## Identified charged hadron production in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV

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#### Abstract

Transverse momentum distributions and yields for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV at midrapidity are measured by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC). These data provide important baseline spectra for comparisons with identified particle spectra in heavy ion collisions at RHIC. We present the inverse slope parameter $T_{\text {inv }}$, mean transverse momentum $\left\langle p_{T}\right\rangle$, and yield per unit rapidity $d N / d y$ at each energy, and compare them to other measurements at different $\sqrt{s}$ in $p+p$ and $p+\bar{p}$ collisions. We also present the scaling properties such as $m_{T}$ scaling and $x_{T}$ scaling on the $p_{T}$ spectra between different energies. To discuss the mechanism of the particle production in $p+p$ collisions, the measured spectra are compared to next-to-leading-order or next-to-leading-logarithmic perturbative quantum chromodynamics calculations.


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## I. INTRODUCTION

Single-particle spectra of identified hadrons in high-energy elementary collisions have interested physicists for many decades because of their fundamental nature and simplicity. Particle production, in general, can be categorized into two different regimes depending on the transverse momentum of the hadrons. One is soft multiparticle production, dominant at low transverse momentum ( $p_{T} \leqslant 2 \mathrm{GeV} / c$ ), which corresponds to the $\sim 1 \mathrm{fm}$ scale of the nucleon radius described by constituent quarks. Another regime is hard-scattering particle production, evident at high transverse momentum ( $p_{T} \geqslant 2 \mathrm{GeV} / c$ ) owing to the hard scattering of pointlike current quarks, which corresponds to a very short distance scale $\sim 0.1 \mathrm{fm}$ [1] and contributes less than a few percent of the cross section for $\sqrt{s}$ $\leqslant 200 \mathrm{GeV}$. These two different regimes of particle production in $p+p$ collisions indicate that "elementary" $p+p$ collisions are actually rather complicated processes. It is interesting to know where the "soft-hard transition" happens, and its beam energy and particle species dependences, since they have not yet been fully understood.

In soft particle production, cosmic ray physicists observed in the 1950s that the average transverse momentum of secondary particles is limited to $\sim 0.5 \mathrm{GeV} / c$, independent of the primary energy [2,3]. Cocconi, Koester, and Perkins [4] then proposed the prescient empirical formula for the transverse momentum spectrum of meson production:

$$
\begin{equation*}
\frac{d \sigma}{p_{T} d p_{T}}=A e^{-6 p_{T}} \tag{1}
\end{equation*}
$$

where $p_{T}$ is the transverse momentum in $\mathrm{GeV} / c$ and $\left\langle p_{T}\right\rangle=2 / 6=0.333 \mathrm{GeV} / c$. The observation by Orear [5] that large-angle $p+p$ elastic scattering measurements at BNL Alternating Gradient Synchrotron (AGS) energies (10 to 30 GeV in incident energy) "can be fit by a single

[^0]exponential in transverse momentum, and that this exponential is the very same exponential that describes the transverse momentum distribution of pions produced in nucleon-nucleon collisions" led to the interpretation [6] that particle production is "statistical" with Eq. (1) as a thermal Boltzmann spectrum, with $1 / 6=0.167 \mathrm{GeV} / c$ representing the "temperature" $T$ at which the mesons or protons are emitted [7].

It was natural in a thermal scenario [8,9] to represent the invariant cross section as a function of the rapidity $(y)$ and the transverse mass $\left(m_{T}=\sqrt{p_{T}^{2}+m^{2}}\right)$ with a universal temperature parameter $T$. This description explained well the observed successively increasing $\left\langle p_{T}\right\rangle$ of $\pi, K, p$, and $\Lambda$ with increasing rest mass [10-12], and had the added advantage of explaining, by the simple factor $e^{-6\left(m_{K}-m_{\pi}\right)} \sim$ $12 \%$, the low value of $\sim 10 \%$ observed for the $K / \pi$ ratio at low $p_{T}$ at CERN Intersecting Storage Rings (ISR) energies ( $\sqrt{s} \sim 20-60 \mathrm{GeV}$ ) [13].

In 1964, the constituent quark model with $\mathrm{SU}(3)$ symmetry was introduced to explain the hadron flavor spectrum and the static properties of hadrons [14,15]. Later on, a dynamical model was developed to calculate the flavor dependence of identified hadrons in soft multiparticle production [16], together with the inclusive reaction formalism [17-19]. These theoretical studies on the particle production mechanism showed that there was much to be learned by simply measuring a single-particle spectrum, and it brought the study of identified inclusive single-particle production into the mainstream of $p+p$ physics.

One of the controversial issues in understanding soft multiparticle production in the 1950s was whether more than one meson could be produced in a single nucleon-nucleon collision ("multiple production"), or whether the multiple meson production observed in nucleon-nucleus $(p+A)$ interactions was the result of several successive nucleon-nucleon collisions with each collision producing only a single meson ("plural production") [20]. The issue was decided when multiple meson production was first observed in 1954 at the Brookhaven Cosmotron in collisions between neutrons with energies up to 2.2 GeV and protons in a hydrogen-filled cloud chamber [6,21].

Then the observation of multiparticle production occurring not only in nucleon-nucleus $(p+A)$ but also in nucleon-
nucleon $(p+p)$ collisions motivated Fermi and Landau to develop the statistical [22] and hydrodynamical [23] approach to multiparticle production. Belenkij and Landau observed that although the statistical model of Fermi is sufficient to describe the particle numbers in terms of only a temperature and a chemical potential, this model has to be extended to hydrodynamics, when particle spectra are considered. They also noted that the domain of the applicability of ideal relativistic hydrodynamics coincides with the domain of the applicability of thermodynamical models in high-energy $p+p$ collisions [23].

Understanding of the particle production by hard scattering partons has also been advanced by the appearance of a rich body of data in $p+p$ collisions at the CERN ISR [13,24,25] in the 1970s, followed by measurements at the Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s}=200$ [26-33] and 62.4 GeV [34] over the last decade. The hard scattering in $p+p$ collisions was discovered by the observation of an unexpectedly large yield of particles with large transverse momentum and the phenomena of dijets at the ISR [35]. These observations indicate that the hard scattering process occurs between the quark and gluon constituents (or partons) inside the nucleons. This scattering process can be described by perturbative quantum chromodynamics ( $\mathrm{pQCD} \mathrm{)} \mathrm{because} \mathrm{the}$ strong-coupling constant $\alpha_{s}$ of QCD becomes small (asymptotically free) for large-momentum-transfer ( $Q^{2}$ ) parton-parton scatterings. After the initial high- $Q^{2}$ parton-parton scatterings, these partons fragment into high- $p_{T}$ hadrons or jets. In fact, at RHIC energies, single-particle spectra of high- $p_{T}$ hadrons are well described by pQCD [30,33,34]. Furthermore, $x_{T}$ $\left(=2 p_{T} / \sqrt{s}\right)$, which is also inspired by pQCD, is known to be a good scaling variable of the particle production at high $p_{T}$ at both ISR [36] and RHIC [34] energies, so that $x_{T}$ scaling can be used to distinguish between the soft and hard particle productions.

Another important point of measurements in $p+p$ collisions is as a baseline for the heavy ion $(A+A)$ data. The nuclear modification factor $R_{A A}$, for example, uses $p_{T}$ spectra in $p+p$ collisions as a denominator and those in $A+A$ collisions (with the appropriate scaling of number of binary nucleon-nucleon collisions) as a numerator. In addition, $p_{T}$ spectra in $p+p$ provide a reference for bulk properties of $A+A$ collisions, such as the inverse slope parameter $T_{\mathrm{inv}}$, mean transverse momentum $\left\langle p_{T}\right\rangle$, and yield per unit rapidity $d N / d y$. These data in $p+p$ collisions can be treated as baseline values for the smallest $A+A$ collisions.

In this paper, we present measurements of identified charged hadron $p_{T}$ spectra for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ at midrapidity in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV from the PHENIX experiment. First, we compare the results of particle spectra at 200 GeV with those at 62.4 GeV as a function of $p_{T}, m_{T}$, and $m_{T}-m$ (where $m$ is the rest mass). Second, the extracted values from $p_{T}$ spectra, i.e., $T_{\text {inv }},\left\langle p_{T}\right\rangle$, and $d N / d y$, are compared between the two beam energies. For the systematic study of particle production as a function of $\sqrt{s}$, the data are further compared to measurements in $p+p$ and $p+\bar{p}$ collisions at the CERN ISR and Fermi National Accelerator Laboratory (FNAL) Tevatron colliders.

From these measurements, we discuss the following key issues:
(i) Hard scattering particle production: The data are compared with the results of perturbative quantum chromodynamics calculations.
(ii) Transition from soft to hard physics: Since the $p_{T}$ regions presented in this paper can cover the region where the soft-hard transition occurs, the scaling properties in $m_{T}$ and $x_{T}$ with their beam energy and particle species dependences are shown.
(iii) Comparisons with heavy ion data as a baseline measurement: Some of the data in $p+p$ are compared with the existing data in $\mathrm{Au}+\mathrm{Au}$ [37].
The paper is organized as follows. Section II describes the PHENIX detector as it was used in this measurement. Section III discusses the analysis details, including data sets, event selection, track selection, particle identification, corrections applied to the data, and systematic uncertainties. Section IV gives the experimental results for $p_{T}$ spectra for identified charged particles, particle ratios, $m_{T}$ scaling, the excitation function of observables (such as $T_{\mathrm{inv}},\left\langle p_{T}\right\rangle$, and $d N / d y$ ), and $R_{A A}$. Section V compares the results with next-to-leading-order (NLO) $[38,39]$ and next-to-leading-logarithm (NLL) [40,41] pQCD calculations, and discusses soft and hard particle production and the transition between them. Section VI gives the summary and conclusions.

## II. EXPERIMENTAL SETUP

The PHENIX experiment is designed to perform a broad study of $A+A, d+A$, and $p+p$ collisions to investigate nuclear matter under extreme conditions, as well as to measure the spin structure of the nucleon. It is composed of two central arms (called the east and west arm, respectively), two forward muon arms, and global detectors, as shown in Fig. 1. The central arms are designed to detect electrons, photons, and charged hadrons in the pseudorapidity range $|\eta|<0.35$. The global detectors measure the start time, collision vertex, and charged hadron multiplicity of the interactions in the forward pseudorapidity region. The following sections describe those parts of the detector that are used in the present analysis. A detailed description of the complete set of detectors can be found elsewhere [42-46].

The beam-beam counters (BBCs) [45] determine the start time information for time-of-flight measurements and the collision vertex point, as well as providing the main collision trigger. The two BBCs are located at 1.44 m from the nominal interaction point along the beamline on each side. Each BBC comprises 64 Čerenkov telescopes, arranged radially around the beamline. The BBCs measure the number of charged particles in the pseudorapidity region $3.0<|\eta|<3.9$.

Charged particle tracks are reconstructed using the central arm spectrometers [46]. The east arm spectrometer of the PHENIX detector contains the following subsystems used in this analysis: drift chamber (DC), pad chamber (PC), and time-of-flight (TOF) detector. The magnetic field for the central arm spectrometers is supplied by the central magnet


FIG. 1. (Color online) The PHENIX detector configuration for RHIC Run-6 data-taking period.
[43] that provides an axial field parallel to the beam around the collision vertex.

The drift chambers are the closest tracking detectors to the beamline, located at a radial distance of 2.2 m (geometric center; the same for the other detectors). They measure charged particle trajectories in the azimuthal direction to determine the transverse momentum of each particle. By combining the polar angle information from the first layer of PCs, as described below, with the transverse momentum, the total momentum $p$ is determined. The momentum resolution in $p+p$ collisions is $\delta p / p \simeq 0.7 \% \oplus 1.0 \% \times p(\mathrm{GeV} / c)$, where the first term is due to the multiple scattering before the DC and the second term is the angular resolution of the DC. The absolute momentum scale is known as $\pm 0.7 \% \mathrm{rms}$ from the reconstructed proton mass using TOF data.

The pad chambers are multiwire proportional chambers that form three separate layers of the central tracking system. The first layer (PC1) is located at the radial outer edge of each drift chamber at a distance of 2.49 m , while the third layer is at 4.98 m from the interaction point. The second layer is located at a radial distance of 4.19 m in the west arm only. The PC1 and DC , along with the vertex position measured by the BBC, are used in the global track reconstruction to determine the polar angle of each charged track.

The time-of-flight detector serves as the primary particle identification device for charged hadrons by measuring the stop time. The start time is given by the BBC. The TOF detector is located at a radial distance of 5.06 m from the interaction point in the east central arm. This contains 960 scintillator slats
oriented along the azimuthal direction. It is designed to cover $|\eta|<0.35$ and $\Delta \phi=45^{\circ}$ in azimuthal angle. The intrinsic timing resolution is $\sigma \simeq 115 \mathrm{ps}$, which in combination with the BBC timing resolution of 60 ps allows for a $2.6 \sigma \pi / K$ separation at $p_{T} \simeq 2.5 \mathrm{GeV} / c$, and $K / p$ separation out to $p_{T}=4.5 \mathrm{GeV} / c$, using an asymmetric particle-identification (PID) cut, as described below.

## III. DATA ANALYSIS

The two RHIC data sets analyzed are 2005 data for $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$ and 2006 data for $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. Each data set was analyzed separately by taking into account the different run conditions and accelerator performance. In this section, we explain the event selection, track reconstruction, particle identification, and corrections to obtain the $p_{T}$ spectra. The event normalization and systematic uncertainties are also presented.

## A. Event selection

We use the PHENIX minimum bias trigger events, which are determined by a coincidence between north and south BBC signals, requiring at least one hit on both sides of the BBCs. Owing to the limited acceptance, approximately only half of $p+p$ inelastic events result in a BBC trigger. The PHENIX minimum bias data, triggered by BBC in $p+p$ collisions within a vertex cut of $\pm 30 \mathrm{~cm}$, include $\sigma_{\mathrm{BBC}}=23.0 \pm 2.2 \mathrm{mb}$ at $\sqrt{s}=200 \mathrm{GeV}$ and $\sigma_{\mathrm{BBC}}=13.7 \pm 1.5 \mathrm{mb}$ at $\sqrt{s}=62.4 \mathrm{GeV}$ (see Sec. IIIE). We analyze $9.2 \times 10^{8}$ minimum bias events for the $2005 p+p$ data at $\sqrt{s}=200 \mathrm{GeV}$, which is more than 30 times larger than the 2003 data set [26], and $2.14 \times 10^{8}$ minimum bias events for the 2006 data at $\sqrt{s}=62.4 \mathrm{GeV}$.

## B. Track reconstruction and particle identification

As in previous publications [37,47], charged particle tracks are reconstructed by the DC based on a combinatorial Hough transform, which gives the angle of the track in the main bend plane. PC1 is used to measure the position of the hit in the longitudinal direction along the beam axis. When combined with the location of the collision vertex along the beam axis, the PC1 hit gives the polar angle of the track. Only tracks with valid information from both DC and PC1 are used in the analysis. To associate a track with a hit on the TOF detector, the track is projected to its expected hit location on the TOF detector. We require tracks to have a hit on the TOF detector within $\pm 2 \sigma$ of the expected hit location in both the azimuthal and beam directions. The track reconstruction efficiency is approximately $98 \%$ in $p+p$ collisions. Finally, a cut on the energy loss in the TOF scintillator is applied to each track. This $\beta$-dependent energy loss cut is based on a parametrization of the Bethe-Bloch formula. The flight path length is calculated from a fit to the reconstructed track trajectory in the magnetic field. The background due to random association of DC and PC1 tracks with TOF hits is reduced to a negligible level when the mass cut used for particle identification is applied.


FIG. 2. (Color online) Momentum multiplied by charge versus mass squared distribution in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. The lines indicate the PID cut boundaries ( $2 \sigma$ ) for pions, kaons, and protons (antiprotons) from left to right, respectively.

Charged particles are identified using the combination of three measurements: time-of-flight data from the BBC and TOF detector, momentum from the DC, and flight path length from the collision vertex point to the TOF detector hit position. The mass squared is derived from

$$
\begin{equation*}
m^{2}=\frac{p^{2}}{c^{2}}\left[\left(\frac{t_{\mathrm{TOF}}}{L / c}\right)^{2}-1\right] \tag{2}
\end{equation*}
$$

where $p$ is the momentum, $t_{\mathrm{TOF}}$ is the time of flight, $L$ is the flight path length, and $c$ is the speed of light. The charged particle identification is performed using cuts in $m^{2}$ and momentum space. In Fig. 2, a plot of momentum multiplied by charge versus $m^{2}$ is shown together with applied PID cuts as solid curves. We use $2 \sigma$ standard deviation PID cuts in $m^{2}$ and momentum space for each particle species. The PID cut is based on a parametrization of the measured $m^{2}$ width as a function of momentum,

$$
\begin{align*}
\sigma_{m^{2}}^{2}= & \frac{\sigma_{\alpha}^{2}}{K_{1}^{2}}\left(4 m^{4} p^{2}\right)+\frac{\sigma_{\mathrm{MS}}^{2}}{K_{1}^{2}}\left[4 m^{4}\left(1+\frac{m^{2}}{p^{2}}\right)\right] \\
& +\frac{\sigma_{t}^{2} c^{2}}{L^{2}}\left[4 p^{2}\left(m^{2}+p^{2}\right)\right] \tag{3}
\end{align*}
$$

where $\sigma_{\alpha}$ is the angular resolution, $\sigma_{\mathrm{MS}}$ is the multiplescattering term, $\sigma_{t}$ is the overall time-of-flight resolution, $m$ is the centroid of the $m^{2}$ distribution for each particle species, and $K_{1}$ is the magnetic field integral constant term of 101 mrad GeV . The parameters for PID are $\sigma_{\alpha}=0.99 \mathrm{mrad}$, $\sigma_{\mathrm{MS}}=1.02 \mathrm{mrad} \mathrm{GeV}$, and $\sigma_{t}=130 \mathrm{ps}$. For pion identification above $2 \mathrm{GeV} / c$, we apply an asymmetric PID cut to reduce kaon contamination of pions. As shown by the lines in Fig. 2, the overlap regions that are within the $2 \sigma$ cuts for both pions and kaons are excluded. The lower momentum cutoffs are $0.3 \mathrm{GeV} / c$ for pions, $0.4 \mathrm{GeV} / c$ for kaons, and $0.5 \mathrm{GeV} / c$ for protons and antiprotons. The lower momentum cutoff value
for $p$ and $\bar{p}$ is larger than for pions and kaons due to the larger energy loss effect.

For kaons, the upper momentum cutoff is $2 \mathrm{GeV} / c$ since the $\pi+p$ contamination level for kaons is $\approx 8 \%$ at that momentum. The upper momentum cutoff for pions is $p_{T}=$ $3 \mathrm{GeV} / c$ where the $K+p$ contamination reaches $\approx 3 \%$. Electron (positron) and decay muon background at very low $p_{T}$ ( $<0.3 \mathrm{GeV} / c$ ) are well separated from the pion mass-squared peak. For protons the upper momentum cutoff is set at $4.5 \mathrm{GeV} / c$. For protons and antiprotons an additional cut, $m^{2}>0.6\left(\mathrm{GeV} / c^{2}\right)^{2}$, is introduced to reduce the contamination. The contamination background on each particle species is subtracted statistically after applying these PID cuts.

## C. Efficiency corrections

We use a geant [48] based Monte Carlo simulation program of the PHENIX detector, to correct for geometrical acceptance, reconstruction efficiency, in-flight decay for $\pi$ and $K$, multiple-scattering effect, and nuclear interactions with materials in the detector (including $\bar{p}$ absorption). Singleparticle tracks are passed from GEANT to the PHENIX event reconstruction software [47]. In this simulation, the BBC, DC, and TOF detector responses are tuned to match the real data. For example, dead areas of the DC and TOF detector are included, and momentum and time-of-flight resolutions are tuned. The track association to the TOF detector both in azimuth and along the beam axis as a function of momentum and the PID cut boundaries are parametrized to match the real data. A fiducial cut is applied to choose identical active areas on the TOF detector in both the simulation and data.

