Master Thesis

$\pi^0$ production in polarized proton-proton collisions at RHIC PHENIX

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Abstract

RHIC (Relativistic Heavy Ion Collider) was originally built for ion-ion collider but is also the first polarized proton-proton collider. The physics motivation of the polarized proton-proton collision at RHIC is to investigate the structure of the nucleon. The experiment of polarized proton-proton collision started in the year of 2002.

The simplest picture of the nucleon spin is that the nucleon spin are carried by valence quarks. But the polarized deep inelastic scattering experiments showed that the spin of the nucleon carried by quarks is small. This results suggest that gluon and/or orbital angular momentum of quark and gluon in the nucleon contribute to the nucleon spin. RHIC can measure the polarized gluon distribution directly and obtain informations of many aspects of structure of nucleon.

I analyzed the data of $\pi^0$ production in the polarized proton-proton collisions in order to estimate the systematic error from correction factor which is caused by reconstruction efficiency, acceptance, and smearing. The systematic error of correction factor is estimated by comparing the $\pi^0$ pseudo rapidity distributions which are obtained in different conditions. I then evaluated transverse spin asymmetry of $\pi^0$ production using the data of year 2002. In this thesis, I discuss how to calculate transverse spin asymmetry, its result and the future prospect.
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Chapter 1

Introduction

The proton has $\frac{1}{2}$ spin. It was shown from the result of experiment on the specific heat of hydrogen in the 1920's. The quark model was developed in 1960's. The spin of the nucleon $\frac{1}{2}$ has been believed to be carried by the three valence quarks. However, polarized deep inelastic scattering experiments showed that the fraction of the spin of the nucleon carried by quarks is small. This result suggests that gluon and/or orbital angular momentum of quark and gluon in the nucleon contribute to the nucleon spin. A general representation for the spin contents of the proton is written as:

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L$$  \hspace{1cm} (1.1)

where $\Delta \Sigma (= \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$ is the contribution of the quark spins, $\Delta g$ is that of gluon spin and $L$ is that of the orbital angular momentum.

The polarized deep inelastic scattering experiments using the charged particle beams are suited for investigating the polarized quark distributions because of the electromagnetic interaction between quarks and charged leptons. However, the gluon does not have charge, therefore these experiments cannot measure the polarized gluon distribution directly. RHIC has a possibility to measure the polarized gluon distribution directly. The polarized proton-proton collider is suited for measuring the polarized gluon distribution because the proton-proton collisions include gluon-quark and gluon-gluon interactions.

In year 2002, the proton beams of RHIC were transversely polarized. Therefore the data are used to evaluate the single spin transverse asymmetry. The polarization of protons in year 2002 is between 15% and 19% at $\sqrt{s} = 200$ GeV. The integrated luminosity of proton beam in year 2002 is 0.15pb$^{-1}$. I analyzed the data of $\pi^0$ production in the polarized proton-proton collisions in
order to estimate the systematic error in the $\pi^0$ cross section which arises from the correction factor for reconstruction efficiency, acceptance, and smearing. The systematic error of correction factor is estimated by comparing the $\pi^0$ pseudo rapidity distributions which are obtained in different conditions. I also evaluated transverse spin asymmetry of $\pi^0$ production. In this thesis I explain the RHIC and PHENIX experiment in Chapter 2, the $\pi^0$ cross section and pseudo rapidity distribution are discussed in Section 3.2,3.3, the transverse spin asymmetry is discussed in Section 3.4. The conclusion and summary are described in Chapter 4.
Chapter 2

PHENIX experiment

2.1 Relativistic Heavy Ion Collider (RHIC)

The Relativistic Heavy Ion Collider (RHIC) is constructed at Brookhaven National Laboratory for the purpose of studying the Quark Gluon Plasma (QGP) and the spin structure of the nucleon. RHIC is the first heavy ion collider and the first polarized proton-proton collider. The layout of RHIC is shown in Figure 2.1. Only relevant devices for polarized proton-proton collisions are shown. The major machine parameters are listed in Table 2.1.

The polarized protons are supplied from an optical pumped polarized ion source (OPPIS) and injected into the Linac. A solenoidal magnet and a RF dipole installed in Alternating Gradient Synchrotron (AGS) preserve the polarization of the protons up to 24 GeV which is the injection energy to the RHIC main ring. Some aspects of RHIC are changed from the original design in order to accelerate polarized protons. The most important devices for the polarized proton-proton collider are the Spin Rotators and Siberian Snake magnets in RHIC. The Spin Rotators can change the spin direction at collision points as needed for the experiments. The Siberian Snake magnets can rotate the proton spin by 180° around a selected axis in the vertical plane each time the beam passes. For this reason the tilting of the spin due to horizontal magnetic fields is canceled. Thus the major spin resonances at RHIC is eliminated.

The polarization of protons is measured by proton-Carbon Coulomb-Nuclear Interference (pCCNI) polarimeter. The proton-Carbon elastic scattering in the CNI region is calculable and has a large analyzing power. The analyzing power is expected to be as large as 4% at momentum transfer $-t = 2 \times 10^{-3}(\text{GeV}/c)^2$. The recoil Carbon is detected with Silicon-strip detectors (SSD), thus what we measure is the left-right asymmetry of the
cross section in the scattering plane normal to the protons polarization. The Siberian Snake magnets and proton-Carbon CNI polarimeter are discussed in subsection 1.1.2 and 1.1.3.

There are five experiments at RHIC: PHENIX, STAR, BRAHMS, PHOBOS, and pp2pp. The details of PHENIX experiment are discussed in the section 1.3.

Table 2.1: RHIC specification

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Two Concentric Super-conducting magnet Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>3.85 km</td>
</tr>
<tr>
<td>Interaction point</td>
<td>6</td>
</tr>
<tr>
<td>Ion Species</td>
<td>Range from proton to Gold</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>60 ; 120 in enhanced mode</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam type</th>
<th>p + p</th>
<th>Au + Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>Linac-Booster-AGS</td>
<td>Linac-Booster-AGS</td>
</tr>
<tr>
<td>(\sqrt{s}) (Maximum)</td>
<td>500 [GeV]</td>
<td>200 [GeV]</td>
</tr>
<tr>
<td>Luminosity</td>
<td>(2 \times 10^{32}/\text{cm}^2/\text{s})</td>
<td>(2 \times 10^{28}/\text{cm}^2/\text{s})</td>
</tr>
<tr>
<td>Polarization</td>
<td>70%</td>
<td></td>
</tr>
</tbody>
</table>

2.1.1 Siberian Snake magnets

Accelerating polarized beams require the control of both the orbital motion and spin motion. The evolution of the spin direction of a beam of polarized protons in external magnetic fields, such as those existing in a circular accelerator, is governed by the Thomas-BMT equation,

\[
\frac{d\vec{P}}{dt} = -\left(\frac{e}{\gamma m}\right) \left[G\gamma \vec{B}_\perp + (1 + G) \vec{B}_\parallel\right] \times \vec{P}\tag{2.1}
\]

where the polarization vector \(\vec{P}\) is expressed in the frame that moves and rotates with the particle's velocity. This simple precession equation is very similar to the Lorentz force equation;

\[
\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right) \left[\vec{B}_\perp\right] \times \vec{v}\tag{2.2}
\]

