PERFORMANCE OF THE HEAVY FLAVOR TRACKER (HFT) DETECTOR IN STAR EXPERIMENT AT RHIC

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Chapter 1

Introduction

It is well established in Cosmology that the Universe began about 13.8 billion years ago in an event known as the Big Bang. The conditions of the early universe, a few microseconds after the Big Bang, were extremely hot and dense. Under such extreme conditions of temperature and/or density it is expected that nuclear matter exists in an exotic phase of matter, called Quark Gluon Plasma (QGP) [1]. In that phase the constituents of nucleons, the quarks and gluons, are free to move beyond the nucleon boundaries. The creation and study of the properties of such matter is the goal of modern high energy nuclear physics. In order to better understand and study the behavior of matter shortly after the Big Bang, it is required to create matter at conditions of high density and temperature. At the Relativistic Heavy Ion Collider (RHIC), located at Brookhaven National Laboratory (BNL) in Long Island, New York, heavy ions, i.e. atomic nuclei, are accelerated to nearly the speed of light in opposite directions and then collide with each other. The medium created must be probed in order to understand its properties and the nature of the interactions in the medium. The interactions of the constituent particles, quarks and gluons, are governed by Quantum Chromodynamics (QCD), the theory of Strong or Nuclear force. In the debris of these collisions, as we discuss below, we look for clues (signatures) of QGP formation while, at the same time, we map the behavior of nuclear matter at these extreme conditions.
1.1 Quantum Chromodynamics and Color Interactions

Quantum Chromodynamics is the theory that governs the strong interaction between quarks and the force carriers of the strong interaction, the gluons, and plays an important role in the Standard Model of particle physics. The collision of heavy nuclei provides an environment where the properties of strongly interaction matter can be studied. Also by colliding heavy nuclei at ultra-relativistic energies nuclear matter is heated and compressed to the point that might undergo a phase transition to deconfined partonic matter or Quark Gluon Plasma (QGP).

The Standard Model of Particle Physics, developed in the 1970’s, describes the interactions of fundamental particles. The theory was developed to produce a single model that describes all four fundamental forces of nature, electromagnetic, weak nuclear, strong nuclear, and gravitation. In the Standard Model, all fundamental particles may be placed into two categories, half integer spin fermions and integer spin bosons. Bosons are force carriers responsible for the interactions between particles, and the fermions are the fundamental building blocks of matter.

The fermions of the Standard Model can be separated further into two more categories, quarks and leptons, and each comes in three generations. There are six quarks, up, down, strange, charm, bottom and top, and six leptons, electron, electron-neutrino, muon, muon-neutrino, tau and tau-neutrino. Leptons carry integer electric charge and quarks carry fractional electric charges. Every fermion also has a corresponding antiparticle with the opposite electric charge. The bosons of the Standard Model are the photon (γ), force carrier for the electromagnetic force, the W and Z bosons, force carriers for the weak force, and the gluons (g), force carriers for the strong nuclear force. Table 1.1 shows the fundamental particles of the Standard
Model and some of their properties, including their electric charge, mass, spin and how they are split into generations [2].

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quark</th>
<th>Electric Charge($q_e$)</th>
<th>Mass($MeV/c^2$)</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Up ($u$)</td>
<td>$+2/3$</td>
<td>1.7-3.1</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Down ($d$)</td>
<td>$-1/3$</td>
<td>4.1-5.7</td>
<td>1/2</td>
</tr>
<tr>
<td>Second</td>
<td>Charm ($c$)</td>
<td>$+2/3$</td>
<td>1180-1340</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Strange ($s$)</td>
<td>$-1/3$</td>
<td>80-130</td>
<td>1/2</td>
</tr>
<tr>
<td>Third</td>
<td>Top ($t$)</td>
<td>$+2/3$</td>
<td>172900±1500</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Bottom ($b$)</td>
<td>$-1/3$</td>
<td>4130-4370</td>
<td>1/2</td>
</tr>
</tbody>
</table>

| Generation | Lepton | Electric Charge($|q_e|$) | Mass($MeV/c^2$) | Spin |
|------------|--------|--------------------------|-----------------|------|
| First      | Electron ($e$) | -1                      | 0.511           | 1/2  |
|            | Electron Neutrino ($\nu_e$) | 0                      | 0               | 1/2  |
| Second     | Muon ($\mu$) | -1                      | 105.66          | 1/2  |
|            | Muon Neutrino ($\nu_\mu$) | 0                      | 0               | 1/2  |
| Third      | Tau ($\tau$) | -1                      | 1776.84         | 1/2  |
|            | Tau Neutrino ($\nu_\tau$) | 0                      | 0               | 1/2  |

| Force      | Gauge Boson | Electric Charge($|q_e|$) | Mass($GeV/c^2$) | Spin |
|------------|-------------|--------------------------|-----------------|------|
| Electromagnetic | $\gamma$ (Photon) | 0                       | 0               | 1    |
| Weak Nuclear      | $W^\pm$     | $\pm1$                   | 80.3980±0.025   | 1    |
|                      | $Z^0$       | 0                        | 91.1876±0.0021  | 1    |
| Strong Nuclear    | g (8 Gluons) | 0                        | 0               | 1    |

Table 1.1: Quarks, Leptons and Gauge Bosons

A hadron is a composite of two (mesons) or three quarks (baryons), some of which may have identical quantum numbers when the strong nuclear force is neglected. In order to describe how quarks could coexist in a hadron with identical quantum states without being in violation of the Pauli Exclusion Principle, the concept of color charge was introduced. The color charge, analogous to the electric charge is responsible for the color [strong] interaction. Color charge, unlike the electric charge comes in six varieties, red, green, blue for quarks and antired, antigreen and antiblue for antiquarks. Also unlike the electric charge where the photon carries no electric charge,
the eight gluons carry color charge as well. Each gluon represents a mixed state of color and anticolor. So, in addition to being the mediator of the color interaction, the gluons also interact strongly among themselves.

1.1.1 Strong Force and Quark Confinement

The strength of the strong force is characterized by its ‘coupling constant’, $\alpha_s$. The strong nuclear force grows weaker, asymptotically approaching zero, as either the separation between particles decreases or the interaction energy increases. It also grows stronger as the separation between the particles increases. Figure 1.1 shows the strong force coupling as it varies with $Q$, the momentum transfer or the violence of the interaction. High $Q$ values probe small distances and there the strong force vanishes. This feature of the strong force is called asymptotic freedom. Asymptotic freedom, as a feature of QCD, arises from the self-interaction of gluons and the specific number of gluons (8).