We generate $1 \times 10^{7}$ single-particle events for each particle species $\left(\pi^{ \pm}, K^{ \pm}, p\right.$, and $\left.\bar{p}\right)$ with flat $p_{T}$ distributions for high $p_{T}(2-4 \mathrm{GeV} / c$ for pions and kaons, $2-8 \mathrm{GeV} / c$ for $p$ and $\bar{p}$ ) with enhancement at low $p_{T}(<2 \mathrm{GeV} / c)$. Weighting functions to the $p_{T}$ distributions are also used to check the effect of steepness, which is less than $\sim 1 \%$ level on the final yields in the measured $p_{T}$ range. The rapidity range is set to be wider than the PHENIX acceptance, i.e., flat in $-0.6<y<0.6(\Delta y=1.2)$ to deal with particles coming from outside [the denominator of Eq. (4) is weighted with a factor $1 / \Delta y=1 / 1.2$ in order to normalize the yield for unit rapidity]. The efficiencies are determined in each $p_{T}$ bin by dividing the reconstructed output by the generated input as expressed as follows:

$$
\begin{equation*}
\epsilon\left(p_{T}\right)=\frac{\text { no. of reconstructed MC tracks }}{\text { no. of generated MC tracks }} \tag{4}
\end{equation*}
$$

The resulting correction factors $C_{\text {eff }}\left(p_{T}\right)\left[=1 / \epsilon\left(p_{T}\right)\right]$ are multiplied by the raw $p_{T}$ spectra for each $p_{T}$ bin and for each individual particle species (see Sec. III G).

## D. Feed-down corrections

The proton and antiproton $p_{T}$ spectra are corrected for feeddown from weak decays of hyperons. The detailed procedure for the feed-down correction can be found in [26]. We include the following decay modes: $\Lambda \rightarrow p \pi^{-}, \Sigma^{+} \rightarrow p \pi^{0}$, and $\Lambda$
production from $\Sigma^{0}, \Xi^{0}, \Xi^{-}$. The feed-down contributions for antiproton yields are also estimated using the above decay modes for antiparticles.

In order to estimate the fractions of protons and antiprotons from weak decays of hyperons in the measured proton and antiproton $p_{T}$ spectra, we use three input $\Lambda$ and $\bar{\Lambda} p_{T}$ spectra:
(i) measured $\Lambda$ and $\bar{\Lambda} p_{T}$ spectra in PHENIX in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV ,
(ii) measured $p(\bar{p})$ distributions scaled with measured $\Lambda$ $(\bar{\Lambda})$ distributions [31], and
(iii) measured $p(\bar{p})$ distributions scaled with $\operatorname{ISR} \Lambda(\bar{\Lambda})$ distributions [25].

Using each input above, proton and antiproton spectra from weak decays are calculated by using Monte Carlo simulation to take into account decay kinematics, the PHENIX track reconstruction efficiency, and experimental acceptance. Then systematic uncertainties are evaluated from different $\Lambda$ and $\bar{\Lambda}$ spectra inputs. The resulting uncertainties on the final proton and antiproton spectra are of the order of $20 \%-30 \%$ at $p_{T}=0.6 \mathrm{GeV} / c$ and $2 \%-5 \%$ at $p_{T}=4 \mathrm{GeV} / c$. The fractional contribution of the feed-down protons (antiprotons) to the total measured proton (antiproton) spectra, $\delta_{\text {feed }}\left(p_{T}\right)$, is approximately $10 \%-20 \%(5 \%-15 \%)$ at $p_{T}=4 \mathrm{GeV} / c$ for $200 \mathrm{GeV} p+p(62.4 \mathrm{GeV} p+p)$ and it shows an increase at lower $p_{T}$ as shown in Fig. 3. The correction factor for the feed-down correction can be expressed as $C_{\text {feed }}\left(p_{T}\right)=$ $1-\delta_{\text {feed }}\left(p_{T}\right)$, by which the raw $p_{T}$ spectra are multiplied (see Sec. III G).

The feed-down correction for protons is different from that for antiprotons at 62.4 GeV , because of the difference in $\Lambda / p$ and $\bar{\Lambda} / \bar{p}$ ratio at this beam energy. At 62.4 GeV the $\Lambda / p$ ratio is 0.2 , while the $\bar{\Lambda} / \bar{p}$ ratio is $\approx 0.4$ [25], so that the feed-down contribution for antiprotons is bigger than that for protons. At 200 GeV , these two ratios are almost the same [31]; therefore the feed-down corrections for $p$ and $\bar{p}$ become identical.

## E. Cross-section normalization

The BBC serves a dual function as both the minimum bias trigger and the calibrated luminosity monitor. The luminosity $\mathcal{L}$ is defined as the interaction rate for a given cross section, $d N / d t=\mathcal{L} \sigma$, and the total number of events for a given cross section is

$$
\begin{equation*}
N=\sigma \times \int \mathcal{L} d t \tag{5}
\end{equation*}
$$

where $\int \mathcal{L} d t$ is the integrated luminosity. To connect the number of minimum bias triggered events and the integrated luminosity, $\sigma_{\mathrm{BBC}}$ is introduced, where $1 / \sigma_{\mathrm{BBC}}$ corresponds to the integrated luminosity per minimum bias triggered event [Eq. (6)]:

$$
\begin{equation*}
N_{\mathrm{BBC}}=\sigma_{\mathrm{BBC}} \times \int \mathcal{L} d t \tag{6}
\end{equation*}
$$

where $N_{\mathrm{BBC}}$ is the number of minimum bias events and $\int \mathcal{L} d t$ is the corresponding integrated luminosity. $\sigma_{\mathrm{BBC}}$ is measured


FIG. 3. (Color online) Fraction of feed-down protons and antiprotons as a function of $p_{T}$ with systematic uncertainties. Top: 200 GeV $p+p$ (positive and negative functions are common). Bottom: 62.4 GeV $p+p$.
by a Van der Meer scan method (Vernier scan) in PHENIX [34,49].

Vernier scans were performed for $\sqrt{s}=200$ and 62.4 GeV data sets. The $\sigma_{\mathrm{BBC}}$ obtained are $23.0 \pm 2.2$ and $13.7 \pm$ 1.5 mb for $\sqrt{s}=200$ and 62.4 GeV , respectively. The quoted uncertainty is a systematic uncertainty. These values were reported in our measurements of $\pi^{0}$ production [30,34].

Since the minimum bias trigger registers only half of the $p+p$ inelastic cross section, it is expected that there is a trigger bias against particles in the central spectrometers. This was checked with $\pi^{0}$ 's in the electromagnetic calorimeter with high- $p_{T}$ photon triggered events, and with charged tracks in the accelerator's beam crossing (clock) triggered events. The trigger bias $\epsilon_{\text {bias }}$ determined from the ratio $\left(f_{\pi^{0}}\right)$ of the number of $\pi^{0}$ in the high- $p_{T}$ photon triggered sample with and without the BBC trigger requirement [34]. We assume that $\epsilon_{\text {bias }}$ is process dependent and so that it is measured as $\epsilon_{\text {bias }}=f_{\pi^{0}}$. This ratio, $f_{\pi^{0}}$, is $0.79 \pm 0.02$ independent of the transverse momentum for $\sqrt{s}=200 \mathrm{GeV}$. At 62.4 GeV , the trigger bias was found to be transverse momentum dependent [34]. Figure 4 shows that the trigger bias $f_{\pi^{0}}$ is $\approx 40 \%$ up to $p_{T} \approx$ $3 \mathrm{GeV} / c$, and monotonically decreases to $25 \%$ at $p_{T} \approx$


FIG. 4. (Color online) Fraction of the inclusive $\pi^{0}$ yield that satisfied the BBC trigger condition in $62.4 \mathrm{GeV} p+p$. Data points are from Fig. 1 of [34].
$7 \mathrm{GeV} / c$. As described in the previous PHENIX publication [34], this decrease can be understood by the fact that most of the energy is used for the production of high-energy jets which contain the measured high- $p_{T} \pi^{0}$ and charged hadrons, and there is not enough energy left to produce particles for $\sqrt{s}=62.4 \mathrm{GeV} p+p$ collisions at the forward rapidity (3.0 $<|\eta|<3.9$ ) where the BBC is located. This drop can be seen only for 62.4 GeV data. Also, we assume no particle species dependence for this trigger bias. We use this $p_{T}$-dependent trigger bias correction for charged hadrons by using fitted coefficients of a second-order polynomial, as shown in Fig. 4.

With those values, the invariant yield per BBC trigger count $\left(Y / N_{\mathrm{BBC}}\right)$ is related to the invariant cross section $(\sigma)$ using

$$
\begin{equation*}
\sigma=\left(Y / N_{\mathrm{BBC}}\right) \times\left(\sigma_{\mathrm{BBC}} / \epsilon_{\mathrm{bias}}\right) \tag{7}
\end{equation*}
$$

## F. Systematic uncertainties

In order to estimate the systematic uncertainties, $p_{T}$ spectra with slightly different analysis cuts from those we use for the final results are prepared, and these spectra are compared to those with the standard analysis cuts. We checked the following analysis cuts: (1) fiducial, (2) track association windows, and (3) PID.

For each spectrum with modified cuts, the same changes in the cuts are made in the Monte Carlo simulation. The fully corrected spectra with different cut conditions are divided by the spectra with the baseline cut condition, resulting in uncertainties associated with each cut condition as a function of $p_{T}$. The obtained uncertainties are added in quadrature. Tables I and II show the systematic uncertainties on $p_{T}$ spectra for each data set. There are three categories of systematic uncertainty: Type A is a point-to-point error uncorrelated between $p_{T}$ bins, type B is $p_{T}$ correlated, where all points move in the same direction but not by the same factor, while in type C all points move by the same factor independent of $p_{T}$ [50]. In this study, the systematic uncertainties on feed-down correction and PID contamination correction are type B; other systematic uncertainties on applied analysis cuts

TABLE I. Systematic uncertainties on the $p_{T}$ spectra for $\sqrt{s}=200$ $\mathrm{GeV} p+p$ given in percent. The number in parentheses includes the $p_{T}$ dependence of the uncertainties for PID cut, feed-down correction, and PID contamination correction.

| Source | $\pi^{+}$ | $\pi^{-}$ | $K^{+}$ | $K^{-}$ | $p$ | $\bar{p}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Fiducial cut | 5 | 5 | 4 | 5 | 4 | 5 |
| Track matching | 4 | 4 | 5 | 4 | 4 | 4 |
| PID cut | 3 | 3 | 2 | 2 | $2-8$ | $2-10$ |
| Efficiency correction | 2 | 2 | 2 | 2 | 2 | 2 |
| Feed-down correction | - | - | - | - | $4-25$ | $4-25$ |
| PID contamination | - | - | - | - | $0-2$ | $0-2$ |
| Total | 7 | 7 | 7 | 7 | $6(8-25)$ | $7(9-25)$ |

are type C. There are two types of PID-related uncertainties. One is the systematic uncertainty of the yield extraction, which is evaluated by changing the PID boundary in the $m^{2}$ vs momentum plane. The other is the systematic uncertainty of the particle contamination, which is evaluated by using the contamination fraction. The fraction is estimated by fitting $m^{2}$ distributions on each $p_{T}$ slice under the conditions of (1) fixed parameters for $p$ and $\bar{p}$ mass centroid and width, (2) $p$ and $\bar{p}$ mass centroid free with fixed mass width, and (3) $p$ and $\bar{p}$ mass width free with fixed mass centroid.

The systematic uncertainty on the BBC cross section is $9.7 \%$ and $11 \%$ for $\sqrt{s}=200$ and 62.4 GeV , respectively. The systematic uncertainty on the trigger bias is $3 \%$ and $1 \%-5 \%$ for $\sqrt{s}=200$ and 62.4 GeV , respectively (see Sec. IIIE). These uncertainties on normalization (type C) are not included in Tables I and II. All the figures and tables, including the tables in the Appendix, do not include the normalization uncertainties, unless explicitly noted.

## G. Invariant cross section

The differential invariant cross section is determined as

$$
\begin{align*}
E \frac{d^{3} \sigma}{d p^{3}}= & \frac{1}{2 \pi p_{T}} \frac{\sigma_{\mathrm{BBC}}}{N_{\mathrm{BBC}} C_{\mathrm{bias}}^{\mathrm{BBC}}\left(p_{T}\right)} \\
& \times C_{\mathrm{eff}}\left(p_{T}\right) C_{\mathrm{feed}}\left(p_{T}\right) \frac{d^{2} N}{d p_{T} d y} \tag{8}
\end{align*}
$$

TABLE II. Systematic uncertainties on the $p_{T}$ spectra for $\sqrt{s}=$ $62.4 \mathrm{GeV} p+p$ given in percent. The number in parentheses includes the $p_{T}$ dependence of the uncertainties for feed-down correction and PID contamination correction.

| Source | $\pi^{+}$ | $\pi^{-}$ | $K^{+}$ | $K^{-}$ | $p$ | $\bar{p}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Fiducial cut | 6 | 5 | 6 | 5 | 7 | 5 |
| Track matching | 2 | 2 | 3 | 3 | 3 | 3 |
| PID cut | 2 | 2 | 3 | 3 | 4 | 4 |
| Efficiency correction | 2 | 2 | 2 | 2 | 2 | 2 |
| Feed-down correction | - | - | - | - | $1-16$ | $3-50$ |
| PID contamination | - | - | $0-5$ | $0-5$ | - | - |
| Total | 7 | 6 | 7 | 7 | $9(9-18)$ | $7(8-50)$ |

where $\sigma$ is the cross section, $p_{T}$ is the transverse momentum, $y$ is the rapidity, $N_{\text {BBC }}$ is the number of minimum bias events, $\sigma_{\text {BBC }}$ is the minimum bias cross section measured by the BBC, $C_{\text {eff }}\left(p_{T}\right)$ is the acceptance correction factor including detector efficiency, $C_{\text {bias }}^{\mathrm{BBC}}\left(p_{T}\right)$ is the trigger bias, $C_{\text {feed }}\left(p_{T}\right)$ is the feeddown correction factor only for protons and antiprotons, and $N$ is the number of measured tracks.

## IV. RESULTS

In this section, we show the transverse momentum distributions and yields for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}$ $=200$ and 62.4 GeV at midrapidity measured by the PHENIX experiment. We also present the transverse mass ( $m_{T}$ ) spectra, the inverse slope parameter $T_{\text {inv }}$, mean transverse momentum $\left\langle p_{T}\right\rangle$, yield per unit rapidity $d N / d y$, and particle ratios at each energy, and compare them to other measurements at different $\sqrt{s}$ in $p+p$ and $p+\bar{p}$ collisions. The measured $T_{\mathrm{inv}},\left\langle p_{T}\right\rangle$, and $d N / d y$ in $p+p 200 \mathrm{GeV}$ are also compared with those in published results for $\mathrm{Au}+\mathrm{Au}$ at 200 GeV . The nuclear modification factor $R_{A A}$ for $200 \mathrm{GeV} \mathrm{Au}+\mathrm{Au}$ obtained using the present study in $p+p 200 \mathrm{GeV}$ is also presented.

## A. $\boldsymbol{p}_{\boldsymbol{T}}$ spectra

Figure 5 shows transverse momentum spectra for $\pi^{ \pm}, K^{ \pm}$, $p$, and $\bar{p}$ in 200 and $62.4 \mathrm{GeV} p+p$ collisions. Feed-down correction for weak decays is applied for $p$ and $\bar{p}$, and the same correction factors are consistently used for all figures throughout Sec. IV unless otherwise specified. Each of the $p_{T}$ spectra is fitted with an exponential functional form:

$$
\begin{equation*}
\frac{1}{2 \pi p_{T}} \frac{d^{2} \sigma}{d y d p_{T}}=A \exp \left(-\frac{p_{T}}{T}\right) \tag{9}
\end{equation*}
$$

where $A$ is a normalization factor and $T$ is an inverse slope parameter for $p_{T}$. The fitting parameters and $\chi^{2} / \mathrm{NDF}$ (where NDF is the number of degrees of freedom) obtained by using Eq. (9) for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and $62.4 \mathrm{GeV} p+p$ collisions are tabulated in Table III. The fitting range is fixed as $p_{T}=0.5-1.5 \mathrm{GeV} / c$ for $\pi^{ \pm}, 0.6-2.0 \mathrm{GeV} / c$ for $K^{ \pm}$, and $0.8-2.5 \mathrm{GeV} / c$ for $p, \bar{p}$ at both collision energies.

Figure 5 shows that pions, protons, and antiprotons exhibit an exponential spectral shape at low $p_{T}$ and a power-law shape at high $p_{T}$, while kaons are exponential in the measured $p_{T}$ range. The transition from exponential to power law can be better seen at $p_{T} \sim 2 \mathrm{GeV} / c$ for pions and at $p_{T} \sim 3 \mathrm{GeV} / c$ for protons and antiprotons at both energies. The fractions of soft and hard components gradually change in the transition region.

Ratios of the $p_{T}$ spectra at 200 GeV to those at 62.4 GeV are shown in the bottom plot of Fig. 5. The left panel shows the ratios for positively charged particles and the right panel those for the negatively charged particles. The data for neutral pions $[30,34]$ are also shown on both panels. The ratios show a clear increase as a function of $p_{T}$ for all the ratios. Since hard scattering is expected to be the dominant particle production process at high $p_{T}$, this strong $p_{T}$ dependence indicates two features: (1) the spectral shape is harder for

200 GeV compared to that for 62.4 GeV , and (2) there is a universal shape for all particle species up to $p_{T}=2-3 \mathrm{GeV} / c$. In the same figure, the results from NLO pQCD calculations with the de Florian-Sassot-Stratmann (DSS) fragmentation function [38,39] for pions with different factorization, fragmentation, and renormalization scales (which are equal) are also shown. The agreement is relatively poor, due to the disagreement between the NLO pQCD calculation $[38,39]$ with DSS fragmentation function and measurement for pions at $\sqrt{s}=62.4 \mathrm{GeV}$. As we will discuss in detail in Sec. V C, it is found that NLL pQCD [40,41] gives a better description of the data for $p+p$ at 62.4 GeV .

Please note that each line in pQCD is calculated for each $\mu\left(=p_{T} / 2, p_{T}, 2 p_{T}\right)$ value. The hard scale resides in the hard scattering, which is expected to be the same regardless of hadron species. The theoretical uncertainty in the ratio of NLO $[38,39](200 \mathrm{GeV}) /(62.4 \mathrm{GeV})$ significantly cancels. The same comparison of ratio for NLL results cannot be made due to the unreliability of resummation in NLL pQCD at 200 GeV in the low- $p_{T}$ region [51].

## B. $m_{T}$ spectra

In $p+p(\bar{p})$ collisions at high energies, the transverse mass $\left(m_{T}\right)$ spectra of identified hadrons show a universal scaling behavior, and this fact is known as $m_{T}$ scaling. In order to check the $m_{T}$ scaling and to gain a further insight into the particle production mechanism especially at high $p_{T}$ at RHIC energies, transverse mass spectra in 200 and $62.4 \mathrm{GeV} p+p$ collisions are shown in Fig. 6. The data for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and 62.4 GeV are from this study. The $\pi^{0}$ spectra are taken from the PHENIX measurements [30,34]. From the STAR experiment, $\pi^{ \pm}, p$, and $\bar{p}$ spectra in $200 \mathrm{GeV} p+p$ are taken from [33]; and $K_{s}^{0}, \Lambda$, and $\bar{\Lambda}$ spectra in 200 GeV $p+p$ are taken from [31]. The $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ spectra in $63 \mathrm{GeV} p+p$ are from [13], and $\Lambda$ and $\bar{\Lambda}$ spectra in 63 GeV $p+p$ are from the ISR experiment [25]. For both energies one can see similar spectral shapes that differ in normalization. To see the similarities or differences of spectral shapes in $m_{T}$ more clearly, we normalize the yield of each particle species to that of charged pions in the range $m_{T}=1.0-1.5 \mathrm{GeV} / c^{2}$. The scaling factors are given in Table IV.

