Feasibility Study for the Measurement of J/ψ Particles in sPHENIX

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\( J/\psi \) Particles in sPHENIX

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Chapter 1

Charmonium Overview

One of the most interesting problems of physics has always been the defining features of the states of matter and the transitions between them. Strongly interacting matter introduces a whole new chapter for such studies. When nuclear matter gets to a high enough density and temperature it undergoes a phase transition to a form of matter called the Quark Gluon Plasma (QGP). In this state of matter, hadrons such as protons and neutrons are deconfined into quarks and gluons.

A $J/\psi$ particle is a tightly bound state of a charm and anti-charm quark. Its large binding energy makes it a very useful probe of nuclear matter and it is now considered a promising probe of the QGP.

High-energy heavy ion collisions produce hot, dense nuclear matter that is useful for studying QCD and the standard model. Finding the $J/\psi$ and interpreting it was a significant step in developing the Standard Model and has been a valuable probe of the nucleon and the nucleus. In this chapter, we will review the history of the $J/\psi$, then go over its production methods.
1.1 History

In November of 1974, two different experiments at Brookhaven National Laboratory (BNL) [1] and Stanford Linear Accelerator Center (SLAC) [2] simultaneously and independently observed a resonance of mass 3.1 GeV/c². The AGS at BNL accelerated protons up to 28 GeV onto a beryllium target and measured electron-positron pairs in two forward spectrometers. One advantage of this experiment is in the search for new particles since all masses are simultaneously explored. However, one shortcoming of this experiment was in measuring the width of the resonance with precision.

![Figure 1.1: The first experimental observations of the J/ψ by experiments at BNL (left) [1] and SLAC (right) [2]](image)

At SLAC, the $e^+e^-$ collider SPEAR was designed to search for new particles using a different method. In this method, the beam energy was adjusted to precisely match
the mass of the hypothetical particle. Then, a measurement of the particle production was made. The beam energy was then incremented in 200 MeV steps. Therefore, as long as the width of the particle was broader than 200 MeV, any particle within the explored energy range would be observed. At these intervals, the narrow resonance observed at AGS could have been overlooked, but the new resonance was measured in hadronic, $e^+e^-$, and $\mu^+\mu^-$ decay channels, showing the same narrow resonance with a width less than 1.3 MeV/$c^2$.

Both groups received credit for the discovery. The group from SLAC called the discovered particle the $\psi$ and the group from BNL called it the J particle.

1.2 Description

The J/$\psi$ and other charmonium states have been well understood theoretically since their discovery. Charmonium is the bound state of a charm and anti-charm quark. We will consider it to be a simple two body system for this discussion. The relative velocities are $\beta \approx 0.5$, which is relatively small compared to systems of lighter quarks ($\beta \approx 0.8$), the charm anti-charm pair may be treated non-relativistically. The charm quark has a coulombic charge of $2/3$ that of an electron and the anti-charm quark has the opposite coloumbic charge. Therefore, they are attracted by the electrostatic potential,

\[ V_{\text{electric}}(r) = -\frac{q^2}{4\pi r}. \]

Quarks also carry a color charge, resulting in an additional attractive force from the strong confining linear potential,
\[ V_{\text{color}}(r) = \kappa r, \]

where \( \kappa \) is the string tension coefficient. Putting these terms together, we get the Hamiltonian

\[ H = \frac{p^2}{2\mu} - \frac{q^2}{4\pi r} + \kappa r. \]

Solving a Schrödinger equation that includes this asymptotic behavior of QCD, the spectrum of states can be derived [3]. The applicable quantum numbers are the same as that for positronium. Spectroscopic notation for the various states of charmonium is then \( n^{2S-1}L^PC \). Charm quarks are fermions with spin 1/2, so in the \( J/\psi \) they can have their spins opposite to each other to form the spin singlet state \( (S = 0) \) or they can be aligned to form the spin triplet \( (S = 1) \). The principle quantum number associated with radial excitations is \( n \). \( J \) is the total angular momentum \( L + S_z \). Additionally, charmonium states are eigenstates with parity \( P = (-1)^L \) and charge conjugation \( C = (-1)^{L+S} \). A great spectrum of charmonium states have been observed.