Small $Q$ values probe large distances where the strength grows rapidly. If we try to separate the quarks inside a hadron, as the distance between quarks grows, the interaction between them also grows stronger eventually making it more favorable (energetically) to create a quark-antiquark pair rather than separate them. This inability to separate quarks is called confinement, and is the reason that free quarks have not been observed.

In the realm where $\alpha_s^2 << 1$, also high $Q$ or high temperature and density, perturbation theory may be used for calculations. As $\alpha_s$ increases, perturbative techniques may no longer be used making low temperature, low density calculations very complicated.
1.1.2 Deconfinement and Quark-Gluon Plasma

When nuclear matter is compressed to very high density and temperatures, it is expected to undergo a phase transition to QGP. Conditions sufficient for the formation of QGP have not existed naturally since shortly after the Big Bang. QGP is formed when energy densities are in excess of 1 GeV/fm$^3$ and temperatures are in excess of 1 Trillion degrees Kelvin. A sketch of a possible QCD phase diagram is shown in Figure 1.2. The horizontal axis is essentially the ‘nuclear density’ (‘squeezing of nuclei’) axis and the vertical axis is the Temperature or ‘heating’ axis. The diagram shows that there are two primary phases of nuclear matter, the hadronic phase at low temperature and baryon density, and the QGP phase at high temperature and baryon density. One can cross the boundary to deconfined QGP either by squeezing nuclear
matter [along the horizontal axis], by heating nuclear matter [thus creating many new overlapping particles in the interaction volume], or by both. Nuclear collisions do both since they heat and squeeze the interacting nucleons. The arrow in the left part of the figure shows the path taken by the early universe where only energy existed not matter yet. The lower right arrow shows the path taken by neutron stars in their formation (cold but dense nuclear matter). High energy nuclear collisions, such as those conducted at RHIC and the Large Hadron Collider (LHC), follow paths somewhere in-between. The QCD phase diagram is an area of intense study, because the location and nature of the transition line and the possible existence of a critical point have to be determined.
1.2 Nuclear Collisions

In order to study QGP matter, it must first be created in the laboratory. Ultra-relativistic heavy ion collisions offer an environment capable of studying matter at extreme temperatures and densities since they provide hot nuclear matter in bulk, in large volumes (relative to elementary p-p collisions). RHIC and the Large Hadron Collider (LHC) at CERN both offer opportunities to collide heavy nuclei across a few orders of magnitude in energy to study the formation of QGP, and search for the QCD critical point. In this section we discuss nuclear collisions and the signatures for QGP formation, in particular heavy flavor physics.

When nuclei collide at ultra-relativistic energies a strongly interacting ‘fluid’ is produced and its properties may be explored (see also Figure 1.3). Initially the two nuclei approach each other at almost the speed of light. The particular parton configuration just before the interaction is the ‘initial configuration or condition’. The initial violent interactions of the partons in the two nuclei produce hundreds of new particles that interact with other nearby partons thus producing a hot and nearly-thermalized medium. This hot and dense ‘fireball’ starts to expand and cool down. At the moment the ‘temperature’ of the medium falls below the rest mass of the pion, we say that the medium achieved ‘chemical equilibrium or chemical freeze-out’, in the sense that inelastic interactions (i.e. particle production) cease. From that point on the ‘chemistry’, the particle composition of the system is frozen. The particles can still exchange momenta through elastic interactions until the point where the density falls below a certain threshold, e.g. when the medium is so dilute that the mean free path of the particles in it is comparable to its size. At that moment we say that the medium reached ‘kinematic freeze-out’ and the particle spectra stay ‘frozen’ from
then on.

Figure 1.3: Stages and time evolution of a head-on high-energy nuclear collision

Different kinds of information can be extracted through the study of the produced-particle yields and spectra. For example, careful study and analysis of the kinematics and statistical properties of the particles produced allows the determination of the thermal properties of the medium produced (like the achieved temperature). Other more specific analyses probe selectively the various stages of the interaction and also look for specific ‘signatures’, specific ‘signals’ that may help prove the formation of the QGP phase during the collision.

1.3 Signatures of QGP Formation - Hard Partons and Heavy Flavor

Experimental results from previous studies have stimulated impressive theoretical advances in the past two decades on the thermodynamic and hydrodynamic properties of the hot and strongly interacting matter and the propagation of partons through the medium [3]. However, the complexities of heavy ion collisions and hadron formation
are a challenge to models and so far there is no single model that can completely
describe all aspects of a heavy ion collision. In the following we will discuss some
physics aspects that are relevant to the HFT detector and its physics goals.

High transverse momentum ($p_T$) partons are created in energetic quark–quark
(see also Fig. 1.4 [left panel]) or quark–gluon scattering during the early stages of a
collision and they typically emerge back-to-back due to $p_T$ conservation [4, 5, 6]. After
a hard scattering, the parton undergoes fragmentation to create a high-energy cluster
(jet) of particles in vacuum, or it interacts with the surrounding medium, if such a
medium exists, and then fragments. High $p_T$ parton production and fragmentation
in elementary collisions ($e^+e^-$ or $p-p$) and has been studied in detail. In nucleus–
nucleus collisions the situation is more complex. If the parton is created in the outer
surface of the overlapping interaction zone and its momentum vector points away
from the bulk medium the situation will be identical to that in elementary collisions.
In all other cases the parton will interact with the produced dense and hot medium
produced in the collision.

A high momentum parton traversing hot nuclear matter is subjected to energy
loss. There are two ways that energy loss occurs (see also Fig. 1.4 [right panel]). One
way to lose energy is via elastic collisions where the initial parton loses (redistributes)
its momentum through elastic collisions with other partons in the medium. The other
way is via inelastic collisions, e.g. induced gluon radiation. The contribution of the
elastic collisions to the total energy loss was thought to be negligible and it was
initially ignored in model calculations. The parton energy loss per unit length is a
very important parameter that characterizes the properties of the created medium.
For example, in the extreme case of a weakly interacting QGP the energy loss is
expected to be relatively low. Low is expected to be also the energy loss inside cold nuclear matter; something that can be studied in p–A interactions. In the case of strongly interacting matter the energy loss is expected to be relatively high.

