EXPERIMENTAL REVIEW OF SOME PREDICTIONS OF THE DRELL-YAN MODEL IN HADROPRODUCTION OF DIMUONS*

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Predictions of the Drell-Yan model in hadroproduction of dimuons are reviewed. A comparison is made with the experimental situation, both actual and in the near future.

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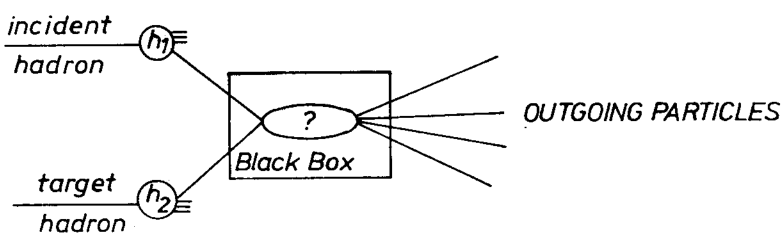
I. Introduction

During the past 10 years, the analysis of dimuons produced in collisions between incident hadrons and nuclear targets have shed much light on the knowledge of fundamental constituents of particles and on the mechanisms involved in their interactions.

Several excellent recent papers have reported on the situation of hadroproduction of dileptons (Ref. [11]).

The first kind of experiments (the so called deep inelastic scattering D.I.S. of leptons experiments) have reached part of this goal in probing nuclear matter with incident point--like particles (e, μ, ν). This type of probe enables us to obtain a precise idea about the constitution of nucleons. Unfortunately this kind of method cannot be used for unstable particles. In that case, the most natural and unique way is to look at hadron-hadron collisions.



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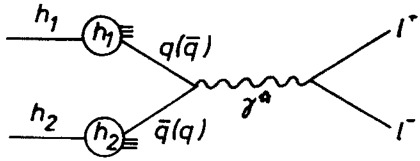
One can hope that the study of the outgoing particles will allow us to collect information on the structure of incident and/or target particles. The problem then is to know what happens in the black box.

In 1970, in the frame work of the quark-parton model, Drell and Yan [2] have proposed a model which describes the mechanism occurring in hadron-hadron collisions. The graph corresponding to this model is:



The contents of the black box are:

— $q_i - \bar{q}_t$ (or $\bar{q}_i - q_t$) annihilation into a virtual photon (i for incident, t for target);

— decay of the photon into two leptons of opposite charge.

At this stage, the interaction is purely electromagnetic. This graph allows to calculate the inclusive cross section of lepton pair production in hadron collisions. Besides the cross section is directly proportional to the number of $q_i\bar{q}_t(\bar{q}_i q_t)$ couples which can annihilate. Thus valence-valence, sea-sea and valence-sea terms will contribute to the cross section. It should be noticed that q and $\bar{q}$ have to be of the same flavour.

The differential cross-section is then given by the following formula:

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3x_1x_2s} \cdot \tfrac{1}{3} \cdot \sum_i \frac{Q_i^2}{x_1x_2} \left[f_i^q(x_1) \cdot g_i^{\bar{q}}(x_2) + f_i^{\bar{q}}(x_1) \cdot g_i^q(x_2)\right], \tag{1}$$

where $\dfrac{4\pi\alpha^2}{3x_1x_2s}$ is the point-like electromagnetic annihilation cross-section at an equivalent energy of $M_{\mu\mu}^2$; $\frac{1}{3}$ is the colour factor; Q_i is the quark electric charge ($\frac{1}{3}$ or $\frac{2}{3}$); x_1 and x_2 are the fraction of momentum taken by the quarks, respectively, in hadron h_1 or hadron h_2; $\dfrac{f_i(x)}{x}$ is the probability for a quark to carry the fraction x of the available energy $\sqrt{s}/2$; the summation runs over all quark flavours (in practice only u, d, s). At this point, some comments on the Drell-Yan formula can be made:

a) Notice that f and g are called the structure functions respectively of the incident hadron h_1 and the target nucleon h_2. One of the important reasons to study hadroproduction of dileptons is that the structure functions used in the Drell-Yan formula are the same as those determined in D.I.S. of e, μ and ν experiments. This fact allows a good cross-check of the same functions which are obtained by two different methods. In that case, the space--like Q^2 variable in D.I.S. corresponds to the time-like $M_{\mu\mu}^2$.

b) Another interesting aspect which can be derived from the Drell-Yan formula if the following: if f and g are known, then due to the fact that no free parameters exist in the formula, we are able to compute an absolute value for the cross-section. On the other hand, if the cross-section is experimentally measured and if g (structure function of the nucleon of the target) is known (from D.I.S. experiment for example), the Drell-Yan formula enables us to determine the structure function of unstable incident hadrons such as pions or kaons.

c) In the Drell-Yan model, the transverse momentum of lepton pairs is due only to the transverse momentum of the quarks which annihilate. Therefore, the dilepton transverse momentum is expected to be small and independent of the overall center of mass energy.

d) For different reactions, the relative yield of dileptons produced depends on the quark content of interacting particles.

These brief qualitative comments on the Drell-Yan formula lead us to the predictions of the model.

II. Predictions of the Drell-Yan model

1. Nuclear effects

Due to the nature of the collisions (hard scattering), the quark-antiquark annihilations are point-like interactions which is consistent with the fact that quarks are dimensionless objects. Therefore no shadow effects of nucleons in the target should occur as is the case in coherent processes. For hard scattering processes of point like constituents, a linear dependence with the number of partons is expected, i.e. if the cross section is parametrised as A^α (where A is the atomic number of the target) $\alpha = 1$ is predicted by the Drell-Yan model.

2. Scaling behaviour

The Drell-Yan formula should be written as:

$$\frac{d^2\sigma}{dMdX} = \frac{8\pi\alpha^2}{3M^3}\,\tfrac{1}{3}\sum_i \frac{q_i^2}{x_1+x_2}\,H(x_1, x_2) \tag{2}$$

with $X = x_1 - x_2$, $M^2 = x_1 x_2 s$, $H(x_1, x_2)$ = product of beam × target structure functions. This relation can be rewritten as:

$$M^3\,\frac{d^2\sigma}{dMdX} = C\cdot F(x_1, x_2) = C\cdot F\left(\frac{M^2}{s}, X\right), \tag{3}$$

where C is a dimensionless factor and F is called the scaling function. If the structure functions do not depend on the M^2 scale, F is expected to be independent of s and to be only a function of the scaling variable $\sqrt{\tau} = M/\sqrt{s}$.