Figure 7 shows the $m_{T}$ spectra with such scaling factors implemented. These normalization scaling factors are determined to match the yield of each particle species to that of charged pions in the range of $m_{T}=1.0-1.5 \mathrm{GeV} / c^{2}$. The bottom panels on the plots in Fig. 7 are the ratio of data to the fitting result using a Tsallis function [52] for $\pi^{0}$ data at 200 GeV [30] and 62.4 GeV [34]. Above $m_{T}>1.5 \mathrm{GeV} / c^{2}$, these figures indicate a clear separation between meson and baryon spectra. The meson spectra are apparently harder than the baryon spectra in this representation. This effect can be seen more clearly on the $\sqrt{s}=200 \mathrm{GeV}$ data set than on data measured at 62.4 GeV . Such a baryon-meson splitting in $m_{T}$ spectra have been reported by the STAR experiment in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$ [31]. The authors of [31] argued that, for a given jet energy, mesons might be produced with higher transverse momentum than baryons, because meson production in jet fragmentation requires only


FIG. 5. (Color online) (Top, middle) Transverse momentum distributions for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=($ left $) 200$ and (right) 62.4 GeV at midrapidity. Only statistical uncertainties are shown. (Middle plots) Each spectrum is fitted with an exponential function. (Lower panels of middle plots) Ratio of the exponential fit to data for each particle species. (Bottom) Ratios of $p_{T}$ spectra for $\pi^{ \pm}, \pi^{0}[30,34]$, $K^{ \pm}, p$, and $\bar{p}$ in $200 \mathrm{GeV} p+p$ collisions to those in $62.4 \mathrm{GeV} p+p$ collisions. Statistical and systematic uncertainties are combined in quadrature. The trigger cross section uncertainty is not included. The lines represent the NLO pQCD calculations [38,39] (DSS fragmentation function) for pions with different factorization, fragmentation, and renormalization scales (which are equal).
a (quark, antiquark) pair, while baryon production requires a (diquark, antidiquark) pair.

Instead of using the scaling factors obtained from the low$m_{T}$ region as listed in Table IV, one can introduce another set
of scaling factors to match $m_{T}$ spectra at higher $m_{T}$, because the spectral shapes for different particle species in the high- $p_{T}$ region in the 200 GeV data are also very similar [28]. In this case, $m_{T}$ spectra for baryons overshoot those for mesons at low

TABLE III. Fitting results for $A, T$ of Eq. (9) for $p_{T}$ spectra for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and $62.4 \mathrm{GeV} p+p$ collisions. The fitting range is fixed as $p_{T}=0.5-1.5 \mathrm{GeV} / c$ for $\pi^{ \pm}, 0.6-2.0 \mathrm{GeV} / c$ for $K^{ \pm}$, and $0.8-2.5 \mathrm{GeV} / c$ for $p, \bar{p}$ at both collision energies.

| $\sqrt{s}$ <br> $(\mathrm{GeV})$ | Hadron | $A$ | $T$ <br> $(\mathrm{GeV} / c)$ | $\chi^{2} / \mathrm{NDF}$ |
| :---: | :---: | :---: | :---: | :---: |
| 200 | $\pi^{+}$ | $80.1 \pm 7.2$ | $0.220 \pm 0.004$ | $11.5 / 8$ |
|  | $\pi^{-}$ | $80.7 \pm 7.5$ | $0.220 \pm 0.004$ | $13.5 / 8$ |
|  | $K^{+}$ | $6.45 \pm 0.50$ | $0.296 \pm 0.005$ | $29.4 / 12$ |
|  | $K^{-}$ | $6.62 \pm 0.51$ | $0.293 \pm 0.004$ | $18.8 / 12$ |
|  | $p$ | $3.24 \pm 0.38$ | $0.318 \pm 0.006$ | $3.3 / 15$ |
|  | $\bar{p}$ | $2.83 \pm 0.35$ | $0.318 \pm 0.006$ | $2.8 / 15$ |
| 62.4 | $\pi^{+}$ | $78.0 \pm 7.0$ | $0.203 \pm 0.003$ | $9.0 / 8$ |
|  | $\pi^{-}$ | $81.0 \pm 6.2$ | $0.200 \pm 0.003$ | $11.1 / 8$ |
|  | $K^{+}$ | $6.17 \pm 0.52$ | $0.264 \pm 0.004$ | $15.6 / 12$ |
|  | $K^{-}$ | $6.01 \pm 0.49$ | $0.254 \pm 0.004$ | $10.0 / 12$ |
|  | $p$ | $4.61 \pm 0.48$ | $0.275 \pm 0.005$ | $2.8 / 15$ |
|  | $\bar{p}$ | $2.95 \pm 0.36$ | $0.267 \pm 0.005$ | $2.9 / 15$ |

$m_{T}$ [28]. In Sec. IV C, we discuss the spectral shape at low $m_{T}$ in detail, by taking into account the hadron mass effect.


TABLE IV. Normalization scaling factors for $m_{T}$ spectra for Fig. 7. The scaling factors for the STAR experiment are determined from [31,33] and those for the ISR results are determined from [25].

| $\sqrt{s}$ |  |  |  |  |  |  |  |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $(\mathrm{GeV})$ | Expt. | $\pi^{+}$ | $\pi^{-}$ | $\pi^{0}$ | $K^{+}$ | $K^{-}$ | $K_{s}^{0}$ | $p$ | $\bar{p}$ | $\Lambda$ | $\bar{\Lambda}$ |
| 200 | PHENIX | 1.0 | 1.0 | 0.9 | 2.4 | 2.4 | - | 1.15 | 1.4 | - | - |
| 200 | STAR | 1.0 | 1.0 | - | - | - | 2.4 | 0.75 | 0.75 | 0.8 | 0.9 |
| 62.4 | PHENIX | 1.0 | 1.0 | 0.9 | 2.32 | 2.88 | - | 0.9 | 1.5 | - | - |
| 63 | ISR | - | - | - | - | - | - | - | - | 0.4 | 0.5 |

## C. $\boldsymbol{m}_{T}-m$ spectra

Figure 8 shows the $m_{T}-m$ spectra for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and $62.4 \mathrm{GeV} p+p$ collisions, respectively. When analyzing these $m_{T}-m$ spectra of various identified hadrons, one discusses the spectral shape mainly in the low- $\left(m_{T}-m\right)$ region. Each of these spectra is fitted with an exponential functional form:

$$
\begin{equation*}
\frac{1}{2 \pi m_{T}} \frac{d^{2} \sigma}{d y d m_{T}}=A \exp \left(-\frac{m_{T}-m}{T_{\mathrm{inv}}}\right), \tag{10}
\end{equation*}
$$

where $A$ is a normalization factor and $T_{\mathrm{inv}}$ is called the inverse slope parameter. The fitting parameters and $\chi^{2} / \mathrm{NDF}$


FIG. 6. (Color online) Transverse mass distributions for $\pi^{ \pm}, \pi^{0}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=$ (left) 200 and (right) 62.4 GeV at midrapidity for (upper) positive and (lower) negative hadrons. Only statistical uncertainties are shown. The references for STAR data are $\pi^{ \pm}, p$, and $\bar{p}$ [33] and $K_{s}^{0}$, $\Lambda$, and $\bar{\Lambda}$ [31]. The references for ISR data are $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ [13] and $\Lambda$ and $\bar{\Lambda}$ [25].


FIG. 7. (Color online) Scaled transverse mass distributions for $\pi^{ \pm}, \pi^{0}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=$ (upper) 200 and (lower) 62.4 GeV at midrapidity for (upper left) positive, (upper right) negative, and (lower) $\pm$ hadrons. Only statistical uncertainties are shown. (Upper) The STAR spectra for $K_{s}^{0}, \Lambda, \bar{\Lambda}$ are from [31]. (Lower) The ISR spectra for $\Lambda, \bar{\Lambda}$ are from [25]. Arbitrary scaling factors are applied to match the yield of other particles to that of charged pions in the range of $m_{T}=1.0-1.5 \mathrm{GeV} / c^{2}$. The lower panels of each plot show the ratio to the $\pi^{0}$ Tsallis fit [52].
obtained by using Eq. (10) for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and 62.4 GeV $p+p$ collisions, are tabulated in Table V. The fitting range is fixed as $m_{T}-m=0.3-1.0 \mathrm{GeV} / c^{2}$ for all particle species at both collision energies. We obtain smaller $\chi^{2} / \mathrm{NDF}$ for protons and antiprotons than those for pions and kaons, because of the larger systematic uncertainties for $p$ and $\bar{p}$ at low $p_{T}$ due to the uncertainties of weak decay feed-down corrections. As seen in Fig. 8 the spectra are exponential in the low- $\left(m_{T}-m\right)$ range. At higher transverse mass, the spectra become less steep, corresponding to an emerging power law behavior. The transition from exponential to power law can be seen at $m_{T}-m=1-2 \mathrm{GeV} / c^{2}$ for all particle species.

The dependence of $T_{\text {inv }}$ on hadron mass is shown in Fig. 9. These slope parameters are almost independent of the energy of $\sqrt{s}=62.4$ and 200 GeV . The inverse slope parameter of kaons is similar to that of protons while the slope parameter of pions has slightly smaller values. It may be possible that the lower $T_{\text {inv }}$ values for pions are due to pions from resonance decays (e.g., $\rho, \Lambda$ ), although such an effect is reduced by the lower transverse momentum cut. An alternative explanation is that hydrodynamical collective behavior may develop even in the small $p+p$ system, which we explore in Sec. V A.

In Fig. 10, the collision energy dependence of $T_{\text {inv }}$ is shown by compiling results from past experiments [24,33,53-56]. The values of $T_{\text {inv }}$ reported here are obtained by fitting all the $p_{T}$ spectra in the same way. The fitting range is $m_{T}-m=$ $0.3-1.0 \mathrm{GeV} / c^{2}$ for all particle species in all collision systems. The $T_{\text {inv }}$ values for RHIC energies are consistent with earlier experimental results at other energies [24,53-56]. For both pions and kaons, the inverse slope parameters increase with collision energy from $T_{\text {inv }}=120 \mathrm{MeV} / c^{2}$ to $170 \mathrm{MeV} / c^{2}$ ( $240 \mathrm{MeV} / c^{2}$ ) for pions (kaons) up to $\sqrt{s}=200 \mathrm{GeV}$. According to Tevatron data, $T_{\text {inv }}$ seems to be saturated at $\sqrt{s}$ above 200 GeV . The inverse slope parameters of protons and antiprotons indicate an increase at lower $\sqrt{s}$ which keeps on increasing even at Tevatron energies. We look forward to data from the Large Hadron Collider to further clarify these issues.

## D. Particle ratios

Figures 11 and 12 show particle ratios such as antiparticle-to-particle, $K / \pi$, and $p / \pi$ as a function of $p_{T}$. The STAR data are from [57] and the ISR data are from [24]. The $\pi^{-} / \pi^{+}$ and $K^{-} / K^{+}$ratios show a flat $p_{T}$ dependence at both 200


FIG. 8. (Color online) $m_{T}-m$ spectra for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=$ (upper) 200 and (lower) 62.4 GeV at midrapidity. Only statistical uncertainties are shown. Each spectrum is fitted with the exponential form of Eq. (10) in the range of $m_{T}-m$ $=0.3-1.0 \mathrm{GeV} / c^{2}$. Solid lines represent the functions in the fitted range; dashed lines show the extrapolation of these functions beyond this range. (Lower panels) Ratio of the exponential fit to data for each particle species.
and 62.4 GeV energies. The $\pi^{-} / \pi^{+}$ratio is almost unity at both energies. The $K^{-} / K^{+}$ratio is consistent with unity at $\sqrt{s}=200 \mathrm{GeV}$, while it decreases to $0.8-0.9$ in the measured $p_{T}$ range at 62.4 GeV . On the other hand, the $\bar{p} / p$ ratio seems to be a decreasing function of $p_{T}$ at 200 GeV , from the value of $\approx 0.8$ at $p_{T}=1.0 \mathrm{GeV} / c$ to 0.6 at $p_{T}=4.5 \mathrm{GeV} / c$. Note that we fitted the $\bar{p} / p$ ratio for $200 \mathrm{GeV} p+p$ from $p_{T}=1-4.5 \mathrm{GeV} / c$ to a linear function, $a+b p_{T}$, which gives $a=0.93 \pm 0.02$ and $b=-0.07 \pm 0.01$. This decrease, also seen at lower $\sqrt{s}$ [24], might be the result of a difference of fragmentation between quark jet and gluon jet in the high- $p_{T}$ region as suggested by the DSS fragmentation functions [51]. However, the NLO pQCD calculation $[38,39]$ using the DSS fragmentation functions (lines on the panels for $\bar{p} / p$ ratios) shows that this effect is in disagreement with the measured $\bar{p} / p$ ratios. At 62.4 GeV , we cannot draw conclusions about the significance of the decrease of the $\bar{p} / p$ ratios as a function

TABLE V. Fitting results for $A, T_{\text {inv }}$ of Eq. (10) for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in 200 and $62.4 \mathrm{GeV} p+p$ collisions. The fitting range is fixed as $m_{T}-m=0.3-1.0 \mathrm{GeV} / c^{2}$ for all particle species at both collision energies.

| $\sqrt{s}$ <br> $(\mathrm{GeV})$ | Hadron | $A$ | $T_{\text {inv }}$ <br> $\left(\mathrm{GeV} / c^{2}\right)$ | $\chi^{2} / \mathrm{NDF}$ |
| :--- | :---: | :---: | :---: | :---: |
| 200 | $\pi^{+}$ | $73.4 \pm 7.1$ | $0.190 \pm 0.005$ | $5.6 / 5$ |
|  | $\pi^{-}$ | $74.8 \pm 7.2$ | $0.189 \pm 0.005$ | $3.1 / 5$ |
|  | $K^{+}$ | $3.25 \pm 0.29$ | $0.232 \pm 0.007$ | $3.6 / 6$ |
|  | $K^{-}$ | $2.99 \pm 0.27$ | $0.239 \pm 0.008$ | $3.6 / 6$ |
|  | $p$ | $0.85 \pm 0.14$ | $0.245 \pm 0.014$ | $1.0 / 7$ |
|  | $\bar{p}$ | $0.74 \pm 0.13$ | $0.241 \pm 0.014$ | $0.5 / 7$ |
| 62.4 | $\pi^{+}$ | $61.7 \pm 5.9$ | $0.182 \pm 0.005$ | $3.1 / 5$ |
|  | $\pi^{-}$ | $65.2 \pm 5.3$ | $0.179 \pm 0.004$ | $4.7 / 5$ |
|  | $K^{+}$ | $2.44 \pm 0.22$ | $0.219 \pm 0.007$ | $2.6 / 6$ |
|  | $K^{-}$ | $2.21 \pm 0.20$ | $0.213 \pm 0.006$ | $4.6 / 6$ |
|  | $p$ | $0.81 \pm 0.10$ | $0.227 \pm 0.010$ | $1.1 / 7$ |
|  | $\bar{p}$ | $0.49 \pm 0.07$ | $0.221 \pm 0.010$ | $0.3 / 7$ |

of $p_{T}$ due to large statistical fluctuations. It is important to note the agreement of the ISR measurements of the antiparticle-toparticle ratios as a function of $p_{T}$ at $\sqrt{s}=62.4 \mathrm{GeV}$ (Fig. 11) with the present measurements except for the $\bar{p} / p$ ratio, where there is a large discrepancy. The $\bar{p} / p$ ratio integrated over all $p_{T}$ decreases from 0.8 at 200 GeV to 0.5 at 62.4 GeV (see further discussion in Sec. IVE). At low $p_{T}$, the large systematic uncertainties of the $\bar{p} / p$ ratio are due to the uncertainties of the weak decay feed-down corrections.

Figure 12 presents the ratios of $K^{+} / \pi^{+}, K^{-} / \pi^{-}, p / \pi^{+}$, $p / \pi^{0}, \bar{p} / \pi^{-}$, and $\bar{p} / \pi^{0}$ as a function of $p_{T}$. Both the $K^{+} / \pi^{+}$ and the $K^{-} / \pi^{-}$ratios increase with increasing $p_{T}$ up to the $p_{T}=2 \mathrm{GeV} / c$ limit of the measurement. Both the $p / \pi^{0}$ and the $\bar{p} / \pi^{0}$ ratios seem to increase with $p_{T}$ for $p_{T}>2 \mathrm{GeV} / c$, although the $\bar{p} / \pi^{0}$ ratio is relatively flat at $\sqrt{s}=200 \mathrm{GeV}$ in the same transverse momentum region. Clearly, better statistics are required to reach a firm conclusion. As a function of $\sqrt{s}$ the $K^{+} / \pi^{+}, \bar{p} / \pi^{-}$, and $\bar{p} / \pi^{0}$ ratios do not change significantly, while the $K^{-} / \pi^{-}$ratio increases and the $p / \pi^{+}$and $p / \pi^{0}$ ratios decrease significantly for $p_{T}>1 \mathrm{GeV} / c$ as the collision energy is increased from $\sqrt{s}=62.4$ to 200 GeV .


FIG. 9. Inverse slope parameter $T_{\text {inv }}$ for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV . The fitting range is $m_{T}-m=0.3-1.0 \mathrm{GeV} / c^{2}$ for all particle species at both collision energies. The errors are statistical and systematic combined. The statistical errors are negligible.


FIG. 10. (Color online) Inverse slope parameter $T_{\text {inv }}$ for $\pi^{+}+\pi^{-}, K^{+}+K^{-}, p$, and $\bar{p}$ in $p+p$ and $p+\bar{p}$ collisions versus collision energy $\sqrt{s}$. The fitting range is $m_{T}-m=0.3-1.0 \mathrm{GeV} / c^{2}$ for all particle species for all collision systems. The errors are statistical and systematic combined. The statistical errors are negligible. The other experimental data are taken from [24,33,53-56].


FIG. 11. (Color online) $\pi^{-} / \pi^{+}, K^{-} / K^{+}$, and $\bar{p} / p$ ratios as a function of $p_{T}$ in $p+p$ collisions at $\sqrt{s}=$ (left) 200 and (right) 62.4 GeV . Systematic uncertainties are shown as vertical shaded band. The STAR data are from [57] and the ISR data are from [24]. For $\bar{p} / p$ ratios, the NLO pQCD calculations using the DSS fragmentation functions $[38,39]$ are also shown as (solid lines) $\mu=p_{T}$ and (dashed lines) $\mu=2 p_{T}, p_{T} / 2$.


FIG. 12. (Color online) (Top) $K^{+} / \pi^{+}$and $K^{-} / \pi^{-}$ratios, (middle) $p / \pi^{+}$, and (bottom) $\bar{p} / \pi^{-}$ratios, and (bottom) $p / \pi^{0}$ and $\bar{p} / \pi^{0}$ ratios as a function of $p_{T}$ in $p+p$ collisions at $\sqrt{s}=(\mathrm{left})$ 200 and (right) 62.4 GeV . Systematic uncertainties are shown as vertical shaded bands.


FIG. 13. Mean transverse momentum $\left\langle p_{T}\right\rangle$ as a function of mass in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV . The errors are statistical and systematic combined. The statistical errors are negligible.

## E. $\left\langle p_{T}\right\rangle$ and $d N / d y$

The mean transverse momentum $\left\langle p_{T}\right\rangle$ and particle yield per unit rapidity $d N / d y$ are determined by integrating the measured $p_{T}$ spectrum for each particle species. For the unmeasured $p_{T}$ region, we fit the measured $p_{T}$ spectrum with a Tsallis function [52] given below, as in a related publication [28], and also with an $m_{T}$ exponential function, and then extrapolate the function obtained to the unmeasured $p_{T}$ region. The $p_{T}$ ranges for fitting are $0.4-3.0 \mathrm{GeV} / c$ for pions, $0.4-2.0 \mathrm{GeV} / c$ for kaons, and $0.5-4.0 \mathrm{GeV} / c$ for protons and antiprotons.

