Hyperon (Λ^0, $\overline{\Lambda}^0$, $\Xi^{\pm}$, and $\Omega^{\pm}$) Production in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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Abstract

We report a set of measurements of inclusive invariant transverse momentum differential cross sections of hyperons reconstructed in the central region ($|\eta| < 1$). Using the CDF II detector at the Tevatron Collider, events are collected with a minimum-bias trigger in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. The invariant differential cross sections are also presented for different charged particle multiplicity intervals.

Ever since their discovery from cosmic ray interactions [1], particles containing strange quarks have been extensively studied at particle colliders (e^+e^- [2],ep [3], $p\bar{p}$ [4] and pp [5]). The data have been used to test QCD and build phenomenological models extending QCD predictions beyond what can be calculated from first principles. The interest in particles containing strange quarks increased with the introduction of the quark-gluon plasma mechanism. Formation of quark-gluon plasma in a collision could manifest itself with an enhanced production of strange particles such as kaons and hyperons [6].

There is ample data on the production of particles with one strange quark, but very little available on particles with two or more [7, 8]. Previous studies of hyperons from colliders such as RHIC [9], $Sp\bar{p}S$ [10], and the Tevatron [11, 12] were limited by low sample statistics and the range of hyperon momentum component transverse to the beam direction (p_T) considered. In this Letter, we report on a new study of the hyperons Λ^0 (quark content uds), Ξ^- (dss), and Ω^- (sss) and their corresponding antiparticles ($\overline{\Lambda}^0$, Ξ^+, and Ω^+). For these hyperons, the inclusive invariant p_T differential cross sections are measured up to p_T of 10 GeV/c based on $\sim$ 100 million minimum-bias events collected with the CDF II detector between March 2002 and February 2008.

The CDF II detector is described in detail elsewhere [13]. The components most relevant to this analysis are those that comprise the tracking system, which lies within a uniform axial magnetic field of 1.4 Tesla. The inner tracking volume is composed of a system of eight layers of silicon microstrip detectors ranging in radius from 1.5 and 28.0 cm [14] in the pseudorapidity region $|\eta| < 2$ [15]. The remainder of the tracking volume is occupied by the Central Outer Tracker (COT). The COT is a cylindrical drift chamber containing 96 sense wire layers grouped in eight alternating superlayers of axial and stereo wires [16]. Its active volume covers 40 to 140 cm in radius and $|z| < 155$ cm. The transverse momentum resolution of tracks reconstructed using COT hits is $\sigma(p_T)/p_T^2 \sim 0.0017/(\mathrm{GeV}/c)$.

Events for this analysis are collected with the "minimum-bias" (MB) trigger which ensures to contain at least one $p\bar{p}$ interaction if there is a coincidence in time of signals in both forward and backward gas Cherenkov counters [17] covering the forward regions $3.7 < |\eta| < 4.7$. The MB trigger is rate-limited to keep the final trigger output at 1 Hz. Primary or event vertices are identified by the convergence of reconstructed tracks along the beam axis. Events are accepted which contain a reconstructed vertex in the fiducial region $|z_{vtx}| \leq 60$ cm centered around the nominal CDF position ($z = 0$). When an event has more than one vertex, the highest quality vertex, usually the one with the most associated tracks is selected and it is required there be no other vertices within ±5 cm of this vertex. This selection introduces a bias toward high multiplicity events as the instantaneous luminosity increases. To combine events collected at different average instantaneous luminosities, we determine a per-event weight as a function of the track multiplicity N_{ch} in order to match the multiplicity distribution of a data sample where the average number of interactions is less than 0.3 per bunch crossing. For the N_{ch} calculation, tracks are required to have a high track-fit quality with χ^2 per degree-of-freedom less than 2.5, and more than five hits in at least two axial and two stereo COT segments. It is further required that tracks satisfy $|\eta| < 1$, impact parameter d_0 [18] less than 0.25 cm, the distance along the z-axis (δZ_0) between the event vertex and the track position at the point of closest approach to the vertex in the $r-\phi$ plane be less than 2 cm and $p_T > 0.3$ GeV/c. The p_T selection is to minimize the inefficiency of the track-finding algorithm for low momentum tracks.