3. Beam dependence

The Drell-Yan cross section is directly related to the number of $q-\bar{q}$ annihilations which could occur between projectile and target quarks (valence and sea) having the same flavour. Due to the fact that targets are composed of protons (uud) and neutrons (ddu), the yield of dimuons will be expected to be higher with incident particles containing valence $\bar{u}$ or $\bar{d}$ than for protons, especially at high masses where valence quarks dominate. The Drell-Yan formula allows us to make some predictions on the relative yield of dileptons produced with various beam particles.

4. Angular distribution

In our case, dimuons are produced after the decay of a virtual photon which was created by the annihilation of two quarks of spin 1/2. A transverse polarisation is then expected for the muons and their angular distribution in the dilepton rest frame should be:

$$\frac{dN}{d\cos\theta} \propto 1+\cos^2\theta,$$

where θ is the polar angle of emission of a muon with respect to the $q\bar{q}$ line of flight. The determination of this direction is complicated by the fact that the dimuon and hence the original $q\bar{q}$ system has a transverse momentum. In order to approach this polarization axis, the lines of flight of the pion and of the proton are used.

5. Absolute cross-section

Since no free parameter is needed in the general expression (1) for the cross-section, then if the structure functions of incident and target particles are known, the Drell-Yan cross-section can be exactly computed. Proton-proton and antiproton-proton collisions are well suited for testing this prediction.

To conclude this chapter, it is now clear that the study of hadroproduction of dileptons is a mine of information concerning the behaviour of fundamental constituents in collisions and it is thus the only way to determine the structure functions of unstable particles.

III. Difficulties with the Drell-Yan model

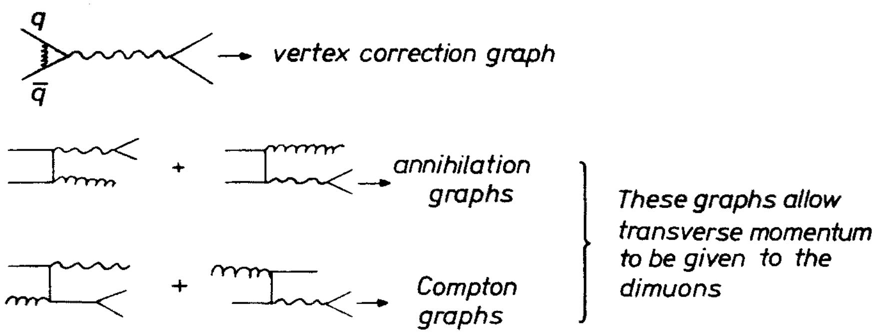
1. Introduction of gluon effects

The Drell-Yan model seems to be relevant for describing hadrons collisions, but unfortunately nature is much more complicated! As soon as high statistics of dilepton data became available, two main problems arose:

i) The dimuon transverse momentum was found to be larger than expected: clearly in that case, the angular distributions should be affected!

ii) The experimental dimuon cross section was found to be much larger than that computed in the Drell-Yan frame work.

The problem arising with these experimental results is to find the origin of the discrepancy between experiment and the simple Drell-Yan model. A solution is clearly that gluons do exist in nature and the Drell-Yan process in the lowest order diagram of the general QCD theory which itself is the leading candidate for the theory of strong interactions [3]. Due to the fact that gluons are present in the particles, their emission or absorption are responsible for new graphs which resemble QED diagrams used for calculating radiative corrections. These lowest order diagrams are:



2. Some qualitative comments on dilepton transverse momentum

The quark-parton model can be easily extended by assigning a transverse momentum to the quarks. But the experimental results show that $P_T^{\mu\mu}$ is much larger than expected and increases dramatically with s. In that case, a dynamical explanation is then required and can be provided by QCD theory. The hypothesis is that $P_T^{\mu\mu}$ is the sum of the "primordial" transverse momentum k_T of constituents inside the hadrons and of terms arising from gluon effects (k_T is expected to be of the order of 300–400 MeV).

In the QCD frame work (Ref. [4]) the annihilation and Compton graphs which should allow the calculation of the $P_T^{\mu\mu}$ distribution at large P_T, give the following prediction for the average value of P_T:

$$\langle P_T \rangle = C + \alpha_s(M^2) \cdot f(\tau) \cdot \sqrt{s},$$

where C is a constant, independent of the incident energy of the hadrons which should be equal to the intrinsec transverse momentum. $f(\tau)$ is a function of τ, positive but not monotonic, which has a maximum around $\sqrt{\tau} \approx 0.3$–0.4 and falls to 0 at $\tau = 0$ and $\tau = 1$ [5].

A more general study has led Dokshitzer et al. [6] to perturbative calculations in the "leading logarithm approximation" taking into account all terms in $\log(P_T^2/M^2)$. The result of their work has been to find better agreement in the shape of the $P_T^{\mu\mu}$ distribution with data than with the simple order in α_s calculations.

The presence of dileptons produced with large transverse momentum has some effects on the angular distribution [7].

To conclude this chapter, we can summarize that which QCD theory brings to the understanding of the dimuon data:

— It allows for large dilepton transverse momentum.
— It explains the change expected in the angular distribution.
— It predicts a different value of the cross section than that of the naive Drell-Yan model (See Chap. V. 5).
— In addition, if higher-order graphs are included, scaling violation will be generated (as observed in DIS of lepton experiments) due to gluon emission.

The consequence of these predictions is to replace the "naive" Drell-Yan model which was proposed in the framework of the parton-quark model, by the so-called "educated" Drell-Yan model developed within the QCD framework.

IV. Some experimental comments on hadroproduction of dimuons

1. Main experimental features

In a hadroproduction of dimuons experiment, we need only the inclusive detection in the final state of two muons of opposite charge. We have to make sure that the 2 muons are not decay products of π or K mesons. In addition, the leptons have to be produced "promptly" (i.e. within $\leqslant 10^{13}$ sec.) in the primary interaction. Due to the low cross-section of dilepton production, the use of high intensity and high energy beams is strongly advised. But, in that case, high multiplicity of secondary particles is expected. A good way to get rid of this problem is then to perform a dump experiment in which secondary hadrons are largely killed. But this experimental condition leads to a poor resolution that can be achieved, due to the multiple scattering of particles in the dump that crucialy affects the measurement of the momenta and angles of the muons. Clearly a compromise has to be found between all these parameters in order to get the best experimental conditions possible. Finally, the acceptance of the apparatus should be as large as possible, especially for the study of the angular distribution.

