Dimuon Scaling Comparison at 44 and 62 GeV

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Measurements of $pp \to \mu^+\mu^- + X$ at $\sqrt{s} = 44$ and 62 GeV are compared. The data are taken under identical conditions utilizing clean proton-proton collisions from the CERN intersecting storage rings and confirm scaling to 5%. The observed $\mu^+\mu^-$ yield is a factor of 1.6 ± 0.2 larger than estimated from a simple parton model but is consistent with QCD. The p_T dependence of the muon pairs agrees well with expectations from QCD.

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We have measured inclusive dimuon production at the CERN intersecting storage rings at center-of-mass energies of $\sqrt{s} = 44$ and 62 GeV with integrated luminosities of 0.42×10^{38} and 1.12×10^{38} cm^{-2}, yielding 3184 and 13 766 $\mu^+\mu^-$ events, respectively. The apparatus description, the $\mu\mu$ mass spectrum at 62 GeV, the production dynamics of the muon pairs, and the analysis procedure all have been reported.[1,2] In this paper we discuss the following physics results:

(A) Scaling.—Here we present the comparison of the new 44-GeV data with the 62-GeV measurement for both the continuum and the $J/\psi, \Upsilon$ resonances. Using the same apparatus and the same analysis ensures a clean comparison of the mass spectra, as shown in Fig. 1(a). The systematic differences between both measurements due to luminosity and event selection are estimated to be < 5%. Describing the continuum with the scaling variable $\tau = m^2/s$, the data were compared with an *Ansatz*[1]

$$d\sigma/dm = A[(1-\sqrt{\tau})^{10}/m^3\sqrt{\tau}] + B\Upsilon(m), \qquad (1)$$

where $\Upsilon(m)$ is the superposition of the three Υ resonances[3] appearing as Gaussians of $\sigma(m) = 11\%$ resolution in our apparatus. For $m > 4.5$ GeV, the fit yields the following:

$\sqrt{s}$ (GeV)	A (nb GeV^2)	B (pb/GeV)	χ^2/DF
62	5.76 ± 0.17	3.7 ± 0.6	16.3/26
44	5.47 ± 0.34	0.7 ± 0.4	16.7/18

The *Ansatz*[1] fits well. The continuum contribution is shown as lines in Fig. 1(a). It is characterized by the value of A, which is the same for both energies within 5% or one standard deviation, hence confirming scaling[4] between the two measurements. The J/ψ was measured over a region of $0.1 < X < 0.3$ in the Feynman variable, $X = p/p_{\max}$. We obtain $B_{\mu\mu}\, d\sigma/dX(\langle X\rangle = 0.2) = 41 \pm 12$ nb and 15 ± 8 nb at $\sqrt{s} = 62$ GeV and $\sqrt{s} = 44$ GeV, respectively.

Scaling was also found in relative measurements[3] at lower energies of $\sqrt{s} = 18$–27.4 GeV at Fermi National Accelerator Laboratory. In general, QCD does not predict scaling. According to QCD, the cross section for producing muon pairs expressed in $m^3 d^2\sigma/dm\, dX|_{X=0}$, shown in Fig. 1(b), is expected to decrease with increasing energy $\sqrt{s}$, at large $\sqrt{\tau}$, and to increase at small $\sqrt{\tau}$. Only in the region of $0.1 \leqslant \sqrt{\tau} \leqslant 0.25$, QCD predicts very small deviations of $\leqslant 3\%$ from exact scaling, as estimated by Field[5] for $\Lambda \simeq 100$ MeV. This is in agreement with our data, as shown in Fig. 1(b).

(B) Deviations from Drell-Yan.—The measured cross sections in the continuum regions $5 < m < 8$ GeV and $m > 12.5$ GeV can be compared with the simple Drell-Yan *Ansatz*[4]:

$$\left.\frac{m^3 d^2\sigma}{dm\, dX}\right|_{X=0}$$

$$= \frac{2\pi\alpha^2\sqrt{s}}{9m}\left[\tfrac{4}{9}\bar{u}(x)\right]\left[4u_v(x) + d_v(x) + \tfrac{21}{4}\bar{u}(x)\right], \qquad (2)$$