![Figure 1.4: Example of quark-quark hard scattering [left panel]. Sketch of elastic and inelastic parton energy loss in a dense and hot medium [right panel].](image)

Initial studies verified that indeed in central Au+Au collisions at 200 GeV/c the high $p_T$ hadrons are greatly suppressed relative to properly normalized p-p interactions [7, 8]. An example is shown in Fig. 1.5 [left panel]. The $R_{AA}$ variable in the vertical axis is the ratio of the particle yield in Au+Au collisions divided by the properly normalized yield in p-p collisions. The normalization factor is the number of binary nucleon-nucleon collisions expected to occur in the specific centrality range in Au+Au collisions and it is used to take out trivial ‘volume’ differences between p-p and Au+Au. If nuclear collisions are nothing but a mere superposition of elementary nucleon-nucleon collisions this ratio will be one. In the figure the red and purple points are neutral pions $\pi^0$ and charged hadrons $h^\pm$ (mostly charged pions) form PHENIX and STAR experiments respectively. We observe that above a certain value
of $p_T$ (> 4 GeV/c) the ratio is as low as 20%. We also see that direct photons (dark purple squares) are compatible with a ratio of $\approx 1$ at all $p_T$ values since photons do not interact strongly and therefore pass through the hot medium without any loss.

We also see in the same figure (yellow line) that QCD models or parton energy loss are successful in calculating the magnitude of the effect only when they assumed very high gluon densities in the medium, an indirect signal of the presence of partonic matter. These initial results from light flavor studies at RHIC demonstrated that a hot partonic medium has been developed during the system evolution in heavy ion collisions and the next task was to test whether heavy flavor behaves the same way and whether the medium has reached thermal equilibrium.

Figure 1.5: Energy loss for hadrons (left panel) and heavy flavor (right panel).
1.3.1 Heavy Flavor

The results from light flavor were followed by similar studies using particles containing heavy flavor quarks (c and b). At that time the experiments were lacking high precision vertex detectors to directly reconstruct the weak decays of heavy flavor particles. Instead they used the semi-leptonic decay channels (an electron in the final state) to reconstruct heavy flavor mesons. This is called ‘non-photonic’ electrons method since its major background is electrons from photon conversion in the apparatus. Another disadvantage of this method is that we do not have the complete kinematic information of the original hadron, since we do not fully reconstruct the decay, so we need to use the ‘smeared’ electron $p_T$ as the kinematic variable.

The initial studies (see red points in Fig. 1.5 [right panel]) [10, 11] showed a suppression of heavy flavor at high $p_T$ values comparable to that for the light hadrons (shown as a grey bar in the figure). This came as a surprise since the QCD model calculations that were successful in predicting the light flavor suppression were predicting a much smaller magnitude of suppression for the heavy quarks. After careful analysis it was realized that elastic collisions with the dense medium make a significant contribution to the total energy loss and they are not negligible [9]. At the same time the experiments were upgrading their apparatuses with high precision vertex trackers so that they could fully reconstruct heavy flavor weak decays, e.g. $D^0 \rightarrow K^- + \pi^+$. The STAR collaboration built the Heavy Flavor Tracker (HFT), a four layer silicon vertex tracker using cutting edge silicon pixel technology in the two innermost layers. Aspects of the performance of the HFT, as built, is the topic of this thesis.
Chapter 2

The STAR Experiment at RHIC

The Relativistic Heavy Ion Collider (RHIC) [12] is located at Brookhaven National Laboratory in Long Island, New York. RHIC is the only dedicated heavy-ion accelerator designed to study matter at extreme densities and temperatures, to search for possible phase transitions in nuclear matter from the hadronic phase to quark gluon plasma (QGP). With a circumference of 3.8 km, the RHIC accelerator uses two independent superconducting rings to accelerate atomic nuclei to nearly the speed of light, with the possibility of colliding them at six interaction points around the ring. Originally, there were four active experiments in RHIC, the now decommissioned smaller experiments, BRAHMS and PHOBOS, as well as two larger and currently active experiments STAR and PHENIX. This chapter briefly discusses the design of RHIC and STAR experiment, highlighting the Heavy Flavor Tracker (HFT), the primary detector system used in this analysis.

2.1 RHIC

The RHIC accelerator began physics operation in June of year 2000, colliding Au+Au beams at an initial center of mass energy of 130 GeV making it the first facility to collide relativistic heavy ions. RHIC is designed to handle high luminosity beams and a wide range of beam species and energies, and has the unique capability of working with polarized proton beams. RHIC has used beams of p+p, d+Au, Cu+Cu, Au+Au, and U+U with center of mass energies ranging from 7.7 GeV upto
500 GeV for polarized p+p collisions. Heavy nuclei can be accelerated to the top center-of-mass energy of 200 GeV per nucleon pair. The RHIC accelerator complex consists of a series of pre-accelerators (the Tandem Van De Graaff facility (TVDG) or a LINAC (LInear ACcelerator), the BOOSTER synchrotron and the Alternating Gradient Synchrotron (AGS)) plus the main RHIC ring. Figure 2.1 shows a sketch of the RHIC facility.

![Figure 2.1: The RHIC accelerator complex with its system of pre-accelerators.](image)

The TVDG facility is also used to partially strip the electrons away from the heavy nuclei. To produce a Au–ion beam, gold atoms are first produced in the Pulsed Sputter Ion Source, in the TVDG facility, where they are initially ionized with a charge of -1e. These ions are then accelerated through the TVDG facility to an energy of about 1 MeV per nucleon. Next, the ions are passed through a thin
gold foil, ionizing them to a net charge of $+32 \text{ e}$. The ions are then accelerated in the booster synchrotron to an energy of $95 \text{ MeV per nucleon}$. Upon exit from the booster synchrotron, they are further stripped to a net charge of $+77 \text{ e}$ and transferred to the Alternating Gradient Synchrotron Booster (AGS). The AGS has a diameter of $257 \text{ m}$, and is used to accelerate the beams to $9 \text{ GeV per nucleon}$. After exiting the AGS, the ions are stripped of their remaining electrons leaving a charge of $+79 \text{ e}$ as they are injected in the RHIC ring. In the case of a proton beam, protons are supplied by the 200 MeV linear accelerator (Linac). Upon exit from the Linac, the proton beam is injected into the booster synchrotron prior to moving on to the AGS. Prior to being injected into the RHIC ring, the beams of ions are divided into two separate beams. The separated beams are then circulated around the RHIC (called blue and yellow) rings in opposite directions.