2. Kinematical variables

From the measurements of the momentum of the muons, one can compute the dimuon mass $M_{\mu\mu}$. The total energy $\sqrt{s}$ is known and the following relations are derived:

$$M^2_{\mu\mu} = x_1 x_2 s,$$

$$x_{\mu\mu} = \frac{2P_L}{\sqrt{s}} = x_1 - x_2, \tag{3}$$

where P_L is the longitudinal momentum of the dimuon in the total center of mass energy system, x_1 and x_2 are defined in chapter I (see relation (1)). From the set of equations (3), one can calculate:

$$x_{1,2} = \tfrac{1}{2}\left(\pm x_{\mu\mu} + \sqrt{x^2_{\mu\mu} + 4M^2_{\mu\mu}/s}\right).$$

Note that in the naive Drell-Yan model the P_T of the dimuons is neglected.

3. Kinematical mass range

Three regions in mass are usefull for testing the Drell-Yan model.

i) $\varrho, \omega, \phi < M_{\mu\mu} < \Psi, \Psi'$. This region between the ϱ, ω, ϕ resonances and the Ψ family is problematic because other possible mechanisms than the Drell-Yan process are competitive (Ref. [1]). In addition there are some difficulties in separating the Drell-Yan events from the arounding bumps due essentially to the poor experimental resolution.

TABLE I

Collaboration	Incident particle	P_{inc}	Target	x_F acceptance	$M_{\mu\mu}$ range	N. Evnts.	Typical features of experiment	Ref.
ISR: ABCS (e^+e^-)	p	28 $\sqrt{s} = 53$ 62	p	$-0.2 \to 0.2$	$4 \to 18$	1000	Transition radiation detector and liquid argon calorimeter	[9]
ISR: CHFMNP	p	$\sqrt{s} = 62$	p	$-0.1 \to 0.5$	$5 \to 25$	2500	Iron toroids spectrometer	[10]
FERMILAB: CFS	p	200–300 400	Be, Cu Pt	$-0.1 \to 0.1$	$5 \to 20$	180000	Two arm spectrometer	[11]
FERMILAB: CIP	$\pi^\pm$	225	C, Cu, W	$0.0 \to 1$	$4 \to 8.5$	π^- 2200 π^+ 400	Chicago Cyclotron magnet	[12]
FERMILAB: MNTW	p	400	Fe	$-0.2 \to 1$	$4.5 \to 18$	$> 10^5$	Spectrometer	[13]
CERN SPS: SISI	π^-	150	Be	$-0.2 \to 0.8$	$3.9 \to 8.0$	1500	Goliath spectrometer	[14]
CERN SPS: Ω	$K^\pm, \pi^\pm$ $p, \bar{p}$	40	W		$2.0 \to 2.7$	several 10^3	Omega spectrometer	[15]
CERN SPS: NA3	$K^\pm, \pi^\pm$ $p, \bar{p}$	150 200 280 400	Pt, H_2	$-0.3 \to 1$	$4 \to 14$	π^- 50000 π^+ 2200 π^- 1000 $\bar{p}$ 320 p 1300 (+ > 50000p)	Lezard spectrometer	[16]
CERN SPS: NA10	π^-	280	C, W, Cu		$4 \to 14$	~ 2000	Spectrometer	[17]

ABCS — Athens, Brookhaven, CERN, Syracuse; CHFMNP — CERN, Harvard, Frascati, MIT, Naples, Pisa; CFS — Columbia, Fermilab, Stony Brook; CIP — Chicago, Illinois, Princeton; MNTW — Michigan, Northeastern, Tufta, Washington; SISI — Saclay, Imperial College, Southampton, Indiana; Ω — Birmingham, CERN, Ecole Polytechnique; NA3 — Saclay, CERN, Collége de France, Ecole Polytechnique, LAL Orsay; Na10 — Zurich, Ecole Polytechnique, Strasbourg.

ii) Ψ, $\Psi' < M_{\mu\mu} <$ Υ family. These region is well suited for testing the Drell-Yan model and a large amount of data is now available.

iii) Υ family $< M_{\mu\mu} <$ new bump? This third region would be very interesting in order to test the mass dependence of the structure functions but the data currently available are statistically very limited.

Figure 1 shows the mass spectrum of the Na3 collaboration [8]. Between the J/Ψ and Υ resonances, for masses from 4 GeV to 8.5 GeV, the large number of dimuons events

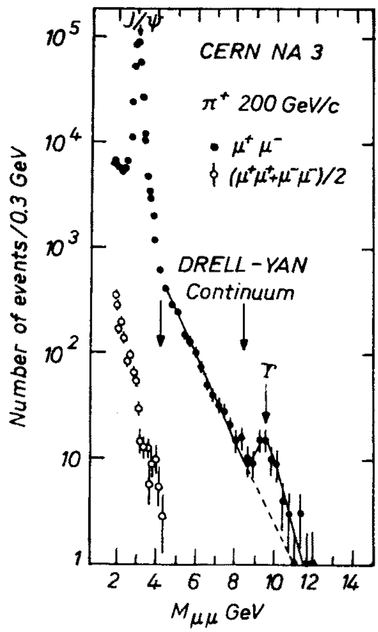


Fig. 1

for several kinds of incident hadrons ($\pi^{\pm}$, $K^{\pm}$, p and $\tilde{\text{p}}$) at several energies allows a good analysis of the Drell-Yan model. In order to test the Drell-Yan process many other experiments have brought data which have been reported in Table I. This Table also gives the characteristic features of each experiment.

V. Experimental results

1. Nuclear dependence

Due to the low cross section of dimuon production, experimentalists usually use heavy nuclear targets instead of hydrogen even though the interpretation of data is much simpler with a hydrogen target. The measured cross section "per nucleus" must then be converted into the cross section "per nucleon" in order to be able to compare results on different high density targets. The cross section is parametrised as A^{α} where A is the atomic number. Table II summarizes the results of α for several experiments.

