

## Nuclear Dependence of High- $x_t$ Hadron and High- $\tau$ Hadron-Pair Production in $p$ - $A$ Interactions at $\sqrt{s} = 38.8$ GeV

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(Received 26 December 1990; revised manuscript received 18 October 1991)

We present a high-statistics, species-identified measurement of the W-to-Be per-nucleon cross-section ratio,  $R_{W/Be}$ , for high- $x_t$  hadrons and high- $\tau$   $h^+h^-$  pairs produced in  $p$ - $A$  collisions at  $\sqrt{s} = 38.8$  GeV. The data extend to 0.62 in  $x_t$  and 0.39 in  $\sqrt{\tau}$ . For single hadrons,  $R_{W/Be}$  peaks at  $p_t \approx 5$  GeV/ $c$  and decreases to  $\approx 1$  for mesons with  $p_t > 8$  GeV/ $c$ . At fixed  $p_t$ ,  $R_{W/Be}$  falls with  $\sqrt{s}$ . For symmetric pairs with  $\sqrt{\tau} > 0.28$ ,  $R_{W/Be} = 0.84 \pm 0.02 \pm 0.07$ , suggesting a nuclear suppression of high- $z$  fragmentation.  $R_{W/Be}$  increases with  $p_{out}$ , indicative of constituent multiple scattering.

PACS numbers: 13.85.Ni, 13.87.Fh, 25.40.Ve

We have studied the production of high- $x_t$  charged hadrons and high- $\tau$   $h^+h^-$  pairs in collisions of 800-GeV protons with tungsten and beryllium targets. Here we present W-to-Be per-nucleon cross-section ratios, designated  $R_{W/Be}$  [1]. The single-hadron data cover  $0.21 < x_t < 0.62$ , where  $x_t = 2p_t/\sqrt{s}$ , and proton-nucleon center-of-momentum angles between  $76^\circ$  and  $95^\circ$ . The pair results are for "back-to-back" pairs (i.e., the  $p_t$  vectors approximately antiparallel) with  $0.21 < \sqrt{\tau} < 0.39$ , where  $\tau = m^2/s$ . These data extend previous measurements [2-6] to higher values of  $p_t$ , mass, and  $\sqrt{s}$ .

Since high- $x_t$  hadrons result from parton fragmentation at high momentum fraction  $z$  [7], where  $z = p_{hadron}/p_{parton}$ , their production can serve as a probe of underlying parton-level processes. Back-to-back hadron pairs with a large component of momentum out of the scattering plane (high  $p_{out}$ ) signal more complicated interac-

tions than a single parton-parton elastic scatter, such as rescattering of an outgoing parton. (We define  $p_{out}$  as the momentum component of the lower- $p_t$  hadron perpendicular to the plane defined by the beam and the higher- $p_t$  hadron.)

The apparatus, described in detail elsewhere [5,8], is a focusing pair spectrometer, located in the Meson East laboratory at Fermilab. 800-GeV primary protons extracted from the Tevatron were incident on the targets described in Table I. Beam flux (typically  $10^{10}/s$ ) was measured by a secondary-emission monitor. The fraction of protons incident on the target was monitored with a four-counter telescope viewing the target at  $90^\circ$  in the laboratory. Noninteracting beam and hadron secondaries with laboratory production angles less than 30 mrad were absorbed in a tungsten collimator and a 5-m-long copper beam dump positioned 5 m from the target. The dump

TABLE I. Properties of targets. "Outgoing interaction lengths" gives the average for a pion created at  $90^\circ$  in the proton-nucleon frame.

Material	$A$	Length (cm)	Height (mm)	Interaction lengths	Outgoing interaction lengths	Integrated luminosity ( $10^{39} \text{ cm}^{-2}$ )	Fraction of protons on target
Be	9.01	5.560	0.546	0.137	0.009	9.04	0.946
Be		5.928	1.067	0.146	0.017	1.38	0.995
W	183.85	1.316	1.062	0.137	0.049	1.90	0.995

was located within a large spectrometer magnet which provided a 7.6-GeV/c vertical  $p_t$  kick, sweeping low-momentum charged particles out of the aperture. High- $p_t$  positive (negative) particles passing over (under) the beam dump were reanalyzed in a second magnet ( $p_t$  kick=0.9 GeV/c, directed oppositely to that of the first magnet) located 27 m from the target. Particle trajectories were measured between the two magnets by six multiwire proportional chambers, and downstream of the magnets by two stations of six drift chambers each. Resolutions of 1.0% in  $p_t$  and 0.4% in mass were obtained. The resolution in  $p_{out}$  for a pair of mass  $m$  was 0.02 $m$ . Hadrons were identified with a ring-imaging Cherenkov detector [9]. Hodoscope planes and a steel/scintillator calorimeter (with a lead/scintillator electromagnetic portion) provided fast signals used to trigger data acquisition.