The final yield $d N / d y$ is calculated by taking the sum of the yield from the data and the yield from the functional form in the unmeasured $p_{T}$ region. The total inelastic cross sections are assumed to be 42.0 and 35.6 mb for 200 and 62.4 GeV , respectively. For $\left\langle p_{T}\right\rangle$, we integrate the measured $p_{T}$ spectrum with $p_{T}$ weighting, and then divide it by the obtained $d N / d y$. The final values are obtained by averaging the results of the two fits. The systematic uncertainties are evaluated as half of the difference between these fitting values.
(a) The Tsallis distribution is given by Eq. (11) below. In this fitting form, the free parameters are $d N / d y, q$, and $C$,
while the mass $m$ is fixed to the hadron mass. The fitting results are given in Table VI.

$$
\begin{align*}
\frac{1}{2 \pi p_{T}} \frac{d^{2} N}{d y d p_{T}}= & \frac{d N}{d y} \frac{(q-1)(q-2)}{2 \pi q C[q C+m(q-2)]} \\
& \times\left[1+\frac{m_{T}-m}{q C}\right]^{-q} \tag{11}
\end{align*}
$$

(b) The exponential distribution in $m_{T}$ is given by Eq. (12) below. The free fit parameters are the normalization constant $A$ and the inverse slope parameter $T_{\text {inv }}$.

$$
\begin{gather*}
\frac{1}{2 \pi p_{T}} \frac{d^{2} N}{d y d p_{T}}=A \exp \left(-\frac{m_{T}}{T_{\mathrm{inv}}}\right),  \tag{12}\\
\frac{d N}{d y}=2 \pi A\left(m T_{\mathrm{inv}}+T_{\mathrm{inv}}^{2}\right) . \tag{13}
\end{gather*}
$$

The $\left\langle p_{T}\right\rangle$ values obtained are summarized in Table VII. They are plotted in Fig. 13, which indicates a clear increase of $\left\langle p_{T}\right\rangle$ with hadron mass. The values at 200 GeV are almost the same as those for the 62.4 GeV data. If the spectral shape is a pure exponential, $\left\langle p_{T}\right\rangle$ should be equal to $2 T_{\text {inv }}$ analytically.

TABLE VI. Fitting results from using the Tsallis distribution [Eq. (11)] for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV .

| $\sqrt{s}(\mathrm{GeV})$ | Hadron | $d N / d y$ | $q$ | $C$ | $\chi^{2} / \mathrm{NDF}$ |
| :--- | :---: | :---: | :---: | :---: | :---: |
| 200 | $\pi^{+}$ | $0.963 \pm 0.071$ | $8.24 \pm 0.33$ | $0.115 \pm 0.006$ | $4.3 / 23$ |
|  | $\pi^{-}$ | $0.900 \pm 0.063$ | $8.95 \pm 0.39$ | $0.123 \pm 0.006$ | $3.2 / 23$ |
|  | $K^{+}$ | $0.108 \pm 0.006$ | $6.25 \pm 0.64$ | $0.137 \pm 0.011$ | $1.6 / 13$ |
|  | $K^{-}$ | $0.103 \pm 0.005$ | $7.00 \pm 0.78$ | $0.147 \pm 0.011$ | $2.9 / 13$ |
|  | $p$ | $0.044 \pm 0.004$ | $11.1 \pm 1.6$ | $0.184 \pm 0.014$ | $4.1 / 22$ |
| 62.4 | $\bar{p}$ | $0.037 \pm 0.003$ | $12.0 \pm 1.8$ | $0.186 \pm 0.014$ | $1.3 / 22$ |
|  | $\pi^{+}$ | $0.782 \pm 0.056$ | $12.1 \pm 0.9$ | $0.133 \pm 0.007$ | $4.6 / 22$ |
|  | $\pi^{-}$ | $0.824 \pm 0.053$ | $11.9 \pm 0.7$ | $0.128 \pm 0.006$ | $4.8 / 22$ |
|  | $K^{+}$ | $0.076 \pm 0.003$ | $10.2 \pm 1.8$ | $0.165 \pm 0.012$ | $4.9 / 13$ |
|  | $K^{-}$ | $0.067 \pm 0.003$ | $11.6 \pm 2.1$ | $0.164 \pm 0.011$ | $2.2 / 13$ |
|  | $p$ | $0.040 \pm 0.003$ | $24.5 \pm 9.9$ | $0.201 \pm 0.015$ | $7.1 / 21$ |
|  | $\bar{p}$ | $0.022 \pm 0.002$ | $32.5 \pm 21.0$ | $0.202 \pm 0.018$ | $7.9 / 21$ |



FIG. 14. (Color online) Mean transverse momentum $\left\langle p_{T}\right\rangle$ for $\pi^{+}+\pi^{-}, K^{+}+K^{-}, p$, and $\bar{p}$ as a function of $\sqrt{s}$ in $p+p$ and $p+\bar{p}$ collisions $[24,33,53,54,58]$. The errors are statistical and systematic combined. The statistical errors are negligible.

By comparing Tables V and VII, we see that the measured $\left\langle p_{T}\right\rangle$ is almost $2 T_{\text {inv }}$ for pions. But for kaons and (anti)protons, the measured $\left\langle p_{T}\right\rangle$ is systematically larger than $2 T_{\text {inv }}$. This demonstrates that the spectral shape at low $p_{T}$ is not a pure exponential especially for kaons and (anti)protons.

The collision energy dependence of $\left\langle p_{T}\right\rangle$ for each particle type is shown in Fig. 14. Data shown here are as follows: lowerenergy data [53], ISR data [24], Tevatron data [54,58], and RHIC data from STAR [33] and PHENIX (present study). The $\left\langle p_{T}\right\rangle$ values for all the other experiments have been determined by fitting the $p_{T}$ spectra. For pions, the $\left\langle p_{T}\right\rangle$ shows a linear increase in $\ln (\sqrt{\mathrm{s}})$. For kaons and (anti)protons the increase is much faster than that for pions. However, systematic issues at both lower- and higher-center-of-mass energies remain to be resolved.

Figure 15 shows the dependence of $\left\langle p_{T}\right\rangle$ on the centrality of the collisions (given by the number of participating nucleons, $N_{\text {part }}$ ) for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{N N}}$ $=200 \mathrm{GeV}$ [37] as compared to minimum bias $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$ (present analysis). The error bars in the figure represent the statistical errors. The systematic errors from cut conditions are shown as shaded boxes on the

TABLE VII. Mean transverse momentum $\left(\left\langle p_{T}\right\rangle\right)$ and particle yield $(d N / d y)$ for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV . The errors are statistical and systematic combined, but the statistical errors are negligible.

| $\sqrt{s}$ <br> $(\mathrm{GeV})$ | Hadron | $\left\langle p_{T}\right\rangle$ <br> $(\mathrm{GeV} / c)$ | $d N / d y$ |
| :--- | :---: | :---: | :---: |
| 200 | $\pi^{+}$ | $0.379 \pm 0.021$ | $0.842 \pm 0.127$ |
|  | $\pi^{-}$ | $0.385 \pm 0.014$ | $0.810 \pm 0.096$ |
|  | $K^{+}$ | $0.570 \pm 0.012$ | $0.099 \pm 0.010$ |
|  | $K^{-}$ | $0.573 \pm 0.014$ | $0.096 \pm 0.009$ |
|  | $p$ | $0.696 \pm 0.025$ | $0.043 \pm 0.003$ |
| 62.4 | $\bar{p}$ | $0.698 \pm 0.023$ | $0.035 \pm 0.002$ |
|  | $\pi^{+}$ | $0.373 \pm 0.013$ | $0.722 \pm 0.066$ |
|  | $\pi^{-}$ | $0.366 \pm 0.016$ | $0.750 \pm 0.079$ |
|  | $K^{+}$ | $0.558 \pm 0.012$ | $0.072 \pm 0.004$ |
|  | $K^{-}$ | $0.544 \pm 0.013$ | $0.064 \pm 0.004$ |
|  | $p$ | $0.710 \pm 0.023$ | $0.034 \pm 0.002$ |
|  | $\bar{p}$ | $0.709 \pm 0.040$ | $0.018 \pm 0.001$ |

right for each particle species. The systematic errors from extrapolations, which are scaled by a factor of 2 for clarity, are shown at the bottom for each particle species. It is found that $\left\langle p_{T}\right\rangle$ for all particle species increases from the most peripheral to midcentral collisions, and appears to saturate from the midcentral to central collisions. The $\left\langle p_{T}\right\rangle$ in $p+p$ are consistent with the expectation from the $N_{\text {part }}$ dependence in $\mathrm{Au}+\mathrm{Au}$, and are similar to the values in peripheral $\mathrm{Au}+\mathrm{Au}$.

The $d N / d y$ values at midrapidity are summarized in Table VII. They are plotted in Fig. 16 as a function of hadron mass for both 200 and 62.4 GeV collision energies. There are differences in the yield between 200 and 62.4 GeV especially for kaons and antiprotons, continuing the trend observed at lower $\sqrt{s}$ [24]. It is interesting to note that even in the situation


FIG. 15. (Color online) Mean transverse momentum as a function of centrality ( $N_{\text {part }}$ ) for pions, kaons, protons, and antiprotons at $\sqrt{s_{N N}}$ $=200 \mathrm{GeV}$ in the present $p+p$ analysis (lowest $N_{\text {part }}$ points, red) and previous $\mathrm{Au}+\mathrm{Au}$ [37] analysis (all higher $N_{\text {part }}$ points, black). The left (right) panel shows the $\left\langle p_{T}\right\rangle$ for positive (negative) particles. The error bars are statistical errors. The systematic errors from cut conditions are shown as shaded boxes on the right for each particle species. The systematic errors from extrapolations, which are scaled by a factor of 2 for clarity, are shown in the bottom for protons and antiprotons (dash-dotted lines), kaons (dotted lines), and pions (dashed lines).


FIG. 16. Particle yield $d N / d y$ as a function of mass in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV . The errors are statistical and systematic combined. The statistical errors are negligible.
that $d N / d y$ is different between $\sqrt{s}=200$ and $62.4 \mathrm{GeV},\left\langle p_{T}\right\rangle$ is quite similar for both energies.

Figure 17 shows $d N / d y$ as a function of collision energy for each particle species. Our results on $d N / d y$ are consistent with those at ISR energies [24]. It should be noted that STAR quotes the nonsingle diffractive (NSD) multiplicity while our measurement quotes the inelastic multiplicity, normalizing the integrated measured inclusive cross section by the total inelastic cross section [59]. At $\sqrt{s}=200 \mathrm{GeV}$, the inelastic cross section ( $\sigma^{\text {inel }}$ ) is 42 mb [60], and the single diffractive (SD) cross section is almost equal to the double diffractive (DD) cross section, $\sigma_{N N}^{\mathrm{SD}} \approx \sigma_{N N}^{\mathrm{DD}} \approx 4 \mathrm{mb}$ [61]. As the single diffractive cross section refers only to the projectile proton in a $p+p$ fixed target measurement, one has to subtract the SD cross section for each proton from the inelastic cross section to


FIG. 17. (Color online) (Upper) Particle yield $d N / d y$ at midrapidity for $\left(\pi^{+}+\pi^{-}\right) / 2$ and $\left(K^{+}+K^{-}\right) / 2$ as a function of $\sqrt{s}$ in $p+p$ collisions [24,29]. The errors are statistical and systematic combined, but the statistical errors are negligible. The $d N / d y$ from STAR is determined for NSD $p+p$ events. (Lower) Similar plots for $p$ and $\bar{p}$ with feed-down correction applied to our data. The $d N / d y$ from STAR is determined for NSD $p+p$ events, and is not corrected for weak decay feed-down.


FIG. 18. (Color online) Particle yield per unit rapidity $(d N / d y)$ per participant pair $\left(0.5 N_{\text {part }}\right)$ at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ as a function of $N_{\text {part }}$ for pions, kaons, protons, and antiprotons in the present $p+p$ analysis (lowest $N_{\text {part }}$ points, red) and previous $\mathrm{Au}+\mathrm{Au}$ [37] analysis (all higher $N_{\text {part }}$ points, black). The left (right) panel shows the $d N / d y$ for positive (negative) particles. The error bars represent the quadratic sum of statistical errors and systematic errors from cut conditions. The lines represent the effect of the systematic error on $N_{\text {part }}$, which affects all curves in the same way.
determine the NSD cross section [62]. The resulting NSD cross section ( $\sigma^{\mathrm{NSD}}$ ) should be $42-2 \times 4 \mathrm{mb}=34 \mathrm{mb}$. The ratio of the NSD multiplicity to the inelastic multiplicity is $\sigma^{\text {inel }} / \sigma^{\text {NSD }}$ $=42 / 34=1.24$, i.e., the NSD multiplicity is $24 \%$ higher than the inelastic multiplicity, and this effect can actually be seen in the experimental data [63].

We would like to point out also that the NSD charged particle multiplicity at $\sqrt{s}=200 \mathrm{GeV}$ by STAR is $\approx 20 \%$ larger than other NSD results [63]. By taking this fact and the difference between NSD and inelastic cross sections into account, one can understand the $\approx 50 \%$ difference in yields between STAR and the present analysis, for pions and kaons, as shown in Fig. 17. For protons and antiprotons the difference between STAR and the present analysis is larger than those in pions and kaons. In addition to the effects we have mentioned above, the weak decay feed-down correction can contribute to it, since we remove $p$ and $\bar{p}$ from the weak decay (see Sec. III D), while STAR does not.

Figure 18 shows the collision centrality dependence of $d N / d y$ per participant pair $\left(0.5 N_{\text {part }}\right)$ in $p+p$ (present analysis) and $\mathrm{Au}+\mathrm{Au}$ [37] collisions at $\sqrt{s_{N N}}=200 \mathrm{GeV}$. The error bars on each point represent the quadratic sum of the statistical errors and systematic errors from cut conditions. The statistical errors are negligible. The lines represent the effect of the systematic error on $N_{\text {part }}$, which affects all curves in the same way. The data indicate that $d N / d y$ per participant pair increases for all particle species with $N_{\text {part }}$ up to $\approx 100$, and saturates from the midcentral to the most central collisions. As seen in Fig. 15 for $\left\langle p_{T}\right\rangle$, the $d N / d y$ values in $p+p$ are consistent with the expectation from the $N_{\text {part }}$ dependence in $\mathrm{Au}+\mathrm{Au}$.

TABLE VIII. Inverse slope parameter $T_{\text {inv }}$ for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ for $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV . The fit ranges are $0.2-1.0 \mathrm{GeV} / c^{2}$ for pions and $0.1-1.0 \mathrm{GeV} / c^{2}$ for kaons, protons, and antiprotons in $m_{T}-m$. These fit ranges are chosen in order to perform a comparison with $T_{\text {inv }}$ in $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC [37]. The errors are statistical and systematic combined, but the statistical errors are negligible.
\(\left.$$
\begin{array}{lccc}\hline \hline \begin{array}{l}\sqrt{s} \\
(\mathrm{GeV})\end{array}
$$ \& Hadron \& \begin{array}{c}T_{inv} <br>

\left(\mathrm{MeV} / c^{2}\right)\end{array} \& \chi^{2} / \mathrm{NDF}\end{array}\right]\)|  |  |  |  |
| :--- | :---: | :---: | :---: |
| 200 | $\pi^{+}$ | $183 \pm 4$ | $12.9 / 6$ |
|  | $\pi^{-}$ | $184 \pm 4$ | $7.5 / 6$ |
|  | $K^{+}$ | $221 \pm 5$ | $10.0 / 8$ |
|  | $K^{-}$ | $225 \pm 6$ | $12.4 / 8$ |
| 62.4 | $p$ | $236 \pm 10$ | $2.3 / 10$ |
|  | $\bar{p}$ | $235 \pm 10$ | $1.2 / 10$ |
|  | $\pi^{+}$ | $178 \pm 4$ | $5.7 / 6$ |
|  | $\pi^{-}$ | $174 \pm 3$ | $9.8 / 6$ |
|  | $K^{+}$ | $216 \pm 5$ | $3.0 / 8$ |
|  | $K^{-}$ | $209 \pm 5$ | $5.3 / 8$ |
|  | $p$ | $230 \pm 8$ | $1.4 / 9$ |
|  | $\bar{p}$ | $225 \pm 9$ | $2.0 / 9$ |

## F. Nuclear modification factor $\boldsymbol{R}_{A A}$

In order to quantify the modification effect in nucleusnucleus $(A+A)$ collisions with respect to nucleon-nucleon collisions, the nuclear modification factor $R_{A A}$ is used. $R_{A A}$ is the ratio between the yield in $A+A$ scaled by the average number of binary nucleon-nucleon collisions ( $\left\langle N_{\text {coll }}\right\rangle$ ) and the yield in $p+p$, as defined by the following equation:

$$
\begin{equation*}
R_{A A}\left(p_{T}\right)=\frac{\left(1 / N_{A A}^{\mathrm{evt}}\right) \mathrm{d}^{2} N_{A A} / d p_{T} d y}{\left\langle T_{A A}\right\rangle \times d^{2} \sigma_{p p} / d p_{T} d y} \tag{14}
\end{equation*}
$$

where $\left\langle T_{A A}\right\rangle$ is the nuclear thickness function, defined as follows: $\left\langle T_{A A}\right\rangle=\left\langle N_{\text {coll }}\right\rangle / \sigma_{p p}^{\text {inel }}$. For the total $A+A$ interaction cross section $\sigma_{A A}^{\mathrm{int}}$ (minimum bias $A+A$ collisions), $\left\langle T_{A A}\right\rangle=$ $A^{2} / \sigma_{A A}^{\mathrm{int}}$.

In general, $R_{A A}$ is expressed as a function of $p_{T}$ and collision centrality for $A+A$ collisions. Due to the dominance of hard scatterings of partons at high $p_{T}, R_{A A}$ is expected to be around unity above $p_{T} \approx 2 \mathrm{GeV} / c$, if there is no yield modification by the nucleus in $A+A$. If there is a suppression (enhancement), $R_{A A}$ is less than (greater than) unity. For the total $A+A$ interaction cross section at a given $p_{T}$ integrated over centrality (minimum bias $A+A$ collisions) $\sigma_{A A}\left(p_{T}\right)=A^{2} \sigma_{p p}\left(p_{T}\right)$ and $R_{A A}\left(p_{T}\right) \equiv 1.0$.

Figure 19 shows the $R_{A A}$ of $\pi^{ \pm}, \pi^{0}, K^{ \pm}, p$, and $\bar{p}$ in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ at $0 \%-5 \%$ collision centrality. The data for identified charged hadrons in $\mathrm{Au}+\mathrm{Au}$ at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ are taken from [37] measured by the PHENIX experiment, and those for $p+p$ are taken from the present analysis at $\sqrt{s}=200 \mathrm{GeV}$. The $R_{A A}$ for neutral pions is taken from [64]. The overall normalization uncertainty on $R_{A A}(13.8 \%)$ is shown as a shaded box around unity (at $p_{T}=$ $0.1 \mathrm{GeV} / c)$; it is the quadratic sum of (1) the uncertainty of the $p+p$ inelastic cross section (9.7\%) and (2) the uncertainty $\left\langle N_{\text {coll }}\right\rangle(9.9 \%)$.


FIG. 19. (Color online) $R_{A A}$ of $\pi^{ \pm}, \pi^{0}, K^{ \pm}, p$, and $\bar{p}$ in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ at $0 \%-5 \%$ collision centrality. The data for identified charged hadrons in $\mathrm{Au}+\mathrm{Au}$ at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ are taken from [37] and those for $p+p$ from the present analysis at $\sqrt{s}=200 \mathrm{GeV}$. The neutral pion data (PHENIX) are taken from [64]. The statistical uncertainties are shown as bars and the systematic uncertainties are shown as shaded boxes on each data point. The overall normalization uncertainty on $R_{A A}(13.8 \%)$ is shown in the shaded box around unity (at $p_{T}=0.1 \mathrm{GeV} / c$ ), which is the quadratic sum of (1) the uncertainty of $p+p$ inelastic cross sections ( $9.7 \%$ ) and (2) the uncertainty $\left\langle N_{\text {coll }}\right\rangle(9.9 \%)$.

For pions $R_{A A}$ is greatly suppressed by a factor of $\approx 5$, compared to $p+p$. This suppression effect is understood to be due to jet quenching or energy loss of partons in the hot and dense medium created in $\mathrm{Au}+\mathrm{Au}$ central collisions at RHIC energies $[65,66]$. For kaons there is a similar trend as for pions over a more limited $p_{T}$ range. For protons and antiprotons there is an enhancement in $p_{T}=2-4 \mathrm{GeV} / c$. As reported in [26,37,67], possible explanations of the observed enhancements include the quark recombination model [68-70] and/or strong partonic and hadronic radial flow [71].