TABLE II

Experiment	Targets	Beam (GeV)	Result	Ref.
		proton		
CFS	Pt, Be	200–300–400	$1.007 \pm 0.018 \pm 0.028$	[11]
CIP	Cu, C, W	π^- 225	1.12 ± 0.05	[12]
NA3	Pt, H_2	π^- 200	1.02 ± 0.03	[18–19]
		π^+ 200	0.95 ± 0.04	
		$(\pi^- - \pi^+)$ 200	1.03 ± 0.05	
		π^- 150	1.00 ± 0.02	
		π^- 280	1.00 ± 0.02	
NA10	C, W, Cu	π^- 280	$0.97 \pm 0.02 \pm 0.02$	[17]

With the exception of the CIP result for α, all the results are compatible with $\alpha = 1$ as expected by the Drell-Yan model. The 2.5 standard deviation from 1 observed in the CIP result is directly connected to the absolute normalisation factor K as discussed elsewhere [20]. Notice the interesting result of the NA3 experiment concerning the $(\pi^- - \pi^+)$ data. Indeed, in that case, the possible contribution of hadronic processes to muon pair production disappears in the difference as it is the same for π^+ and π^-.

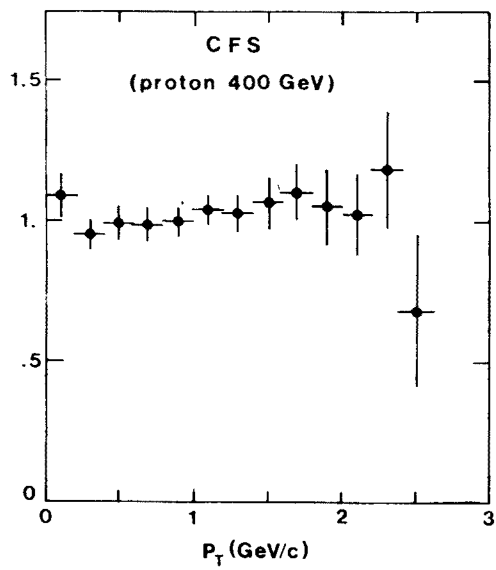


Fig. 2

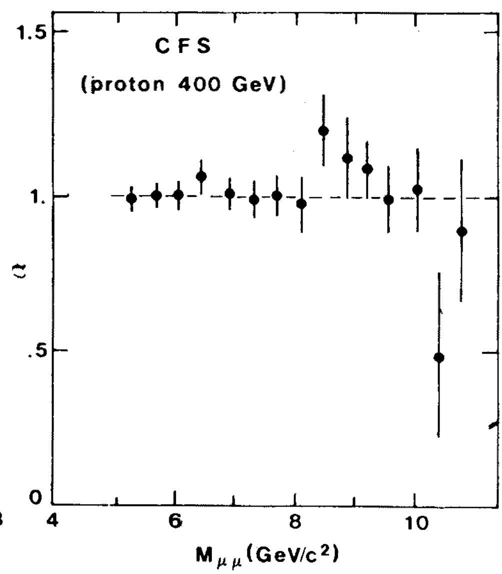


Fig. 3

Figures 2 and 3 show that no dependence of α is observed with $P_T^{\mu\mu}$ and $M_{\mu\mu}$ for incident protons at 400 GeV. For incident π's, no obvious $P_T^{\mu\mu}$ and x_F dependences have been observed in the CIP experiment or in the NA10 experiment for $P_T^{\mu\mu}$. The NA3 analysis of pion data [19] at 150, 200 and 280 GeV on hydrogen and platinuum targets used simultaneously shows that the ratio of the cross section is in good agreement with the Drell-Yan

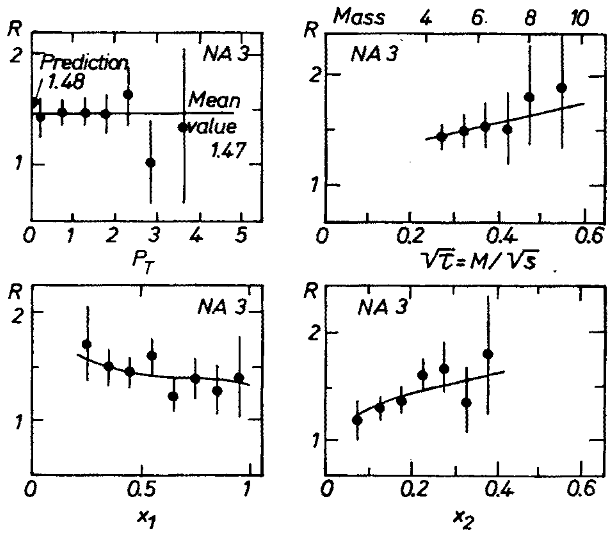


Fig. 4. $R = \frac{A\sigma(\pi^- H_2 \to \mu^+\mu^-)}{\sigma(\pi^- Pt \to \mu^+\mu^-)}$ (π^- at 150 GeV). Lower part — Drell-Yan model prediction

prediction within a 10% error which is mainly due to systematics. Variation of this ratio with the dimuon mass, x_1 and x_2 is also in good agreement and no variation with the transverse momentum is observed as shown in Fig. 4.

2. Scaling

If scaling invariance is assumed (see Chap. II.2) $M^3 \frac{d^2\sigma}{dMdX}$ should be a function only of $\tau = \frac{M^2_{\mu\mu}}{s}$ (τ is called the scaling variable).

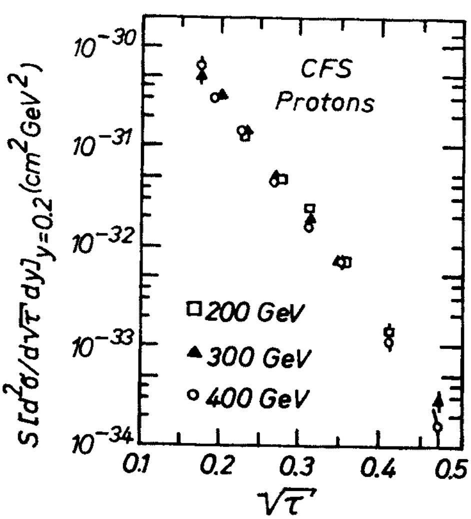


Fig. 5

Figure 5 shows the data of the CFS collaboration (protons at 200–300–400 GeV). In Fig. 6, a comparison between the proton data at 400 GeV and dielectron data at the ISR is presented. In the range of $\sqrt{\tau}$ (between 0.1 and 0.5) the present data on protons are