Comparison of these two equations readily shows that, in a purely vertical field, the spin rotates \(G\gamma\) times factor than the orbital motion. Here
$G = 1.7928$ is the anomalous magnetic moment of the proton and $\gamma = E/m$. $G\gamma$ gives the number of full spin precession for every revolution and is also called the spin tune $\nu_{sp}$. At top RHIC energies $\nu_{sp}$ reaches about 400. The acceleration of polarized beams in circular accelerators is complicated by the presence of numerous depolarizing spin resonances. During acceleration, a spin resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields: imperfection resonances, which are driven by magnet errors and misalignments, and intrinsic resonances, driven by the focusing fields. The strengths of both types of resonances increases with beam energy. The resonances condition for imperfection depolarizing resonances arise when

$$\nu_{sp} = G\gamma = n,$$  \hspace{1cm} (2.3)

where $n$ is an integer. Imperfection resonances are therefore separated by only 523MeV energy steps. The condition for intrinsic resonances is

$$\nu_{sp} = kP \pm \nu_y,$$  \hspace{1cm} (2.4)

where $k$ is an integer, $\nu_y$ is the vertical betatron tune and $P$ is the super periodicity. With a localized spin rotator that rotates the spin by the angle $\delta$ about a horizontal axis the spin tune is given by

$$\cos (\pi \nu_{sp}) = \cos (\pi G\gamma) \cos (\delta/2)$$  \hspace{1cm} (2.5)

The spin tune can never reach an integer for any non-zero $\delta$ and therefore all imperfection resonances are avoided. A full Siberian snake is a 180° spin rotator, will make the spin tune a half-integer and energy independent. Therefore, neither imperfection nor intrinsic resonance conditions can ever be met. In the presence of strong resonances the spin rotation of the snake has to be much larger than the total spin rotation from the resonances. In the AGS a 5% solenoidal partial snake that rotates the spin by 9° is sufficient to avoid depolarization from imperfection resonances up to the required RHIC transfer energy of about 25 GeV. Full spin flip at the four strong intrinsic resonances can be achieved with a strong artificial RF spin resonance excited coherently for the whole beam by driving large coherent vertical betatron oscillations. The remaining polarization loss in the AGS is caused by coupling resonances and weak intrinsic resonances. Faster acceleration rate and a future, much stronger partial Snake should eliminate depolarization in the AGS. The full Siberian snakes (two for each ring) and the spin rotators (four for each collider experiment) for RHIC each consist of four 2.4m long, 4T helical dipole magnet modules each having a full 360° helical twist. The 9 cm diameter bore of the helical magnets can accommodate 3 cm orbit excursions at injection.
2.1.2 The proton-Carbon CNI polarimeter for RHIC

Small angle elastic scattering of hadrons in the CNI region has long been advocated for polarimetry. The predicted asymmetry is significant and largely independent of energy above a few GeV. The analyzing power can be calculated. The value is about 3-5%. The cross section over the whole RHIC energy range from 23GeV to 250GeV is large. The CNI process has been proposed for RHIC polarimetry using a hydrogen jet target and in collider mode using the pp2pp experiment. Both measurements use the proton-proton Coulomb-Nuclear Interference (ppCNI). It is also possible to use a Carbon target the proton-Carbon Coulomb-Nuclear Interference (pCCNI). That is simpler and cheaper than a hydrogen jet target. It does not require collision of the beams of the both rings like the pp2pp experiment. The analyzing power for pCCNI is similar to ppCNI and the cross section is large.

The p-Carbon CNI polarimeter sits within the beam, thus the proton scattered forward is difficult to detect. Besides, the low energy Carbons stop in target because the energy of the recoil Carbon is 100-600keV. The analyzing power of CNI process is given by;

\[
A_N = \frac{8\pi Z_\alpha p_A}{m_p^2 \sigma_{tot}} \frac{y^{2/3}}{1+y^2} (\mu - 1 - 2\tau_A)
\]  

(2.6)

where \(\mu\) is the anomalous magnetic moment of the proton, \(m_p\) is the proton mass, \(y = \frac{\sigma_{tot}}{8\pi Z_\alpha}\), and \(\tau_A = \frac{g}{\sqrt{m_A^4}}\) is the unknown contribution due to the hadronic spin-flip term \(g\). The total cross section \(\sigma_{tot}\) is only weakly energy dependent over the whole RHIC energy range. The analyzing power of proton-Carbon elastic scattering was determined as a function of \(t\) using the formula;

\[
A_N = \frac{1}{P} \frac{\sqrt{N_L^1 \cdot N_R^1} - \sqrt{N_L^1 \cdot N_R^\dag}}{\sqrt{N_L^1 \cdot N_R^1} + \sqrt{N_L^1 \cdot N_R^\dag}}
\]

(2.7)

where \(N_L^1 (N_R^1)\) denotes the number of events, in which the scattered proton was in the left (right) side and the recoil carbon was in the right (left) side to the beam axis with the polarization direction up (down). Equation2.7 cancels out the acceptance difference between the left and right detector arm and beam intensity difference between the up and down polarized states. The beam polarization is obtained to compare Equation2.6 with Equation2.7.
2.2 Spin physics at RHIC

2.2.1 Unpolarized partons in high energy scattering

The QCD improved parton model has been successfully applied to many high energy processes involving hadrons in the initial or final state. In this framework, a cross section is written in a factorized functions with a partonic subprocess cross section. The predictive power of perturbative QCD follows from the universality of the distribution functions.

As an example, we consider the production of a hadron with large $p_T$ in a collision of unpolarized protons. The cross section of the process $pp \rightarrow hX$ is written as a convolution in the parton model framework:

$$\frac{d\sigma^{pp\rightarrow hX}}{dP} = \sum_{f_1, f_2, f} \int dx_1 dx_2 dz f_1^p(x_1, \mu^2) f_2^p(x_2, \mu^2)$$

$$\times \frac{d^2 \sigma^{f_1 f_2 \rightarrow f X'}}{dP}(x_1 p_1, x_2 p_2, p_h/z, z, \mu) D_f^h(z, \mu^2), \quad (2.8)$$

where $p_1$ and $p_2$ are the incident proton momenta. Here $P$ means any appropriate set of the kinematic variables of the reaction. $f_i^p(x, \mu^2)$ ($i=1,2$) is the probability density for finding a parton of type $f_i$ in the proton, which has taken fraction $x$ of the momentum of proton. $D_f^h(z, \mu^2)$ is the probability density for finding a $h$ with momentum fraction $z$ in the parton $f$. The $\sigma^{f_1 f_2 \rightarrow f X'}$ are the hard-scattering cross sections for initial partons $f_1$ and $f_2$ producing a final-state parton $f$ plus unobserved $X'$.

2.2.2 Polarized parton distributions

One of the purposes of PHENIX experiment is to study the spin structure of the nucleon. The possible parton distribution functions are summarized in Table 2.2. The proton’s spin is carried by quarks and gluons and is shown by proton-spin sum rule;

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L \quad (2.9)$$

where $L$ is the orbital angular momentum of quarks and gluons in the proton.