2.2 The STAR Experiment

Our work is conducted at the Solenoidal Tracker at RHIC (STAR) experiment [13]. The main, central body of the STAR detector consists of a large solenoidal magnet, surrounding an array of detectors. Momentum determination is done in the STAR Time Projection Chamber (TPC) and it requires a strong, uniform magnetic field. A strong field is necessary to bend high momentum tracks, but the position resolution is sensitive to inhomogeneity in the field so a uniform field is also needed. The STAR magnet was designed to produce a very uniform field along the $z$ axis over the range $0.25 < |B_z| < 0.5 \text{ T}$ (or 2.5 to 5 kGauss).
2.2.1 TPC

The Time Projection Chamber (TPC) [14] is the main tracking detector in STAR. It has cylindrical shape with a 4 m diameter and a length of 4.2 meters. It provides full tracking out to ±1.8 units of pseudorapidity and can identify particles with transverse momenta down to 100 MeV. As particles traverse the P10 gas (90% Argon, 10% Methane) which fills it, they ionize the gas molecules. The central membrane of the TPC is held at −31 kV, and the end-caps are grounded; this creates a very uniform longitudinal electric field. The electrons from the ionized gas molecule drifts down to the end of the TPC until they reaches the pad-planes. The two pad-planes each consist of 12 sectors. Each sector has 45 rows of pads. The sectors are divided into inner (60 < R < 127 cm) and outer (127 < R < 189 cm) sub-sectors.
In normal operation, the drifting electron is accelerated toward the anode wires until it has enough energy to ionize another gas molecule. Near the anode wires, the electrons are subject to a very high electric field and are strongly accelerated. This avalanche deposits charge on the anode wires when the electrons are grounded out there. This charge induces a current in the pad below the wire; the induced current is the raw data measured by the TPC. The benefit of the Argon in P10 gas is that it is easily ionized. The Methane acts as a quencher of the anode avalanche.

2.2.2 The HFT

![Figure 2.3: A perspective [left], side [right-lower] and transverse [right-upper] view of a model of HFT. The blue-red cylinders are the Pixel detector, the brown layer is the IST and the outer dark shape with the triangular shapes the SSD.](image)

The HFT is a silicon vertex detector that resides inside the TPC, between the beam pipe and the inner field cage of the TPC. Its purpose is to extend the TPC tracks towards the event vertex by providing high precision points (hits) very close to the beam line. It consists of three different silicon technologies arranged in four
layers (Fig. 2.3).

The outermost layer is the Silicon Strip Detector (SSD)[15], a double-sided silicon strip detector. It is made out of 20 ladders arranged in a cylinder at a radius of about 22 cm from the beam line. The ladders are directly mounted on a carbon fiber support structure. It provides two-dimensional hit position for charged particles, improving the extrapolation of TPC tracks through the inner HFT hits. The SSD covers the pseudorapidity range of $|\eta| < 1.2$. Each ladder is composed of 16 sensors (wafers) along the beam axis, is 1060 mm long and air cooled. Each sensor has 768 strips per side crossing at 35 mrad. The resolution of SSD is about 30 microns in $R\phi$ and 800 microns in $z$ direction.

![Figure 2.4: One half of the PXL detector mounted on the support/insertion structure. We can see the five carbon-fiber trapezoidal sectors and the outer ladders mounted on them and also the calibration balls on the right end used for survey purposes.](image)

The next layer is the Intermediate Silicon Tracker (IST) which is a (single sided)
silicon pad detector located at a radius of 14 cm. It is made of 24 ladders arranged in a cylinder. Each ladder has 16 sensors. The pad-size is $0.6 \times 6 \text{mm}^2$ resulting in an effective resolution of $170 \times 1700 \mu\text{m}^2$, where the high resolution side is on the transverse plane and the other along the $z$ direction. The main purpose of the IST and SSD is to connect the tracks from TPC to the two inner layers, the PIXEL detector.

The Silicon Pixel Detector (PXL) is the two inner layers of HFT at 2.8 cm and 8 cm from the beam axis (Figs 2.3, 2.4). It is based on the state-of-the-art Monolithic Active Pixel Sensor (MAPS) technology with pixel size of about $20 \times 20 \mu\text{m}^2$. Its hit resolution is better than ten microns in both $R\phi$ and $z$ directions. It has a total of 40 ladders (10 inner and 30 outer) mounted on 10 trapezoidal carbon fiber structures (sectors). The sectors are mounted in two halves for insertion purposes. Each PXL ladder has 10 sensors of $2 \times 2 \text{cm}^2$ size, so it has about 20 cm long active area. Each of the 400 sensors has about a million active pixels and it is thinned down to a 50 micron thickness in order to keep radiation thickness to a minimum. The average, total radiation thickness in the inner layer is less that $0.4\% X_0$. The position of each pixel inside the HFT has been surveyed and determined to an accuracy of better than 10 microns on average. The PXL detector has been designed so that can be replaced in about a day in case of radiation or other damage. The PXL detector defines the track pointing resolution and also determines the vertices position of secondary decay vertices very precisely.

2.2.3 Trigger and DAQ

During a run, many nuclear collisions take place. We need to filter out uninteresting events, such as those that are not well covered by the detector. We do this
through the use of a multi-level trigger system. The STAR Data AcQuisition (DAQ) electronics are capable of reading out entire events (in heavy ion collisions) at the rate of about 1000 Hz. Primary event selection is done mainly in the trigger levels 0, 1, and 2 (L0, L1, L2). These triggers get input from the Fast Detectors, e.g. a scintillator-based Vertex Position Detector (VPD), the Time of Flight (TOF) detector and two Zero Degree Calorimeters (East and West ZDC). These detectors provide per-event information at the rate of 10 MHz, 5 orders of magnitude faster than the Slow Detectors, which include tracking detectors such as the TPC.

The Level 3 (L3) trigger uses data from the slow detectors once it is digitized and actually performs a fast reconstruction of the event. This means that the L3 trigger software turns the pixel information from the tracking detectors into particle trajectory information, and ultimately particle identification (PID) data. It can then accept or reject the event on more complicated conditions such as the position of the interaction vertex, the event multiplicity etc. The L3 reconstruction also allows the immediate display of events in the STAR control room.
Chapter 3

Data Analysis and Results

3.1 Overview of Event Reconstruction

During an experimental run the Data Acquisition System (DAQ) is responsible for gathering, organizing and storing all the unprocessed (raw) information from all detector subsystems for each individual, triggered event. After the run is over a sample of the gathered data is analyzed for calibration and performance studies like the ones appearing in this thesis. When the calibrations are finished and the appropriate structures in the Data Base (Db) for each run are filled, one can start the so-called DST production (DST=data summary tapes). The task here is to calibrate and process the raw information for each event and write out all the information that is needed for further physics analysis. Examples of information written out is the multiplicity of the event, its position in space, the momentum and direction of each track etc.