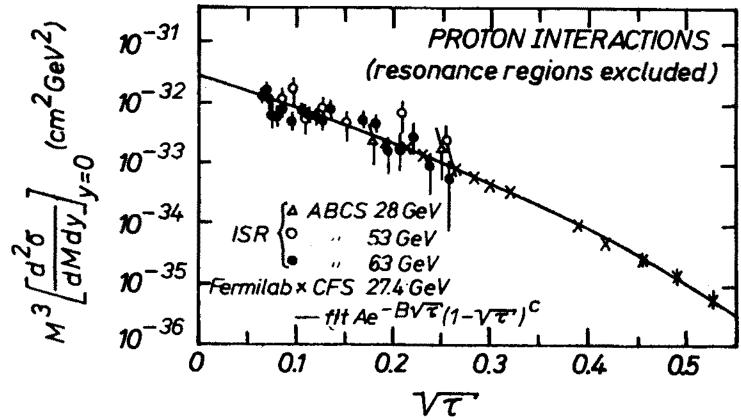


Fig. 6

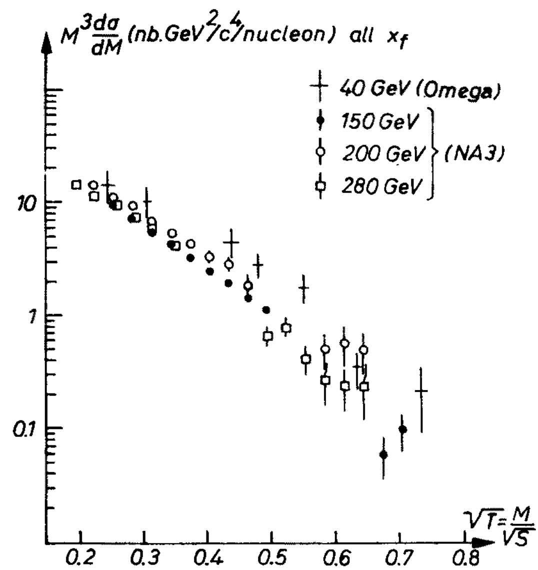


Fig. 7

consistent with the scaling prediction to within the experimental accuracy of the measurements.

A comparison between the π^- data of the NA3 experiment and the Ω results [15] are presented in Fig. 7. Although the Ω data seem to show a small systematic deviation relative to the NA3 data, this is not a clear manifestation of Q^2 dependence of the structure function as observed in D.I.S. of leptons. Indeed, we have to be very carefull in our conclusions because the scaling violation should be of the order of magnitude of the systematical errors. However, the experimental problems such as normalisation between different experiments and the small span in the center of mass energy of presently available data, are crucial considerations before one can draw any conclusions. The most conservative approach is to state that within present experimental accuracy (at the level of 20%), the data support the scaling invariance prediction as expected by the naive Drell-Yan model.

3. Beam dependence

The Drell-Yan formula (1) shows that the differential cross section is directly proportional to all possible $q-\bar{q}$ arrangements between projectile and targets constituents of the same flavour. The yield of dileptons produced should be different because the quark contents of the incident hadrons are different.

Figure 8 shows the ratio of dimuons produced by π^-'s and p's at 225 GeV. This ratio is in rather good agreement with a prediction (Ref. [1a]) given by a naive quark counting rule and represented by the dashed line.

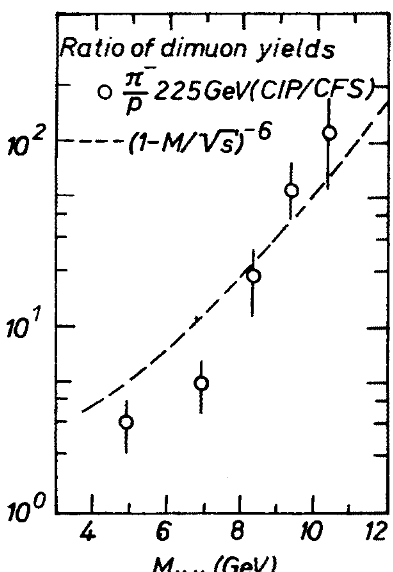


Fig. 8

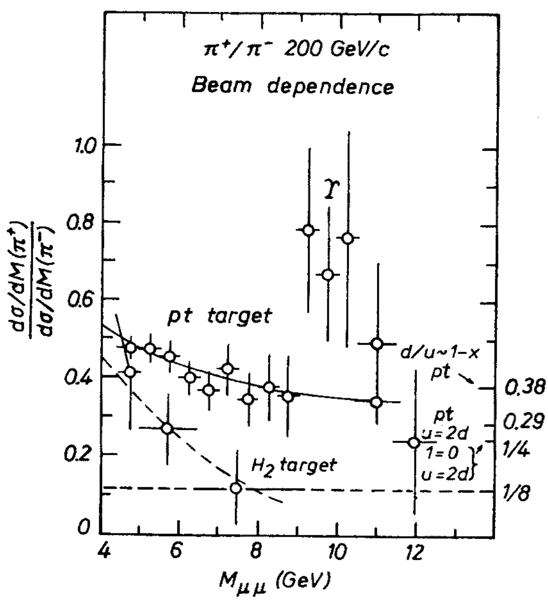


Fig. 9

The π^+/π^- ratio is shown in figure 9 provided by the NA3 collaboration. This ratio decreases with $M_{\mu\mu}$ to limits given by several models [8] for both platinuum and hydrogen targets. The Υ region clearly shows a different behaviour which confirms that its production is not due only to quark fusion processes. The Drell-Yan prediction is represented respectively by the solid line for the platinuum target and the dashed line for the hydrogen target.

Because of the several different incident particles available to NA3, this experiment has measured some ratios of dimuon yields summarized in Table III for $M_{\mu\mu}$ masses between 4.1 and 8.5 GeV on a platinuum target at 200 GeV:

TABLE III

Ratio	Valence quark contents	Naive prediction	Experimental result
K^-/π^-	$\frac{\bar{u}s}{\bar{u}d}$	1	0.98 ± 0.1
$\bar{p}/\pi^-$	$\frac{\bar{u}\bar{u}\bar{d}}{\bar{u}d}$	~ 1	1.07 ± 0.2
π^+/π^-	$\frac{u\bar{d}}{\bar{u}d}$	0.4–0.5	0.51 ± 0.01
K^+/π^-	$\frac{u\bar{s}}{\bar{u}d}$	small	0.23 ± 0.02
p/π^-	$\frac{uud}{\bar{u}d}$	small	0.23 ± 0.02

The errors quoted are mainly due to relative luminosity estimates. The experimental results are in fairly good agreement with the naive predictions of the Drell-Yan model.