## V. DISCUSSION

In this section, we discuss (1) soft particle production at low $p_{T}$, including the possibility of radial flow in $p+p$ collisions, and (2) the transition from the soft to the hard process, and hadron fragmentation at high $p_{T}$, where we show the $x_{T}$ scaling of measured spectra, and make a comparison with NLO $[38,39]$ and NLL $[40,41]$ pQCD calculations.

## A. Radial flow

In heavy ion collisions at RHIC energies, it is found that the inverse slope parameter ( $T_{\text {inv }}$ ) of $m_{T}-m$ spectra has a clear dependence on the hadron mass, i.e., heavier particles have larger inverse slope parameters [37,72]. $T_{\text {inv }}$ increases almost linearly as a function of particle mass; $T_{\text {inv }}$ is largest when the nucleus-nucleus collision has a small impact parameter (central collisions). Also, $T_{\text {inv }}$ is smallest for the collisions with a large impact parameter (peripheral collisions), as shown in


FIG. 20. (Color online) Mass dependence of inverse slope parameter $T_{\text {inv }}$ in $m_{T}-m$ spectra for (left) positive and (right) negative hadrons in $p+p$ collisions at $\sqrt{s}=200$ and 62.4 GeV , as well as for peripheral, midcentral, and central $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{N N}}=200$ GeV [37]. The errors are statistical and systematic combined, smaller than the symbols. The statistical errors are negligible. The fit ranges are $0.2-1.0 \mathrm{GeV} / c^{2}$ for pions and $0.1-1.0 \mathrm{GeV} / c^{2}$ for kaons, protons, and antiprotons in $m_{T}-m$ [37]. The dotted lines represent a linear fit of the results for each data set as a function of mass using Eq. (15).

Fig. 20.This experimental observation can be interpreted as the existence of a radial flow generated by violent nucleon-nucleon collisions in two colliding nuclei and developed both in the quark-gluon plasma phase and in hadronic rescatterings [71]. The radial flow velocity increases the transverse momentum of particles proportional to their mass; thus $T_{\text {inv }}$ increases linearly as a function of particle mass. It is interesting to determine whether or not such an expansion is observed in high-energy $p+p$ collisions [58].

Figure 20 shows the mass dependence of the inverse slope parameter $T_{\text {inv }}$ in $m_{T}-m$ spectra for positive (left) and negative (right) particles in $p+p$ collisions at $\sqrt{s}=$ 200 and 62.4 GeV (also shown in Fig. 9) as well as for peripheral, midcentral, and central $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{N N}}=200 \mathrm{GeV}$ [37]. The fit ranges are $m_{T}-$ $m=0.2-1.0 \mathrm{GeV} / c^{2}$ for pions, and $m_{T}-m=0.1-$ $1.0 \mathrm{GeV} / c^{2}$ for kaons, protons, and antiprotons, which are chosen in order to perform a fair comparison with $T_{\text {inv }}$ in $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC [37]. The values of $T_{\text {inv }}$ in $p+p$ for these fit ranges (see Table VIII) are all lower by roughly one standard deviation than the values in Table V for the common fit range of $m_{T}-m=$ $0.3-1.0 \mathrm{GeV} / c^{2}$.

In general, the inverse slope parameters increase with increasing particle mass in both $\mathrm{Au}+\mathrm{Au}$ and $p+p$ collisions at 200 GeV . However, this increase is only modest in $p+p$ collisions and slightly weaker than in $60 \%-92 \%$ central $\mathrm{Au}+\mathrm{Au}$ collisions at 200 GeV .

Also note that there is a mean multiplicity dependence of the transverse momentum spectra in $p+p$ collisions [54] that is not discussed in the present paper.

We use a radial flow picture [73,74] with the fitting function

$$
\begin{equation*}
T=T_{0}+m\left\langle u_{t}\right\rangle^{2}, \tag{15}
\end{equation*}
$$

where $T_{0}$ is a hadron freeze-out temperature and $\left\langle u_{t}\right\rangle$ is a measure of the strength of the (average radial) transverse flow. The relationship between the averaged transverse velocity
$\left(\left\langle\beta_{t}\right\rangle\right)$ and $\left\langle u_{t}\right\rangle$ is given by

$$
\begin{equation*}
\left\langle\beta_{t}\right\rangle=\left\langle u_{t}\right\rangle / \sqrt{1+\left\langle u_{t}\right\rangle^{2}} \tag{16}
\end{equation*}
$$

The dotted lines in Fig. 20 represent the linear fit to the $p+$ $p$ collisions at $\sqrt{s}=200$ and 62.4 GeV which are compared to those in $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{\mathrm{s}_{\mathrm{NN}}}=200 \mathrm{GeV}$ in three different collision centrality classes. The fit results in $p+p$ are also given in Table IX. For the $\mathrm{Au}+\mathrm{Au}$ most central data $(0 \%-5 \%),\left\langle u_{t}\right\rangle \approx 0.49 \pm 0.07$, while in $p+p,\left\langle u_{t}\right\rangle \approx$ 0.28 at both 62.4 and 200 GeV . While this radial flow model is consistent with the data in central and midcentral $\mathrm{Au}+$ Au , i.e., the $\pi / K / p$ points are on a straight line, it does not give a good description of either peripheral $\mathrm{Au}+\mathrm{Au}$ or $p+$ $p$ collisions (poor $\chi^{2}$ in Table IX). Also the data from the STAR experiment [29] show that the transverse flow velocity $\langle\beta\rangle$ extracted by the blast wave model fitting [73] in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}(0.244 \pm 0.081)$ is smaller than those in central and midcentral $\mathrm{Au}+\mathrm{Au}$ collisions at the same energy $[\approx 0.6$ in $\mathrm{Au}+\mathrm{Au}$ at $\sqrt{s}=200 \mathrm{GeV}(0 \%-5 \%)]$. These observations provide evidence for the absence of radial flow in $p+p$ collisions, where the $\pi / K / p$ points are obviously not on a straight line (Fig. 9), and that the radial flow develops only for a larger system.

TABLE IX. The extracted fit parameters of the freeze-out temperature $\left(T_{0}\right)$ and the measure of the strength of the average radial transverse flow ( $\left.\left\langle u_{t}\right\rangle\right)$ using Eq. (15). The fit results shown here are for positive and negative particles, and for the two different energies.

| $\sqrt{s}$ <br> $(\mathrm{GeV})$ | $\pm$ | $T_{0}$ <br> $\left(\mathrm{MeV} / c^{2}\right)$ | $\left\langle u_{t}\right\rangle$ | $\chi^{2} / \mathrm{NDF}$ |
| :--- | :---: | :---: | :---: | :---: |
| 200 | Positive | $175 \pm 5$ | $0.28 \pm 0.02$ | $4.1 / 1$ |
|  | Negative | $176 \pm 5$ | $0.28 \pm 0.02$ | $6.0 / 1$ |
| 62.4 | Positive | $170 \pm 5$ | $0.27 \pm 0.02$ | $5.4 / 1$ |
|  | Negative | $165 \pm 4$ | $0.28 \pm 0.02$ | $3.8 / 1$ |



FIG. 21. (Color online) (Upper left) $x_{T}$ scaling power $n_{\text {eff }}$ as determined from the ratios of yields as a function of $x_{T}$, for (open circles) neutral pions, (open squares) protons, and (open triangles) antiprotons using $p+p$ data at $\sqrt{s}=200$ and 62.4 GeV energies. The error of each data point is from the systematic and statistical errors of $p_{T}$ spectra. The other plots show $x_{T}$ spectra for (lower left) pions ( $\pi^{ \pm}, \pi^{0}$ ), (upper right) protons, and (lower right) antiprotons in $p+p$ collisions at different $\sqrt{s}$ at midrapidity. Only statistical uncertainties are shown. The dashed curves are the fitting results.

## B. $x_{T}$ scaling

From the measurements of $p_{T}$ spectra of hadrons in $p+p$ collisions, it is known that fragmentation of hard scattered partons is the dominant production mechanism of high- $p_{T}$ hadrons. It has been predicted theoretically from general principles that such a production mechanism leads to a data scaling behavior called " $x_{T}$ scaling" [36], where the scaling variable is defined as $x_{T}=2 p_{T} / \sqrt{s}$. Such a data scaling behavior was seen first on preliminary ISR data at CERN as reported in [36].

In the kinematic range corresponding to the $x_{T}$ scaling limit, the invariant cross section near midrapidity can be written as

$$
\begin{equation*}
E \frac{d^{3} \sigma}{d p^{3}}=\frac{1}{p_{T}^{n_{\mathrm{eff}}}} F\left(x_{T}\right)=\frac{1}{\sqrt{s}^{n_{\mathrm{eff}}}} G\left(x_{T}\right) \tag{17}
\end{equation*}
$$

where $F\left(x_{T}\right)$ and $G\left(x_{T}\right)$ are universal scaling functions. The parameter $n_{\text {eff }}$ is characteristic for the type of interaction between constituent partons. For example, for single-photon or vector gluon exchange, $n_{\text {eff }}=4$ [1]. Because of higherorder effects, the running of the strong coupling constant $\alpha_{s}=\alpha_{s}\left(Q^{2}\right)$, the evolution of the parton distribution functions
and fragmentation functions, and nonvanishing transverse momentum $k_{T}$ of the initial state, $n_{\text {eff }}$ in general is not a constant but a function of $x_{T}$ and $\sqrt{s}$, i.e., $n_{\text {eff }}=\mathrm{n}_{\text {eff }}\left(x_{T}, \sqrt{s}\right)$. This $n_{\text {eff }}$ corresponds to the logarithmic variation of yield ratios at the same $x_{T}$ for different $\sqrt{s}$ [75]. Note that the $x_{T}$ scaling power $n_{\text {eff }}$ is different from the exponent $n$ that characterizes the power-law behavior of the single-particle invariant spectrum at high $p_{T}$.

The value of $n_{\text {eff }}$ depends on both the value of $\sqrt{s}$ and the range of $x_{T}$ and, depending on the reaction, tends to settle at an asymptotic value between 6 and 4.5 where hard scattering dominates and higher-twist effects are small. This fact can also be used to determine the transition between soft and hard particle production mechanisms.

Earlier measurements of $n_{\text {eff }}\left(x_{T}, \sqrt{s}\right)$ in $p+p$ collisions found values in the range of $5-8$ [35,36,76-79]. Here we present the PHENIX results for the $x_{T}$ scaling of pions, protons, and antiprotons and compare them with earlier data measured at various different values of $\sqrt{s}$. Due to the limited $p_{T}$ range of our kaon measurements, kaons are not included in these comparisons.

TABLE X. Summary of $x_{T}$ scaling power $n_{\text {eff }}$ in $p+p$ collisions. The errors are systematic error from the fitting.

| Hadron | $A$ | $n_{\text {eff }}$ | $m$ | $\chi^{2} / \mathrm{NDF}$ |
| :--- | :---: | :---: | :---: | :---: |
| $\pi$ | $0.82 \pm 0.08$ | $6.35 \pm 0.23$ | $8.16 \pm 0.22$ | $156 / 31$ |
| $p$ | $1.12 \pm 0.17$ | $6.52 \pm 0.59$ | $7.41 \pm 0.29$ | $40 / 38$ |
| $\bar{p}$ | $0.84 \pm 0.04$ | $6.15 \pm 0.05$ | $7.26 \pm 0.07$ | $30 / 38$ |

We have evaluated the $x_{T}$ scaling power $n_{\text {eff }}$ using two different methods that are both based on Eq. (17):

Method 1 is based on the linear variation of the logarithm of the ratio of the yields at different $\sqrt{s}$ :

$$
\begin{equation*}
n_{\mathrm{eff}}\left(x_{T}\right)=\frac{\log \left[\operatorname{yield}\left(x_{T}, 62.4\right) / \operatorname{yield}\left(x_{T}, 200\right)\right]}{\log (200 / 62.4)} \tag{18}
\end{equation*}
$$

The $n_{\text {eff }}\left(x_{T}\right)$ is shown in Fig. 21 as a function of $x_{T}$ for neutral pions, protons, and antiprotons for $p+p$ collisions at RHIC.

Method 2 is based on fitting the $x_{T}$ distributions for a given type of particle measured at different energies. A common fitting function is defined as follows:

$$
\begin{equation*}
E \frac{d^{3} \sigma}{d p^{3}}=\left(\frac{A}{\sqrt{s}}\right)^{n_{\mathrm{eff}}} x_{T}^{-m} \tag{19}
\end{equation*}
$$

limiting the fitting region to the high-transverse-momentum region ( $p_{T}>2 \mathrm{GeV} / c$ ).

The $x_{T}$ distributions for pions, protons, and antiprotons are shown in Fig. 21. PHENIX data are presented together with earlier data of $[24,30,34,80]$. Dashed curves show the fitting results. The obtained $n_{\text {eff }}$ values are summarized in Table X.

The exponent $n_{\text {eff }}$ of the $x_{T}$ scaling is found to have similar values for different particles, in the range of 6.3-6.5 for pions, protons, and antiprotons. The data points deviate from the $x_{T}$ scaling in the transverse momentum region of $p_{T}<2 \mathrm{GeV} / c$. This scaling violation may be interpreted as a transition from hard to soft multiparticle production. For the highest $x_{T}$ points for protons and antiprotons (but not for pions) the asymptotic $x_{T}$ curve gets steeper. Further measurements at larger $x_{T}$, possibly at lower center-of-mass energies, are needed to clarify this point.

## C. Comparison to NLO and NLL pQCD calculations

In Figs. 22 and 23, our results for pion, proton, and antiproton $p_{T}$ spectra at $\sqrt{s}=200$ and 62.4 GeV in $p+p$ collisions are compared to the NLO pQCD calculations $[38,39]$. Because of the limited $p_{T}$ reach in the measurements, the results for charged kaons are not compared to the NLO pQCD calculations. In these NLO pQCD calculations for $\eta<1$ from Vogelsang [51], the cross section is factorized into initial parton distribution functions (PDFs) in the colliding protons, short-distance partonic hard scattering cross sections which can be evaluated using perturbative QCD, and parton-to-hadron fragmentation functions (FFs).


FIG. 22. (Color online) Transverse momentum distributions for (upper) positive and (lower) negative particles at $\sqrt{s}=200 \mathrm{GeV}$ in $p+p$ collisions. Only statistical uncertainties are shown. The normalization uncertainty ( $9.7 \%$ ) is not included. NLO pQCD calculations $[38,39]$ (DSS fragmentation functions) are also shown. Solid lines are for $\mu=p_{T}$, and dashed lines are for $\mu=p_{T} / 2,2 p_{T}$. The lower panel in each plot shows the ratio of (data -pQCD result)/pQCD result for each particle species.

For the description of the initial parton distributions, the Coordinated Theoretical-Experimental Project on QCD (CTEQ6M5) [81] PDFs are used. Different scales $\mu=$ $p_{T} / 2, p_{T}, 2 p_{T}$ are utilized, which represent factorization, renormalization, and fragmentation scales. These provide initial conditions for the pQCD cross section calculations. Partons are then fragmented to hadrons with the help of the de Florian-Sassot-Stratmann (DSS) set of fragmentation functions which have charge separation [82]. There are several other FFs, such as the Albino-Kniehl-Kramer (AKK) [83] and the Kniehl-Kramer-Potter (KKP) [84]. Only the results for DSS FFs are shown in this paper, because they give better agreement with our measurements than other FFs. For example, in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$ the yields for $(p+\bar{p}) / 2$ in AKK (KKP) FFs are a factor of 2 smaller (larger) than the present measurement.


FIG. 23. (Color online) Transverse momentum distributions for (upper) positive and (lower) negative particles at $\sqrt{s}=62.4 \mathrm{GeV}$ in $p+p$ collisions. Only statistical uncertainties are shown. The normalization uncertainty ( $11 \%$ ) is not included. (Left) NLO [38,39] and (right) NLL pQCD calculations [40,41] (DSS fragmentation functions) are also shown. Solid lines are for $\mu=p_{T}$, and dashed lines are for $\mu=p_{T} / 2,2 p_{T}$. The lower panel in each plot shows the ratio of (data - pQCD result)/pQCD result for each particle species.

It is known that pion production in $\sqrt{s}=200 \mathrm{GeV}$ $p+p$ collisions is reasonably well described by pQCD down to $p_{T} \sim 2 \mathrm{GeV} / c$ and up to $p_{T} \sim 20 \mathrm{GeV} / c$ [30,33]. However, there are large variations in the $p$ and $\bar{p}$ yields among various fragmentation functions [33], as we mentioned above. From the comparisons between baryon data and pQCD calculations at both $\sqrt{s}=200$ and 62.4 GeV , it is potentially interesting to obtain a constraint on the fragmentation function, particularly the gluon fragmentation function for $p$ and $\bar{p}$.

For the DSS fragmentation function, there is good agreement between the data and NLO pQCD calculations for pions and protons at 200 GeV , but not so good agreement with $\bar{p}$. It is more clearly shown in Fig. 11 that the $\bar{p} / p$ ratio at 200 GeV is not correctly described with the NLO + DSS framework, which indicates that there is still room to improve the DSS fragmentation functions. The left-side plots of Fig. 23 show that for 62.4 GeV NLO + DSS pQCD calculations underestimate yields by a factor of 2 or 3 for all species. However, as it is still on the edge of the scale
uncertainty of the NLO calculation, NLO pQCD agrees with the data within the large uncertainties.

As shown in [34], the NLL calculations [40,41] give much better agreement with the data for $\pi^{0}$ in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. This means the resummed calculation is necessary to describe the cross section at 62.4 GeV . On the other hand, the resummation for $\sqrt{s}=200 \mathrm{GeV}$ is not reliable, since the resummation can be done for a larger $x_{T}=2 p_{T} / \sqrt{s}$, which is not accessible for $\sqrt{s}=200 \mathrm{GeV}$ data due to the $p_{T}$ limitation of particle identifications for charged hadrons in PHENIX. The right-side plots of Fig. 23 show the $p_{T}$ distributions for $\pi^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at 62.4 GeV , together with the results of NLL pQCD calculations [40,41]. The DSS FFs are used. It is found that the agreement between NLL pQCD and data is better than that for NLO pQCD.

The presented $p_{T}$ spectra extend to the semihard $3-4 \mathrm{GeV} / c$ region for pions and (anti)protons, which make them useful as a baseline to study in further detail the nuclear modification factor in $A+A$ collisions. More detailed measurements at larger $p_{T}$ are necessary for the further understanding of

FFs and their particle species dependence at each beam energy.

## VI. SUMMARY AND CONCLUSION

We have presented transverse momentum distributions and yields for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s}=$ 200 and 62.4 GeV at midrapidity, which provide an important baseline for heavy-ion-collision measurements at RHIC. The inverse slope parameter $T_{\text {inv }}$, mean transverse momentum $\left\langle p_{T}\right\rangle$, and yield per unit rapidity $d N / d y$ are compared to the measurements at different $\sqrt{s}$ in $p+p$ and $p+\bar{p}$ collisions. While $T_{\text {inv }}$ and $\left\langle p_{T}\right\rangle$ show a similar value for all particle species between 200 and $62.4 \mathrm{GeV}, d N / d y$ shows a relatively large difference, especially for kaons and antiprotons, between 200 and 62.4 GeV . The $\bar{p} / p$ ratio is $\sim 0.8$ at 200 GeV and $\sim 0.5$ at 62.4 GeV and the $p_{T}$ dependence of the $p / \pi^{+}\left(p / \pi^{0}\right)$ ratio varies between 62.4 and 200 GeV . Together with the measured $d N / d y$, this gives insight into baryon transport and production at midrapidity.

We also analyzed the scaling properties of identified particle spectra, such as the $m_{T}$ scaling and $x_{T}$ scaling. Baryons and mesons are split in the $m_{T}$ spectral shape at both 200 and 62.4 GeV . This splitting can be understood as the difference of hard production yields between baryons and mesons. The $x_{T}$ scaling power $n_{\text {eff }}$ shows similar values for pions, protons, and antiprotons.

