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QUARK-LEPTON CONTACT INTERACTIONS AND HIGH-MASS ISOLATED DILEPTONS AT LHC

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Abstract

Quark-lepton effective contact interactions at large scales can be probed by the shape of the isolated dilepton invariant-mass distribution at LHC. After removing the $t\bar{t}$ background by a suitable invariant-mass cut m_0, we study the improved statistical Λ-bounds thus obtainable in terms of the fermionic current chirality, beam luminosity, cut m_0, and binwidth Δm. The limitations imposed on these bounds by systematic uncertainties are also examined.

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1 Introduction

Although the Standard Model (SM) is consistent within errors with all experimental data so far, there is a general consensous that it must not be our final answer to physics and its many free parameters should be predictable by a more general theory, possibly involving new particles and interactions at a distant energy scale Λ. Such effects will manifest themselves at energies below Λ through small deviations from the SM, which can be described by an effective lagrangian containing non-renormalizable $SU(3) \otimes SU(2) \otimes U(1)$-invariant operators [1].

In this work we study a particular dimension-6 operator, namely [1-5]

$$L_\Lambda = \eta_{JJ} \frac{g^2}{\Lambda^2_{JJ}} J^q_{\Lambda\mu} J^{l\mu}_\Lambda, \tag{1}$$

where the currents in contact

$$J^f_{i\mu} = \bar{f} \gamma_\mu (a^f_i + b^f_i \gamma_5) f, \quad f = q, l \quad (i = \Lambda) \tag{2}$$

are formed by the ordinary SM quark and lepton fields and have the same general structure with the fermionic current entering in the neutral part of the SM lagrangian

$$L^{SM}_i = -ie J^f_{i\mu} A^\mu_i \quad (i = \gamma, Z^0). \tag{3}$$

Other dimension-6 structures, e.g. $\bar{q}l\bar{l}q$, which involve helicity non-diagonal terms, lead to essentially similar cross sections(modulo possible factors of 2) [5]. This extra contribution will give rise to excess high-mass isolated dileptons in hadron collsions, due to the interference of (1) with the SM, and most importantly, for $g^2/4\pi \sim \mathcal{O}(1)$ at very high masses, due to the square of (1) itself. We choose to concentrate on this particular signal since the dilepton cross section will be relatively unambiguously extracted from the multievent ($\sim$ 20) recordings expected with the projected LHC luminosities and will thus be a competent probe to new physics, complementary e.g. to cross sections involving missing energy, at the first stages of the machine' s operation.

A contact interaction of the form (1) is traditionally ascribed to fermion compositeness [2], provided that the quarks and the leptons contain common constituents, e.g. α, see Fig.1a. Indeed, this interaction may be a low-energy remnant of the exchange of the rest of their constituents, e.g. β, γ, which provide the particular quark and lepton quantum numbers (c.f. $\pi\pi$ scattering by ρ-exchange at c.m. energies $\sqrt{s} \ll M_\rho$, where the pion constituents are ordinary quarks). However, such a contact interaction may be of an entirely different dynamical origin, namely due to the exchange of a heavy virtual exotic particle, e.g. of a leptoquark [6] in the $\hat{t}$-channel - Fig.1b, or of an additional neutral vector boson Z$'$ [7] in the $\hat{s}$-channel -Fig.1c (c.f. low-energy effective Fermi theory of W-exchange). In these cases $\Lambda \sim M_{EX}$ (the mass of the exchanged particle) but e.g. for $g^2/4\pi \sim\mathcal{O}(\alpha)$ only the interference of (1) with the SM is important and the pronounced tail of dilepton events at very high invariant masses is absent. Next - to -leading contributions, giving rise e.g. to l^+l^-+ jet events, may help to distinguish among such posibilities.

Statistical bounds on the energy scale Λ_{JJ} of possible quark-lepton effective contact interactions have been obtained by means of the processes $e^+e^- \to$ jets and $e^+e^- \to$ jets + l^+l^- at e^+e^- colliders [4,5]. The best bounds, so far, namely

$$\Lambda_{LL} > 2.2(1.6)\ \text{TeV}, \quad \text{for } qe(q\mu) \text{ with } \eta_{LL} = -1 \tag{4}$$

$$\text{or} \quad \Lambda_{LL} > 1.7(1.4)\ \text{TeV}, \quad \text{with } \eta_{LL} = +1 \tag{5}$$

to 95% CL, have been obtained by means of the total dilepton cross section

for high invariant masses at the Fermilab Tevatron [8,9].