4. Angular distribution

Due to the fact that the virtual photon is produced in an annihilation of 2 quarks of spin $\frac{1}{2}$, the γ^* should be transversely polarized and the μ angular distribution can be

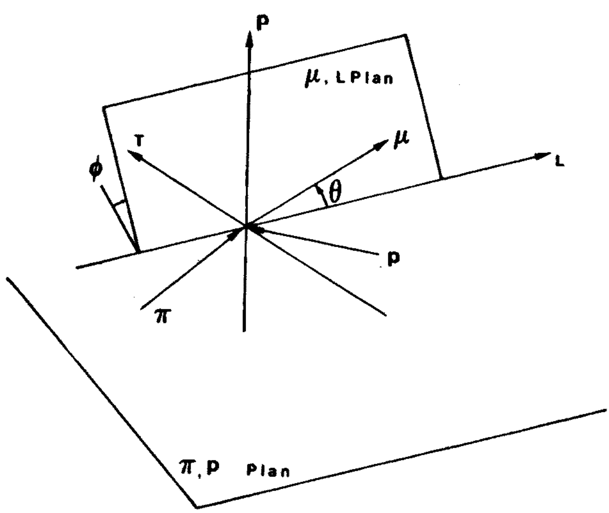


Fig. 10

written as follows:

$$\frac{dN}{d\cos\theta} \propto 1+\lambda\cos^2\theta$$

with $\lambda = 1$ expected by the Drell-Yan model, where θ is the angle between one μ and the $q\bar{q}$ line of flight ($\vec{L}$) in the c.m.s. of the dimuon.

This definition is the source of an experimental problem: how can $\vec{L}$ be determined?
if $P_T^{\mu\mu}$ is 0, then $\vec{L}$ coincides with the beam axis,
if $P_T^{\mu\mu}$ is not 0, then $\vec{L}$ becomes more complicated.

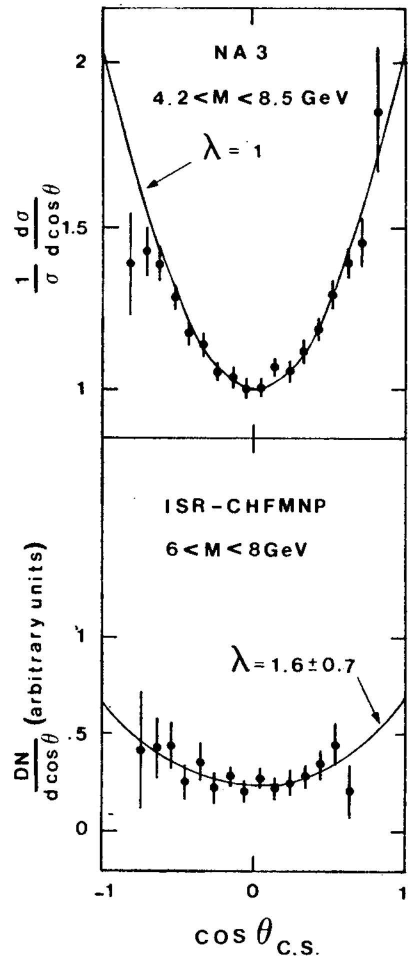


Fig. 11, Fig. 12

Because experimentally $P_T^{\mu\mu}$ is not equal to zero, one must choose an $\vec{L}$ direction and we present 3 possibilities (see Fig. 10). In the case of πp collisions:

i) $\vec{L} = \vec{\pi}$: we are in the *t*-channel frame also called Gottfried-Jackson (G–J) frame. In that case, $P_T^{\mu\mu}$ is given by the target nucleon.

ii) $\vec{L} = \vec{p}$: this is the *u*-channel frame and $P_T^{\mu\mu}$ is given by the π.

iii) $\vec{L}$ is the external bissectrice between $\vec{\pi}$ and $\vec{p}$ directions (Collins-Soper frame (C-S)). This is an intermediate situation where $P_T^{\mu\mu}$ is given by the proton *and* the pion.

a) Experimental measurement of λ

Figures 11 and 12 show the experimental data for incident π's and protons from NA3 and CHFMNP experiments respectively, presented in the C-S frame. The data are in good agreement with $\lambda = 1$ within the experimental accuracy.

b) More accurate analysis of the angular distribution

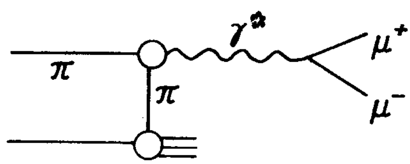
The general form of the angular distribution can be written:

$$W(\theta, \phi) = W_T(1+\cos^2\theta)+W_L\sin^2\theta+W_\Delta\sin 2\theta\cos\phi+W_{\Delta\Delta}\sin 2\theta\cos 2\phi,$$

where the W's are functions of $M_{\mu\mu}$, $X_F^{\mu\mu}$ and $P_T^{\mu\mu}$.

Several models have been proposed. We will only mention 3 of them:

i) One pion exchange (OPE) model of Sarma [21]. The diagram is the following:



This graph gives rise to a $\sin^2\theta$ term in the angular distribution. Qualitatively, a polarization dependence with x_1 is predicted: at small x_1 only transverse polarization is present as expected by the Drell-Yan model, while there appears a partial longitudinal polarization at x_1 close to 1.

ii) A second model of gluon emission was proposed by Collins (Ref. [22]) in which the P_T of the dimuon was provided by 1st order QCD corrections of the annihilation graphs (see Chap. III.1).

iii) Lam and Wu Ki Tung (Ref. [23]) assumed that $P_T^{\mu\mu}$ was due to the primordial momentum of the quarks and predicted ϕ terms for the angular distribution in the C-S and G-J frames.