We search for $\Lambda^0 \to p\pi^-$ decays using tracks with opposite-sign charge and $p_T > 0.325$ GeV/c. In this Letter, any reference to a specific charge state implies the antiparticle state as well. For each two-track system we calculate their intersection coordinate in the $r - \phi$ plane. Once this intersection point, referred to as the secondary vertex, is found, the z-coordinate of each track (Z_1 and Z_2) is calculated at that point. If the distance $|Z_1 - Z_2|$ is less than 1.5 cm, the tracks are considered to originate from a Λ^0 decay. The pair is traced back to the vertex and we require δZ_0 be less than 2 cm, and the d_0 be less than 0.25 cm. To further reduce backgrounds, we require the Λ^0 decay length L_{Λ^0}, the distance in the $r-\phi$ plane between the primary and secondary vertices, to be greater than 2.5 cm and less than 50 cm.

The invariant mass $M_{p\pi}$ of the two-track system is calculated by attributing the proton mass to the track with the higher p_T as expected by the kinematics of a Λ^0 decay. Fig. 1 shows the invariant mass for Λ^0 candidates with $|\eta| < 1$. This distribution is divided into 15 p_T intervals and the number of Λ^0 in each p_T interval is deter minded by fitting the invariant mass distributions using a Gaussian function for the signal and a third-order polynomial for the underlying combinatorial background. We fit the data in the mass range $1.10 - 1.16$ GeV/c^2. The polynomial fit to the background is subtracted bin-by-bin from the data entries in the Λ^0 mass window ($1.111 - 1.121$ GeV/c^2) to obtain the number of Λ^0 hyperons. This number is divided by the acceptance to obtain the invariant differential p_T distribution as described later.

The fitting procedure is one source of systematic uncertainties. This uncertainty is estimated by changing the mass range of the fit, the functional form for the signal to a double Gaussian, and the background modeling function to a second-order polynomial. The number of Λ^0 is recalculated for each variation and for each p_T interval. The systematic uncertainty is determined as the sum in quadrature of the fractional change in the number of Λ^0 from each modified fit. It decreases from $\pm 10\%$ at the lowest p_T (1.2 GeV/c) and decreases to less than $\pm 5\%$ above 1.75 GeV/c p_T.

The cascade reconstruction decay mode is $\Xi^- \to \Lambda^0\pi^- \to (p\pi^-)\pi^-$. The previously reconstructed Λ^0 candidates are used, but without the d_0 and δZ_0 requirements. We select Λ^0 candidates in the Λ^0 mass window and calculate the coordinate of the intersection point in the $r-\phi$ plane between the Λ^0 candidate and a third track. The z-axis coordinates at this point are calculated for the third track (Z_3) and the Λ^0 candidate (Z_4). The three-track system is considered a Ξ^- candidate decay if the distance $|Z_3 - Z_4| < 1.5$ cm. We also require the decay length of the Ξ^- candidate to be greater than 1 cm and that of the Λ^0 candidate to be between 2.5 and 50 cm. To enhance the selection of Λ^0 from Ξ^- decays, we ask the difference between the Ξ^- and Λ^0 decay lengthes to be greater than 1 cm. Finally, it is required that the d_0 of the Ξ^- candidate be less than 0.25 cm and the distance δZ_0 along the z-axis between the Ξ^- and the primary vertex be less than 2 cm.

The invariant mass $M_{\Lambda^0\pi}$ is calculated by fixing the mass of the Λ^0 candidate to 1.1157 GeV/c^2 [19] and assigning the pion mass to the third track. The subscript Λ^0 implies the Λ^0 candidates to lie within the Λ^0 mass window. Fig. 1 shows the invariant mass for Ξ^- candidates with $|\eta| < 1$ overlaid with the fitted curve.