2 Cross -sections

The dilepton invariant-mass distribution for pp collisions in the dilepton c.m. frame is of the general form

$$s\frac{d\sigma}{dm^2} = 2z_0(1+\frac{1}{3}z_0^2)\sum_q C_q(m^2)L_q(m^2, s) \tag{6}$$

where z_0 is the cut in the dilepton c.m. production angle θ^*, namely we allow for events with $|cos\theta^*| < cos\theta_0 \equiv z_0$, and

$$L_q(m^2, s) = \int_{m^2/s}^{1}\frac{dx}{x}F_{q/p}(\frac{m^2}{sx}, m^2)F_{\bar{q}/p}(x, m^2) \tag{7}$$

is the effective "luminosity" of $q\bar{q}$ subcollisions at a scale $Q^2 = m^2 = \hat{s}$ as appropriate for a Drell-Yan process. In our numerical calculations we take $\theta_0 = 20^0$. The functions

$$C_q(m^2) = \frac{1}{16\pi m^2}\sum_{i,j=1}^{3} v_{ij}^q v_{ij}^l X_i^*(m^2)X_j(m^2) \tag{8}$$

are related to the $q\bar{q} \to l^+l^-$ subprocess cross section,

$$\begin{aligned} \frac{d\hat{\sigma}_q}{d\hat{t}} &= \frac{1}{16\pi\hat{s}^2} < \sum|\mathcal{M}|_q^2 > \\ & \frac{1}{16\pi\hat{s}^2}2\sum_{i,j=1}^{3} X_i^*(\hat{s})X_j(\hat{s})[A_{ij}^{+q}(\frac{\hat{u}}{\hat{s}})^2 + A_{ij}^{-q}(\frac{\hat{t}}{\hat{s}})^2] \end{aligned} \tag{9}$$

in which the photon, the Z_0 and the contact interaction (1) are allowed to interfere in an obvious notation ($i,j = \gamma, Z^0, \Lambda$). The factors

$$X_\gamma(\hat{s}) = e^2 \tag{10}$$

$$X_z(\hat{s}) = \frac{e^2\hat{s}}{\hat{s} - m_z^2 + im_z\Gamma_z} \tag{11}$$

$$X_\Lambda(\hat{s}) = \eta_{JJ}\frac{4\pi\hat{s}}{\Lambda_{JJ}^2} \tag{12}$$

are related to the propagators for γ, Z^0 exchange or to the contact term (1) and

$$A_{ij}^{\pm q} = v_{ij}^q v_{ij}^l \pm a_{ij}^q a_{ij}^l \ , \tag{13}$$

where

$$v_{ij}^f = a_i^f a_j^f + b_i^f b_j^f \ , \quad a_{ij}^f = a_i^f b_j^f + b_i^f a_j^f \tag{14}$$

are expressed in terms of the vector and axial-vector parts of the relevant currents (2). Our notation is fixed by the form (3) of the SM lagrangian. For example, we have $a_\gamma^f = e_f$ (the electric charge of fermion f measured in units of $|e|$) and $b_\gamma^f = 0$, while $a_{Z^0}^f, b_{Z^0}^f$ are parametrized in terms of the weak mixing angle in the standard way [9]. In all our calculations presented below we take $sin^2\theta_w = 0.23 \pm 0.00$. It has been customary in the litterature to classify the terms (1) according to the chirality of the currents in contact. Following this practice, we shall consider a contact interaction of two left-handed currents, i.e. $a_\Lambda^f = \frac{1}{2}, b_\Lambda^f = -\frac{1}{2}$ (LL), which gives more conservative results at LHC energies, two right-handed currents, $a_\Lambda^f = b_\Lambda^f = \frac{1}{2}$ (RR), and also of two vector currents $a_\Lambda^f = 1, b_\Lambda^f = 0$ (VV), as well as two axial-vector currents, $a_\Lambda^f = 0, b_\Lambda^f = 1$ (AA). As usual we choose phase factors η_{JJ} of unit magnitude, $|\eta_{LL}| = |\eta_{RR}| = |\eta_{VV}| = |\eta_{AA}| = 1$. A heavy virtual exotic particle with a coupling strength g_{EX} to quarks and leptons will have a mass of the order $M_{EX} \sim \Lambda\, g_{EX} / \, g$. In the following,we fix the strength of the contact interaction to $g^2/4\pi = 1$, which is a usual practice.This means that e.g. for $g_{EX} \sim g_W$, we have $M_{EX} \sim \Lambda/5$.

Exact calculations of the QCD corrections to a general Drell-Yan process are now available to $\mathcal{O}(\alpha_s^2)$, where it is found that the qg subprocess has a negative contribution relative to $q\bar{q}$, giving rise to an overall $\sim 5 - 10\%$ correction to the Born cross section in the LHC energy range and beyond depending on the structure-function set used [10]. Hence, in the results

presented below we do not include the QCD correction since it is overwhelmed by the uncertainty due to the proton structure functions.

The dilepton production cross section via the Drell-Yan process $q\bar{q} \to \gamma, Z^0 \to l^+l^-$ (i.e. $i,j = 1,2$) for large dilepton invariant masses is shown in Fig.2. The measurability levels shown correspond to a bin cross section limit $\Delta\sigma = (d\sigma/dm)\Delta m > 1.96/L$. Depending on the binwidth considered (typically $\Delta m \simeq 50-200$ GeV) the invariant-mass distribution is measurable beyond $m \sim 2$ TeV up to ~ 5 TeV for integrated luminosities $L > 10\ fb^{-1}$ up to 1000 fb^{-1}. For $m > 0.5(1.0)$ TeV the integrated dilepton Drell-Yan cross section is about 0.23 pb (9 fb).