Event-by-event corrections were computed for trigger and track-reconstruction inefficiencies, absorption in the apparatus, and decays in flight. Geometric acceptance corrections were applied and affected  $R_{W/Be}$  by less than 1% in all  $p_t$  bins. For the pair data, the background of accidental  $h^+h^-$  pairs was estimated and subtracted. The background rate, shown in Table II, was assumed to be proportional to the product of the rates for positive and negative hadrons and to the mean square number of incident protons per beam bunch; the latter was determined for each beam spill by counting coincidences in two widely separated monitor counters. The shape of the random-pair background was determined using a sample of simulated pairs generated by overlaying single-hadron events. To correct for the dependence of reconstruction efficiency on detector rates, yields were binned in the number of monitor-counter random coincidences per spill and an efficiency-correction factor was determined for each bin. For each target, overall efficiency-correction factors were computed as luminosity-weighted averages of the per-bin factors. Applying these corrections increased  $R_{W/Be}$  by about 5% for single hadrons and 13% for hadron pairs.

Figure 1 shows the  $p_t$  dependence of  $R_{W/Be}$  for single hadrons. The error bars represent statistical errors added in quadrature with a systematic error due to particle identification [1]. Systematic normalization uncertainties result in a 5% scale error in  $R_{W/Be}$  (limit of error), dominated by the uncertainty in the efficiency-correction factors. Also shown in Fig. 1 are previous results [2] ob-

TABLE II. Background-to-signal ratio vs mass and  $p_{out}$  for Be and W target data.

Mass (GeV/c <sup>2</sup> )	Background/signal		$p_{out}$ (GeV/c)	Background/signal	
	Be	W		Be	W
7.8	0.101	0.513	0.2	0.016	0.107
9.2	0.017	0.104	1.0	0.026	0.156
11.4	0.002	0.010	2.2	0.113	0.472

tained at 400 GeV, which have been converted from  $a$  to  $R_{W/Be}$  using  $R_{W/Be} = (A_W/A_{Be})^{a-1}$ . For pions and kaons,  $R_{W/Be}$  drops monotonically for  $p_t > 6$  GeV/c, reaching values compatible with 1 for  $p_t > 8$  GeV/c. If the  $p_t$  region between 4 and 6 GeV/c is fitted by a smooth curve, the maximum  $R_{W/Be}$  is  $1.33 \pm 0.01$  for  $\pi^+$  and  $1.35 \pm 0.02$  for  $\pi^-$ . For  $K^+$ ,  $R_{W/Be}$  drops from a value of  $1.49 \pm 0.02$  at  $p_t$  of 4.2 GeV/c, while for  $K^-$ ,  $R_{W/Be}$  peaks at  $1.66 \pm 0.07$ . The largest nuclear enhancements are observed for  $p$ 's and  $\bar{p}$ 's: The maximum  $R_{W/Be}$  is  $2.1 \pm 0.1$  for protons and  $2.5 \pm 0.7$  for antiprotons.

The species dependence seen in Fig. 1 is partially explained by existing constituent multiple scattering models [10-12]. Such models account for the strong nuclear dependence of  $K^-$ , whose production should be dominated by the scattering and fragmentation of gluons, in terms of the increased probability for rescattering in nuclear matter of gluons relative to that of quarks [10]. For  $p_t$  between 4 and 9 GeV/c,  $R_{W/Be}^{K^+}$  is on average  $0.12 \pm 0.02$  larger than  $R_{W/Be}^{K^-}$ . This difference could result from a larger  $K^+/\pi^+$  ratio in the high- $z$  fragmentation of gluons as compared to  $u$  quarks. The fraction of  $K^+$ 's of gluonic origin can be estimated from the  $K^-/K^+$  ratio,  $0.36 \pm 0.02$  at  $p_t$  of 5 GeV/c in  $p$ -Be interactions [1]. Alternatively, the larger nuclear enhancement of  $K^+$  could reflect a nuclear enhancement of the  $K^+/\pi^+$  ratio in high- $z$  quark or gluon fragmentation. High- $p_t$  protons