We also compared the results in $p+p$ collisions at 200 GeV with those in $\mathrm{Au}+\mathrm{Au}$ collisions at 200 GeV in the same experiment. It is found that $T_{\mathrm{inv}},\left\langle p_{T}\right\rangle$, and $d N / d y$ change smoothly from $p+p$ to $\mathrm{Au}+\mathrm{Au}$, and all the values in $p+p$ are consistent with expectations from the $N_{\text {part }}$ dependence in $\mathrm{Au}+\mathrm{Au}$. For the nuclear modification factor $R_{A A}$, there is a large suppression for pions, while there is an enhancement for protons and antiprotons at $p_{T}=2-4 \mathrm{GeV} / c$. The observed suppression can be understood by the energy loss of partons in the hot and dense medium created in $\mathrm{Au}+\mathrm{Au}$ central collisions at RHIC energies [65,66]. Possible explanations of the observed enhancements for protons and antiprotons include quark recombination [68-70] and/or strong partonic and hadronic radial flow [71].

Identified particle spectra are extended to the semihard $3-4 \mathrm{GeV} / c$ region for pions and (anti)protons, which makes it possible to study in further detail the nuclear modification factor of identified particles in $A+A$ collisions. NLO pQCD calculations $[38,39]$ with DSS fragmentation functions show good agreement for pions and protons at 200 GeV , while there is less good agreement for $\bar{p}$. This indicates that fragmentation functions should be further improved.

For 62.4 GeV , NLO pQCD calculations underestimate by a factor of 2 or 3 the yields for all particle species. In contrast, NLL pQCD calculations [40,41] give a better agreement with the data. This suggests that resummed calculations are necessary to describe the cross section at 62.4 GeV .

From comparisons to some calculations such as those in the NLO or NLL pQCD framework, one can discuss the mechanism of soft and hard particle production in $p+p$ collisions. There is a transition between these two regions ("soft-hard transition") at $p_{T} \sim 2 \mathrm{GeV} / c$ for pions, and at
$p_{T} \sim 3 \mathrm{GeV} / c$ for (anti)protons, or equivalently, $m_{T}-m=$ $1-2 \mathrm{GeV} / c^{2}$ for all particle species at both energies. The fractions of soft and hard components gradually change in the transition region. The new measurements presented in this work indicate that understanding the behavior of $T_{\text {inv }}$ and $\left\langle p_{T}\right\rangle$ of identified particles in $p+p$ collisions requires clarifying the $\sqrt{s}$ dependence through further measurements both at higher $\sqrt{s}$ at the Large Hadron Collider and with lower-energy scans at RHIC.

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## APPENDIX: TABLE OF CROSS SECTIONS

The cross sections for $\pi^{ \pm}, K^{ \pm}, p$, and $\bar{p}$ in $p+p$ collisions at $\sqrt{s} y=200$ and 62.4 GeV at midrapidity are tabulated in Tables XI-XVIII. Statistical and systematic uncertainties are also shown. The normalization uncertainty $(9.7 \%$ for $200 \mathrm{GeV}, 11 \%$ for 62.4 GeV ) is not included. For protons and antiprotons, there are two kinds of table, i.e., with and without the feed-down weak decay corrections.

TABLE XI. $\pi^{+}$and $\pi^{-}$cross sections $\left[E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $9.7 \%$ ) is not included.
$\overline{p_{T}(\mathrm{GeV} / c)} \quad \pi^{+} \quad \pi^{-}$

| 0.35 | $2.77 \times 10^{1} \pm 3.0 \times 10^{-1} \pm 1.9$ | $2.63 \times 10^{1} \pm 3.7 \times 10^{-1} \pm 1.8$ |
| :---: | :---: | :---: |
| 0.45 | $1.45 \times 10^{1} \pm 1.5 \times 10^{-1} \pm 1.0$ | $1.40 \times 10^{1} \pm 2.0 \times 10^{-1} \pm 9.8 \times 10^{-1}$ |
| 0.55 | $7.76 \pm 8.6 \times 10^{-2} \pm 5.4 \times 10^{-1}$ | $7.91 \pm 1.2 \times 10^{-1} \pm 5.5 \times 10^{-1}$ |
| 0.65 | $4.39 \pm 5.3 \times 10^{-2} \pm 3.1 \times 10^{-1}$ | $4.44 \pm 7.0 \times 10^{-2} \pm 3.1 \times 10^{-1}$ |
| 0.75 | $2.65 \pm 3.5 \times 10^{-2} \pm 1.9 \times 10^{-1}$ | $2.69 \pm 4.6 \times 10^{-2} \pm 1.9 \times 10^{-1}$ |
| 0.85 | $1.59 \pm 2.2 \times 10^{-2} \pm 1.1 \times 10^{-1}$ | $1.60 \pm 2.9 \times 10^{-2} \pm 1.1 \times 10^{-1}$ |
| 0.35 | $2.77 \times 10^{1} \pm 3.0 \times 10^{-1} \pm 1.9$ | $2.63 \times 10^{1} \pm 3.7 \times 10^{-1} \pm 1.8$ |
| 0.45 | $1.45 \times 10^{1} \pm 1.5 \times 10^{-1} \pm 1.0$ | $1.40 \times 10^{1} \pm 2.0 \times 10^{-1} \pm 9.8 \times 10^{-1}$ |
| 0.55 | $7.76 \pm 8.6 \times 10^{-2} \pm 5.4 \times 10^{-1}$ | $7.91 \pm 1.2 \times 10^{-1} \pm 5.5 \times 10^{-1}$ |
| 0.65 | $4.39 \pm 5.3 \times 10^{-2} \pm 3.1 \times 10^{-1}$ | $4.44 \pm 7.0 \times 10^{-2} \pm 3.1 \times 10^{-1}$ |
| 0.75 | $2.65 \pm 3.5 \times 10^{-2} \pm 1.9 \times 10^{-1}$ | $2.69 \pm 4.6 \times 10^{-2} \pm 1.9 \times 10^{-1}$ |
| 0.85 | $1.59 \pm 2.2 \times 10^{-2} \pm 1.1 \times 10^{-1}$ | $1.60 \pm 2.9 \times 10^{-2} \pm 1.1 \times 10^{-1}$ |
| 0.95 | $1.01 \pm 1.5 \times 10^{-2} \pm 7.1 \times 10^{-2}$ | $9.83 \times 10^{-1} \pm 1.9 \times 10^{-2} \pm 6.9 \times 10^{-2}$ |
| 1.05 | $6.45 \times 10^{-1} \pm 1.1 \times 10^{-2} \pm 4.5 \times 10^{-2}$ | $6.30 \times 10^{-1} \pm 1.3 \times 10^{-2} \pm 4.4 \times 10^{-2}$ |
| 1.15 | $4.18 \times 10^{-1} \pm 7.2 \times 10^{-3} \pm 2.9 \times 10^{-2}$ | $4.36 \times 10^{-1} \pm 9.5 \times 10^{-3} \pm 3.1 \times 10^{-2}$ |
| 1.25 | $2.76 \times 10^{-1} \pm 5.0 \times 10^{-3} \pm 1.9 \times 10^{-2}$ | $2.79 \times 10^{-1} \pm 6.3 \times 10^{-3} \pm 2.0 \times 10^{-2}$ |
| 1.35 | $1.88 \times 10^{-1} \pm 3.6 \times 10^{-3} \pm 1.3 \times 10^{-2}$ | $1.90 \times 10^{-1} \pm 4.4 \times 10^{-3} \pm 1.3 \times 10^{-2}$ |
| 1.45 | $1.29 \times 10^{-1} \pm 2.6 \times 10^{-3} \pm 9.0 \times 10^{-3}$ | $1.29 \times 10^{-1} \pm 3.1 \times 10^{-3} \pm 9.0 \times 10^{-3}$ |
| 1.55 | $9.07 \times 10^{-2} \pm 1.9 \times 10^{-3} \pm 6.4 \times 10^{-3}$ | $9.05 \times 10^{-2} \pm 2.3 \times 10^{-3} \pm 6.3 \times 10^{-3}$ |
| 1.65 | $6.52 \times 10^{-2} \pm 1.4 \times 10^{-3} \pm 4.6 \times 10^{-3}$ | $6.47 \times 10^{-2} \pm 1.7 \times 10^{-3} \pm 4.5 \times 10^{-3}$ |
| 1.75 | $4.48 \times 10^{-2} \pm 9.9 \times 10^{-4} \pm 3.1 \times 10^{-3}$ | $4.69 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 3.3 \times 10^{-3}$ |
| 1.85 | $3.45 \times 10^{-2} \pm 8.1 \times 10^{-4} \pm 2.4 \times 10^{-3}$ | $3.40 \times 10^{-2} \pm 9.3 \times 10^{-4} \pm 2.4 \times 10^{-3}$ |
| 1.95 | $2.49 \times 10^{-2} \pm 6.1 \times 10^{-4} \pm 1.7 \times 10^{-3}$ | $2.56 \times 10^{-2} \pm 7.4 \times 10^{-4} \pm 1.8 \times 10^{-3}$ |
| 2.05 | $1.83 \times 10^{-2} \pm 4.7 \times 10^{-4} \pm 1.3 \times 10^{-3}$ | $1.81 \times 10^{-2} \pm 5.5 \times 10^{-4} \pm 1.3 \times 10^{-3}$ |
| 2.15 | $1.37 \times 10^{-2} \pm 3.8 \times 10^{-4} \pm 9.6 \times 10^{-4}$ | $1.33 \times 10^{-2} \pm 4.3 \times 10^{-4} \pm 9.3 \times 10^{-4}$ |
| 2.25 | $1.13 \times 10^{-2} \pm 3.5 \times 10^{-4} \pm 7.9 \times 10^{-4}$ | $1.03 \times 10^{-2} \pm 3.6 \times 10^{-4} \pm 7.2 \times 10^{-4}$ |
| 2.35 | $8.21 \times 10^{-3} \pm 2.8 \times 10^{-4} \pm 5.7 \times 10^{-4}$ | $7.48 \times 10^{-3} \pm 2.8 \times 10^{-4} \pm 5.2 \times 10^{-4}$ |
| 2.45 | $6.73 \times 10^{-3} \pm 2.5 \times 10^{-4} \pm 4.7 \times 10^{-4}$ | $6.34 \times 10^{-3} \pm 2.7 \times 10^{-4} \pm 4.4 \times 10^{-4}$ |
| 2.55 | $5.39 \times 10^{-3} \pm 2.3 \times 10^{-4} \pm 3.8 \times 10^{-4}$ | $4.96 \times 10^{-3} \pm 2.3 \times 10^{-4} \pm 3.5 \times 10^{-4}$ |
| 2.65 | $4.27 \times 10^{-3} \pm 2.0 \times 10^{-4} \pm 3.0 \times 10^{-4}$ | $3.47 \times 10^{-3} \pm 1.8 \times 10^{-4} \pm 2.4 \times 10^{-4}$ |
| 2.75 | $3.02 \times 10^{-3} \pm 1.6 \times 10^{-4} \pm 2.1 \times 10^{-4}$ | $2.82 \times 10^{-3} \pm 1.6 \times 10^{-4} \pm 2.0 \times 10^{-4}$ |
| 2.85 | $2.45 \times 10^{-3} \pm 1.4 \times 10^{-4} \pm 1.7 \times 10^{-4}$ | $2.23 \times 10^{-3} \pm 1.5 \times 10^{-4} \pm 1.6 \times 10^{-4}$ |
| 2.95 | $1.82 \times 10^{-3} \pm 1.2 \times 10^{-4} \pm 1.3 \times 10^{-4}$ | $1.66 \times 10^{-3} \pm 1.2 \times 10^{-4} \pm 1.2 \times 10^{-4}$ |

TABLE XII. $K^{+}$and $K^{-}$cross sections $\left[E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $9.7 \%$ ) is not included.

| $p_{T}(\mathrm{GeV} / c)$ | $K^{+}$ | $K^{-}$ |
| :--- | :---: | ---: |
| 0.45 | $1.96 \pm 5.0 \times 10^{-2} \pm 1.4 \times 10^{-1}$ | $1.89 \pm 7.0 \times 10^{-2} \pm 1.3 \times 10^{-1}$ |
| 0.55 | $1.35 \pm 3.0 \times 10^{-2} \pm 9.4 \times 10^{-2}$ | $1.37 \pm 4.3 \times 10^{-2} \pm 9.6 \times 10^{-2}$ |
| 0.65 | $8.71 \times 10^{-1} \pm 1.9 \times 10^{-2} \pm 6.1 \times 10^{-2}$ | $8.28 \times 10^{-1} \pm 2.3 \times 10^{-2} \pm 5.8 \times 10^{-2}$ |
| 0.75 | $5.86 \times 10^{-1} \pm 1.3 \times 10^{-2} \pm 4.1 \times 10^{-2}$ | $5.60 \times 10^{-1} \pm 1.6 \times 10^{-2} \pm 3.9 \times 10^{-2}$ |
| 0.85 | $3.95 \times 10^{-1} \pm 8.7 \times 10^{-3} \pm 2.8 \times 10^{-2}$ | $3.87 \times 10^{-1} \pm 1.1 \times 10^{-2} \pm 2.7 \times 10^{-2}$ |
| 0.95 | $2.60 \times 10^{-1} \pm 5.8 \times 10^{-3} \pm 1.8 \times 10^{-2}$ | $2.54 \times 10^{-1} \pm 7.3 \times 10^{-3} \pm 1.8 \times 10^{-2}$ |
| 1.05 | $1.72 \times 10^{-1} \pm 3.9 \times 10^{-3} \pm 1.2 \times 10^{-2}$ | $1.83 \times 10^{-1} \pm 5.5 \times 10^{-3} \pm 1.3 \times 10^{-2}$ |
| 1.15 | $1.26 \times 10^{-1} \pm 3.0 \times 10^{-3} \pm 8.9 \times 10^{-3}$ | $1.16 \times 10^{-1} \pm 3.5 \times 10^{-3} \pm 8.1 \times 10^{-3}$ |
| 1.25 | $8.52 \times 10^{-2} \pm 2.1 \times 10^{-3} \pm 6.0 \times 10^{-3}$ | $8.97 \times 10^{-2} \pm 2.8 \times 10^{-3} \pm 6.3 \times 10^{-3}$ |
| 1.35 | $6.08 \times 10^{-2} \pm 1.5 \times 10^{-3} \pm 4.3 \times 10^{-3}$ | $6.23 \times 10^{-2} \pm 2.0 \times 10^{-3} \pm 4.4 \times 10^{-3}$ |
| 1.45 | $4.59 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 3.2 \times 10^{-3}$ | $4.27 \times 10^{-2} \pm 1.4 \times 10^{-3} \pm 3.0 \times 10^{-3}$ |
| 1.55 | $3.29 \times 10^{-2} \pm 9.0 \times 10^{-4} \pm 2.3 \times 10^{-3}$ | $3.21 \times 10^{-2} \pm 1.1 \times 10^{-3} \pm 2.2 \times 10^{-3}$ |
| 1.65 | $2.39 \times 10^{-2} \pm 6.6 \times 10^{-4} \pm 1.7 \times 10^{-3}$ | $2.23 \times 10^{-2} \pm 7.4 \times 10^{-4} \pm 1.6 \times 10^{-3}$ |
| 1.75 | $1.86 \times 10^{-2} \pm 5.3 \times 10^{-4} \pm 1.3 \times 10^{-3}$ | $1.81 \times 10^{-2} \pm 6.2 \times 10^{-4} \pm 1.3 \times 10^{-3}$ |
| 1.85 | $1.49 \times 10^{-2} \pm 4.4 \times 10^{-4} \pm 1.0 \times 10^{-3}$ | $1.36 \times 10^{-2} \pm 4.7 \times 10^{-4} \pm 9.5 \times 10^{-4}$ |
| 1.95 | $1.13 \times 10^{-2} \pm 3.5 \times 10^{-4} \pm 7.9 \times 10^{-4}$ | $1.03 \times 10^{-2} \pm 3.7 \times 10^{-4} \pm 7.2 \times 10^{-4}$ |

TABLE XIII. $p$ and $\bar{p}$ cross sections [ $\left.E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $9.7 \%$ ) is not included. Feed-down weak decay corrections are not applied.