As it is done for the Λ^0 case, the Ξ^- candidates are divided in p_T intervals and the number of Ξ^- in each interval is determined by fitting the corresponding $M_{\Lambda^0\pi}$ invariant mass distribution using a Gaussian function for the signal and a third-order polynomial for the background. The fitted background is then subtracted bin-by-bin from the data entries in the signal region (1.31 to 1.33 GeV/c^2) to obtain the Ξ^- yield in every p_T interval. The systematic uncertainty of the fit procedure is estimated the same way as for the Λ^0 and is found to change by no more than $\pm 5\%$ in all p_T intervals.

To reconstruct Ω^- decays we follow the same procedure as for the Ξ^- and apply the same selection criteria except the third track is assigned the kaon mass. The search decay mode is

$\Omega^- \to \Lambda^0 K^- \to (p\pi^-)K^-$. Because of the larger background, the procedure to extract the Ω^- signal yield is slightly different than what is performed in the previous cases. Track pairs with $M_{p\pi^-}$ in the mass ranges $1.095 - 1.105$ and $1.127 - 1.137$ GeV/c^2 are combined with the third track to obtain the invariant mass distribution of the combinatorial background. This distribution is subtracted from the $M_{\Lambda^0 K^-}$ distribution after normalizing to the number of events in the mass window $1.69 < M_{\Lambda^0 K^-} < 1.74$ GeV/c^2. The background subtracted $M_{\Lambda^0 K^-}$ invariant mass distribution is shown in Fig. 1.

The distribution is divided in p_T intervals, and we use the method described above to extract the Ω^- signal from the corresponding invariant mass distributions in each p_T interval with the mass window 1.66 to 1.68 GeV/c^2. The systematic uncertainty due to the fitting procedure is also calculated in a similar matter as Ξ^- with the exception of the double Gaussian variation because of low statistics. One additional source of the uncertainty is from the combinatorics background subtraction, which is evaluated by reducing the normalization of the background to 80% of the original value. The overall uncertainties are about $\pm 10\%$ for all p_T intervals.

The geometric and kinematic acceptance is estimated with Monte Carlo simulations [20]. In each simulation, the resonance states are generated with fixed p_T corresponding to 14 different points ranging from 0.75 to 10 GeV/c and flat in rapidity $|y| < 2$. In each sample the generated resonance is combined with either one or four inelastic MB event generated with the PYTHIA [21] generator. The default acceptance is derived from the sample with four MB events and the difference of the acceptance values between the two samples is one of our systematic uncertainties in acceptance. Based on a study with tracks from K_s^0 decay, the sample with four MB events reproduces the low p_T tracking efficiency in real data within the uncertainty.

The detector response to particles produced in the simulation is modeled with the CDF II detector simulation that in turn is based on the GEANT-3 Monte Carlo program [22]. Simulated events are processed and selected with the same analysis code used for the data. The acceptance is defined as the ratio of the reconstructed number of resonances over the generated number, excluding resonances contained in the MB events. Acceptance values are calculated separately for the particles and their corresponding antiparticles and the average of the two is used as the default value since the acceptances for the two states are similar. The acceptance values obtained for the 14 p_T points are fitted with a fourth order polynomial function and the fitted curve is used to correct the number of each hyperon state in the data.

The modeling of the MB events overlapping with the examined resonance and the selection criteria applied contribute systematic uncertainty to the acceptance calculation. The contribution from the modeling of the MB events is already mentioned. Acceptance variations due to the selection criteria are examined by changing the track p_T threshold to ± 0.025 GeV/c from the nominal value and the $|Z_1 - Z_2|$ track separation to ± 0.5 cm from the nominal value. We also study the criteria applied directly to select the candidates of each resonance state, like the δZ_0 (increased from 2 to 5 cm), the d_0 (lowered to 0.10 cm) and the decay length requirement for the Λ^0 case (varied to 1 and 5 cm). For Ξ^- and Ω^- cases we also vary the difference between the Λ^0 and Ξ^- or Ω^- decay lengthes from 1 to 3 cm. The systematic uncertainty associated with the Ω^- hyperon acceptance is derived from the Ξ^- uncertainty estimate since the reconstruction follows the same criteria. For each considered variation, a new acceptance curve as a function of p_T is obtained and the percentage change between the new p_T distribution and the one with the default selection requirements is taken as the uncertainty in the acceptance for the specific p_T interval. The square root of the quadratic sum of the uncertainties from each variation is taken as the total conservative uncertainty on the acceptance in a given p_T bin. This uncertainty is added quadratically to the systematic uncertainty due to the fitting procedure described earlier for the total systematic uncertainty.