1.3 Direct Production Methods

Production of charmonium has been studied under many conditions. There are three models used to describe \( J/\psi \) production, the Color Evaporation Model, the Color Singlet Model, and the Color Octet Model. These models have to address the perturbative, short-range process of the quark anti-quark production and the non-perturbative, long-range evolution of the pair into a physical state. While all
observed matter is color neutral, there are two possible classes of states in which a $c\bar{c}$ may be generated, a color singlet or a color octet. The color singlet is already color neutral, but the color octet state has a color that must be neutralized by radiating a colored gluon before it can be observed. Models which have formation of colored states have to account for this neutralization in the long-range evolution of the pair.

In the Color Evaporation Model, both color singlet and color octet states evolve non-perturbatively into a $J/\psi$ [4]. Any $c\bar{c}$ pair with an invariant mass between two times the mass of a charm quark and two times the mass of a D meson is considered independent of its spin and color state. Here, we assume that any color can be radiated by a soft gluon in an interaction with the collision-induced color field. Then, the charm and anti-charm quarks could combine with lighter quarks to make charmed mesons or they could pair up and evolve into one of the charmonium states. The cross section of a charmonium state $H$ is given by

$$d\sigma^{CEM}(H + X) = f_H \int_{2m_c}^{2M_D} dM_{c\bar{c}} \frac{d\sigma(c\bar{c} + X)}{dM_{c\bar{c}}}$$

where $f_H$ is a phenomenological parameter used to designate the constant fraction of the mass region which evolves to a particular charmonium bound state [5]. This model is not able to make predictions about production of different charmonium states as the predicted production ratios of different states are energy independent. This is consistent with hadron production data at Fermilab [6]. This is also consistent with the longitudinal momentum distribution over a range of energies and projectile-target systems though the normalization must be determined from the data itself. This model doesn’t have any predictive power of the transverse momentum distribution at low $p_T$. In addition, this model is unable to predict polarization in $J/\psi$ production.

In the Color Singlet Model, the $c\bar{c}$ pair is initially produced in the color singlet
state with spin $S$ and orbital angular momentum quantum number $L$ and total angular momentum quantum number $J$ to evolve to a bound state $^{2S+1}L_J$ [7]. The color of the $c\bar{c}$ pair is radiated out by a hard gluon as shown in Figure 2.2. The relative momentum of the charm anti-charm pair inside the charmonium is assumed to be small compared to the quark mass so the pair will not fly apart and form $D$ and $\bar{D}$ mesons.

![Diagram](image)

Figure 1.2: The process used in the Color Singlet Model [7]

In the Color Singlet Model, we assume gluon emission happens on the perturbative scale, which is only valid if all momentum scales are reasonably large. But, for the $J/\psi$ to become color neutral, a gluon must be emitted. This limits the model to a low $p_T$, so then the $p_T$-integrated yield has a region of phase space where this emitted gluon is “soft”. Traditionally, quarkonium production has not been calculated with this model at low energies; however hadroproduction of charmonium is not well described even at $\sqrt{s} = 50 GeV$ [8]. In this model, $J/\psi$ direct production is under-predicted by a factor of 5.

The Color Octet Model uses non-relativistic QCD and was developed by Caswell and Lepage in 1986 [9]. It utilizes both the color-singlet and color-octet production mechanisms. Some of these production mechanisms are applicable to hadroproduction and are diagrammed in Figure 2.3 along with the related $p_T$ scaling. Although it uses
non-relativistic QCD, relativistic effects that are neglected in the Color Singlet Model are considered in the Color Octet Model by including relativistic corrections.