In summary, all these type of calculations give the following predictions:

— a longitudinal term of order P_T^2/M^2

— a $\sin 2\theta \cos\phi$ term of order P_T/M

— a $\sin 2\theta \cos 2\phi$ term of order $\frac{1}{2}P_T^2/M^2$.

The NA3 experiment has analysed its data in the following way (Ref. [19]). The angular distribution is written as:

$$W(\theta, \phi) \propto (1+\cos^2\theta)+A\sin^2\theta+B\sin 2\theta\cos\phi+C\sin^2\theta\cos 2\phi,$$

where A is related to the previous λ parameter by: $A = \dfrac{1-\lambda}{\lambda+1}$. The parameters A, B, C have been determined in the 3 different frames and we have studied their P_T/M dependence (for $0.4 < x_1 < 0.8$ and $4.5 < M_{\mu\mu} < 8.5$ GeV).

C-S frame. $\lambda \sim 0.8$, $B \sim (-0.6 \pm 0.2)\, P_T/M$, $C \sim (1.5 \pm 0.5)\, P_T^2/M^2$. Figure 13 shows the P_T/M dependence of λ, B and C. Curves are sketched using a linear (for B) and quadratic (for C) dependence of P_T/M.

G-J frame. $B \sim (-1.4 \pm 0.2)\, P_T/M$, $C \sim (2 \pm 0.5)\, P_T^2/M^2$. Either in the C-S or G-J frames the relative magnitudes of the B and C terms may simply result from the choice of the reference frame.

***u*-channel.** Figure 14 shows the results of B, C, λ in the u-channel frame. $B \sim 0$, $C \sim (\pm 0.5)\, P_T^2/M^2$. If one makes the assumption that the true physical angular distribution is $1 + \cos^2 \theta$ with the line of flight of quarks as the $\vec{L}$ axis, then the mean axis of quarks should be the u-channel frame where B and C are small. Moreover, no x_1 dependence of λ, B and C is observed in the u-channel frame.

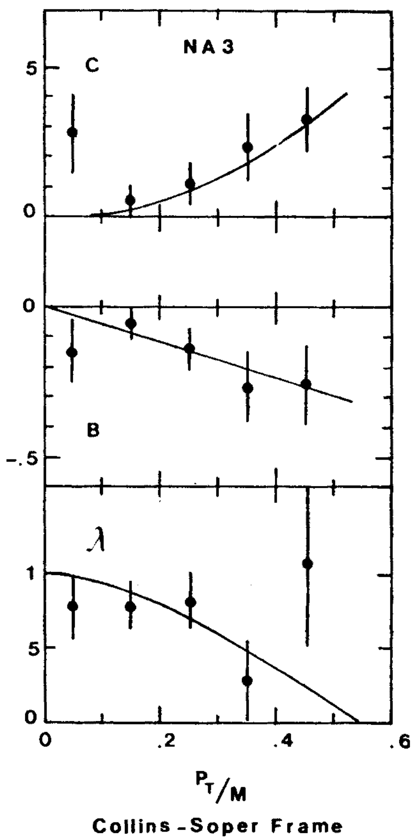


Fig. 13

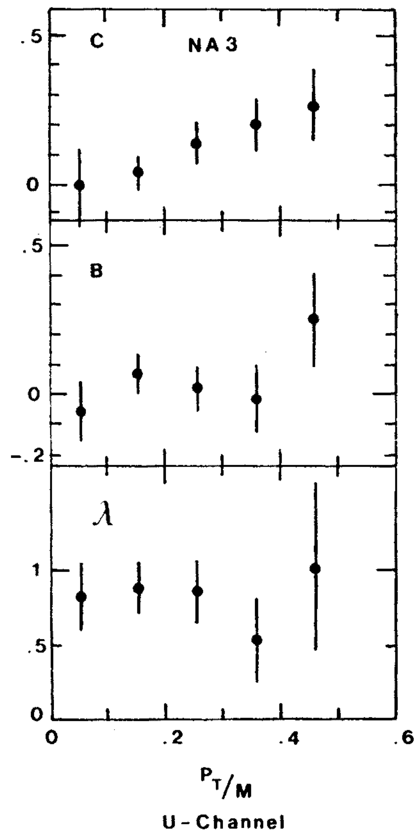
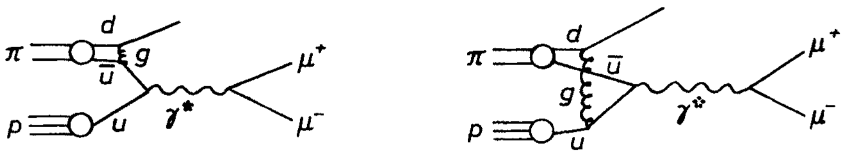


Fig. 14

c) Higher twist model of Berger and Brodsky

This model (Ref. [24]) is a specific model for the case of dimuon production with incident pions at large x_1 ($x_1 \geqslant 0.7$). The graphs are:



The corresponding cross section is then:

$$d\sigma \propto (1-x_1)^2\,(1+\cos^2\theta)+\tfrac{4}{9}\,\frac{\langle k_T^2\rangle}{M^2}\sin^2\theta+\tfrac{2}{3}\,\frac{\langle k_T\rangle}{M}(1-x_1)\sin 2\theta\cos\phi,$$

where: $\langle k_T^2\rangle$ is the average of the square of the transverse momentum of the quark. The main ideas of this model are:

i) it works only for x_1 greater than 0.7;

ii) the first term shows a structure function of the π which behaves as $(1-x_1)^2$ and a transverse polarization is expected;

iii) the second term predicts a longitudinal polarization with the presence of a scale breaking term (due to the $1/M^2$ factor);

iv) the third term shows the existence of an interference term.

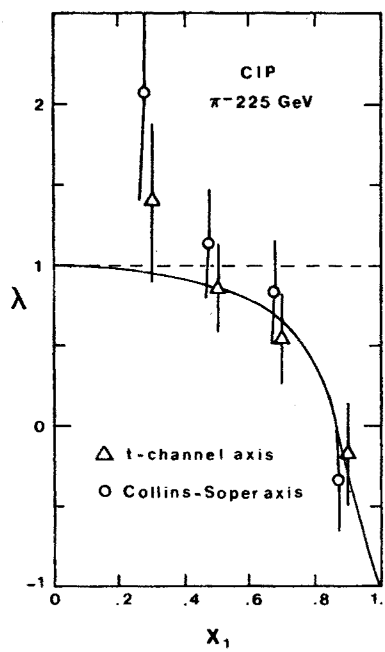


Fig. 15

In order to test this model, a good acceptance for x_1 close to 1 is needed. Fig. 15 shows the result of the CIP experiment for π^- at 225 GeV at Fermilab. The data are in good agreement with the Berger and Brodsky model which corresponds to the solid line in the figure.