Typically raw detector information is processed first into clusters or hits followed by tracking [if applicable]. Then the event vertex is determined and tracks are fitted with the hypothesis of emanating from the event vertex. The ones that are successfully fitted with the vertex point on them we call Primary and the rest Global tracks. Other detector information is also associated with each track based on specific criteria.
3.1.1 Hit and Track Reconstruction

We will concentrate here on cluster/hit and track reconstruction in the TPC and HFT as the main tracking devices in the central region of the experiment. In the TPC the secondary electrons that are formed by collisions of the produced charged particles in the collision with electrons of gas atoms produce ionization clusters. These ionization clusters then drift towards the TPC end-caps where they get amplified and recorded. Offline software reconstructs these clusters on a 2+1 dimensional coordinate system as defined by the TPC pad plane (X-Y) and the drift (Z) direction. A cluster is a blob of charge and a space-point is determined as the ‘center’ [weighted mean] of this blob which we call a ‘hit’. The hits correspond to the points along the particle trajectory. Some times, in high multiplicity events, overlapping clusters must be de-convoluted into two or more individual hits.

The HFT hit reconstruction process is similar in the sense that ‘clusters’ are formed from raw data and then a centroid is determined, the hit coordinates. The HFT is made from three different technologies and the hit finding process is slightly different in each one. For example the SSD is a double-side silicon strip detector so first we make a list of ‘fired’ strips in each side and then we match the two sides based on geometry and charge information to form hit candidates. After that an algorithm decides which candidates become accepted hits. In the IST the hit is assigned to the geometrical center of the fired pad. The PIXEL detector typically gets several pixels fired every time a track crosses an active area. The geometrical mean position of the cluster becomes the hit position.

The process of taking the reconstructed hits and combining them into tracks is
called Tracking. The process starts typically in the outer part of the TPC where a short series of hits close to each other, a track ‘seed’ is found. Searching for track-seeds in the low hit density regions of the outer pad-rows of a sector makes the seed-finding more efficient. The track finder fits the hits in the seed with a helix hypothesis and then extends (projects) it inwards to the next pad-row looking for another hit. In this step the effects of Multiple Coulomb Scattering (MCS) and energy loss in the material crossed are taken into account. If a hit is found the whole string of hits is re-fitted and the process continues until all pad-rows are used. In reality of course this task is more complex especially in a high hit density environment and/or in the presence of gaps (dead pad-rows) in the detector.

After finishing tracking in the TPC, the found tracks are extended to the outer layer of HFT, the SSD, where silicon hits are now added to TPC tracks. The process continues inwards in all four layers of HFT. After this outside-in tracking step is completed, it is followed by a clean-up, or ‘filtering’, step to reject hits not belonging to track. The resulting sample of tracks is called global tracks.

Based on the reconstructed global tracks in the event and extrapolating them to the beam line, one can estimate the position of the primary vertex (the place where the collision occurred) as described below. After the event vertex is determined all global tracks that point near the primary vertex are fitted with the hypothesis that they originate at the event vertex, i.e. they are fitted with the event vertex as a ‘hit’ on the track. If the fit is successful then the new, updated parameters of the track are saved in a track sample called primary tracks for obvious reasons.
3.1.2 Event Vertex Finding

We use two independent ways to determine the position of the event vertex. One is based on timing information between the two Vertex Position Detectors (VPD) [17] on each side of STAR outside the TPC and around the beam pipe (see also Fig. 2.2). The particles that reach these detectors, traveling practically at the speed of light, arrive at the VPDs at slightly different times, depending on the \( z \)-position of the primary vertex. The timing difference gives directly the \( z \) position of the event vertex. The VPDs are used in the trigger to select events that are inside the HFT coverage. Let us recall that the PXL ladder is about 20 cm long, so the coverage of both PXL layers is \( \pm 10 \text{cm} \). The trigger setting was to select events within \( \pm 5 \text{cm} \) from the HFT center.

The other method is to use (offline) track information. The task to find the event vertex using TPC or TPC+HFT tracks is straightforward. First all the reconstructed global tracks are extrapolated to the beam line where a ‘seed’ vertex is determined. The seed vertex point is estimated by using for maxima of the projected track density along the \( z \)-coordinate. Then, by using \( \chi^2 \) minimization techniques, we can determine the position of the event vertex, which is the point that minimizes the average distance from the track sample.

Figure 3.1 [left and right-upper panel] shows the correlation of the \( z \) location (beam direction) of the event vertex \((V_z)\) as triggered in the VPD versus that estimated by TPC tracking. The left panel is a large scale view of the distributions that covers the whole length of TPC. The right-upper panel is a zoomed-in version of the same correlation inside the acceptance of the HFT detector \((-10 < z < +10 \text{cm})\).
Figure 3.1: [left plot] The estimated $z$-position of the event vertex using the VPDs versus the same position estimated by using the TPC tracks. The upper plot in the right column is a zoomed version of this plot. The lower panel in the right column shows the distribution of the difference between the two vertex estimates together with a gaussian fit [red line]. We observe a slight offset of $2.5\,mm$ and a width of about $0.5\,mm$ between the two estimates.

The diagonal red band in the middle shows the nice correlation between the two vertices. We also see that the red band extends only to about $\pm 5\,cm$ which was the trigger setting. Due to resolution effects the band actually extends to about another centimeter on each side. In order to find the VPDs resolution we need to look at the distribution of the difference between the two vertices. This is shown in the lower-right panel of Fig. 3.1. The gaussian fit of the distribution gives a $\sigma_Z$ of about $5\,mm$ with an overall shift (bias) of about $2.5\,mm$. Both numbers are compatible with the VPD design parameters.

A $V_Z$ quality cut of $| V_Z | < 5\,cm$ was used in our analysis in order to avoid possible acceptance effects at the edges of the HFT detector.
3.2 Pileup Hits in PIXEL detector

For the single-track efficiency studies we present below we use detailed and realistic simulations. In order to have a realistic collision environment in the simulations one needs to account for possible background sources. The sources of background differ from detector to detector. Here we will focus on background in the PXL detector and ignore the (negligible) background in the IST and SSD. For the PXL detector, the two sources of background hits are:

1) Out of time, non-triggered collisions falling into the same readout time-frame as the triggered event (pileup events).

2) Electron-positron pairs created in strong electromagnetic interactions between the non-touching beam particles, called Ultra Peripheral Collisions (UPC) electrons.

Both sources are related to the (relatively) slow readout time, about 200 microseconds, of the PXL sensors. This should be compared to a few hundreds of nanoseconds for the IST and SSD readout times. The background hits created from these two sources were carefully estimated and included in our simulations. We collectively call them ‘pileup’. We validated the correctness of the estimates by comparing the measured PXL hits densities from data to the estimated hit densities (see Fig. 3.2).