\[ (a) \text{ leading-order colour-singlet: } g + g \rightarrow c e^3 S^{(1)} + g \]

\[ \rightarrow c e^3 S^{(1)} + g + \ldots \sim \alpha_3^3 \frac{(2m_e)}{p_T^3} \]

\[ (b) \text{ colour-singlet fragmentation: } g + g \rightarrow c e^3 S^{(0)} + gg + g \]

\[ \rightarrow c e^3 S^{(0)} + gg + g + \ldots \sim \alpha_3^3 \frac{1}{p_T^3} \]

\[ (c) \text{ colour-octet fragmentation: } g + g \rightarrow c e^3 S^{(0)}_8 + g \]

\[ \rightarrow c e^3 S^{(0)}_8 + g + \ldots \sim \alpha_3^3 \frac{1}{p_T} e^{t} \]

\[ (d) \text{ colour-octet } t\text{-channel gluon exchange: } g + g \rightarrow c e^3 S^{(0)}_8^3 + g \]

\[ \rightarrow c e^3 S^{(0)}_8^3 + g + \ldots \sim \alpha_3^3 \frac{(2m_e)^2}{p_T} e^{t} \]

Figure 1.3: Production diagrams for J/ψ and their corresponding \(p_T\) dependence

This model does well reproducing direct J/ψ production at high \(p_T\) in \(p\bar{p}\) collisions. Still, at low \(p_T\), the Color Octet Model is sensitive to the intrinsic motion of the initial parton inside the colliding nucleon, resulting in the decay of both color singlet and color octet predictions.
1.4 Production and Suppression in Nuclear Targets

In heavy-ion collisions, large amounts of energy are deposited in small volumes. The Relativistic Heavy Ion Collider at Brookhaven National Lab accelerates gold nuclei to energies of 100 GeV per nucleon and since there are 197 nucleons in a Au nucleus, the total energy of the nucleus is 19.7 TeV. The nuclear radius determines the volume over which this energy is distributed, the radius of a gold ion being about 7 fm. However, these highly relativistic nuclei will experience a Lorentz contraction, resulting in a volume that is much less than that of colliding spheres.

Each nucleus is made of nucleons, so it is useful for us to first break down what happens when two nucleons collide. The inelastic cross section of nucleon-nucleon collisions, $\sigma_{NN_{in}}$ is a large fraction of the total cross section, approximately 75% of the total. If this were untrue, would cause the constituent protons and neutrons to scatter. In a nucleon-nucleon collision the baryon number is two and, since baryon number must be conserved, the baryon number must be two in the final state. Usually, the collision results in each nucleon losing about half its initial energy, primarily in the production of particles. The volume of the collision can be separated into two regions in the longitudinal direction. Rapidity is given by $y = \tanh^{-1}(p_z/E)$, where $p_z$ is the longitudinal momentum and $E$ is the energy of the particle. Since colliding nucleons usually keep some of their initial energy and baryon number must be conserved, there is a good probability that in the regions with the largest rapidity there will be particles that resemble incident particles. These particles that look like the incident particles are called leading particles and the regions with the largest rapidity are called fragmentation regions. The produced particles make up the intermediate region, which is useful for exploring the properties of hot, dense hadronic matter.
In the aftermath of a collision of two nuclei, pions are primarily created, making up 80-90% of the produced particles. In addition to the pion is the \( \rho \) meson in what may be significant numbers. As the system expands and cools, there is no longer sufficient energy to alter the chemical content of the system resulting in chemical freeze-out. The amount of various particle species will determine the particle production ratios observed in the laboratory. As the expansion continues the density of particles continues to decrease so that particles no longer collide elastically with each other resulting in kinetic freeze-out. The temperature at which kinetic freeze-out happens is preserved in the \( p_T \) spectra of the particles. There are many scenarios used to describe this medium: measured particle momenta and spectra indicate a thermalize medium and azimuthal anisotropy measurements suggest hydrodynamic flow.

In the standard model, particles are separated into fundamental particles leptons, quarks, and bosons. There are six types of quarks which are arranged into couples, the down (d) and up (u), the strange (s) and charm (c), and the bottom (b) and top (t). The first of each couple carries an electric charge of \(-1/3\) that of an electron and the second of each couple carries an electric charge of \(2/3\) that of an electron. Additionally, each quark will carry a color charge, the interactions of these color charges being the subject of quantum chromodynamics.