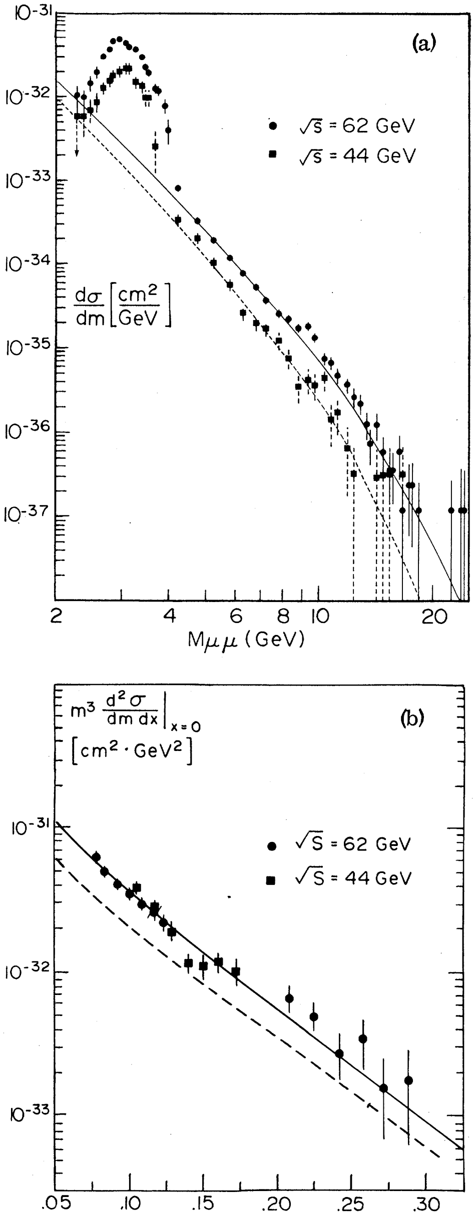

FIG. 1. (a) Differential mass spectra of measured muon pairs compared to the continuum part of the fit Eq. (1) for 62 and 44 GeV. (b) Scaling comparison of the 44- and 62-GeV data. The dashed line is the Drell-Yan prediction Eq. (2) with structure functions from inelastic neutrino scattering. The solid line is our fit to the sea distribution in Eq. (2); see text. Resonance regions are omitted.

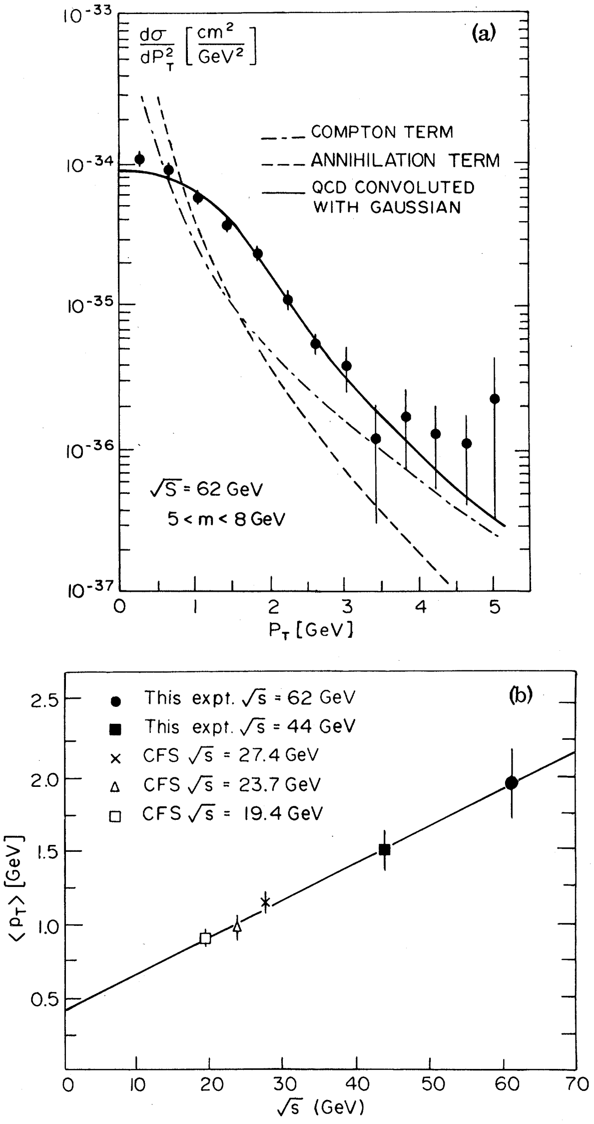

FIG. 2. (a) p_T dependence at $\sqrt{s}$ = 62 GeV in comparison with first-order QCD contributions and intrinsic quark motion reproducing the shape. (b) $\langle p_T\rangle$ at constant $\sqrt{\tau} = 0.2$ as function of $\sqrt{s}$. The line is in accordance with QCD expectations.