2.2.3 Prompt photon production

The polarized proton-proton collider measures polarized gluon distribution function $\Delta g$ directly. The RHIC probes $\Delta g$ as shown in Figure 2.2, in the following reactions;
• High-$p_T$ photon production, $pp \rightarrow \gamma X$

• Jet production, $pp \rightarrow jetX$

• Heavy-flavor production, $pp \rightarrow c\bar{c}X, b\bar{b}X$

The asymmetry $A_{LL}$ for prompt-photon production in case of gluon-Compton in leading-order can then be written as

\[ A_{LL} \approx \frac{\Delta g(x_{\text{gluon}})}{g(x_{\text{gluon}})} \times \frac{\sum_q e_q^2 [\Delta g(x_{\text{quark}}) + \Delta \bar{q}(x_{\text{quark}})]}{\sum_q e_q^2 [q(x_{\text{quark}}) + \bar{q}(x_{\text{quark}})]} \times a_{LL}(gq \rightarrow \gamma q), \tag{2.10} \]

where $a_{LL}(gq \rightarrow \gamma q)$ is the spin asymmetry for the subprocess $gq \rightarrow \gamma q$. It is calculable in perturbative QCD. $A_{LL}$ in a collider experiment for both beams longitudinally polarized can be written in general as following;

\[ A_{LL} = \frac{(\sigma_{++} + \sigma_{--}) - (\sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}, \tag{2.11} \]

where $\sigma_{++}, \sigma_{+-}, \sigma_{-+}, \sigma_{--}$ are cross sections of all the four helicity combinations. Thus $\Delta g$ is determined from Equation 2.10 and 2.11.

2.2.4 Quark and anti-quark helicity distributions

The helicity distributions can be measured by Weak Boson Production. The leading-order production of $W$s, $u\bar{d} \rightarrow W^+$, is shown in Figure 2.4. The asymmetry $A_L$ is written as

\[ A_L^{W^+} = \frac{u_-(x_1)\bar{d}(x_2) - u_+(x_1)\bar{d}(x_2)}{u_-(x_1)\bar{d}(x_2) + u_+(x_1)\bar{d}(x_2)} \tag{2.12} \]

\[ = \frac{\Delta u(x_1)}{u(x_1)}, \tag{2.13} \]

\[ A_L^{\bar{W}^+} = \frac{\bar{d}^+_1(x_1)u(x_2) - \bar{d}^+_1(x_1)u(x_2)}{\bar{d}^+_1(x_1)u(x_2) + \bar{d}^+_1(x_1)u(x_2)} \tag{2.14} \]

\[ = \frac{\Delta \bar{d}(x_1)}{\bar{d}(x_1)}. \tag{2.15} \]

The helicity distributions of quarks and anti-quarks is extracted by measuring 2.13 and 2.15.

In addition to the helicity distributions of quarks and anti-quarks, RHIC is also sensitive to the transversity distributions. The details of transversity distributions are discussed in the Chapter 3.
Table 2.2: This table shows Parton distributions of the nucleon in the leading order. Labels of + and - denote helicities, and ↑,↓ denote transverse polarizations. x denotes Bjorken-x.

<table>
<thead>
<tr>
<th>Type of distribution</th>
<th>Quarks</th>
<th>Gluons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolarized distribution</td>
<td>$q(x) = q^+ + q^- = q^\uparrow + q^\downarrow$</td>
<td>$g(x) = g^+ + g^-$</td>
</tr>
<tr>
<td>Helicity distribution</td>
<td>$\Delta q(x) = q^+ - q^-$</td>
<td>$\Delta g(x) = g^+ - g^-$</td>
</tr>
<tr>
<td>Transversity distribution</td>
<td>$\delta q(x) = q^\uparrow - q^\downarrow$</td>
<td></td>
</tr>
</tbody>
</table>

### 2.3 Experimental setup of PHENIX

The PHENIX detector shown in Figure 2.5 has four arms. The central arms consist of tracking systems for charged particles and electromagnetic calorimetry. The calorimeter is the outermost subsystem on the central arms and enables measurements of photons and electrons. The tracking system uses three sets of Pad Chambers (PC) to provide precise three-dimensional space points needed for track recognition. The Drift Chambers (DC) has a good momentum and mass resolution. The Time Expansion Chamber (TEC) and Time-of-Flight (ToF) and Ring-Imaging CHerenkov (RICH) provide particle identification. The muon arms consist Muon Tracking Chamber and Muon Identifier. The Muon Tracking Chambers with three stations of multi-plane drift chambers provide muon tracking. The Muon Identifier consists of alternating layers of steel absorbers and streamer tubes of the Iarocci type.

The PHENIX has three detectors beside the four arms. They are Zero-Degree-Calorimeters (ZDC), Beam-Beam Counters (BBC) and Multiplicity-Vertex Detector (MVD). The ZDC is used as Minimum Bias Trigger. A pair of BBCs provide a measure of the time of flight of forward particles to determine the time of collision, provide the collision position vertex along the beam axis. The MVD provides multiplicity and precise determination of vertex position. The parameters of PHENIX detector subsystems are shown Table 2.3, where $\eta$ is the pseudo rapidity defined with Equation 3.10, $\phi$ is the azimuthal angle.
Table 2.3: Summary of the PHENIX detector subsystems.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>$\eta$ coverage</th>
<th>$\phi$ coverage</th>
<th>Major purpose and Future plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVD</td>
<td>$\pm 2.6$</td>
<td>$360^\circ$</td>
<td>Reaction plane determination.</td>
</tr>
<tr>
<td>BBC</td>
<td>$\pm (3.1 \text{ to } 3.9)$</td>
<td>$360^\circ$</td>
<td>Start timing, fast vertex.</td>
</tr>
<tr>
<td>NTC</td>
<td>$\pm (1 \text{ to } 2)$</td>
<td>$320^\circ$</td>
<td>Minimum bias trigger.</td>
</tr>
<tr>
<td>ZDC</td>
<td>$\pm 2$ mrad</td>
<td>$360^\circ$</td>
<td></td>
</tr>
<tr>
<td>Drift chambers (DC)</td>
<td>$\pm 0.35$</td>
<td>$90^\circ \times 2$</td>
<td>$\Delta m/m = 0.4%$ at $m=1\text{GeV}$. Good mass resolution.</td>
</tr>
<tr>
<td>Pad chambers (PC)</td>
<td>$\pm 0.35$</td>
<td>$90^\circ \times 2$</td>
<td>Pattern recognition, tracking for non-bend direction.</td>
</tr>
<tr>
<td>TEC</td>
<td>$\pm 0.35$</td>
<td>$90^\circ$</td>
<td>Pattern recognition.</td>
</tr>
<tr>
<td>RICH</td>
<td>$\pm 0.35$</td>
<td>$90^\circ$</td>
<td>Electron identification.</td>
</tr>
<tr>
<td>ToF</td>
<td>$\pm 0.35$</td>
<td>$45^\circ$</td>
<td>Good hadron identification, $\sigma &lt; 100\text{ps}$.</td>
</tr>
<tr>
<td>T0</td>
<td>$\pm 0.35$</td>
<td>$45^\circ$</td>
<td>Improve ToF timing for p-p and p-A.</td>
</tr>
<tr>
<td>PbSc EMCal</td>
<td>$\pm 0.35$</td>
<td>$90^\circ + 45^\circ$</td>
<td>For both calorimeters, photon and electron detection.</td>
</tr>
<tr>
<td>PbGl EMCal</td>
<td>$\pm 0.35$</td>
<td>$45^\circ$</td>
<td></td>
</tr>
<tr>
<td>Muon Tracker ($\mu$ TS)</td>
<td>$-1.15 \text{ to } -2.25$</td>
<td>$360^\circ$</td>
<td>Tracking for muons.</td>
</tr>
<tr>
<td></td>
<td>($\mu$ TN)</td>
<td>$-1.15 \text{ to } -2.44$</td>
<td></td>
</tr>
<tr>
<td>Muon Tracker ($\mu$ IDS)</td>
<td>$-1.15 \text{ to } -2.25$</td>
<td>$360^\circ$</td>
<td>Muon/Hadron separation.</td>
</tr>
<tr>
<td></td>
<td>($\mu$ IDN)</td>
<td>$-1.15 \text{ to } -2.44$</td>
<td></td>
</tr>
<tr>
<td>Magnet: central (CM)</td>
<td>$\pm 0.35$</td>
<td>$360^\circ$</td>
<td>Up to $1.15 \text{Tr}\bar{n}$.</td>
</tr>
<tr>
<td>muon (MMS)</td>
<td>$-1.1 \text{ to } -2.2$</td>
<td>$360^\circ$</td>
<td>$0.72 \text{Tr}\bar{n}$ for $\eta = 2$</td>
</tr>
<tr>
<td>muon (MMN)</td>
<td>$1.1 \text{ to } 2.4$</td>
<td>$360^\circ$</td>
<td>$0.72 \text{Tr}\bar{n}$ for $\eta = 2$</td>
</tr>
</tbody>
</table>
Polarized Proton Collisions at BNL