Quarks are point-like and confined to one or more other quarks in a hadron by a binding potential which increases linearly with their distance of separation. Even though they are point like, hadrons have an associated finite spacial extent over which the quarks are spread. If nucleons were elementary and incompressible, there would be a high density limit of matter when in a state of close packing, but instead the composite nucleon will begin to overlap other nucleons as they are packed more densely. In this state, the quark is no longer bound to the nucleon and is now free...
to move about within the larger system. If that color-deconfined system is also in thermal equilibrium, a Quark Gluon Plasma is formed. In a nuclear collision where energy densities reach ten times that of normal nuclear matter, QGP will be formed.

Since the J/ψ is created in initial hard collisions, not only will that matter in which the J/ψ is surrounded by change with time as the system evolves, but the J/ψ itself must evolve. If this time is significant relative to the time the J/ψ spends inside the medium this must also be considered. Many different approaches have been made to calculate this effect.

Formation time may be approximated in a simple model. If we assume the c ¯c originate at the same point in space the virial theorem can be used to approximate the relative velocity of the quarks as they move away from each other. The time it takes the quarks to separate the distance characteristic to a particular charmonium state can be calculated. The cross section of the charmonium on a nucleus is then proportional to its time dependent radial separation [10].

In 1986 Matsui and Satz predicted that the color screening of a c ¯c would be a signature of quark gluon plasma formation [11]. They proposed that if quark gluon plasma is formed in a nucleus-nucleus collision, then any c ¯c pair which would have evolved into bound charmonium would be color screened from one another. Instead of a final state of bound charm the c and ¯c would instead pair with the more abundant lighter quarks to form charmed mesons.

The J/ψ is an interesting probe because it is very tightly bound and its suppression by QGP will be as dramatic as the onset of the QGP itself. The medium of the collision is modeled as color flux tubes connecting the receding primordial nucleons after their passage through one another. In the transverse plane, the color flux tubes are discs. These discs will then overlap, representing communication of the tubes in the percolation sense, forming a cluster. The interesting aspect of percolation is
Figure 1.4: The average cluster size (solid) and its derivative (dotted) as a function of the cluster density[12]

that the progression between low density and high density clusters is not gradual; the average cluster size exhibits a rapid increase at a critical density of clusters as shown in Figure 2.4. It is at this critical onset that there is a phase transition to a QGP. Any probe sensitive to the transition like $J/\psi$ suppression should demonstrate this behavior.
Chapter 2

The Experiment

2.1 The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) is one of two currently operating heavy-ion colliders in the world. RHIC is versatile in that it is able to accelerate, store and collide particle species from $A = 1$ (protons) to $A \sim 200$ (Au) [13]. It is able to accelerate heavy ion beams (e.g. for gold ions) up to 100 GeV per nucleon and protons up to 250 GeV. Counter-rotating beams intersect at six points, where collisions occur. The RHIC beamline is 444.8 cm above the tracks used to move detectors into the collision hall and 523.2 cm above the floor.

The gold ion acceleration scenario is shown in Figure 3.1. There are three accelerators in the injector chain that will boost the energy and strip the electrons from the atoms. Negatively charged gold ions start at the Tandem Van de Graff, where they are partially stripped of their electrons and then accelerated to an energy of 1 MeV/u. The ions are then further stripped of their electrons and sent to the Booster Synchrotron where they are accelerated to 95 MeV/u. The ions are stripped once again at the exit of the Booster and are injected into the Alternating Gradient Syn-
Thegold ions, which were injected into the AGS in 24 bunches, are de-bunched and re-bunched into four bunches and transferred to RHIC through the AGS-to-RHIC Beam Transfer Line.

At RHIC there are two main experiments studying heavy ion collisions, PHENIX and STAR and in the past there were the experiments BRAHMS and PHOBOS. In the near future, there will be the sPHENIX experiment, which is the subject of this thesis.
2.2 The sPHENIX Experiment

The PHENIX detector at RHIC took data for 16 years with the primary goal of observing and studying the QGP. A major upgrade to PHENIX has been proposed called sPHENIX. The sPHENIX detector is built with the specific goal of characterizing the strongly coupled QGP observed in heavy ion collisions at RHIC through measurements of jets and quarkonia.