| $p_{T}(\mathrm{GeV} / \mathrm{c})$ | $p$ | $\bar{p}$ |
| :---: | :---: | :---: |
| 0.55 | $1.02 \pm 2.0 \times 10^{-2} \pm 6.2 \times 10^{-2}$ | $7.88 \times 10^{-1} \pm 1.6 \times 10^{-2} \pm 5.5 \times 10^{-2}$ |
| 0.65 | $7.40 \times 10^{-1} \pm 1.4 \times 10^{-2} \pm 4.5 \times 10^{-2}$ | $6.04 \times 10^{-1} \pm 1.2 \times 10^{-2} \pm 4.2 \times 10^{-2}$ |
| 0.75 | $5.58 \times 10^{-1} \pm 1.1 \times 10^{-2} \pm 3.4 \times 10^{-2}$ | $4.62 \times 10^{-1} \pm 9.1 \times 10^{-3} \pm 3.2 \times 10^{-2}$ |
| 0.85 | $3.77 \times 10^{-1} \pm 7.7 \times 10^{-3} \pm 2.3 \times 10^{-2}$ | $3.18 \times 10^{-1} \pm 6.3 \times 10^{-3} \pm 2.2 \times 10^{-2}$ |
| 0.95 | $2.73 \times 10^{-1} \pm 5.9 \times 10^{-3} \pm 1.6 \times 10^{-2}$ | $2.18 \times 10^{-1} \pm 4.4 \times 10^{-3} \pm 1.5 \times 10^{-2}$ |
| 1.05 | $1.80 \times 10^{-1} \pm 4.0 \times 10^{-3} \pm 1.1 \times 10^{-2}$ | $1.58 \times 10^{-1} \pm 3.3 \times 10^{-3} \pm 1.1 \times 10^{-2}$ |
| 1.15 | $1.27 \times 10^{-1} \pm 2.9 \times 10^{-3} \pm 7.6 \times 10^{-3}$ | $1.08 \times 10^{-1} \pm 2.4 \times 10^{-3} \pm 7.6 \times 10^{-3}$ |
| 1.25 | $9.18 \times 10^{-2} \pm 2.2 \times 10^{-3} \pm 5.5 \times 10^{-3}$ | $7.54 \times 10^{-2} \pm 1.7 \times 10^{-3} \pm 5.3 \times 10^{-3}$ |
| 1.35 | $6.24 \times 10^{-2} \pm 1.6 \times 10^{-3} \pm 3.7 \times 10^{-3}$ | $5.58 \times 10^{-2} \pm 1.3 \times 10^{-3} \pm 3.9 \times 10^{-3}$ |
| 1.45 | $4.80 \times 10^{-2} \pm 1.3 \times 10^{-3} \pm 2.9 \times 10^{-3}$ | $3.73 \times 10^{-2} \pm 8.9 \times 10^{-4} \pm 2.6 \times 10^{-3}$ |
| 1.55 | $3.32 \times 10^{-2} \pm 9.1 \times 10^{-4} \pm 2.0 \times 10^{-3}$ | $2.68 \times 10^{-2} \pm 6.6 \times 10^{-4} \pm 1.9 \times 10^{-3}$ |
| 1.65 | $2.31 \times 10^{-2} \pm 6.5 \times 10^{-4} \pm 1.4 \times 10^{-3}$ | $1.93 \times 10^{-2} \pm 4.9 \times 10^{-4} \pm 1.4 \times 10^{-3}$ |
| 1.75 | $1.70 \times 10^{-2} \pm 5.0 \times 10^{-4} \pm 1.0 \times 10^{-3}$ | $1.39 \times 10^{-2} \pm 3.7 \times 10^{-4} \pm 9.8 \times 10^{-4}$ |
| 1.85 | $1.17 \times 10^{-2} \pm 3.6 \times 10^{-4} \pm 7.0 \times 10^{-4}$ | $9.69 \times 10^{-3} \pm 2.6 \times 10^{-4} \pm 6.8 \times 10^{-4}$ |
| 1.95 | $8.98 \times 10^{-3} \pm 2.9 \times 10^{-4} \pm 5.4 \times 10^{-4}$ | $6.94 \times 10^{-3} \pm 1.9 \times 10^{-4} \pm 4.9 \times 10^{-4}$ |
| 2.05 | $6.68 \times 10^{-3} \pm 2.3 \times 10^{-4} \pm 4.0 \times 10^{-4}$ | $5.12 \times 10^{-3} \pm 1.5 \times 10^{-4} \pm 3.6 \times 10^{-4}$ |
| 2.15 | $4.62 \times 10^{-3} \pm 1.6 \times 10^{-4} \pm 2.8 \times 10^{-4}$ | $3.61 \times 10^{-3} \pm 1.1 \times 10^{-4} \pm 2.5 \times 10^{-4}$ |
| 2.25 | $3.91 \times 10^{-3} \pm 1.5 \times 10^{-4} \pm 2.4 \times 10^{-4}$ | $2.90 \times 10^{-3} \pm 9.2 \times 10^{-5} \pm 2.0 \times 10^{-4}$ |
| 2.35 | $2.63 \times 10^{-3} \pm 1.0 \times 10^{-4} \pm 1.6 \times 10^{-4}$ | $2.09 \times 10^{-3} \pm 7.0 \times 10^{-5} \pm 1.5 \times 10^{-4}$ |
| 2.45 | $1.79 \times 10^{-3} \pm 7.4 \times 10^{-5} \pm 1.1 \times 10^{-4}$ | $1.58 \times 10^{-3} \pm 5.5 \times 10^{-5} \pm 1.1 \times 10^{-4}$ |
| 2.55 | $1.62 \times 10^{-3} \pm 7.0 \times 10^{-5} \pm 1.0 \times 10^{-4}$ | $1.10 \times 10^{-3} \pm 4.2 \times 10^{-5} \pm 7.8 \times 10^{-5}$ |
| 2.65 | $1.15 \times 10^{-3} \pm 5.4 \times 10^{-5} \pm 7.2 \times 10^{-5}$ | $8.85 \times 10^{-4} \pm 3.7 \times 10^{-5} \pm 6.3 \times 10^{-5}$ |
| 2.75 | $8.89 \times 10^{-4} \pm 4.4 \times 10^{-5} \pm 5.6 \times 10^{-5}$ | $6.22 \times 10^{-4} \pm 2.8 \times 10^{-5} \pm 4.4 \times 10^{-5}$ |
| 2.85 | $6.38 \times 10^{-4} \pm 3.5 \times 10^{-5} \pm 4.1 \times 10^{-5}$ | $5.07 \times 10^{-4} \pm 2.4 \times 10^{-5} \pm 3.6 \times 10^{-5}$ |
| 2.95 | $4.97 \times 10^{-4} \pm 3.0 \times 10^{-5} \pm 3.2 \times 10^{-5}$ | $3.80 \times 10^{-4} \pm 2.0 \times 10^{-5} \pm 2.7 \times 10^{-5}$ |
| 3.05 | $4.13 \times 10^{-4} \pm 2.6 \times 10^{-5} \pm 2.7 \times 10^{-5}$ | $3.13 \times 10^{-4} \pm 1.7 \times 10^{-5} \pm 2.3 \times 10^{-5}$ |
| 3.10 | $3.80 \times 10^{-4} \pm 1.8 \times 10^{-5} \pm 2.5 \times 10^{-5}$ | $2.75 \times 10^{-4} \pm 1.1 \times 10^{-5} \pm 2.0 \times 10^{-5}$ |
| 3.30 | $2.33 \times 10^{-4} \pm 1.3 \times 10^{-5} \pm 1.6 \times 10^{-5}$ | $1.92 \times 10^{-4} \pm 9.0 \times 10^{-6} \pm 1.4 \times 10^{-5}$ |
| 3.50 | $1.57 \times 10^{-4} \pm 1.0 \times 10^{-5} \pm 1.1 \times 10^{-5}$ | $1.12 \times 10^{-4} \pm 6.5 \times 10^{-6} \pm 8.6 \times 10^{-6}$ |
| 3.70 | $1.11 \times 10^{-4} \pm 8.9 \times 10^{-6} \pm 8.3 \times 10^{-6}$ | $7.16 \times 10^{-5} \pm 5.2 \times 10^{-6} \pm 5.8 \times 10^{-6}$ |
| 3.90 | $7.25 \times 10^{-5} \pm 7.2 \times 10^{-6} \pm 5.8 \times 10^{-6}$ | $4.40 \times 10^{-5} \pm 4.0 \times 10^{-6} \pm 3.8 \times 10^{-6}$ |
| 4.10 | $6.23 \times 10^{-5} \pm 6.7 \times 10^{-6} \pm 5.3 \times 10^{-6}$ | $3.81 \times 10^{-5} \pm 3.9 \times 10^{-6} \pm 3.6 \times 10^{-6}$ |
| 4.30 | $3.83 \times 10^{-5} \pm 5.5 \times 10^{-6} \pm 3.6 \times 10^{-6}$ | $2.63 \times 10^{-5} \pm 3.3 \times 10^{-6} \pm 2.8 \times 10^{-6}$ |
| 4.50 | $3.22 \times 10^{-5} \pm 5.2 \times 10^{-6} \pm 3.3 \times 10^{-6}$ | $1.82 \times 10^{-5} \pm 2.8 \times 10^{-6} \pm 2.2 \times 10^{-6}$ |

TABLE XIV. $p$ and $\bar{p}$ cross sections [ $\left.E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=200 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $9.7 \%$ ) is not included. Feed-down weak decay corrections are applied.

| $p_{T}(\mathrm{GeV} / c)$ | $p$ | $\bar{p}$ |
| :--- | :---: | :---: |
| 0.55 | $5.93 \times 10^{-1} \pm 1.1 \times 10^{-2} \pm 1.4 \times 10^{-1}$ | $4.56 \times 10^{-1} \pm 9.2 \times 10^{-3} \pm 1.1 \times 10^{-1}$ |
| 0.65 | $4.45 \times 10^{-1} \pm 8.4 \times 10^{-3} \pm 9.4 \times 10^{-2}$ | $3.63 \times 10^{-1} \pm 7.0 \times 10^{-3} \pm 7.8 \times 10^{-2}$ |
| 0.75 | $3.47 \times 10^{-1} \pm 6.9 \times 10^{-3} \pm 6.6 \times 10^{-2}$ | $2.87 \times 10^{-1} \pm 5.6 \times 10^{-3} \pm 5.6 \times 10^{-2}$ |
| 0.85 | $2.42 \times 10^{-1} \pm 4.9 \times 10^{-3} \pm 4.2 \times 10^{-2}$ | $2.04 \times 10^{-1} \pm 4.0 \times 10^{-3} \pm 3.6 \times 10^{-2}$ |
| 0.95 | $1.80 \times 10^{-1} \pm 3.9 \times 10^{-3} \pm 2.9 \times 10^{-2}$ | $1.44 \times 10^{-1} \pm 2.9 \times 10^{-3} \pm 2.4 \times 10^{-2}$ |
| 1.05 | $1.22 \times 10^{-1} \pm 2.7 \times 10^{-3} \pm 1.8 \times 10^{-2}$ | $1.06 \times 10^{-1} \pm 2.2 \times 10^{-3} \pm 1.6 \times 10^{-2}$ |
| 1.15 | $8.77 \times 10^{-2} \pm 2.0 \times 10^{-3} \pm 1.2 \times 10^{-2}$ | $7.48 \times 10^{-2} \pm 1.6 \times 10^{-3} \pm 1.1 \times 10^{-2}$ |
| 1.25 | $6.46 \times 10^{-2} \pm 1.6 \times 10^{-3} \pm 8.4 \times 10^{-3}$ | $5.31 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 7.1 \times 10^{-3}$ |
| 1.35 | $4.47 \times 10^{-2} \pm 1.1 \times 10^{-3} \pm 5.5 \times 10^{-3}$ | $4.00 \times 10^{-2} \pm 9.4 \times 10^{-4} \pm 5.1 \times 10^{-3}$ |
| 1.45 | $3.49 \times 10^{-2} \pm 9.4 \times 10^{-4} \pm 4.1 \times 10^{-3}$ | $2.72 \times 10^{-2} \pm 6.5 \times 10^{-4} \pm 3.3 \times 10^{-3}$ |
| 1.55 | $2.45 \times 10^{-2} \pm 6.8 \times 10^{-4} \pm 2.7 \times 10^{-3}$ | $1.98 \times 10^{-2} \pm 4.9 \times 10^{-4} \pm 2.3 \times 10^{-3}$ |

TABLE XIV. (Continued.)

| $p_{T}(\mathrm{GeV} / c)$ | $p$ | $\bar{p}$ |
| :--- | :---: | :---: |
| 1.65 | $1.73 \times 10^{-2} \pm 4.9 \times 10^{-4} \pm 1.9 \times 10^{-3}$ | $1.45 \times 10^{-2} \pm 3.7 \times 10^{-4} \pm 1.6 \times 10^{-3}$ |
| 1.75 | $1.28 \times 10^{-2} \pm 3.8 \times 10^{-4} \pm 1.3 \times 10^{-3}$ | $1.06 \times 10^{-2} \pm 2.8 \times 10^{-4} \pm 1.2 \times 10^{-3}$ |
| 1.85 | $8.92 \times 10^{-3} \pm 2.7 \times 10^{-4} \pm 8.9 \times 10^{-4}$ | $7.42 \times 10^{-3} \pm 2.0 \times 10^{-4} \pm 7.9 \times 10^{-4}$ |
| 1.95 | $6.95 \times 10^{-3} \pm 2.2 \times 10^{-4} \pm 6.8 \times 10^{-4}$ | $5.37 \times 10^{-3} \pm 1.5 \times 10^{-4} \pm 5.6 \times 10^{-4}$ |
| 2.05 | $5.21 \times 10^{-3} \pm 1.8 \times 10^{-4} \pm 4.9 \times 10^{-4}$ | $4.00 \times 10^{-3} \pm 1.2 \times 10^{-4} \pm 4.0 \times 10^{-4}$ |
| 2.15 | $3.63 \times 10^{-3} \pm 1.3 \times 10^{-4} \pm 3.4 \times 10^{-4}$ | $2.84 \times 10^{-3} \pm 8.7 \times 10^{-5} \pm 2.8 \times 10^{-4}$ |
| 2.25 | $3.10 \times 10^{-3} \pm 1.2 \times 10^{-4} \pm 2.8 \times 10^{-4}$ | $2.30 \times 10^{-3} \pm 7.3 \times 10^{-5} \pm 2.2 \times 10^{-4}$ |
| 2.35 | $2.10 \times 10^{-3} \pm 8.2 \times 10^{-5} \pm 1.9 \times 10^{-4}$ | $1.67 \times 10^{-3} \pm 5.6 \times 10^{-5} \pm 1.6 \times 10^{-4}$ |
| 2.45 | $1.44 \times 10^{-3} \pm 6.0 \times 10^{-5} \pm 1.3 \times 10^{-4}$ | $1.27 \times 10^{-3} \pm 4.4 \times 10^{-5} \pm 1.2 \times 10^{-4}$ |
| 2.55 | $1.31 \times 10^{-3} \pm 5.7 \times 10^{-5} \pm 1.1 \times 10^{-4}$ | $8.89 \times 10^{-4} \pm 3.4 \times 10^{-5} \pm 8.3 \times 10^{-5}$ |
| 2.65 | $9.31 \times 10^{-4} \pm 4.4 \times 10^{-5} \pm 8.0 \times 10^{-5}$ | $7.19 \times 10^{-4} \pm 3.0 \times 10^{-5} \pm 6.6 \times 10^{-5}$ |
| 2.75 | $7.26 \times 10^{-4} \pm 3.6 \times 10^{-5} \pm 6.2 \times 10^{-5}$ | $5.08 \times 10^{-4} \pm 2.3 \times 10^{-5} \pm 4.6 \times 10^{-5}$ |
| 2.85 | $5.23 \times 10^{-4} \pm 2.9 \times 10^{-5} \pm 4.4 \times 10^{-5}$ | $4.16 \times 10^{-4} \pm 2.0 \times 10^{-5} \pm 3.8 \times 10^{-5}$ |
| 2.95 | $4.09 \times 10^{-4} \pm 2.4 \times 10^{-5} \pm 3.4 \times 10^{-5}$ | $3.13 \times 10^{-4} \pm 1.6 \times 10^{-5} \pm 2.8 \times 10^{-5}$ |
| 3.05 | $3.41 \times 10^{-4} \pm 2.2 \times 10^{-5} \pm 2.9 \times 10^{-5}$ | $2.58 \times 10^{-4} \pm 1.4 \times 10^{-5} \pm 2.3 \times 10^{-5}$ |
| 3.10 | $3.14 \times 10^{-4} \pm 1.5 \times 10^{-5} \pm 2.6 \times 10^{-5}$ | $2.28 \times 10^{-4} \pm 9.3 \times 10^{-6} \pm 2.0 \times 10^{-5}$ |
| 3.30 | $1.94 \times 10^{-4} \pm 1.1 \times 10^{-5} \pm 1.6 \times 10^{-5}$ | $1.60 \times 10^{-4} \pm 7.5 \times 10^{-6} \pm 1.4 \times 10^{-5}$ |
| 3.50 | $1.32 \times 10^{-4} \pm 8.6 \times 10^{-6} \pm 1.1 \times 10^{-5}$ | $9.42 \times 10^{-5} \pm 5.4 \times 10^{-6} \pm 8.6 \times 10^{-6}$ |
| 3.70 | $9.35 \times 10^{-5} \pm 7.5 \times 10^{-6} \pm 8.2 \times 10^{-6}$ | $6.03 \times 10^{-5} \pm 4.4 \times 10^{-6} \pm 5.6 \times 10^{-6}$ |
| 3.90 | $6.13 \times 10^{-5} \pm 6.1 \times 10^{-6} \pm 5.6 \times 10^{-6}$ | $3.72 \times 10^{-5} \pm 3.4 \times 10^{-6} \pm 3.6 \times 10^{-6}$ |
| 4.10 | $5.28 \times 10^{-5} \pm 5.7 \times 10^{-6} \pm 5.1 \times 10^{-6}$ | $3.24 \times 10^{-5} \pm 3.3 \times 10^{-6} \pm 3.4 \times 10^{-6}$ |
| 4.30 | $3.26 \times 10^{-5} \pm 4.7 \times 10^{-6} \pm 3.3 \times 10^{-6}$ | $2.23 \times 10^{-5} \pm 2.8 \times 10^{-6} \pm 2.6 \times 10^{-6}$ |
| 4.50 | $2.75 \times 10^{-5} \pm 4.4 \times 10^{-6} \pm 3.0 \times 10^{-6}$ | $1.56 \times 10^{-5} \pm 2.4 \times 10^{-6} \pm 2.0 \times 10^{-6}$ |

TABLE XV. $\pi^{+}$and $\pi^{-}$cross sections $\left[E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $11 \%$ ) is not included.

| $p_{T}(\mathrm{GeV} / c)$ | $\pi^{+}$ | $\pi^{-}$ |
| :--- | :---: | ---: |
| 0.35 | $1.96 \times 10^{1} \pm 1.8 \times 10^{-1} \pm 1.4$ | $2.08 \times 10^{1} \pm 1.5 \times 10^{-1} \pm 1.3$ |
| 0.45 | $1.07 \times 10^{1} \pm 1.1 \times 10^{-1} \pm 7.5 \times 10^{-1}$ | $1.12 \times 10^{1} \pm 8.6 \times 10^{-2} \pm 6.7 \times 10^{-1}$ |
| 0.55 | $5.95 \pm 6.3 \times 10^{-2} \pm 4.2 \times 10^{-1}$ | $5.94 \pm 4.9 \times 10^{-2} \pm 3.6 \times 10^{-1}$ |
| 0.65 | $3.38 \pm 3.9 \times 10^{-2} \pm 2.4 \times 10^{-1}$ | $3.25 \pm 3.0 \times 10^{-2} \pm 1.9 \times 10^{-1}$ |
| 0.75 | $1.91 \pm 2.4 \times 10^{-2} \pm 1.3 \times 10^{-1}$ | $1.92 \pm 2.0 \times 10^{-2} \pm 1.2 \times 10^{-1}$ |
| 0.85 | $1.13 \pm 1.6 \times 10^{-2} \pm 7.9 \times 10^{-2}$ | $1.15 \pm 1.3 \times 10^{-2} \pm 6.9 \times 10^{-2}$ |
| 0.95 | $6.86 \times 10^{-1} \pm 1.0 \times 10^{-2} \pm 4.8 \times 10^{-2}$ | $6.68 \times 10^{-1} \pm 8.4 \times 10^{-3} \pm 4.0 \times 10^{-2}$ |
| 1.05 | $4.30 \times 10^{-1} \pm 7.2 \times 10^{-3} \pm 3.0 \times 10^{-2}$ | $4.06 \times 10^{-1} \pm 5.7 \times 10^{-3} \pm 2.4 \times 10^{-2}$ |
| 1.15 | $2.65 \times 10^{-1} \pm 4.9 \times 10^{-3} \pm 1.9 \times 10^{-2}$ | $2.53 \times 10^{-1} \pm 4.0 \times 10^{-3} \pm 1.5 \times 10^{-2}$ |
| 1.25 | $1.66 \times 10^{-1} \pm 3.5 \times 10^{-3} \pm 1.2 \times 10^{-2}$ | $1.60 \times 10^{-1} \pm 2.9 \times 10^{-3} \pm 9.6 \times 10^{-3}$ |
| 1.35 | $1.08 \times 10^{-1} \pm 2.6 \times 10^{-3} \pm 7.5 \times 10^{-3}$ | $1.03 \times 10^{-1} \pm 2.1 \times 10^{-3} \pm 6.2 \times 10^{-3}$ |
| 1.45 | $7.20 \times 10^{-2} \pm 1.9 \times 10^{-3} \pm 5.0 \times 10^{-3}$ | $6.74 \times 10^{-2} \pm 1.6 \times 10^{-3} \pm 4.0 \times 10^{-3}$ |
| 1.55 | $5.04 \times 10^{-2} \pm 1.5 \times 10^{-3} \pm 3.5 \times 10^{-3}$ | $4.54 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 2.7 \times 10^{-3}$ |
| 1.65 | $3.48 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 2.4 \times 10^{-3}$ | $3.07 \times 10^{-2} \pm 9.7 \times 10^{-4} \pm 1.8 \times 10^{-3}$ |
| 1.75 | $2.33 \times 10^{-2} \pm 9.5 \times 10^{-4} \pm 1.6 \times 10^{-3}$ | $2.25 \times 10^{-2} \pm 8.3 \times 10^{-4} \pm 1.4 \times 10^{-3}$ |
| 1.85 | $1.58 \times 10^{-2} \pm 7.8 \times 10^{-4} \pm 1.1 \times 10^{-3}$ | $1.55 \times 10^{-2} \pm 6.8 \times 10^{-4} \pm 9.3 \times 10^{-4}$ |
| 1.95 | $1.11 \times 10^{-2} \pm 6.7 \times 10^{-4} \pm 7.8 \times 10^{-4}$ | $7.23 \times 10^{-3} \pm 5.2 \times 10^{-4} \pm 4.7 \times 10^{-4} \pm 4.8 \times 10^{-4} \pm 4.3 \times 10^{-4}$ |
| 2.05 | $7.13 \times 10^{-3} \pm 5.2 \times 10^{-4} \pm 5.0 \times 10^{-4}$ | $4.72 \times 10^{-3} \pm 3.9 \times 10^{-4} \pm 2.9 \times 10^{-4}$ |
| 2.15 | $5.63 \times 10^{-3} \pm 5.0 \times 10^{-4} \pm 4.0 \times 10^{-4}$ | $3.32 \times 10^{-3} \pm 3.4 \times 10^{-4} \pm 2.0 \times 10^{-4}$ |
| 2.25 | $4.22 \times 10^{-3} \pm 4.3 \times 10^{-4} \pm 3.0 \times 10^{-4}$ | $2.67 \times 10^{-3} \pm 3.3 \times 10^{-4} \pm 1.7 \times 10^{-4}$ |
| 2.35 | $2.69 \times 10^{-3} \pm 3.7 \times 10^{-4} \pm 1.9 \times 10^{-4}$ | $1.75 \times 10^{-3} \pm 2.9 \times 10^{-4} \pm 1.1 \times 10^{-4}$ |
| 2.45 | $1.96 \times 10^{-3} \pm 3.1 \times 10^{-4} \pm 1.4 \times 10^{-4}$ | $1.49 \times 10^{-3} \pm 2.7 \times 10^{-4} \pm 9.8 \times 10^{-5}$ |
| 2.55 | $1.45 \times 10^{-3} \pm 3.3 \times 10^{-4} \pm 1.1 \times 10^{-4}$ | $1.07 \times 10^{-3} \pm 2.5 \times 10^{-4} \pm 7.3 \times 10^{-5}$ |
| 2.65 | $9.07 \times 10^{-4} \pm 2.2 \times 10^{-4} \pm 7.0 \times 10^{-5}$ | $7.62 \times 10^{-4} \pm 2.5 \times 10^{-4} \pm 5.4 \times 10^{-5}$ |
| 2.75 | $1.09 \times 10^{-3} \pm 3.0 \times 10^{-4} \pm 8.6 \times 10^{-5}$ | $5.10 \times 10^{-4} \pm 2.0 \times 10^{-4} \pm 3.7 \times 10^{-5}$ |
| 2.85 | $6.48 \times 10^{-4} \pm 2.3 \times 10^{-4} \pm 5.3 \times 10^{-5}$ |  |
|  |  |  |