\[ L_{\text{max}} = 2 \times 10^{32} \text{s}^{-1} \text{cm}^{-2} \]
- 70% Polarization
\[ \sqrt{s} = 50 - 500 \text{ GeV} \]

**RHIC**

**PHOBOS**

**PHENIX**

**STAR**

**BRAHMS**

**2x10^{11} Pol. Protons / Bunch**
\[ \varepsilon = 20 \pi \text{ mm mrad} \]

**AGS**

**Booster**

**Linac**

**OPPIS:**
\[ 500 \mu A, 300 \mu s, 7.5 \text{ Hz} \]

Figure 2.1: The layout of RHIC accelerator complex. Only relevant devices for polarized proton-proton collisions are shown.
Figure 2.2: The probes of measuring $\Delta g$ is shown. (a)quark-gluon Compton process for prompt-photon production, (b)gluon-gluon and gluon-quark scattering for jet production, (c)gluon-gluon fusion producing a heavy quark pair.

Figure 2.3: Leading order analyzing powers for various reactions as functions of the partonic center-of-mass system scattering angle. Left is longitudinal polarization, right is transverse polarization.
Figure 2.4: The production of a $W^+$ in a pp collision in the leading order. Proton on the top is polarized while proton on the bottom is unpolarized. $u_+^-$ is the negative polarized $u$ quark in positive polarized proton. (a)$\Delta u$ is probed in the polarized proton. (b)$\Delta d$ is probed.
Figure 2.5: The PHENIX detector system. Labeled arrows point to the detector subsystem.
Chapter 3

Analysis of $\pi^0$ production in proton-proton collisions

3.1 Electromagnetic Calorimeter (EMCal)

The Electromagnetic Calorimeter (EMCal) enables to measure the energies and spatial position of photons and electrons. The EMCal consists of the Pb-Scintillator and the Pb-glass calorimeter. The Pb-Scintillator has six sectors of azimuthal coverage and the Pb-glass calorimeter has two sectors (Figure3.1). In this thesis, as the analysis for $\pi^0$ is presented, I explain only relevant device of Pb-Scintillator. The parameters of Pb-Scintillator are listed in Table3.1. The Pb-Scintillator calorimeter was tested at the AGS (BNL) and SPS (CERN). The resulting nonlinearity is shown Figure3.3 and energy resolution is given by;

\[
\frac{\sigma_E}{E} = 2.1\% \oplus \frac{8.1\%}{\sqrt{E[GeV]}}, \tag{3.1}
\]

where $\oplus$ denotes a square of the quadratic sum, $\alpha \oplus \beta = \sqrt{\alpha^2 + \beta^2}$. The position resolution is given by;

\[
\sigma_x = 1.4(mm) + \frac{5.9(mm)}{\sqrt{E[GeV]}}. \tag{3.2}
\]

The EMCal system provides two types of trigger which is 2x2 trigger and 4x4 trigger. The 2x2 trigger requires that $2 \times 2$ towers sum of energy is more than 0.8 GeV. The 4x4 trigger requires that $4 \times 4$ towers sum of energy more than 2.1 GeV (4x4a) and 2.8 GeV (4x4b).
Table 3.1: Parameters of Pb-Scintillator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of channels</td>
<td>15552</td>
</tr>
<tr>
<td>number of sectors</td>
<td>6</td>
</tr>
<tr>
<td>$\eta$ coverage</td>
<td>0.7</td>
</tr>
<tr>
<td>$\phi$ coverage</td>
<td>90° + 45°</td>
</tr>
<tr>
<td>depth</td>
<td>375 [mm]</td>
</tr>
<tr>
<td>radiation length($X_0$)</td>
<td>18</td>
</tr>
</tbody>
</table>

### 3.2 $\pi^0$ cross section

The $\pi^0$ invariant mass is calculated with the following formula;

$$M = 2 \cdot \sqrt{E_1 \cdot E_2 \cdot \sin\left(\frac{\theta}{2}\right)}, \quad (3.3)$$

where $E_1$ and $E_2$ are the energy of two $\gamma$'s, $\theta$ is the angle of the between $\gamma_1$ and $\gamma_2$. The $\pi^0$ invariant mass spectrum is shown in Figure 3.7. The red line and green line shows the result of the fit. The fitting function is a gaussian + polynomial. The number of $\pi^0$ is obtained by subtracting the background in the histogram.

For the minimum-bias event, the cross section was computed by;

$$\sigma(p_T) = \frac{1}{2\pi} \cdot \frac{1}{L} \cdot \frac{N_{\pi^0}^{\text{corr}}}{p_T \cdot dp_T} \quad (3.4)$$

$$N_{\pi^0}^{\text{corr}} = \frac{N_{\pi^0}}{\epsilon_{\pi^0}^{\text{mb}}(p_T) \cdot C_{\text{reco}}(p_T)} \quad (3.5)$$

$$L = \frac{N_{\text{BBC}}}{42.0 \cdot 0.51} \quad (3.6)$$

where $N_{\pi^0}$ is the number of reconstructed $\pi^0$ in the min-bias trigger after the background subtraction, $\epsilon_{\pi^0}^{\text{mb}}(p_T)$ is the bias of minimum bias trigger, $C_{\text{reco}}(p_T)$ is the reconstruction efficiency, acceptance and $p_T$ smearing correction, and $N_{\text{BBC}}$ is the number of BBC triggered events with $z$-position of vertex less than ±30 cm.