Figure 3.2 [upper row] shows the correlation between the total number of TPC tracks and the number of hits in each HFT layer for IST, PXL2 [outer PXL layer] and PXL1 [inner PXL layer] in simulations with pileup. As shown in this figure the number of IST and TPC hits are proportional and also both start from the origin (0,0), i.e. there no pileup in the IST since it is fast detector. In the same figure we see that even for very small TPC track numbers (peripheral events), there is an offset in PXL2 and PXL1 layers and that the offset is about twice in the inner PXL1 layer.
Figure 3.2: [upper row] Correlation of the reconstructed TPC tracks versus the number of reconstructed HFT hits in each layer in simulations with pileup. [lower row] Correlation of the reconstructed TPC tracks versus the numbers of reconstructed HFT hit in each layer in Data at typical running conditions.
relative to PXL2. The offset corresponds to the background hits from pileup minimum bias events and UPC electrons that were added in the simulation. The multi-strip structure is due to a finite number of pile-up input files; each strip corresponds to a production set using the same pile-up input file.

Figure 3.2 [lower row] shows the same correlation but now using Data minimum bias collisions, not simulation. As shown in this figure the offsets in PXL1 and PXL2 with vanishing number of TPC tracks are similar to those found in Hijing simulations in the previous figure (if anything the simulation seems to overestimate the level of background). The hit distributions shown in the figure were extracted from typical Au+Au 200 Gev collisions.

Pile-up hits in the PXL detector are useful when one tries to estimate the single track reconstruction efficiency of HFT using simulations, since they provide a hit environment similar to that encountered in the real experiment.

3.3 Particle Identification Using Time-of-Flight [TOF] and Ionization [dE/dx]

The Particle IDentification (PID) is a crucial aspect of most particle physics experiments. Special detectors are used that detect the unique signatures left by the stable particles as they pass through them. Charged hadrons can be identified from determining their mass and charge. The mass can be deduced from measurements of the momentum and the velocity or ionization. The momentum (and charge sign) are obtained by measuring the curvature of the particles track in a magnetic field. To obtain the particle velocity there are several methods but here we use and discuss the Time-Of-Flight (TOF) method [16]. Ionization information is measured in the TPC. Each method works in different momentum ranges or for specific particle types. The
TOF measurements yield the velocity of a charged particle by measuring the flight time over a given distance along the track trajectory. Provided the momentum is also known, the mass of the particle can then be estimated.

As elementary particles travel through the detector material they lose energy, aka dE/dx, through ionization production from collisions with atomic electrons. Another result of these collisions with the atoms is a small change in their direction, aka Multiple Coulomb Scattering [MCS]. We use the dE/dx information, together with the Time-of-Flight [ToF] information to better identify the particle type from its mass and charge. In the following paragraphs we briefly describe the main features of these two particle identification methods.

We begin by discussing the dE/dx mechanism in some more detail. As particles traverse the detector media, gas in the TPC or silicon in the HFT etc, they collide with the atoms, i.e. interact electromagnetically with atomic electrons of the media, causing a loss of energy and the creation of what we call primary ionization (see also Fig. 3.3). In some of the hard collisions the atomic electron acquires such a large energy that it causes secondary ionization. Due to the presence of the external electric field the electrons will start drifting towards the TPC anodes at the edges of the detector where they get amplified and recorded.

The rate of energy loss can be approximated by the Bethe-Bloch formula as shown below, (the Bethe-Bloch formula gives us quantitatively the amount of energy ‘lost’ or deposited by the particle on the average per unit length due to the numerous collisions it suffers as it passes through the material):

\[-\frac{dE}{dx} = K z^2 Z \frac{1}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln 2 + \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

Here, \( T_{\text{max}} = \frac{(2 m_e c^2 \beta^2 \gamma^2)}{(1 + \frac{2 \gamma m_e}{M} + (\frac{m_e}{M})^2) \text{ is the maximum kinetic energy which} \]

\[ \]
Figure 3.3: A sketch of ionization energy loss (dE/dx) in the gas volume of the TPC. can be imparted to a free electron in a single collision. \( Z \) is the charge number of medium, \( K = 4\pi N_A r_e^2 m_e^2 c^2 \) is a constant, \( z \) is the charge of incident particle, \( A \) is the atomic mass of medium, \( m_e \) is the electron mass, \( M \) is the mass of incident particle, \( r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} \) is the classical electron radius, \( \beta \) is the particle’s relativistic velocity \((v/c)\), \( N_A \) is Avogadro’s number, \( I \) is the mean excitation energy and \( \delta \) is the density effect correction to ionization energy loss. Energy loss, however, is a stochastic process and so there are fluctuations in energy loss per finite unit length.

Figure 3.4 shows the dE/dx distribution as a function of track momentum. Clearly, the heavier-particle bands (protons and kaons) have higher values of dE/dx than pions at lower momenta. The relativistic rise separates the electron dE/dx from the other particles except at the crossover with kaons at 0.55 GeV/c and pions at 0.2 GeV/c.

In addition to energy loss, charged particles suffer multiple scattering from nuclei.
Figure 3.4: Energy loss \( \frac{dE}{dx} \) as a function of track momentum for different particle species.

through small angles which is called Multiple Coulomb Scattering (MCS). The scattering angle \( \theta_0 \) away from the direction of propagation is estimated to have a RMS value of:

\[
\theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} \beta \cdot \frac{z}{X_0} \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 ln \frac{x}{X_0} \right]
\]

Here \( p, \beta, \) and \( z \) are the momentum, relativistic velocity, and atomic number of incident particle, and \( x/X_0 \) is the thickness of the scattering medium in units of radiation length \( X_0 \).

We very briefly discuss here the TOF method since it is presented in more detail in [18]. Using the Time-of-Flight (TOF) [or more precisely the particle’s velocity (\( \beta \))] information and the particle’s momentum we can estimate its rest mass (\( m \)). We
Figure 3.5: The combined power of both the TOF \([m^2]\) versus the dE/dx for two momentum ranges: (0.1-1.5 GeV/c) [left panel] and (0.7-0.8 GeV/c) [right panel]

know that \(p = m\beta\gamma\) or \(p^2 = m^2\beta^2\gamma^2\) and also that

\[
\gamma = \frac{1}{\sqrt{1-\beta^2}} \quad \text{or} \quad \gamma^2 = \frac{1}{1-\beta^2} \quad \text{and after combining} \quad p^2 = \frac{m^2\beta^2}{1-\beta^2}.
\]

Solving for \(m^2\) we get:

\[
m^2 = p^2\left(1 - \beta^2\right) = p^2\left(\frac{1}{\beta^2} - 1\right)
\]

Figure 3.5 shows the mass squared \([m^2]\) versus the dE/dx for two momentum ranges. The left panel shows the PID discrimination in the momentum range of [0.1-1.5 GeV/c]. This is the full momentum range we show pointing resolution results below. The right panel is the same distribution for the momentum range of [0.7-0.8 GeV/c] since 750 MeV/c is the kaon momentum where we have set a specific design goal. We see that there is a clean separation between pions, kaons and protons.
when the two PID methods are combined. Further, more tight, \( m^2 \) cuts selected the central peaks of each distribution for a very clean species sample.