TABLE XVI. $K^{+}$and $K^{-}$cross sections $\left[E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $11 \%$ ) is not included.

| $p_{T}(\mathrm{GeV} / c)$ | $K^{+}$ | $K^{-}$ |
| :--- | :---: | ---: |
| 0.45 | $1.18 \pm 2.7 \times 10^{-2} \pm 8.2 \times 10^{-2}$ | $1.06 \pm 1.9 \times 10^{-2} \pm 7.4 \times 10^{-2}$ |
| 0.55 | $8.18 \times 10^{-1} \pm 1.8 \times 10^{-2} \pm 5.7 \times 10^{-2}$ | $7.48 \times 10^{-1} \pm 1.3 \times 10^{-2} \pm 5.2 \times 10^{-2}$ |
| 0.65 | $6.07 \times 10^{-1} \pm 1.3 \times 10^{-2} \pm 4.3 \times 10^{-2}$ | $5.30 \times 10^{-1} \pm 9.6 \times 10^{-3} \pm 3.7 \times 10^{-2}$ |
| 0.75 | $3.72 \times 10^{-1} \pm 8.4 \times 10^{-3} \pm 2.6 \times 10^{-2}$ | $3.43 \times 10^{-1} \pm 6.7 \times 10^{-3} \pm 2.4 \times 10^{-2}$ |
| 0.85 | $2.50 \times 10^{-1} \pm 6.1 \times 10^{-3} \pm 1.8 \times 10^{-2}$ | $2.14 \times 10^{-1} \pm 4.6 \times 10^{-3} \pm 1.5 \times 10^{-2}$ |
| 0.95 | $1.73 \times 10^{-1} \pm 4.7 \times 10^{-3} \pm 1.2 \times 10^{-2}$ | $1.40 \times 10^{-1} \pm 3.4 \times 10^{-3} \pm 9.8 \times 10^{-3}$ |
| 1.05 | $1.12 \times 10^{-1} \pm 3.3 \times 10^{-3} \pm 7.8 \times 10^{-3}$ | $6.17 \times 10^{-2} \pm 2.5 \times 10^{-3} \pm 6.3 \times 10^{-3} \pm 1.9 \times 10^{-3} \pm 4.3 \times 10^{-3}$ |
| 1.15 | $7.94 \times 10^{-2} \pm 2.7 \times 10^{-3} \pm 5.6 \times 10^{-3}$ | $4.35 \times 10^{-2} \pm 1.5 \times 10^{-3} \pm 3.0 \times 10^{-3}$ |
| 1.25 | $4.88 \times 10^{-2} \pm 1.9 \times 10^{-3} \pm 3.4 \times 10^{-3}$ | $2.84 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 2.0 \times 10^{-3}$ |
| 1.35 | $3.41 \times 10^{-2} \pm 1.5 \times 10^{-3} \pm 2.4 \times 10^{-3}$ | $1.96 \times 10^{-2} \pm 9.2 \times 10^{-4} \pm 1.4 \times 10^{-3}$ |
| 1.45 | $2.45 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 1.7 \times 10^{-3}$ | $1.34 \times 10^{-2} \pm 7.6 \times 10^{-4} \pm 9.4 \times 10^{-4}$ |
| 1.55 | $1.63 \times 10^{-2} \pm 9.5 \times 10^{-4} \pm 1.1 \times 10^{-3}$ | $9.77 \times 10^{-3} \pm 6.2 \times 10^{-4} \pm 7.0 \times 10^{-4}$ |
| 1.65 | $1.28 \times 10^{-2} \pm 8.0 \times 10^{-4} \pm 9.1 \times 10^{-4}$ | $6.65 \times 10^{-3} \pm 4.8 \times 10^{-4} \pm 4.9 \times 10^{-4}$ |
| 1.75 | $9.56 \times 10^{-3} \pm 6.8 \times 10^{-4} \pm 7.1 \times 10^{-4}$ | $4.87 \times 10^{-3} \pm 4.2 \times 10^{-4} \pm 3.8 \times 10^{-4}$ |
| 1.85 | $6.34 \times 10^{-3} \pm 5.4 \times 10^{-4} \pm 5.0 \times 10^{-4}$ | $3.45 \times 10^{-3} \pm 3.7 \times 10^{-4} \pm 2.9 \times 10^{-4}$ |
| 1.95 | $5.28 \times 10^{-3} \pm 5.1 \times 10^{-4} \pm 4.4 \times 10^{-4}$ |  |

TABLE XVII. $p$ and $\bar{p}$ cross sections $\left[E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $11 \%$ ) is not included. Feed-down weak decay corrections are not applied.

| $p_{T}(\mathrm{GeV} / c)$ | $p$ | $\bar{p}$ |
| :--- | :---: | :---: |
| 0.65 | $4.63 \times 10^{-1} \pm 7.1 \times 10^{-3} \pm 4.2 \times 10^{-2}$ | $3.09 \times 10^{-1} \pm 4.6 \times 10^{-3} \pm 2.2 \times 10^{-2}$ |
| 0.75 | $3.28 \times 10^{-1} \pm 5.4 \times 10^{-3} \pm 3.0 \times 10^{-2}$ | $2.19 \times 10^{-1} \pm 3.6 \times 10^{-3} \pm 1.5 \times 10^{-2}$ |
| 0.85 | $2.49 \times 10^{-1} \pm 4.5 \times 10^{-3} \pm 2.2 \times 10^{-2}$ | $1.59 \times 10^{-1} \pm 2.9 \times 10^{-3} \pm 1.1 \times 10^{-2}$ |
| 0.95 | $1.69 \times 10^{-1} \pm 3.4 \times 10^{-3} \pm 1.5 \times 10^{-2}$ | $7.50 \times 10^{-1} \pm 2.3 \times 10^{-3} \pm 7.7 \times 10^{-3}$ |
| 1.05 | $1.20 \times 10^{-1} \pm 2.7 \times 10^{-3} \pm 1.1 \times 10^{-2}$ | $4.95 \times 10^{-3} \pm 5.3 \times 10^{-3}$ |
| 1.15 | $8.12 \times 10^{-2} \pm 2.1 \times 10^{-3} \pm 7.3 \times 10^{-3}$ | $3.32 \times 10^{-2} \pm 1.1 \times 10^{-3} \pm 3.5 \times 10^{-3} \pm 2.3 \times 10^{-3}$ |
| 1.25 | $5.81 \times 10^{-2} \pm 1.7 \times 10^{-3} \pm 5.2 \times 10^{-3}$ | $2.37 \times 10^{-2} \pm 9.4 \times 10^{-4} \pm 1.7 \times 10^{-3}$ |
| 1.35 | $3.95 \times 10^{-2} \pm 1.4 \times 10^{-3} \pm 3.6 \times 10^{-3}$ | $1.53 \times 10^{-2} \pm 7.1 \times 10^{-4} \pm 1.1 \times 10^{-3}$ |
| 1.45 | $2.55 \times 10^{-2} \pm 9.9 \times 10^{-4} \pm 2.3 \times 10^{-3}$ | $1.07 \times 10^{-2} \pm 6.0 \times 10^{-4} \pm 7.5 \times 10^{-4}$ |
| 1.55 | $1.84 \times 10^{-2} \pm 8.4 \times 10^{-4} \pm 1.7 \times 10^{-3}$ | $7.03 \times 10^{-3} \pm 4.7 \times 10^{-4} \pm 4.9 \times 10^{-4}$ |
| 1.65 | $1.37 \times 10^{-2} \pm 7.2 \times 10^{-4} \pm 1.2 \times 10^{-3}$ | $4.49 \times 10^{-3} \pm 3.7 \times 10^{-4} \pm 3.1 \times 10^{-4}$ |
| 1.75 | $9.31 \times 10^{-3} \pm 5.8 \times 10^{-4} \pm 8.4 \times 10^{-4}$ | $3.39 \times 10^{-3} \pm 3.4 \times 10^{-4} \pm 2.4 \times 10^{-4}$ |
| 1.85 | $5.90 \times 10^{-3} \pm 4.4 \times 10^{-4} \pm 5.3 \times 10^{-4}$ | $2.12 \times 10^{-3} \pm 2.4 \times 10^{-4} \pm 1.5 \times 10^{-4}$ |
| 1.95 | $4.02 \times 10^{-3} \pm 3.6 \times 10^{-4} \pm 3.6 \times 10^{-4}$ | $1.58 \times 10^{-3} \pm 2.2 \times 10^{-4} \pm 1.1 \times 10^{-4}$ |
| 2.05 | $3.11 \times 10^{-3} \pm 3.1 \times 10^{-4} \pm 2.8 \times 10^{-4}$ | $1.04 \times 10^{-3} \pm 1.7 \times 10^{-4} \pm 7.3 \times 10^{-5}$ |
| 2.15 | $1.99 \times 10^{-3} \pm 2.5 \times 10^{-4} \pm 1.8 \times 10^{-4}$ | $5.99 \times 10^{-4} \pm 1.5 \times 10^{-4} \pm 4.9 \times 10^{-5}$ |
| 2.25 | $1.37 \times 10^{-3} \pm 2.1 \times 10^{-4} \pm 1.2 \times 10^{-4}$ | $3.13 \times 10^{-4} \pm 1.3 \times 10^{-4} \pm 4.1 \times 10^{-4} \pm 2.2 \times 10^{-5}$ |
| 2.35 | $8.94 \times 10^{-4} \pm 1.5 \times 10^{-4} \pm 8.0 \times 10^{-5}$ | $2.43 \times 10^{-4} \pm 8.3 \times 10^{-5} \pm 1.7 \times 10^{-5}$ |
| 2.45 | $6.34 \times 10^{-4} \pm 1.3 \times 10^{-4} \pm 5.7 \times 10^{-5}$ | $1.80 \times 10^{-4} \pm 7.9 \times 10^{-5} \pm 1.3 \times 10^{-5}$ |
| 2.55 | $6.33 \times 10^{-4} \pm 1.4 \times 10^{-4} \pm 5.7 \times 10^{-5}$ | $1.74 \times 10^{-4} \pm 7.5 \times 10^{-5} \pm 1.2 \times 10^{-5}$ |
| 2.65 | $4.56 \times 10^{-4} \pm 1.2 \times 10^{-4} \pm 4.1 \times 10^{-5}$ | $2.39 \times 10^{-4} \pm 9.1 \times 10^{-5} \pm 1.7 \times 10^{-5}$ |
| 2.75 | $4.11 \times 10^{-4} \pm 1.1 \times 10^{-4} \pm 3.7 \times 10^{-5}$ | $6.57 \times 10^{-5} \pm 5.0 \times 10^{-5} \pm 4.7 \times 10^{-6}$ |
| 2.85 | $2.40 \times 10^{-4} \pm 9.5 \times 10^{-5} \pm 2.2 \times 10^{-5}$ | $7.07 \times 10^{-5} \pm 2.8 \times 10^{-5} \pm 5.1 \times 10^{-6}$ |
| 2.95 | $1.63 \times 10^{-4} \pm 6.6 \times 10^{-5} \pm 1.5 \times 10^{-5}$ | $4.14 \times 10^{-5} \pm 3.2 \times 10^{-5} \pm 3.1 \times 10^{-6}$ |
| 3.10 | $9.65 \times 10^{-5} \pm 3.7 \times 10^{-5} \pm 8.9 \times 10^{-6}$ | $5.21 \times 10^{-5} \pm 3.2 \times 10^{-5} \pm 4.0 \times 10^{-6}$ |
| 3.30 | $9.05 \times 10^{-5} \pm 4.1 \times 10^{-5} \pm 8.5 \times 10^{-6}$ | 2.0 |

TABLE XVIII. $p$ and $\bar{p}$ cross sections [ $\left.E d^{3} \sigma / d p^{3}\left(\mathrm{mb} \mathrm{GeV}^{-2} c^{3}\right)\right]$ in $p+p$ collisions at $\sqrt{s}=62.4 \mathrm{GeV}$. Statistical (second column) and systematic (third column) uncertainties are shown for each particle species. The normalization uncertainty ( $11 \%$ ) is not included. Feed-down weak decay corrections are applied.

| $p_{T}(\mathrm{GeV} / c)$ | $p$ | $\bar{p}$ |
| :--- | :--- | :--- |
| 0.65 | $2.95 \times 10^{-1} \pm 4.5 \times 10^{-3} \pm 6.6 \times 10^{-2}$ | $1.18 \times 10^{-1} \pm 1.8 \times 10^{-3} \pm 6.5 \times 10^{-2}$ |
| 0.75 | $2.38 \times 10^{-1} \pm 3.9 \times 10^{-3} \pm 3.8 \times 10^{-2}$ | $1.20 \times 10^{-1} \pm 2.0 \times 10^{-3} \pm 3.4 \times 10^{-2}$ |
| 0.85 | $1.96 \times 10^{-1} \pm 3.5 \times 10^{-3} \pm 2.5 \times 10^{-2}$ | $1.05 \times 10^{-1} \pm 1.9 \times 10^{-3} \pm 1.9 \times 10^{-2}$ |
| 0.95 | $1.40 \times 10^{-1} \pm 2.8 \times 10^{-3} \pm 1.6 \times 10^{-2}$ | $5.12 \times 10^{-2} \pm 1.7 \times 10^{-3} \pm 1.1 \times 10^{-2}$ |
| 1.05 | $1.03 \times 10^{-1} \pm 2.3 \times 10^{-3} \pm 1.1 \times 10^{-2}$ | $5.9 \times 10^{-2} \pm 1.4 \times 10^{-3} \pm 6.6 \times 10^{-3}$ |
| 1.15 | $7.18 \times 10^{-2} \pm 1.9 \times 10^{-3} \pm 7.1 \times 10^{-3}$ | $2.81 \times 10^{-2} \pm 1.1 \times 10^{-3} \pm 4.0 \times 10^{-3}$ |
| 1.25 | $5.23 \times 10^{-2} \pm 1.5 \times 10^{-3} \pm 5.1 \times 10^{-3}$ | $2.04 \times 10^{-2} \pm 8.1 \times 10^{-4} \pm 2.6 \times 10^{-3} \pm 1.8 \times 10^{-3}$ |
| 1.35 | $3.60 \times 10^{-2} \pm 1.2 \times 10^{-3} \pm 3.4 \times 10^{-3}$ | $1.33 \times 10^{-2} \pm 6.2 \times 10^{-4} \pm 1.1 \times 10^{-3}$ |
| 1.45 | $2.34 \times 10^{-2} \pm 9.1 \times 10^{-4} \pm 2.2 \times 10^{-3}$ | $9.42 \times 10^{-3} \pm 5.2 \times 10^{-4} \pm 7.8 \times 10^{-4}$ |
| 1.55 | $1.70 \times 10^{-2} \pm 7.7 \times 10^{-4} \pm 1.6 \times 10^{-3}$ | $6.19 \times 10^{-3} \pm 4.1 \times 10^{-4} \pm 5.1 \times 10^{-4}$ |
| 1.65 | $1.27 \times 10^{-2} \pm 6.7 \times 10^{-4} \pm 1.2 \times 10^{-3}$ | $3.97 \times 10^{-3} \pm 3.3 \times 10^{-4} \pm 3.2 \times 10^{-4}$ |
| 1.75 | $8.67 \times 10^{-3} \pm 5.4 \times 10^{-4} \pm 8.1 \times 10^{-4}$ | $3.00 \times 10^{-3} \pm 3.0 \times 10^{-4} \pm 2.4 \times 10^{-4}$ |
| 1.85 | $5.51 \times 10^{-3} \pm 4.1 \times 10^{-4} \pm 5.1 \times 10^{-4}$ | $1.88 \times 10^{-3} \pm 2.2 \times 10^{-4} \pm 1.5 \times 10^{-4}$ |
| 1.95 | $3.76 \times 10^{-3} \pm 3.3 \times 10^{-4} \pm 3.5 \times 10^{-4}$ | $1.41 \times 10^{-3} \pm 2.0 \times 10^{-4} \pm 1.1 \times 10^{-4}$ |
| 2.05 | $2.91 \times 10^{-3} \pm 2.9 \times 10^{-4} \pm 2.7 \times 10^{-4}$ | $9.24 \times 10^{-4} \pm 1.5 \times 10^{-4} \pm 7.4 \times 10^{-5}$ |
| 2.15 | $1.86 \times 10^{-3} \pm 2.4 \times 10^{-4} \pm 1.7 \times 10^{-4}$ | $6.21 \times 10^{-4} \pm 1.3 \times 10^{-4} \pm 5.0 \times 10^{-5}$ |
| 2.25 | $1.28 \times 10^{-3} \pm 2.0 \times 10^{-4} \pm 1.2 \times 10^{-4}$ | $5.25 \times 10^{-4} \pm 1.2 \times 10^{-4} \pm 4.2 \times 10^{-5}$ |
| 2.35 | $8.39 \times 10^{-4} \pm 1.4 \times 10^{-4} \pm 7.7 \times 10^{-5}$ | $2.78 \times 10^{-4} \pm 9.4 \times 10^{-5} \pm 2.2 \times 10^{-5}$ |
| 2.45 | $5.95 \times 10^{-4} \pm 1.2 \times 10^{-4} \pm 5.5 \times 10^{-5}$ | $2.16 \times 10^{-4} \pm 7.4 \times 10^{-5} \pm 1.7 \times 10^{-5}$ |
| 2.55 | $5.94 \times 10^{-4} \pm 1.3 \times 10^{-4} \pm 5.5 \times 10^{-5}$ | $1.60 \times 10^{-4} \pm 7.0 \times 10^{-5} \pm 1.3 \times 10^{-5}$ |
| 2.65 | $4.28 \times 10^{-4} \pm 1.1 \times 10^{-4} \pm 3.9 \times 10^{-5}$ | $1.55 \times 10^{-4} \pm 6.6 \times 10^{-5} \pm 1.2 \times 10^{-5}$ |
| 2.75 | $3.86 \times 10^{-4} \pm 1.1 \times 10^{-4} \pm 3.6 \times 10^{-5}$ | $2.13 \times 10^{-4} \pm 8.1 \times 10^{-5} \pm 1.7 \times 10^{-5}$ |
| 2.85 | $2.25 \times 10^{-4} \pm 8.9 \times 10^{-5} \pm 2.1 \times 10^{-5}$ | $5.85 \times 10^{-5} \pm 4.4 \times 10^{-5} \pm 4.7 \times 10^{-6}$ |
| 2.95 | $1.54 \times 10^{-4} \pm 6.2 \times 10^{-5} \pm 1.4 \times 10^{-5}$ | $6.30 \times 10^{-5} \pm 2.5 \times 10^{-5} \pm 5.2 \times 10^{-6}$ |
| 3.10 | $9.06 \times 10^{-5} \pm 3.4 \times 10^{-5} \pm 8.5 \times 10^{-6}$ | $3.69 \times 10^{-5} \pm 2.8 \times 10^{-5} \pm 3.1 \times 10^{-6}$ |
| 3.30 | $8.50 \times 10^{-5} \pm 3.8 \times 10^{-5} \pm 8.1 \times 10^{-6}$ | $4.64 \times 10^{-5} \pm 2.8 \times 10^{-5} \pm 4.0 \times 10^{-6}$ |
| 3.50 | $2.00 \times 10^{-5} \pm 1.7 \times 10^{-5} \pm 2.0 \times 10^{-6}$ |  |
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