For the high-$p_T$ trigger (2x2 trigger) events, the cross section was computed by;

$$\sigma(p_T) = \frac{1}{2\pi} \cdot \frac{1}{L} \cdot \frac{N_{\pi^0}^{\text{corr}}}{p_T \cdot dp_T} \quad (3.7)$$

$$N_{\pi^0}^{\text{corr}} = \frac{\epsilon_{\pi^0}^{\text{high}}(p_T) \cdot \epsilon_{\pi^0}^{\text{mb}}(p_T) \cdot C_{\text{reco}}(p_T)}{N_{\pi^0}} \quad (3.8)$$
Figure 3.1: The two central spectrometer arms around the collision point shown in a plane perpendicular to the beam line.

\[
L = \frac{N_{\text{bbc}}}{42.0 \cdot 0.51} \cdot \frac{N_{\text{mb, AND, 2x2}}^{\text{trig}}}{N_{\text{trig}}^{\text{mb}}} \tag{3.9}
\]

where \( \varepsilon_{\pi^0}^{\text{high}}(p_T) \) is the efficiency of the high-\( p_T \) trigger (2x2 trigger). The \( \pi^0 \) cross section is measured from \( p_T = 1 \text{ GeV} \) to \( 15 \text{ GeV} \), as shown in Figure 3.6.

In cases of Minimum Bias trigger and 2x2 trigger the results are consistent with each other within systematic error.

The major origins of systematic error are listed Table 3.2.

### 3.3 Pseudo rapidity distribution of \( \pi^0 \)

The computation of the correction factor (\( C_{\text{reco}}(p_T) \)) is used to evaluate the number of \( \pi^0 \). \( C_{\text{reco}} \) was computed from a Monte Carlo simulation of the calorimeter which had been tuned using results from the test beam measurements and the analyzed data itself. But \( C_{\text{reco}} \) corresponds to Minimum Bias trigger and assumes that the collision vertex is \( z = 0 \). To investigate the effect of \( C_{\text{reco}} \), I used \( \pi^0 \) pseudo rapidity distribution. Pseudo rapidity is defined as:

\[
\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right), \tag{3.10}
\]
where \(\theta\) is the angle of the between \(\pi^0\) direction and beam axis.
To obtain the number of \(\pi^0\), I fitted \(\pi^0\) invariant mass spectrums. There are six types of method to fit;

- Fit type 0 : gaussian + quadratic polynomial, fitting region is from 0.06 GeV to 0.20 GeV.
- Fit type 1 : gaussian + quadratic polynomial, fitting region is from 0.05 GeV to 0.25 GeV.
- Fit type 2 : gaussian + quadratic polynomial, fitting region is from 0.05 GeV to 0.30 GeV.
- Fit type 3 : gaussian + cubic polynomial, fitting region is from 0.06 GeV to 0.20 GeV.
- Fit type 4 : gaussian + cubic polynomial, fitting region is from 0.05 GeV to 0.25 GeV.
- Fit type 5 : gaussian + cubic polynomial, fitting region is from 0.05 GeV to 0.30 GeV.

I show the result of the fit from FigureB.1 to FigureB.96. The number of \(\pi^0\) used is the mean value from the results of the six different of type of
Figure 3.3: Energy linearity of Pb-Scintillator. The solid lines show total systematic uncertainties in the analysis.

fit. Figure3.9, Figure3.10, Figure3.11, Figure3.12 are plots of the number of $\pi^0$. Figure3.13, Figure3.14, Figure3.15, and Figure3.16 are the number of $\pi^0$ divided by $C_{\text{reco}}$.

The pseudo rapidity distribution is flat in the region of PHENIX acceptance. In Figure3.13 the distribution is almost flat. But Figure3.14, Figure3.15, Figure3.16 are not flat and points at $\eta = \pm 0.35$ are higher than other points.

I estimated edge effect with the following method. The number of $\pi^0$ divided $C_{\text{reco}}$ of edge is estimated by fitting at $-0.25 < \eta < 0.25$. Fitting function is a linear function. I computed ratio with the following formula;

$$ratio(p_T) = \frac{\sum_{-0.35 < \eta < 0.35} N(\eta)}{\sum_{-0.25 < \eta < 0.25} N(\eta) + N'(-0.35) + N'(0.35)}$$  (3.11)

where $N$ is the number of $\pi^0$ divided by $C_{\text{reco}}$ and $N'$ is estimated by fitting at $-0.25 < \eta < 0.25$. The result of $ratio(p_T)$ is listed Table3.3. Table3.3 shows the ratio of the number of $\pi^0$ after corrected by $C_{\text{reco}}(p_T)$. In case case of assuming vertex = bbcz, the number of $\pi^0$ after the correction is larger by about 10% than in case of assuming vertex = 0 at the region of low $p_T$. The effect from the differences between Minimum Bias trigger and $2\times2$ trigger is less than the vertex effect and is only a few %. Therefore the assumption of
Figure 3.4: Energy resolution of Pb-Scintillator. The blue line shows the fit with the linear formula. The red line shows the fit with the quadratic formula.

conditions, which are trigger and vertex, for computing $C_{reco}(p_T)$ is factor of systematic error.

3.4 Transverse single spin asymmetry

Transverse single spin asymmetry is very interesting. Within the normal framework of perturbative QCD and the factorization theorem at twist-2 for collinear massless parton configurations, no single spin transverse asymmetry is expected. RHIC can investigate the origin of such asymmetry if it exists. In year 2002, since the beams were transversely polarized, these data are used to evaluate the single spin transverse asymmetry. The polarization of protons in year 2002 is from 15% to 19%. The integrated luminosity of proton beam in year 2002 is 0.15pb$^{-1}$.

I calculated the single spin transverse asymmetry, acceptance asymmetry and luminosity asymmetry using following formula. The single spin transverse asymmetry, if it exists, is due to some physics causes while acceptance asymmetry and luminosity asymmetry are solely to test the detector and the
Figure 3.5: Position resolution of Pb-Scintillator. The dashed line shows the fit result.

\[ A_N^B = \frac{\sqrt{N_{B1W} \cdot N_{B1E}} - \sqrt{N_{B1W} \cdot N_{B1E}}}{\sqrt{N_{B1W} \cdot N_{B1E}} + \sqrt{N_{B1W} \cdot N_{B1E}}} \]  

(3.12)

\[ \delta A_N^B \approx \frac{1}{\sqrt{2(\sqrt{N_{B1W} \cdot N_{B1E}} + \sqrt{N_{B1W} \cdot N_{B1E}})}} \]  

(3.13)

\[ A_N^Y = \frac{\sqrt{N_{Y1W} \cdot N_{Y1E}} - \sqrt{N_{Y1W} \cdot N_{Y1E}}}{\sqrt{N_{Y1W} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1E}}} \]  

(3.14)

\[ \delta A_N^Y \approx \frac{1}{\sqrt{2(\sqrt{N_{Y1W} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1E}})}} \]  

(3.15)

where B and Y means Blue ring and Yellow ring, \( \uparrow, \downarrow \) means spin direction, W and E means West arm and East arm. and \( \delta A_N \) is statistical error of \( A_N \). Equation3.12 and Equation3.14 cancel out the acceptance difference between the left and right detector arm and luminosity difference between the up and down polarized state.

\[ A_{\text{acceptance}}^B = \frac{\sqrt{N_{B1W} \cdot N_{B1W}} - \sqrt{N_{B1E} \cdot N_{B1E}}}{\sqrt{N_{B1W} \cdot N_{B1W}} + \sqrt{N_{B1E} \cdot N_{B1E}}} \]  

(3.16)
Table 3.2: The causes of systematic error.