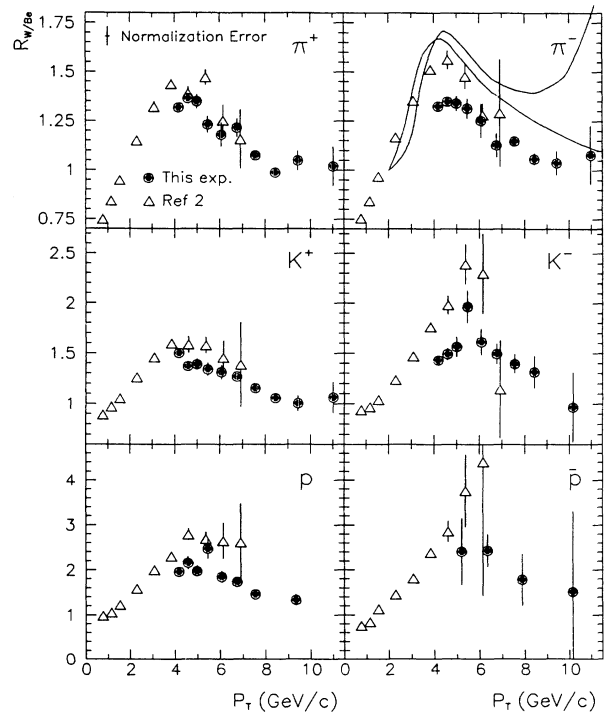


FIG. 1. W-to-Be ratio of per-nucleon cross sections,  $R_{W/Be}$ , vs  $p_t$  for each hadron species. Also shown are results [2] at  $\sqrt{s} = 27.4$  GeV and model calculations [12] for  $\pi^-$  at  $\sqrt{s} = 27.4$  GeV (upper curve) and  $\sqrt{s} = 51.3$  GeV (lower curve).

can be produced from either a scattered pointlike diquark [1,13] or from a scattered valence quark which pulls a diquark from the vacuum. Thus, the larger enhancement for protons compared to  $\pi^+$ 's indicates either that diquarks have a larger rescattering cross section than  $u$  quarks or that the process of binding a diquark to a  $u$  quark at high  $z$  is enhanced in nuclei. Quantitative evaluation of these effects requires detailed model calculations not available in the current literature.

Figure 2 shows the  $\sqrt{s}$  dependence of  $R_{W/Be}$  for  $p_t=4.61$  GeV for each hadron species. The drop of  $R_{W/Be}$  with  $\sqrt{s}$  for  $\pi^-$  is steeper than predicted by the model calculations [12] shown.

For high- $\tau$  hadron pairs, the ratio  $R_{W/Be}$  is plotted versus mass and  $p_{out}$  in Fig. 3. Also shown are the results of Streets *et al.* [6] converted from  $\alpha$  to  $R_{W/Be}$  as described above. In what follows, we quote the statistical error, followed by the systematic uncertainty in the background subtraction. The error bars in Fig. 3 represent these two errors added in quadrature. For pairs, we estimate an additional 8% scale error in  $R_{W/Be}$  (limit of error) due to normalization uncertainties.  $R_{W/Be}$  drops smoothly with increasing mass from  $1.05 \pm 0.04 \pm 0.09$  at  $7.8$  GeV/ $c^2$  to  $0.84 \pm 0.02 \pm 0.01$  for mass above  $11$  GeV/ $c^2$ .  $R_{W/Be}$  rises from  $0.86 \pm 0.01 \pm 0.02$  at low  $p_{out}$  to  $1.23 \pm 0.06 \pm 0.09$  for  $p_{out} > 1.8$  GeV/ $c$ . The rise of  $R_{W/Be}$  with  $p_{out}$  strongly indicates constituent rescattering