For the Λ^0 case, the acceptance uncertainty decreases from about 25% at $p_T \sim 1$ GeV/c to 10% at $p_T \sim 2$ GeV/c and then rises again slowly to 15% for $p_T > 7$ GeV/c. The corresponding acceptance uncertainty for the Ξ^- case decreases from about 15% at $p_T \sim 2$ GeV/c to 10% for $p_T > 4$ GeV/c.

The inclusive invariant p_T differential cross section for each hyperon resonance is calculated as $Ed^3\sigma/dp^3 = (\sigma/N_{evt})d^3N/Ap_Tdp_Tdyd\phi = (\sigma/2\pi N_{evt})\Delta N/Ap_T\Delta p_T\Delta y$ where σ is our triggered MB cross section, N_{evt} is the number of events, ΔN is the number of hyperons observed in each p_T interval (Δp_T) after background subtraction, A is the acceptance in the specific p_T interval, and Δy the rapidity range used in the acceptance calculation (-2 to 2).

Fig. 2 shows the results for the inclusive invariant p_T differential cross section for the three hyperon resonances. The uncertainties shown for each data point include the statistical and all systematic uncertainties described above except the one associated with the total minimum-bias cross section [23].

TABLE I: The results of power law function fits to the inclusive invariant p_T differential cross sections shown in Fig. 2 for $p_T > 2$ GeV/c. The parameter p_0 is fixed to 1.3 GeV/c in all fits. The K_s^0 values are from Ref. [24] at $\sqrt{s} = 1.8$ TeV. The uncertainties shown do not include the MB cross section uncertainty [23]. The last line of the table gives the χ^2 per degree-of-freedom of the fit to data.

Parameter (units)	K_s^0 [24]	Λ^0	$\Xi^\pm$	$\Omega^\pm$
A (mb/GeV$^2c^3$)	45 ± 9	210 ± 25	14.9 ± 2.5	1.50 ± 0.75
p_0 (GeV/c)	1.3	1.3	1.3	1.3
n	7.7 ± 0.2	8.81 ± 0.08	8.26 ± 0.12	8.06 ± 0.34
χ^2/dof	8.1/11	5.7/15	15.8/15	10.5/7

TABLE II: The results of exponential function fits to the inclusive invariant p_T differential cross sections shown in Fig. 2 for the p_T ranges given in the second row. The uncertainties shown do not include the MB cross section uncertainty [23]. The last line of the table gives the χ^2 per degree-of-freedom of the fit to data.

Parameter (units)	Λ^0	Λ^0	$\Xi^\pm$	$\Omega^\pm$
p_T range (GeV/c)	[1.2, 2.5]	[1.2, 4]	[1.5, 4]	[2, 4]
B (mb/GeV$^2c^3$)	4.68 ± 1.04	3.16 ± 0.35	0.16 ± 0.043	0.024 ± 0.011
b (GeV^{-1}c)	2.30 ± 0.12	2.10 ± 0.04	1.75 ± 0.08	1.80 ± 0.19
χ^2/dof	1.0/7	7.2/12	4.0/8	6.3/3

The inclusive invariant p_T differential cross section is modeled by a power law function, $A(p_0)^n/(p_T + p_0)^n$, for $p_T > 2$ GeV/c. In order to compare with the previous CDF K_s^0 result [24], p_0 is fixed at 1.3 GeV/c, and the results are shown in Table I. The data below $p_T \sim 2$ GeV/c cannot be described well by the power law function even if p_0 is allowed to float. For this region, the data is better described by an exponential function, $B\exp[-b \cdot p_T]$. The results of this fit are shown in Table II, and the slope b is consistent with previous measurements [11, 12].