### 3.4 Track pointing, DCA resolution

The ability to reconstruct secondary vertices is proportional to the track pointing accuracy near the primary vertex. The HFT greatly improved the track-pointing resolution in STAR to allow for a direct and full topological reconstruction of heavy-meson decays. This pointing accuracy, or resolution, is typically estimated near the event vertex and more precisely at the point where the Distance of Closest Approach (DCA) of the track/helix to the vertex is minimum as the name suggests. There are several factors that contribute to the final track pointing resolution both systematic and random. For example a systematic factor is the possible mis-alignment of some detector elements. The net effect in this case would be a systematic displacement of the track in a specific direction and this will affect the mean pointing value of a track sample. In reality we use the appearance of such shifts to align the detector elements, i.e. we bring the means to zero.

Other, random factors that contribute to the DCA resolution is the vertex position error, the error due to finite detector resolution and the error due to multiple scattering. All these factors are added quadratically to deliver the final number:

\[
\sigma_{DCA}^2 = \sigma_{vertex}^2 + \sigma_{track}^2 + \sigma_{MCS}^2
\]

By using high multiplicity Au+Au events we can keep the vertex error to values below 10 microns [18]. The second term is fixed for a given detector resolution and geometry and the third term depends inversely proportional to momentum as we discussed in section 3.3 above.
Figure 3.6: Raw, per track, DCA-XY distribution as function of the reconstructed track momentum (left panel). DCA-XY distribution in momentum range $0.7 < p < 0.8 \text{GeV}/c$ (right panel). The red line is a double Gaussian fit to the data points.

Figure 3.6 [left panel] shows the raw, per track, transverse (DCA-XY) distribution as function of the reconstructed track momentum for all hadrons [mostly pions]. Clearly, the distribution is centered around zero for all momenta. The DCA resolution for a given momentum interval is estimated by plotting and fitting this distribution in specific momentum slices. The right panel of the same figure shows the same, DCA-XY, distribution for the momentum slice around the range between 0.7 and 0.8 GeV/c. We see the distribution is Gaussian with a small amount of outliers. The source of outliers is tracks with wrong pixel hits, ‘ghost’ tracks. We use a double Gaussian fit function (red line) to fit the broad outliers and the central peak. The fitted sigma value of the central Gaussian is $42 \mu \text{m}$, a value dominated mostly by pions.
By repeating the same procedure for many momentum intervals we can obtain the dependence of the resolution to momentum \((p)\) or \(1/p\). Figure 3.7 shows the obtained DCA-XY resolution as function of \(1/p\). In the same figure we see a fit to the functional form we discussed in the previous paragraph where \(A\) refers to the detector resolution term and \(B\) to multiple scattering. (the vertex error contributions here are negligible and are effectively compounded in the \(A\) parameter). Notice that the y-axis intercept gives \(A\), the infinite momentum limit \((1/p \rightarrow 0)\) and that the line slope at low momentum values \((1/p >> A)\) gives \(B\). Both values agree well with estimates using the expected detector resolution and PXL thickness.

Figure 3.8 shows DCA-XY results for this data sample [left panel] and a full system simulation with pileup [upper-right panel] as a function of momentum. The different
sets of color points represent protons [blue], kaons [black] and pions [red] based on the event generator information for the Simulation and PID analysis for Data. As shown in this figure the DCA-XY distribution represents a remarkable agreement in shape and scale between Data and Simulations.

One of the design goals for HFT was to achieve a DCA-XY(Z) resolution below 60 microns for 750 MeV/c kaons, since they represent the mean momentum of kaons from a realistic sample of D^0 decays. Clearly, the dca of kaon with momentum of 0.750 GeV/c is below the threshold value of 60 microns in both Data and Simulation. The lower panel in the figure shows the actual double Gaussian fit for kaons in this momentum range [0.7-0.8 GeV/c]. The obtained value (parameter p5 in the figure insert) is 47 microns.

Figure 3.8: DCA-XY resolution results as a function of momentum for Data [left panel] and full system simulations with pileup [right upper panel]. The right-lower panel of the figure shows the DCA-XY distribution for Kaon in the momentum range of 0.7-0.8 GeV/c.
3.5 Tracking Efficiency of the HFT system

The single track reconstruction efficiency is another critical performance parameter for a vertex detector since it enters quadratically in the final $D^0$ efficiency (two-body decay), or to the third power for $D^\pm$ (three body decay) etc. The single-track reconstruction efficiency with the HFT system is defined as the probability of reconstructing the track with at least one correct hit in the SSD and/or the IST layer and two correct hits in the two PXL layers (one in each layer) for all good TPC tracks. A correct hit is a reconstructed hit that matches the corresponding hit of simulated input track. A good TPC track is a track that has more than 15 correct hits in the TPC. We say at least one hit in each layer since, due to ladder overlaps, there is a finite probability for a track to leave two hits in the IST and PXL2 layers. For PXL1 layer this probability, due to geometry, is negligible.

For calculating single-pion reconstruction efficiency, we used Au+Au collisions in a realistic simulation environment. Here we ran a complete set of Hijing\textsuperscript{1} events through the GEANT simulation engine with the expected PXL piled-up hits included, and then process them through the STAR detector simulators and offline reconstruction chain. As we discussed earlier in this chapter all PXL events contain hits from multiple collisions (pileup). According to the expected hit density based on the RHIC collision luminosity and the UPC electron production rates, we embed additional hits on the PXL layers to get a realistic environment for our estimate of the HFT single tracking efficiency. We combine the PXL hits generated during the GEANT simulation with the pileup ones before we pass them to tracking.