<table>
<thead>
<tr>
<th>( N_{\delta} )</th>
<th>Run dependence</th>
<th>10% (Minimum bias)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6% (2x2)</td>
</tr>
<tr>
<td></td>
<td>Background subtraction</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Excluded Hot/Bad towers</td>
<td>2-3%</td>
</tr>
<tr>
<td>( C_{\text{reco}} )</td>
<td>Energy non-linearity</td>
<td>0-10%</td>
</tr>
<tr>
<td></td>
<td>Fast MC statistical error</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Edge tower</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Position resolution</td>
<td>0-1%</td>
</tr>
<tr>
<td></td>
<td>Energy resolution</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>Energy absolute calibration</td>
<td>3-8%</td>
</tr>
<tr>
<td>( \frac{Z^{s2}}{m_{\delta}} )</td>
<td>2x2 High ( p_T ) trigger threshold</td>
<td>10%</td>
</tr>
</tbody>
</table>

\[
\delta A^B_{\text{acceptance}} \approx \frac{1}{\sqrt{2(\sqrt{N_{B1W} \cdot N_{B1W}} + \sqrt{N_{B1E} \cdot N_{B1E}})}} \quad (3.17)
\]

\[
A^Y_{\text{acceptance}} = \frac{\sqrt{N_{Y1E} \cdot N_{Y1E}} - \sqrt{N_{Y1W} \cdot N_{Y1W}}}{\sqrt{N_{Y1E} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1W}}} \quad (3.18)
\]

\[
\delta A^Y_{\text{acceptance}} \approx \frac{1}{\sqrt{2(\sqrt{N_{Y1W} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1E}})}} \quad (3.19)
\]

Equation 3.16 and Equation 3.18 cancel out the physics asymmetry and luminosity difference between the up and down polarized state.

\[
A^B_{\text{luminosity}} = \sqrt{N_{B1W} \cdot N_{B1E}} - \sqrt{N_{B1W} \cdot N_{B1E}} \quad (3.20)
\]

\[
\delta A^B_{\text{luminosity}} \approx \frac{1}{\sqrt{2(\sqrt{N_{B1W} \cdot N_{B1E}} + \sqrt{N_{B1W} \cdot N_{B1E}})}} \quad (3.21)
\]

\[
A^Y_{\text{luminosity}} = \frac{\sqrt{N_{Y1W} \cdot N_{Y1E}} - \sqrt{N_{Y1W} \cdot N_{Y1E}}}{\sqrt{N_{Y1W} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1E}}} \quad (3.22)
\]

\[
\delta A^Y_{\text{luminosity}} \approx \frac{1}{\sqrt{2(\sqrt{N_{Y1W} \cdot N_{Y1E}} + \sqrt{N_{Y1W} \cdot N_{Y1E}})}} \quad (3.23)
\]
Table 3.3: Estimated edge effect

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>Minimum bias and vertex=0</th>
<th>Minimum bias and vertex=bbcz</th>
<th>2x2 and vertex=0</th>
<th>2x2 and vertex=bbcz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 &lt; $p_T$ &lt; 1.5</td>
<td>99.2%</td>
<td>113.4%</td>
<td>108.8%</td>
<td>125.9%</td>
</tr>
<tr>
<td>1.5 &lt; $p_T$ &lt; 2.0</td>
<td>109.7%</td>
<td>114.9%</td>
<td>103.9%</td>
<td>118.1%</td>
</tr>
<tr>
<td>2.0 &lt; $p_T$ &lt; 2.5</td>
<td>97.3%</td>
<td>108.3%</td>
<td>98.7%</td>
<td>109.8%</td>
</tr>
<tr>
<td>2.5 &lt; $p_T$ &lt; 3.0</td>
<td>103.2%</td>
<td>107.5%</td>
<td>96.4%</td>
<td>105.2%</td>
</tr>
<tr>
<td>3.0 &lt; $p_T$ &lt; 3.5</td>
<td>87.3%</td>
<td>97.6%</td>
<td>98.4%</td>
<td>106.9%</td>
</tr>
<tr>
<td>3.5 &lt; $p_T$ &lt; 4.0</td>
<td>99.9%</td>
<td></td>
<td>106.6%</td>
<td></td>
</tr>
<tr>
<td>4.0 &lt; $p_T$ &lt; 4.5</td>
<td>98.3%</td>
<td></td>
<td>104.4%</td>
<td></td>
</tr>
<tr>
<td>4.5 &lt; $p_T$ &lt; 5.0</td>
<td>94.0%</td>
<td></td>
<td>100.6%</td>
<td></td>
</tr>
</tbody>
</table>

Equation 3.20 and Equation 3.22 cancel out the acceptance difference between the left and right detector arm and the physics asymmetry.

Equation 3.12, 3.14, 3.16, 3.18, 3.20, and 3.22 is called square root formula. The systematic error of asymmetry as above is reduced by using this formula. Equation 3.13, 3.15, 3.17, 3.19, 3.21, and 3.23 is calculated by assuming asymmetry = 0.

Transverse single spin asymmetry is shown in Figure 3.17 and Figure 3.18. These results are calculated by using Equation 3.12, 3.13 in case of Blue ring, and Equation 3.14, 3.15 in case of Yellow ring. Figure 3.17 is in case of Minimum Bias trigger and Figure 3.17 is in case of 2x2 trigger. The Minimum Bias trigger is triggered by ZDC which is located in the direction of beam line. Therefore the number of events of high $p_T$ is small. Figure 3.18 is in case of 2x2 trigger. The 2x2 trigger is triggered by EMCal which is located in perpendicular direction to beam line. Therefore the number of event of high $p_T$ is more than in case of Minimum Bias trigger. In case of Minimum Bias trigger, since high $p_T$ event is very small, data in the range of $p_T > 3[\text{GeV/}c]$ could not be plotted. Physics asymmetry is consistent with zero within statistical error.

Acceptance and luminosity asymmetry are shown in Figure 3.19, and Figure 3.20. Acceptance asymmetry is calculated using Equation 3.16, 3.17 in case of Blue ring, and Equation 3.18, 3.19 in case of Yellow ring. Luminosity asymmetry is calculated using Equation 3.16, 3.17 in case of Blue ring, and Equation 3.18, 3.19 in case of Yellow ring. Figure 3.19 is in case of Minimum Bias trigger and Figure 3.20 is in case of 2x2 trigger. The absolute value of acceptance asymmetry is nearly 0.2 in $p_T > 2[\text{GeV/}c]$. The result is rea-
sonable in this analysis. This analysis used three sectors of EMCal in West arm and two sectors of EMCal in East arm. In the most simplest case of the acceptance asymmetry is $\frac{3-3}{3+2} = 0.2$. Luminosity asymmetry is not zero because the number of up polarization bunches is more than the number of down polarization bunches. Figure3.22 shows the bunch number and the polarization pattern. The polarization pattern means;

- number 0 : empty bunch.
- number 1 : Blue is up, Yellow is up polarization.
- number 2 : Blue is down, Yellow is up polarization.
- number 3 : Blue is up, Yellow is down polarization.
- number 4 : Blue is down, Yellow is down polarization.
- number 5 : Blue and Yellow is 0 polarization.