where $x_1 = x_2 = x + \sqrt{\tau}$. We use the valence proton structure functions from inelastic neutrino scattering[6,7] $u_v(x) = 2.13\sqrt{x}(1-x)^{2.8}$, $d_v(x) = 1.26\sqrt{x}(1-x)^{3.8}$, and $\bar{u}(x) = 0.27(1-x)^{8.1}$. Equation (2) assumes $s(x) = \bar{s}(x) = \frac{1}{4}[\bar{u}(x) + \bar{d}(x)]$ and negligible contributions from c and b quarks.

We have no uncertainty from nuclear target corrections; however, event selection and luminosity introduce a 10% overall uncertainty into the absolute cross sections. Therefore, comparing our cross sections in Fig. 1(b) with the Drell-Yan estimates of Eq. (2) which are shown as a dashed line, we determine[2]

$$K = \frac{\text{measured cross section}}{\text{Drell-Yan prediction}} = 1.6 \pm 0.2.$$

This is different from the values $K \simeq 2.2-2.4$ obtained in Ref. 6; however, our experiment is carried out at much higher c.m. energies and to higher $m_{\mu\mu}^2$ values.

Alternatively we can determine the sea-quark structure function by fitting the 44- and 62-GeV data in the continuum region with Eq. (2) using $u_v(x)$ and $d_v(x)$ as mentioned, and $\bar{u}(x)=\bar{d}(x)=A_s(1-x)^b$. We obtain $\bar{u}(x)= (0.42 \pm 0.05)(1-x)^{(8.3\pm 1.0)}$, with $\chi^2/\mathrm{DF}=6/17$ which is to be compared to $\bar{u}(x)=0.27(1-x)^{(8.1\pm 0.7)}$ from inelastic scattering.[6,7] The shape is in accordance with neutrino measurements[7]; the ratio of A_s is the measured K factor.

At present the precise theoretical value of the K factor is unknown. Adding the order-α_s QCD corrections to the leading result gives $K \simeq 1.7$ (i.e., $1.0+0.7+\ldots$). A precise prediction cannot be made until one is assured that the order-α_s^2 term is small or until one can sum the large contributions to the series.

(C) The p_T distribution.—The order-α_s QCD contributions also manifest themselves by broadening the transverse momentum distribution of the muon pairs. Figure 2(a) compares $d\sigma/dp_T^2$ measured at 62 GeV ($5<m<8$ GeV) with two QCD contributions, both of which are expected to produce high-p_T muon pairs. The first is the gluon emission[5,8] from $q\bar{q}$ annihilation into virtual photons, shown as a dashed line in Fig. 2(a). The second is the Compton term where a quark scatters from another quark before emitting a virtual photon.[5,8] This contribution is shown as a dash-dotted line in Fig. 2(a). The intrinsic quark motion will spread out the p_T distributions. Therefore, both contributions were convoluted with a Gaussian of $\sigma=480$ MeV, which includes additional perturbative and nonperturbative contributions.[5] The result is shown by the solid line and describes the data well.

(D) The rise of $\langle p_T\rangle$.—Figure 2(b) shows $\langle p_T\rangle$ from our data and those of Yoh *et al.*[9] as a function of $\sqrt{s}$ for a constant $\sqrt{\tau}=0.2$. It shows good agreement with QCD predictions of a linear rise of $\langle p_T\rangle$ with $\sqrt{s}$.

We conclude that hadronic production of nonresonant muon pairs at high energies is explained well within the framework of quantum chromodynamics. In particular, the data clearly indicate the presence of the QCD order-α_s terms that involve gluon interactions. These terms cause the absolute rate to be larger than that predicted by the simple parton (Drell-Yan) model and manifest themselves directly in the dynamics of the muon-pair transverse momentum. The experimentally measured large average p_T and its linear rise with $\sqrt{s}$ at fixed $\sqrt{\tau}$ are strong evidence for QCD.

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