Figure 3.9 [left panel] shows the PXL+IST tracking efficiency versus the track

\textsuperscript{1}Hijing is an event generator for heavy ion collisions tuned to RHIC energies.
Figure 3.9: Single track reconstruction efficiency as function of track transverse momentum for pions in minimum bias Au+Au collisions at 200 GeV. The left panel show the efficiency without the SSD [only IST+PXL1,2] and the right panel shows both without the SSD [blue points] and with the SSD [red points] in tracking.

transverse momentum for charged pions from Hijing minimum bias Au+Au at 200 GeV simulations with pileup. The red points in the left panel show the system’s efficiency, i.e. fraction of recovered tracks with good/correct hit associations, while the open circles show the total number of reconstructed tracks, including tracks with wrong hits (ghost tracks). We see that the fraction of ghost tracks increases for lower momenta where multiple scattering and track quality are in general lower.

The right panel shows the efficiency of both combinations, with and without the SSD in tracking. This time the red points of the left figure [without the SSD] are shown as blue square points while the system efficiency with the addition of the SSD in tracking is shown in red. The recoverable fraction of tracks is increasing by 10-15% when the SSD is included in tracking. Clearly, and in either case, the single pion
efficiency at 1 Gev/c is $> 65\%$ which is the design goal. There are current efforts to estimate and further optimize the HFT tracking efficiency in data but those are beyond the scope of this work.
Chapter 4

Summary

We used a calibrated sample of STAR Run14 data that included the new silicon vertex detector, HFT, in the configuration, in order to study and evaluate several critical performance parameters of the HFT system. These included the event vertex reconstruction and selection, the track pointing (DCA) resolution and the single-track reconstruction efficiency. In all cases the system outperformed the originally set design goals. Physics results have been obtained from the Run14 data and presented in the heavy-ion community. These results are now prepared for publication. We will conclude by showing a $D^0$ invariant mass distribution obtained with HFT for a data sample which represents only about 10% of the total events recorded during Run14. It is shown in Figure 4.1 where a clear peak exists in the expected $D^0$ mass value (1.87 GeV). The insert in the figure shows the same distribution without the HFT in tracking. It demonstrates the power of HFT in reducing the combinatorial background through better track pointing resolution. In this particular case the suppression of the background is about four orders of magnitude.

In Run15 (2015) the HFT obtained large samples of $p$–$p$ (about one billion events), $p$–$Au$ and $p$–$Al$ (about 0.6 billion events) that are important to use as reference data ($p$–$p$) and also to study cold nuclear matter effects ($p$–$Au$ and $p$–$Al$). In the upcoming Run16 (2016) the HFT is scheduled to take a large sample of $Au+Au$ 200 GeV data (about two billion events) for more detailed studies and also for charm baryon ($\Lambda_C$) reconstruction.
Figure 4.1: Invariant Mass spectrum of $D^0$ mesons reconstructed with the HFT. The insert shows the power of HFT in reducing the combinatorial background, through better pointing, by several orders of magnitude.
Appendix A

Glossary and Specific contributions

A.1 Glossary

**Rapidity/Pseudo-rapidity**: Rapidity is a relativistic quantity defined as

\[ y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \]

Where \( E = \sqrt{p^2 + m_0^2} \) is the particle’s energy and \( p_z = p \cos \theta \) the momentum projection on the beam axis (\( \theta \) is the polar angle). In the limit where the particle is traveling near the speed of light where \( p \gg m_0 \) or for massless particles (like the photon), rapidity is reduced to

\[ y \approx \frac{1}{2} \ln \left( \frac{p + p_z}{p - p_z} \right) = \frac{1}{2} \ln \left( \frac{1 + \cos \theta}{1 - \cos \theta} \right) = -\ln \tan \left( \frac{\theta}{2} \right) \equiv \eta \]

where \( \eta \) is the pseudo-rapidity and it directly relates to the particle’s emission polar angle.

Rapidity is a Lorentz additive quantity and the shape of a rapidity distribution of a physics quantity stays the same in all reference systems. The value of rapidity is zero for a particle emitted normal to the beam axis (\( p_z = 0 \)) and achieves its maximum value for beam particles.

**DCA**: Distance of Closest Approach is the point where the track helix is closest to a space point, in our case the event vertex. Since all primary tracks come from the event vertex, the resolution of this parameter characterizes the instrument’s pointing or discrimination ability between primary and secondary tracks.
MCS: Multiple Coulomb Scattering. The interaction of charged particles with atomic nuclei as they traverse detector material. The result is the deflection of the particle from its original path by a small angle. In Section 3 we presented the relevant formula.

Luminosity: The luminosity is the flux of beam particle, i.e. the number of particle crossings per unit area per unit time and is equivalent to

\[ L = f \frac{N_1 N_2}{A} \]

where \( f \) is the frequency of bunch crossing, \( N_1 \) and \( N_2 \) are the number of particles in each intersecting bunch, and \( A \) is the transverse area of the interaction region.

Transverse momentum: \( p_T \) (transverse momentum component) is defined as \( p_T = \sqrt{p_x + p_y} \). The \( p_T \) is a Lorentz invariant variable since both \( p_x \) and \( p_y \) are uncharged under a Lorentz boost along \( z \) axis.

The Gaussian or Normal Distribution: The Gaussian distribution plays a central role in all of statistics and is continuous, symmetric distribution whose density is given by

\[ P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \]

where \( \mu \) is the mean and \( \sigma^2 \) is the variance of the distribution.

A.2 Specific contributions

This is a brief summary of the specific contributions the author made to the work presented here.

This work started in March 2015, the time when the Run-14 data sample, the first STAR data with the HFT, was ready for full production after all calibration work finished. Therefore there was a need to recalculate some basic performance parameters like track pointing resolution with a calibrated sample. A small sample
of 660 thousand events (about 45 Million tracks) of minimum bias AuAu 200 GeV was prepared for DCA studies and another sample of about 7.5 Million events for event vertex studies. We used the ROOT analysis framework to examine the event vertex quality, PID performance and also extract the track pointing (DCA) resolution values.

I used and modified Root macros to look at the transverse quantities of the event vertex reconstruction and the performance of VPD [used in the trigger to select the vertex position], assess the trigger quality and refine the cuts in order to get a clean sample. I also worked on the DCA-XY, the transverse, bending plane dca value, made comparisons to Simulations (not my work) and examined the behavior and DCA dependence on various sources. I focused on dE/dx in the PID section. For context purposes I also show the single-track reconstruction efficiency of HFT and the Pileup hit densities in the PXL layers (not my work). As part of this work I had to install the ROOT analysis package in my laptop and get crash courses on Root macros [C++ syntax], histogram making and manipulation, Heavy-Ion physics, the HFT technology and purpose, elements of relativity and LATEX publishing package.

The analysis was concluded by Summer 2015 while writing was done in Summer and Fall of 2015. The resulting plots are now the official DCA plots shown to international conferences.
References