Thus number of up polarization is more than number of down polarization.
Figure 3.6: Absolute cross section for $\pi^0$ production in proton-proton collisions.
Figure 3.7: Invariant mass distribution for pairs of cluster. $\pi^0$ peak is clearly seen.

Figure 3.8: $C_{rec}$ is plotted in each $\eta$ bin and each $p_T$ bin. Black points are the range of $1.0[\text{GeV/c}] < p_T < 1.5[\text{GeV/c}]$. Red points are the range of $1.5[\text{GeV/c}] < p_T < 2.0[\text{GeV/c}]$. Yellow green points are the range of $2.0[\text{GeV/c}] < p_T < 2.5[\text{GeV/c}]$. Blue points are the range of $2.5[\text{GeV/c}] < p_T < 3.0[\text{GeV/c}]$. Pink points are the range of $3.0[\text{GeV/c}] < p_T < 3.5[\text{GeV/c}]$. Light blue points are the range of $3.5[\text{GeV/c}] < p_T < 4.0[\text{GeV/c}]$. Green points are the range of $4.0[\text{GeV/c}] < p_T < 4.5[\text{GeV/c}]$. 
Figure 3.9: The plot of the number of $\pi^0$ in each $\eta$ bin. In case of Minimum bias trigger and assumption of vertex=0. Black points are the range of $1.0[GeV/c] < p_T < 1.5[GeV/c]$. Red points are the range of $1.5[GeV/c] < p_T < 2.0[GeV/c]$. Yellow green points are the range of $2.0[GeV/c] < p_T < 2.5[GeV/c]$. Blue points are the range of $2.5[GeV/c] < p_T < 3.0[GeV/c]$. 

Figure 3.10: The plot of the number of $\pi^0$ in each $\eta$ bin. In case of Minimum bias trigger and vertex=bbc. Black points are the range of $1.0[GeV/c] < p_T < 1.5[GeV/c]$. Red points are the range of $1.5[GeV/c] < p_T < 2.0[GeV/c]$. Yellow green points are the range of $2.0[GeV/c] < p_T < 2.5[GeV/c]$. Blue points are the range of $2.5[GeV/c] < p_T < 3.0[GeV/c]$. 

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Figure 3.11: The plot of the number of $\pi^0$ in each $\eta$ bin. In case of 2x2 trigger and assumption of vertex=0. Black points are the range of $1.0[GeV/c]<p_T<1.5[GeV/c]$. Red points are the range of $1.5[GeV/c]<p_T<2.0[GeV/c]$. Yellow green points are the range of $2.0[GeV/c]<p_T<2.5[GeV/c]$. Blue points are the range of $2.5[GeV/c]<p_T<3.0[GeV/c]$. Yellow points are the range of $3.0[GeV/c]<p_T<3.5[GeV/c]$. Pink points are the range of $3.5[GeV/c]<p_T<4.0[GeV/c]$. Light blue points are the range of $4.0[GeV/c]<p_T<4.5[GeV/c]$. Green points are the range of $4.5[GeV/c]<p_T<5.0[GeV/c]$. 

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Figure 3.12: The plot of the number of $\pi^0$ in each $\eta$ bin. In case of 2x2 trigger and vertex=bbcz. Black points are the range of $1.0[\text{GeV}/c]<p_T<1.5[\text{GeV}/c]$. Red points are the range of $1.5[\text{GeV}/c]<p_T<2.0[\text{GeV}/c]$. Yellow green points are the range of $2.0[\text{GeV}/c]<p_T<2.5[\text{GeV}/c]$. Blue points are the range of $2.5[\text{GeV}/c]<p_T<3.0[\text{GeV}/c]$. Yellow points are the range of $3.0[\text{GeV}/c]<p_T<3.5[\text{GeV}/c]$. Pink points are the range of $3.5[\text{GeV}/c]<p_T<4.0[\text{GeV}/c]$. Light blue points are the range of $4.0[\text{GeV}/c]<p_T<4.5[\text{GeV}/c]$. Green points are the range of $4.5[\text{GeV}/c]<p_T<5.0[\text{GeV}/c]$. 
Figure 3.13: The plot of the number of \( \pi^0 \) divided by \( C_{\text{reco}} \) in each \( \eta \) bin. In case of Minimum bias trigger and vertex=0. Black points are the range of 1.0[GeV/c]< \( p_T \) <1.5[GeV/c]. Red points are the range of 1.5[GeV/c]< \( p_T \) <2.0[GeV/c]. Yellow green points are the range of 2.0[GeV/c]< \( p_T \) <2.5[GeV/c]. Blue points are the range of 2.5[GeV/c]< \( p_T \) <3.0[GeV/c].

Figure 3.14: The plot of the number of \( \pi^0 \) divided by \( C_{\text{reco}} \) in each \( \eta \) bin. In case of Minimum bias trigger and vertex=bbc. Black points are the range of 1.0[GeV/c]< \( p_T \) <1.5[GeV/c]. Red points are the range of 1.5[GeV/c]< \( p_T \) <2.0[GeV/c]. Yellow green points are the range of 2.0[GeV/c]< \( p_T \) <2.5[GeV/c]. Blue points are the range of 2.5[GeV/c]< \( p_T \) <3.0[GeV/c].

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Figure 3.15: The plot of the number of $\pi^0$ divided by $C_{\text{reco}}$ in each $\eta$ bin. In case of 2x2 trigger and assumption of vertex=0. Black points are the range of $1.0[\text{GeV/c}] < p_T < 1.5[\text{GeV/c}]$. Red points are the range of $1.5[\text{GeV/c}] < p_T < 2.0[\text{GeV/c}]$. Yellow green points are the range of $2.0[\text{GeV/c}] < p_T < 2.5[\text{GeV/c}]$. Blue points are the range of $2.5[\text{GeV/c}] < p_T < 3.0[\text{GeV/c}]$. Yellow points are the range of $3.0[\text{GeV/c}] < p_T < 3.5[\text{GeV/c}]$. Pink points are the range of $3.5[\text{GeV/c}] < p_T < 4.0[\text{GeV/c}]$. Light blue points are the range of $4.0[\text{GeV/c}] < p_T < 4.5[\text{GeV/c}]$. Green points are the range of $4.5[\text{GeV/c}] < p_T < 5.0[\text{GeV/c}]$. 
Figure 3.16: The plot of the number of $\pi^0$ divided by $C_{\text{reco}}$ in each $\eta$ bin. In case of 2x2 trigger and assumption of vertex=bbcz. Black points are the range of $1.0[\text{GeV}/c] < p_T < 1.5[\text{GeV}/c]$. Red points are the range of $1.5[\text{GeV}/c] < p_T < 2.0[\text{GeV}/c]$. Yellow green points are the range of $2.0[\text{GeV}/c] < p_T < 2.5[\text{GeV}/c]$. Blue points are the range of $2.5[\text{GeV}/c] < p_T < 3.0[\text{GeV}/c]$. Yellow points are the range of $3.0[\text{GeV}/c] < p_T < 3.5[\text{GeV}/c]$. Pink points are the range of $3.5[\text{GeV}/c] < p_T < 4.0[\text{GeV}/c]$. Light blue points are the range of $4.0[\text{GeV}/c] < p_T < 4.5[\text{GeV}/c]$. Green points are the range of $4.5[\text{GeV}/c] < p_T < 5.0[\text{GeV}/c]$. 


