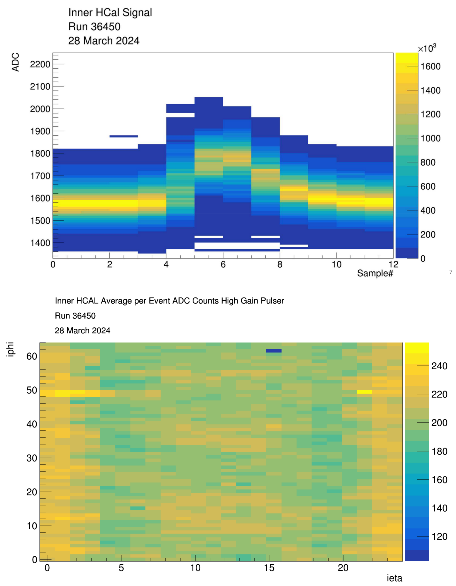
Figure 2.1: The sPHENIX detector. The Zero Degree Calorimeter is not picutred but is located further along the beam pipe.

sPHENIX can be broken into three categories of subsystem: Calorimeters, Tracking and Event characterization. sPHENIX is constructed around a 1.5 Tesla superconducting magnet, cooled by liquid helium, which was previously used on the BABAR experiment at SLAC.

2.1 Calorimetery

2.1.1 Hadronic Calorimeters

sPHENIX's power in jet physics comes in large part from its calorimeter systems, including two seperate hadronic calorimeters. The outer and inner hadronic calorimeter (OHCal and IHCal respectively) are both divided into 24 bins in η with coverage of $|\eta| \leq 1.1$ and full φ coverage with 64 bins in φ, grouped in φ into 32 sectors in each calorimeter. Each hadronic calorimeter therefore has tower size of $\delta\eta = 0.092$ and $\delta\varphi = 0.098$. The outer



(a) Charge Injection Pulse. This system allows for direct testing of electronics without detector response

(b) LED pulse. This allows for testing of the full readback system and light response

Figure 2.2: Top: Presistence Waveform. Bottom: Energy distribution averaged across 10^5 events

hadronic calorimeter is constructed of steel and sits outside of the magnet, with inner radius of $r = 1.82$ m and outer radius of $r = 2.69$ m. The inner hadronic calormeter is constructed of aluminum and sits just inside the magnet, with inner radus of $r = 1/16$ m and outer radius of $r = 1.37$ m. Each tower corresponds to a readout board that sums readout from four scintillator paddles embeded into the calorimeter as show in fig. **??**. These interface boards form a single readout channel, and can be indvidually teste via a pulser system that injects charge into the interface board testing readback independent of scintillator response, and LED system that injects a fixed pulse of light into the scintilators to test behavior of the Silicon Photomultipliers (SiPMs). Output of each of these systems is shown in fig 2.2

Calibration

The hadronic calorimeters were intially calibrated through use of cosmic ray muons, matching the spectra to Monte Carlo generated through EcoMug and GEANT4 [**HCal˙Calib**]. This calibration is updated through out the run via continued cosmic ray studies in between physics data taking in addition to ongoing work on in-situo calibrations using tower-slope methods [4]. These calibrations have yeilded an average conversion factor for the OHCal of and the IHCal of

2.1.2 Electromagnetic Calorimeter

Moving in one layer from the hadronic calorimeter, the Electromagnetic Calorimeter (EMCal) has the same coverage in $\eta - \varphi$ space, but has 16 times as many towers with 96 bins in η and 256 bins in φ. The EMCal is constructed of blocks of tungsten with embedded scintilationg fibers, and had inner radius $r = 0.9$ m and outer radius of $r = 1.16$ m. Similarly to the HCals, the EMCal is also equipped with a pulser and LED, although the increased number of towers and higher varaiblility in response requires that different pulse widths be used for seperate sets of towers to prevent saturation and clipping on the LED pulse.

Calibration

The EMCal was calibrated to the π^0 mass through the $\pi^0 \to \gamma\gamma$ decay channel with additional corrections applied via the tower slope. The mean m_{π^0} and width are used as quality assurance plots to monitor radiation damage to the EMCal on an ongoing basis.