The plots in Fig.2 show the ratio of the differential cross sections for Ξ^- and Λ^0, and Ω^- and Λ^0. In the Ξ^-/Λ^0 ratio there is a gentle rise at low p_T, and the ratio plateaus at $p_T > 4$

GeV/c. It should be noted that the Λ^0 cross section also includes Λ^0 production from the decay of other hyperon states ($\Sigma^0 \rightarrow \Lambda^0\gamma$, $\Xi^{\pm}$, Ξ^0 and $\overline{\Xi}^0$). Due to the short Σ^0 lifetime, Λ^0 from Σ^0 decay cannot be separated from direct Λ^0 production. Simulations of cascade decays indicate that $\sim 50\%$ of Λ^0 from Ξ decay will satisfy our Λ^0 selection criteria, with the fraction of Λ^0 fairly independent of Ξ p_T. The ratio plots in Fig.2 are fitted to a constant and the value 0.17 ± 0.01 is obtained for Ξ^-/Λ^0 and 0.025 ± 0.02 for Ω^-/Λ^0.

Fig. 3 shows the inclusive p_T distributions for two charged particle multiplicity regions, $N_{ch} < 10$ and $N_{ch} > 24$. $N_{ch} = 24$ (10) corresponds to $dN/d\eta \sim 16(7)$, including the track reconstruction efficiency and unreconstructed tracks with $p_T < 0.3$ GeV/c [25]. Due to the low sample statistics of the Ω^-, distributions are only shown for Λ^0 and Ξ^-. We observe a correlation between high p_T particles and high multiplicity events.

In summary, the production properties of Λ^0, Ξ^-, and Ω^- hyperons reconstructed from minimum-bias events at $\sqrt{s} = 1.96$ TeV are studied. The inclusive invariant p_T differential cross sections are modeled well by a power law function above $p_T \sim 2$ GeV/c. With fixed p_0, the fit parameter n decreases by about 10% from Λ^0 to Ω^-. The low p_T regions are modeled by an exponential function. The exponential slope, b, depends on the range of the fit but is around 2, which corresponds to an average p_T of 1 GeV/c under the assumption that the fit can be extrapolated down to $p_T = 0$ GeV/c. The production ratios Ξ^-/Λ^0 and Ω^-/Λ^0 are presented as a function of p_T and are fairly constant. We also find the hyperon inclusive invariant p_T distributions fall off faster with p_T for low multiplicity events than for high multiplicity events.

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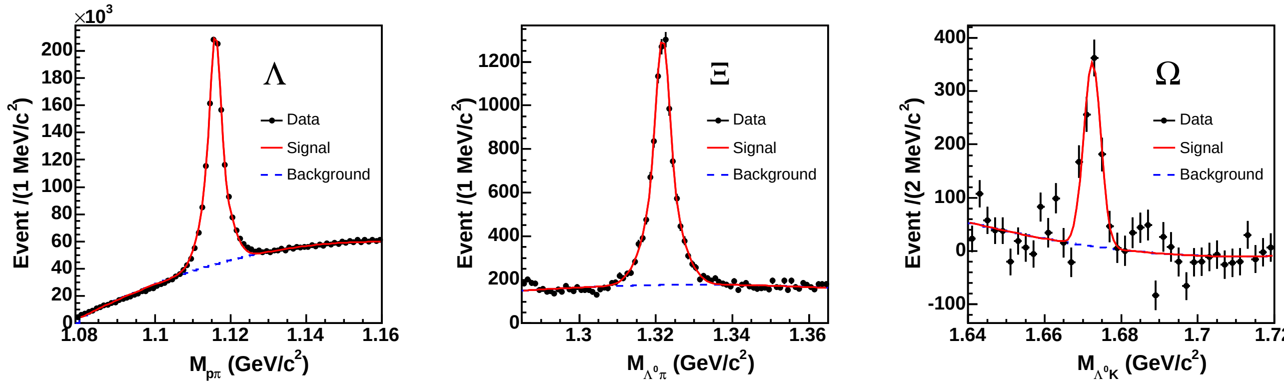

FIG. 1: Reconstructed invariant mass distributions for $M_{p\pi}$ (left), $M_{\Lambda^0\pi}$ (center), and M_{Λ^0K} (right). The background has been subtracted from the M_{Λ^0K} distribution. The solid lines are fitted curves, a third-degree polynomial for the background and either a double ($M_{p\pi}$ and $M_{\Lambda^0\pi}$) or single (M_{Λ^0K}) Gaussian function to model the peak.