The basic components of the detector include a magnetic solenoid, an electromagnetic calorimeter, a hadronic calorimeter and readout electronics. The sPHENIX detector should be able to cover $|\eta| < 1.0$. The measurements of the beamline given in the previous section require the detector to have an outer radius of no more than 400 cm in order to provide room for support. A concept of the detector can be seen in Figure 3.2.

Figure 2.2: Cutaway view of the detector

2.2.1 Magnet and Tracking System

The tracking system in the sPHENIX detector will include the silicon vertex tracker (VTX) system from the PHENIX detector as well as an additional track-
ing system. The VTX is a silicon strip detector consisting of two inner layers at radii 2.5 and 5 cm from the beamline and two outer layers at radii 10 and 14 cm from the beamline. The additional tracking system would be in the radial space from 15-65 cm, still inside the magnetic solenoid. The tracking system will utilize a strip design with 80 $\mu$m $\times$ 3 cm, which gives 1 million channels in the inner layer and 2.2 million channels in the outer layer. The intermediate layer at 40 cm must be on the order of 0.03 radiation lengths to reduce multiple scattering and deliver good momentum resolution.

The required magnetic field for the tracking system is 2T. In order to minimize the amount of material in front of the calorimeters, a thin superconducting solenoid is needed for the magnet. The basic features required of the solenoid were determined to be an inner radius of at least 70 cm and a length of at least 187 cm to cover a pseudorapidity of $|\eta| < 1.1$. The thickness of the solenoid has to be less than one radiation length at normal incidence and the radial thickness must be less than 20 cm.

### 2.2.2 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (EMCal) will be located just outside the coil of the solenoid and, as such, it will have to operate in the strong fringe field of the magnet. As a result, the Electromagnetic Calorimeter is made in an optical accordion design, using tungsten as the absorber material and scintillating fibers as the active medium. The advantage of this is that it is very compact and can be read out with silicon photomultipliers (SiPM’s), providing high gain while working inside a magnetic field.

The EMCal consists of alternating layers of thin sheets of tungsten glued onto
composite layers of scintillating fibers embedded in a matrix of tungsten powder and epoxy. Two uniform thickness tungsten plates with a thickness $\sim 1$ mm would be bent into the accordion shape and cast with a layer of scintillating fibers and a combination of tungsten powder and epoxy in a mold, forming a “sandwich” of the desired shape. The basic structure of the “sandwich” can be seen in Figure 3.3. The waves in the design provide a more uniform response of particles incident at various positions and angles by preventing particles from channeling through the calorimeter, which could happen if the plates were flat. Six of the sandwiches would be glued together to form a tower module measuring $\sim 2.1$ cm in the $\phi$ direction and $\sim 1.39$ m along the beam direction. Then four towers would be joined into sections and arranged azimuthally to form a ring. The scintillating fibers are arranged in a radial pattern coming out from the vertex. At the front of the calorimeter, the fibers are closely spaced together, then they flare out toward the back.

Figure 2.3: The optical accordion “sandwich”, which consists of two tungsten plates of 1 mm thickness and 1 mm layer of scintillating fibers with tungsten powder and epoxy filling the gaps

The calorimeter will be separated into individual towers corresponding to a segmentation in $\eta$ and $\phi$ of about $0.024 \times 0.024$ and will result in about 25,000 readout
channels (256 in \( \phi \), 96 in \( \eta \)). Fibers from the back of the calorimeter will be put into towers measuring \( \sim 2 \times 2 \text{cm} \), where the light from \( \sim 125 \) fibers will be gathered and randomized using a light mixer box and read out with a single SiPM. With this design, the energy resolution should be about \( 15\%/\sqrt{E} \).