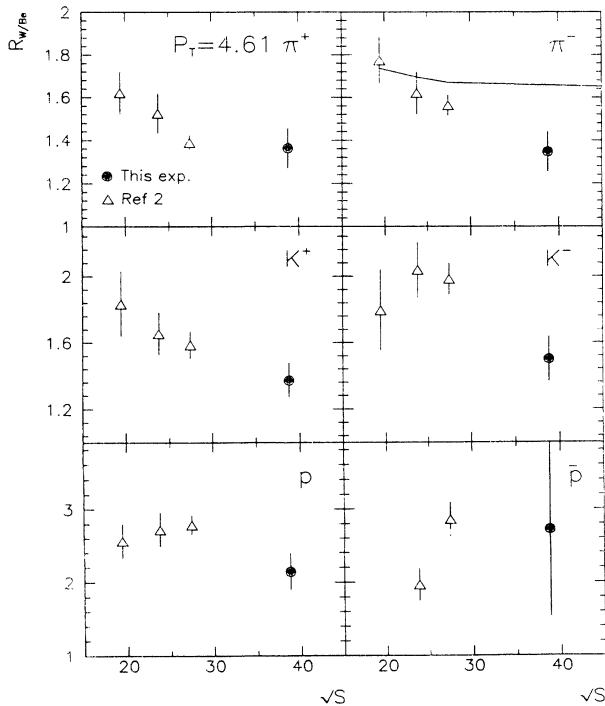


FIG. 2.  $R_{W/Be}$  vs  $\sqrt{s}$  at  $p_t=4.61$  GeV/ $c$  for each hadron species using our results (error bars include scale error) and results from Ref. [2]. Also shown are model calculations [12] for  $\pi^-$ .

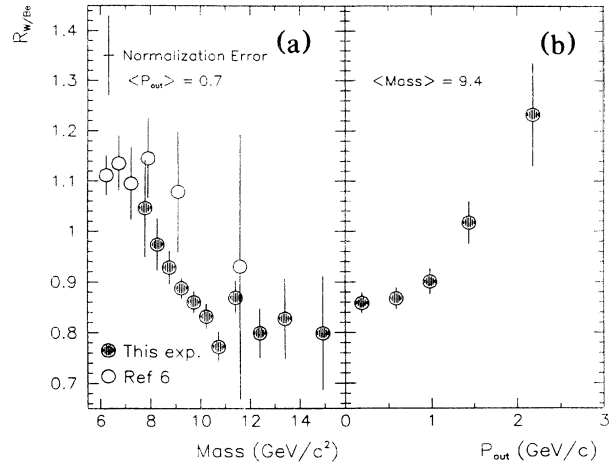


FIG. 3. W-to-Be ratio of per-nucleon cross section,  $R_{W/Be}$ , vs (a) mass and (b)  $p_{out}$  for  $h^+h^-$  pairs.

in the target nucleus.

Previous lower-energy experiments [4,5] have seen a nuclear suppression of high-mass hadron pairs for  $\sqrt{\tau} > 0.35$ . The drop of  $R_{W/Be}$  with mass can be partly explained by the depletion in nuclei of the valence structure functions for  $x > 0.25$  (the European Muon Collaboration effect [14–16]). For hadron pairs with rapidity near zero, the  $x$  of the scattered target parton can be estimated as  $\sqrt{\tau}/\langle z \rangle$ , where  $\langle z \rangle$  is the mean value of  $p_{hadron}/p_{parton}$ . We infer from existing results [7] that  $\langle z \rangle \approx 0.85$  for pairs with mass  $12.4$  GeV/ $c^2$ , corresponding to a target-parton  $x$  of  $0.38$ . At that mass, we measure  $R_{W/Be} = 0.80 \pm 0.05 \pm 0.07$  (includes scale error) or  $\alpha = 0.93 \pm 0.02 \pm 0.03$ . Arnold *et al.* [15] have parametrized the  $x$  dependence of deep-inelastic  $e^-A$  cross sections as  $\sigma_A/\sigma_D = cA^\alpha$ . For  $x=0.38$ , they found that  $\alpha = 0.987 \pm 0.002$ . Similarly, assuming an  $A^\alpha$  form for  $F_2^A$ , the measurements of Benvenuti *et al.* [16] of  $F_2^{Fe}/F_2^D$  correspond to  $\alpha = 0.987 \pm 0.005$  at  $x=0.35$  and  $\alpha = 0.976 \pm 0.009$  at  $x=0.45$ .

Except at the limit of our systematic uncertainties, the European Muon Collaboration effect is too small to account for the observed nuclear suppression of high-mass hadron pairs. Multiple scattering models also cannot accommodate the observed behavior [17]. Another contributing factor could be a nuclear suppression of high- $z$  hadronization. Since the single-hadron cross section is proportional to a single fragmentation function while the pair cross section is proportional to a product of two fragmentation functions, any suppression of high- $z$  fragmentation due to the nuclear medium would exert a stronger effect on pairs than on single hadrons [18].

This work was supported in part by the U.S. Department of Energy, the National Science Foundation, the Commissariat à l’Energie Atomique, and the Japan Ministry of Education, Science and Culture (Monbusho).

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