2.1.3 Zero Degree Calorimeter

The Zero Degree Calorimeter (ZDC) is a small transverse energy hadron detector that positioned outside of the experiment hall, in the tunnels along the beam pipe, 18 m from he interaction point on both side. The ZDC is used to detect spectator neutrons to allow for the calculation of multiplicity and event geometry, makind it an overlapping detector between the calorimeters and the event characterization [5]. The sPHENIX ZDC is one of two detectors that was preserved from PHENIX, with minor repairs and upgrades to improve running. In pp collisions, the ZDC and the Minimum Bias detector

2.2 Tracking

The sPHENIX tracking system consits of the Silicon vertexing detectors and the gas based trackers.

2.2.1 INTT

2.2.2 Micromegas Vertex Detector

The Micromegas Vertex detector (MVTX) is a

2.2.3 Time Projection Chamber

The Time Projection Chamber (TPC)

2.2.4 TPC Outer Tracker

The TPC Outer Tracker (TPOT) was designed as a minimal add-on to improve tracking effeciency and resolution by providing additional track points.

2.3 Event Characterization

2.3.1 sPhenix Event Plane Detector

2.3.2 Minimum Bias Detector

The sPHENIX Minimum Bias Detector (MBD) is the other detector preserved from PHENIX, when it was called the Beam-Beam Counter (BBC). This detector is situated

2.4 Triggers

The sPHENIX detector has a number of triggers at its disposal to allow for online event type selections for the triggered readout system: the EMCal, the HCals, the ZDC, the MBD, the sEPD and–for run 2024–the TPC. Starting in run 2024, available triggers are Minimum Bias

Chapter 3

Monte Carlo Simulations

Chapter 4

Determining Backgrounds and Errors

Part II

Technicalities: The finer points of theory and computing

Chapter 5

The Energy Correlator and the primary vertex

Chapter 6

Jets in Vacuum and the PDF

6.1 Jet Identification Algorithms

As discussed in chapter 1, there are a variety of jet finding algorithms that prioritize different theoretical aspects of the underlying physics while being experimentally realizable [6] [1].

In general, a jet identification algorithm needs to be IRC safe. That is, the jet object needs to display invariance in the Infrared (IR) and Collinear regimes, managing real-virtual cancellation and keeping results meaningful for emission and splitting respectively.

Chapter 7

So exactly how intelligent is AI

Chapter 8

Proof Solving and Validation as Quality Control Mechanisms

Part III

Experimental Output: The Main Event

Chapter 9

So is sPHENIX actually working?

Chapter 10

Measuring the Energy Correlator

Chapter 11

The Power of the ENC: α_s at the few GeV scale

Chapter 12

Event-by-Event distinguishing

Chapter 13

Comparison is the Theft of Joy: What does the LHC say, and how about STAR?

Chapter 14

Entanglement and other Lofty Goals

Part IV

Wrapping it all up

Chapter 15

Observable prospects for Run 25 and the EIC

Chapter 16

Remaining Questions

Chapter 17

Implementation and application for the remaining sPHENIX data

Bibliography

[1] R. Atkin, “Review of jet reconstruction algorithms”, Journal of Physics: Conference Series **645**, 012008 (2015).

[2] A. Adare and et. al., “An upgrade proposal from the phenix collaboration”, `10.48550/ARXIV.1501.06197` (2015).

[3] R. Belmont and et. al., “Predictions for the sphenix physics program”, Nuclear Physics A **1043**, 122821 (2024).

[4] A. Sirunyan and et. al., “Calibration of the cms hadron calorimeters using proton-proton collision data at $\sqrt{s} = 13TeV$”, Journal of Instrumentation **15**, P05002–P05002 (2020).

[5] C. Adler, A. Denisov, E. Garcia, M. Murray, H. Stroebele, and S. White, “The rhic zero degree calorimeters”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **470**, 488–499 (2001).

[6] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, “Better jet clustering algorithms”, JHEP 9708:001,1997 **1997**, 001–001 (1997).