Figure 3.17: Transverse single spin asymmetry in case of Minimum Bias trigger. Green point is Blue ring, red point is Yellow ring.
Figure 3.18: Transverse single spin asymmetry in case of 2x2 trigger. Green point is Blue ring, red point is Yellow ring.
Figure 3.19: Acceptance and luminosity asymmetry in case of Minimum Bias trigger. Yellow and red point are acceptance and luminosity asymmetry of Blue ring. Magenta and blue point are acceptance and luminosity asymmetry of Yellow ring.
Figure 3.20: Acceptance and luminosity asymmetry in case of 2x2 trigger. Yellow and red point are acceptance and luminosity asymmetry of Blue ring. Magenta and blue point are acceptance and luminosity asymmetry of Yellow ring.

Figure 3.21: Bunch filling pattern with respect to the spin states of polarized protons.
Figure 3.22: Relations between the bunch number and the polarization pattern. The vertical axis and horizontal axis mean bunch the number and the polarization pattern, respectively.
Chapter 4

Conclusion and summary

RHIC (Relativistic Heavy Ion Collider) was originally built for ion-ion collider but is also the first polarized proton-proton collider. The physics motivation of the polarized proton-proton collision at RHIC is to investigate of the structure of the nucleon. The experiment of polarized proton-proton collision started in the year of 2002.

I evaluated first the pseudo rapidity distribution of $\pi^0$ and investigated the effect from the reconstruction efficiency, acceptance, and smearing correction factor $C_{\text{reco}}(p_T)$. $C_{\text{reco}}(p_T)$ is computed in case of Minimum Bias trigger and with an assumption that vertex = 0. I plotted the pseudo rapidity distribution of $\pi^0$ in different conditions and compared the number of $\pi^0$ after corrected by $C_{\text{reco}}(p_T)$. I show the ratio of the number of $\pi^0$ after corrected by $C_{\text{reco}}(p_T)$. In case of assuming vertex = bbbc, the number of $\pi^0$ after the correction is larger by about 10% than in case of assuming vertex = 0 at region of low $p_T$. The effect due to the differences between Minimum Bias trigger and 2x2 trigger is less than the vertex effect and is a few %. Therefore the assumption of conditions, which are trigger and vertex, for computing $C_{\text{reco}}(p_T)$ is one of the sources of systematic errors.

I also calculated spin asymmetry using the data of year 2002. In year 2002, proton beam has transverse polarization. I made a plot of physics asymmetry, as well as acceptance asymmetry and luminosity asymmetry. The physics asymmetry is consistent with zero within statistical error. The acceptance and luminosity asymmetry are qualitatively understood, but to discuss further details of these asymmetries strict estimations of systematic error is needed.

In year 2003, the experiment of polarized proton-proton collision will start from March. It is expected that the beam polarization will increase by factor 3 and the luminosity by factor 20. One of the interesting processes is direct photon production as the gluon spin can be studied. When measuring the
direct photon, the largest background is photons from $\pi^0$ decay. Therefore, the evaluation of $\pi^0$ presented in this thesis is the first important step for the background evaluation in the photon spectrum.
 Acknowledgments

I would like to thank Prof. Toshi-Aki Shibata who gave me an opportunity to take part in the PHENIX experiment and encouraged me throughout my graduate school life. I thank very much Yuji Goto. His advice and kindness saved me from various difficulties. I also thank Atushi Taketani and Hideyuki Kobayashi. They discussed with me patiently. I want to thank very much the member of Shibata laboratory. I can not think of having fulfilled life as a researcher without their cooperation.
Appendix A

Optical Alignment System for the Muon Tracking Chamber

I describe the hardware component for which I participated in construction and in data analysis. The Optical Alignment System (OASys) is a monitor of relative position of Muon Tracking Chamber (FigureA.1). The purpose of OASys is to monitor the time dependent movement of Muon Tracking Chamber on a micron scale, and improves position resolution. The OASys consists of a divergent light source at station one, a convex lens at station two, and a CCD camera at station three. There are seven OASys beams surrounding each octant chamber. Therefore, there are $7 \times 8 = 56$ OASys beams in total for one muon arm, as shown in FigureA.2. The divergent light from the light source goes through the lens to the CCD camera. The position resolution of the OASys is a few micron, therefore the OASys is very sensitive to movements of stations. In this thesis, I analyzed the data of the year 2002.

One of the picture of CCD camera is shown in FigureA.3. This picture is then projected to vertical axis and horizontal axis, and two histograms are obtained. These histograms are fitted with the following function;

$$f(x) = p[0] + p[3] \cdot exp\left(-\frac{(x - p[1])^2}{2 \cdot p[2]^2}\right)$$  \hspace{1cm} (A.1)

where $p[i](i=0,1,2,3)$ are parameter. The center of position in spot is determined by this fitting. The result of fit is shown in FigureA.4. The movement of center of position shows relative movement of the each station.

The major cause of relative movement of each station is considered to be Temperature and Magnetic field. I confirmed the effect of Temperature. Correlation between Temperature and position is shown in FigureA.5. This picture is plotted in case of Magnetic field 'on'. As temperature rises by 0.2°,
position changes by 20micron. Muon tracking chamber is made by G10 and duralumin. The G10 of 1m length expands by 22micron as temperature rises 1°. In case of duralumin it expands by 60micron. Therefore the shift of position in FigureA.5 is reasonable. I also confirmed the effect of Magnetic field. Correlation between Magnetic field and position is shown in FigureA.6. Red points are in case of Magnetic field 'ON', blue points are in case of Magnetic field 'OFF'. The top picture shows expansion in horizontal direction. The middle picture shows expansion in vertical direction. The bottom picture shows correlation between Magnetic field and Temperature. When Magnetic field is on, position moves by 50micron in horizontal direction and 100micron in vertical direction. When Magnetic field is on, temperature rises about 0.5°.

I confirmed the movement of position caused by Temperature and Magnetic field. The position resolution of Muon Tracking Chamber is 300micron in year 2002. This is limited mainly by the statistics of the data from proton-proton collisions used for calibration. The typical value of movement of position is about 100micron. Therefore the improvement of position resolution by OASys is small at the moment. However when the position resolution of Muon Tracking Chamber is improved with increased luminosity, the data of OASys will become more important.

Figure A.1: PHENIX Muon Tracking Chamber. There are three stations of the tracking chambers inside the Muon Magnet.
Figure A.2: Basic concept of OASys. The divergent light from light source goes through the lens to the CCD cameras.

Figure A.3: Sample of a CCD image.
Figure A.4: Projection to vertical and horizontal axis of the light intensity.

Figure A.5: Correlation between Temperature and position. As temperature rises, position changes.
Figure A.6: The top picture shows expansion in horizontal direction. The middle picture shows expansion in vertical direction. The bottom picture shows correlation between Magnetic field and Temperature.
Appendix B

Invariant mass spectrums fitting results

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