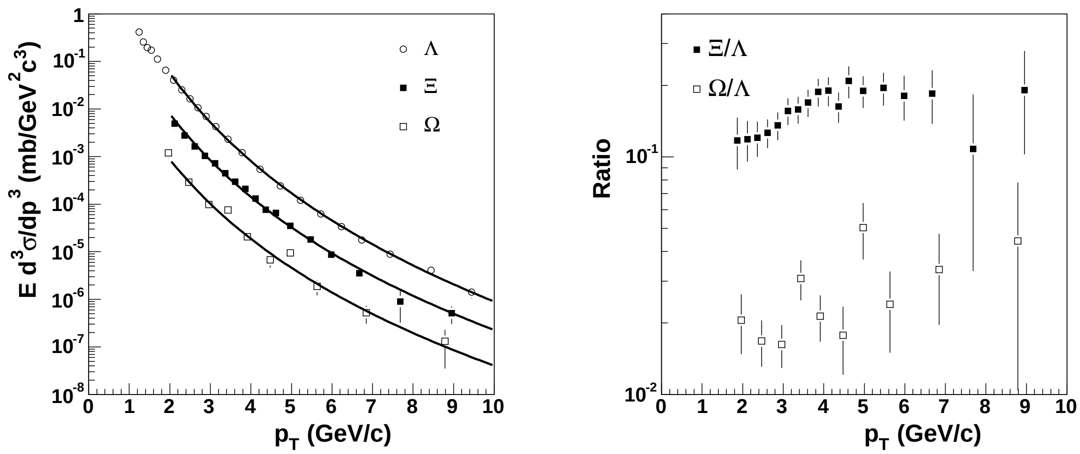

FIG. 2: On the left are the inclusive invariant p_T differential cross section distributions for Λ^0, Ξ^-, and Ω^- within $|\eta| < 1$. The solid curves are from fits to a power law function, with the fitted parameters given in Table I. On the right is shown the ratios of Ξ^-/Λ^0 and Ω^-/Λ^0 as a function of p_T.

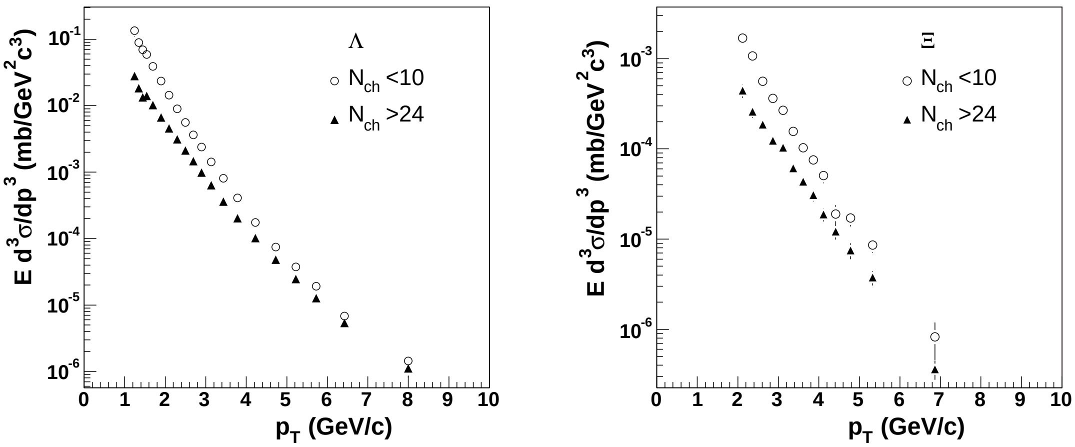

FIG. 3: Inclusive p_T distributions for two charged particle multiplicity regions, $N_{ch} < 10$ and $N_{ch} > 24$. Distributions for Λ^0 are shown on the left while distributions for Ξ^- are shown on the right.