5. Absolute cross section

The Drell-Yan formula (1) allows us to compute the cross section for dimuon production if the hadron structure functions are known. In proton-proton or antiproton-proton collisions, the check of the model is possible as, in that case, the nucleon structure functions have been determined in DIS of leptons.

a) **Proton-nucleon** (uud) × (uud − ddu)

In that case, no valence-valence terms are present. Only valence-sea, sea-valence and sea-sea terms contribute in the calculation of the cross section. If sea quark distributions are not well-known, the calculated cross section could be wrong!

b) **Antiproton-nucleon** ($\bar{u}\bar{u}\bar{d}$ × (uud − ddu)

Now, valence-valence terms are dominant, but the other terms still do exist.

c) ($\bar{p}$ — **nucleon**) − (p — **nucleon**)

This is the best way to test the Drell-Yan prediction as, in that case, only valence-valence terms remain.

However, it is very hard to obtain high intensity $\bar{p}$ beams.

TABLE IV

Exp	Beam	K	Comments
NA3	($\bar{p}$–p) Pt 150 GeV	2.3 ± 0.4	Poor knowledge of the sea distribution cannot explain K as only valence-valence terms are present.
NA3	π^+ Pt 200 GeV	2.4 ± 0.4	
NA3	π^- Pt 200 GeV	2.2 ± 0.3	} Nuclear dependence is excluded to explain K factor.
NA3	π^- He 200 GeV	2.4 ± 0.4	
NA3	(π^-–π^+) Pt	2.2 ± 0.4	This result excludes explaining K as due to contamination events like π decays; indeed such events cancel in the difference as they act in the same way for π^+ and π^-.
NA3	p Pt 200 GeV	2.2 ± 0.4	
NA3	$\bar{p}$Pt 150 GeV	2.3 ± 0.4	
Ω	π^- W 40 GeV	2.45 ± 0.42	
Ω	π^+ W 40 GeV	2.52 ± 0.49	
Ω	(π^-–π^+) 40 GeV	2.22 ± 0.41	
SISI	π^- C 150 GeV	2.8 ± 0.6	
CFS	p W 200–400 GeV	~1.5	
MNTW	p Fe	1.6 ± 0.3	

From a sample of 275 $\bar{p}$ events at 150 GeV, the NA3 collaboration has measured the ($\bar{p}-p$) cross section and has compared the experimental result with the prediction of the Drell-Yan model. The disagreement observed gave rise to the now- well-known K factor:

$$\left[\frac{d^2\sigma}{dx_1 dx_2}\right]_{\text{exp}} = K\left[\frac{d^2\sigma}{dx_1 dx_2}\right]_{\text{D-Y}}.$$

Many other experiments have now measured the K factor in several experimental conditions. Table IV summarizes the results.

In conclusion, K is of the order of 2–2.5. The errors quoted are mainly systematic due to absolute normalisation problems.

Origin of the K factor?

Calculations performed in the QCD framework by many theorists have led to the following conclusions:

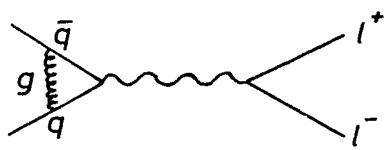
— Scaling violation in DIS of leptons is a direct consequence of QCD effects. In the leading log approximation, these same QCD effects should be responsible for scaling violations in the structure function derived in the framework of the Drell-Yan model.

— Calculations in the 1st order of QCD (25) have shown that the non leading log terms (NLL) give a large correction to the Drell-Yan cross section:

$$\sigma_{\text{DY,QCD, first order}} = K\sigma_{\text{0DY}},$$

K is quasi constant and equal to 1.8 and is about the same for incident π's or p's.

The most important contribution to this K factor corresponds to the vertex corrections shown in the graph:



— In addition Parisi has conjectured (Red. [26]) that all higher order terms of this kind can be exponentiated.

The agreement between the experimental K factor and the theoretical calculation to the 1st order of QCD seems satisfactory. But this might not be the end of the story as higher order terms have still not been calculated and some crucial questions remain open: does the K factor depend of $M_{\mu\mu}$, $P_T^{\mu\mu}$ or/and $x_{\mu\mu}$?

VI. Conclusions

In order to summarize the actual situation concerning the Drell-Yan model, some assertions of Yan given at the last 1981 Morions Workshop on Lepton Pair Production at Les Arcs, are appropriate:

PARTON MODEL = (QCD)^0

and REAL WORLD = PARTON MODEL + QCD CORRECTIONS.

The comparison between the experimental data on hadroproduction of dimuons and the "naive" Drell-Yan model are presented in Table V. In addition, the predictions of the "educated" Drell-Yan model are also shown.

A clear success of the Drell-Yan model is that it allows us to calculate the structure functions of unstable hadrons.

TABLE V

Topics	"Naive" Drell-Yan model	"Educated" Drell-Yan model
A dependence	O.K.	O.K.
Beam dependence	O.K.	O.K.
Scaling	O.K. But ...	— Violation is predicted but higher dilepton masses and more accurate experiments are needed.
Angular distribution	O.K. But ...	— Problem with high P_T still not resolved — Shape of the distribution not clear at x_1 close to 1.
Absolute cross section	No!	— Theoretical calculation of K factor seems satisfactory but is it accidental? The question is still open (higher orders).

The experimental situation for the future is the following:

— NA3 will give results on the K dependence with their proton data at 400 GeV on platinuum targets (more than 50000 events) in a few months.

— NA10 and MNTW are performing high statistic experiments, respectively, with π^+, π^- and protons. The data should soon be available.

— The new CIP collaboration has proposed a specific experiment for a better understanding of the angular distribution at x_1 close to 1.

— Finally, at the Fermilab tevatron a new experiment (CFS extended collaboration) at high masses has been announced.

In conclusion, the study of hadroproduction of dileptons has already yielded many interesting results about the knowledge of fundamental constituents of particles and the future experiments will shed more light on the problems which are still not clearly resolved.

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