### 2.2.3 Hadronic Calorimeter

The Hadronic Calorimeter (HCal) surrounds the EMCal, going from a radius of 112 cm to 212 cm and is segmented longitudinally into two compartments of 1.5 and 3.5 interaction lengths deep. There will be a requirement of the HCal to have an energy resolution better than \( \sigma_E/E = 100%/\sqrt{E} \). The inner and outer segments of the calorimeter are made of tapered absorber plates, making a finned structure with each fin placed at an angle of \( \pm 5^\circ \) with respect to the radius vector perpendicular to the beam axis. In each of the segments, there are 256 fins. The fins in these segments are radially tilted in opposite directions, resulting in a 10° angle with each other, and are staggered by half a fin thickness. The gaps between the fins are 8 mm wide and contain 7 mm thick scintillating tiles. This design prevents particles from going through the calorimeter without encountering the steel absorber.

With the plates positioned as described, particles hitting the calorimeter at normal incidence will cross 22.5 cm of steel in the inner and 57.5 cm of steel in the outer section on average. This will result in a probability of the punch through of particles with momenta above \( \sim 2 \text{ GeV/c} \) of only 1%. Punch through probability varies from 0.93-1.07 depending of the incident angle.

In the gaps between the plates, there are 22 separate scintillator tiles with 11 different shapes that correspond to a detector segmentation in pseudorapidity of \( \Delta \eta \sim 0.1 \). In the azimuthal direction, the hadronic calorimeter is sectioned into 64 wedges,
with each wedge made of four sampling cells (steel plate and scintillating tile) with the scintillating tile’s edges pointing towards the origin. The 22 pseudorapidity segments result in towers of about 10 cm × 10 cm in size at the inner surface of the calorimeter. The total number of channels in the calorimeter is 1408 × 2.

Calorimeter performance is controlled by the sampling fraction and the light collections and readout efficiency. Readout plays a role mostly in the stochastic term in calorimeter resolution through Poisson fluctuations in the number of photoelectrons on the input to analog signal processing. There are many factors that contribute to those fluctuations including the luminous properties of the scintillator, efficiency of the light collection and transmission, and the photon detection efficiency.
Chapter 3

J/ψ Simulations

3.1 J/ψ Acceptance

To determine the J/ψ acceptance, the fraction of J/ψ that can be measured in the sPHENIX experiment, we use PYTHIA [15], a program simulating collisions at high energies between elementary particles. The Pythia program is a standard tool for the generation of events in high-energy collisions between elementary particles. It uses some production rates rigorously derived from theory, while other parts are derived from phenomenological models, with parameters determined from data.

For our study we simulated p+p collisions at center of mass energy of 200 GeV and we configured PYTHIA to generate events containing J/ψ’s that decay into electron-positron pairs. From the momentum components, we can calculate each particle transverse momentum, \( p_T \), and pseudorapidity, \( \eta \), as:

\[
p_T = \sqrt{p_x^2 + p_y^2},
\]

\[
\eta = -\ln \tan(\theta/2).
\]
Figure 3.1: The transverse momentum (left) and pseudorapidity (right) distributions for all J/ψ generated by PYTHIA

where theta is calculated as

$$\theta = \tan^{-1} \frac{p_Y}{p_X}.$$

The J/ψ transverse momentum and pseudorapidity distributions, for all J/ψ generated by PYTHIA, are shown in Figure 3.1.

The sPHENIX detector has capability to detect charged particles within the pseudorapidity range of [-1,1]. Prior electron identification studies have shown that electron identification is good above electron transverse momentum of 2 GeV/c. To account for these detector effects and obtain an estimate of the J/ψ acceptance in the sPHENIX detector, we required both electrons and positrons to have $|\eta| < 1$ and $p_T > 2$ GeV/c.

The pseudorapidity distributions for all J/ψ generated by PYTHIA (blue), J/ψ decaying in electrons both having $|\eta| < 1$ (red), J/ψ decaying in electrons both having $|\eta| < 1$ and $p_T > 2$ GeV (green) are shown in Figure 3.2. We generated 4 million J/ψ events (shown in the blue distribution in Figure 3.2) and found 24,800 J/ψ decaying in electron-positron both having $|\eta| < 1$ and $p_T > 2$ GeV (shown in the green distribution in Figure 3.2) therefore the overall acceptance is 0.6%.

More interesting is to look at acceptance dependence on J/ψ transverse momen-
Figure 3.2: Pseudorapidity distribution of all J/ψ (blue), J/ψ decaying in electrons both having |η| < 1 (red), and J/ψ decaying in electrons both having |η| < 1 and $p_T > 2\text{GeV}$ (green)

tum. The transverse momentum distributions for J/ψ decaying in electrons both having |η| < 1 (blue), J/ψ decaying in electrons both having |η| < 1 and $p_T > 2\text{GeV}$ (red) are shown in Figure 3.3. We observe that with those requirements on the electron positron pair, J/ψ are accepted for transverse momentum greater than 4GeV as shown in Figure 3.4.

### 3.2 GEANT4 Simulations

The sPHENIX Collaboration utilizes a GEANT4 package for its simulations. GEANT4 is a computing platform which simulates the passage of particles through matter using Monte Carlo methods. GEANT4 simulates the particle interacting with the material in the detector. Then, sPHENIX custom software simulates the digitization/amplification process of the detector electronics and produces simulated data that can be analyzed with the same software the Collaboration will use for real data.
Figure 3.3: Transverse momentum distribution of $J/\psi$ decaying in electrons both having $|\eta| < 1$ (blue), and $J/\psi$ decaying in electrons having $|\eta| < 1$ and $p_T > 2 GeV$ (red)

Figure 3.4: The acceptance, i.e. the fraction of $J/\psi$ decaying in electrons having $|\eta| < 1$ and $p_T > 2 GeV$, as a function of the $J/\psi$ transverse momentum

In this project we used the sPHENIX software to simulate $J/\psi$ particles decaying into electron-positron pairs. Electrons and positrons are detected in the tracking system as charged particles and from their curvature in the magnetic field we can measure
their momentum. The electromagnetic calorimeter will measure the energy of the
electrons which will allow electron identification by matching the momentum in the
tracking with the energy in the calorimeter.

We use the sPHENIX reconstruction code that finds the particle trajectory in the
magnetic field to select all electrons and positrons and make pairs. For each pair we
can define a total momentum as:

\[ \vec{p} = \vec{p}_{e^+} + \vec{p}_{e^-} \]

and the total energy:

\[ E = E_{e^+} + E_{e^-} \]

from which we can calculate the invariant mass:

\[ m = \sqrt{E^2 - \vec{p}^2}. \]

An electron-positron pair comes from a J/ψ it will have an invariant mass of
3.097 GeV. Two effects contribute to the reconstructed mass not being the same as the
nominal mass. The first is the detector accuracy in determining the trajectory and the
multiple scattering of the electron in material. In addition, electrons going through
material will accelerate and will emit Bremsstrahlung photons therefore changing the
energy as it goes through the material. The width of the peak is related to the
resolution of the detector. The Bremsstrahlung effect contributes to the long tail
in the invariant mass distribution seen in Figure 3.4. The expected reconstruction
efficiency for J/ψ in the mass window [2.8-3.3] is about 90\% in p+p collisions.
3.3 Projections for First Data Taking

In the first data taking PHENIX expects to collect a sample about 7 billion p+p collisions at center of mass energy of 200 GeV. We know that the inelastic cross section is 40mb from this we can extract the integrated luminosity as:

\[ L = \frac{N_{\text{events}}}{\sigma_{\text{inelastic}}} \]

The J/ψ cross section J/ψ → e+ e− is 180nb and we can extract the number of J/ψ expected in one year of running as:

\[ N_{\text{J/ψ}} = \sigma_{\text{J/ψ}} \times L = \sigma_{\text{J/ψ}} \times \frac{N_{\text{events}}}{\sigma_{\text{inelastic}}} \]

Based on our estimate, we expect 225,000 J/ψ’s will be in the acceptance of the
Figure 3.6: The number of $J/\psi$ expected in one year of sPHENIX data taking in p+p collisions as a function of transverse momentum.

SPHENIX detector, in one year of data taking. The number of $J/\psi$ expected in one year of running as a function of transverse momentum is shown in Figure 3.6.
Appendix A

References