3 Backgrounds

At these energies $t\bar{t}$ production is appreciable (the total cross section is $\sigma^{t\bar{t}}(tot) \simeq 5 \div 1\ nb$ for $m_t \simeq 120 \div 180\ GeV$ [11]) and can also give rise to opposite-side isolated dileptons. To have a crude estimate of this cross section we assume that $t\bar{t}$ production is approximately isotropic with decay branching fractions BR($t \to W^+b$) = 1.0 and BR($W^+ \to l^+\nu$) = 1/9. In order to observe an event with a pair of isolated back-to-back dileptons and no missing energy the $b\nu$ pair should be lost along the beampipes, e.g. within a cone of half-angle θ_0 , while l^+ should stay outside this cone: then l^- is also outside (remember we work at the l^+l^- c.m. frame) and the other pair $\bar{b}\bar{\nu}$ is also lost along the beampipes by momentum conservation. Thus, the total cross section for isolated l^+l^- production with no missing energy outside a cone of half angle θ_0 coming from $t\bar{t}$ production is very roughly

$$\sigma^{t\bar{t}}(l^+l^-) \simeq \sigma^{t\bar{t}}(tot)BR^2(t \to W^+b)BR^2(W^+ \to l^+\nu)(\frac{1-cos\theta_0}{2})^2\ cos\theta_0 \quad . \tag{15}$$

which gives $\sigma^{t\bar{t}}(l^+l^-) \simeq 50 \div 10\ fb$ for $m_t \simeq 120 \div 180\ GeV$ and $\theta_0 = 20^0$. This crude geometrical estimate shows that the Drell-Yan cross section dominates the isolated l^+l^- production for large invariant masses. A Monte-Carlo simulation, though with no stated cuts at LHC [12], shows that l^+l^- production from $t\bar{t}$ is comparable to Drell-Yan at $m \simeq 0.5$ TeV , then for $m > 1$ TeV the Drell-Yan cross section quickly becomes dominant.

By a similar geometrical approach the total cross section for isolated back-to-back dilepton production outside a cone of half-angle θ_0 around the beams, from the process $pp \to W^+W^- + X$ (which is dominant over WZ, ZZ) is crudely estimated to be

$$\sigma^{W^+W^-}(l^+l^-) \simeq \sigma^{W^+W^-}(tot) BR^2(W^+ \to l^+\nu) \frac{1-cos\theta_0}{2}\ cos\theta_0 \quad , \qquad (16)$$

which gives $\sigma^{W^+W^-}(l^+l^-) \simeq 40\ fb$ for a total W^+W^- cross section $\sigma^{W^+W^-}(tot) \simeq 100\ pb$ expected at LHC [13].

Note that the subprocess $W^+W^- \to l^+l^-$ has a much smaller contribution relative to $q\bar{q} \to l^+l^-$ to the dilepton cross section due to the smallness of the W distribution in the proton [14]. This suppresses the effect of the dimension-6 operator [15]

$$L'_\Lambda = \frac{g^2}{\Lambda^2} \bar{l}(1-\gamma_5) l W^+_\mu W^-_\mu \qquad (17)$$

to the l^+l^- cross section in pp collisions.

4 Results and Discussion

In Fig. 2 we also present the modified dilepton invariant-mass distributions due to the presence of the extra contact term (1) between two left-handed currents. Two right-handed currents lead to similar results. However, two

vector or axial-vector currents lead to excess cross sections larger by a factor of four at sufficiently large m/Λ_{JJ}, where the $\propto \Lambda^{-4}$ term dominates (e.g. at $m \simeq 4$ TeV for $\Lambda_{JJ} \simeq 10 - 20$ TeV). In all cases we obtain a negative interference ($\propto \Lambda^{-2}$) with the SM Drell-Yan terms for $\eta_{JJ} > 0$. However, the presence of the $\propto \Lambda^{-4}$ term for a strong coupling strength results to an <u>excess</u> of dilepton events at large invariant masses. Yet, for $\eta_{JJ} > 0$ we have a deficit of events for low invariant masses, roughly for $m/\Lambda_{JJ} \lesssim 0.075$, 0.066 and 0.036 in the $LL \simeq RR$, VV, and AA cases, respectively. Note that a distant extra neutral vector boson Z' with a mass $M_{Z'}$ beyond the measurability limit leads to a small <u>deficit</u> of dilepton events in an extended region, $m < M_{Z'}$.

To quantify on the statistical significance of such an excess or deficit of events we construct fake experimental data, following the SM distribution, within N bins of width Δm above a cut value m_0 up to the observability limit $m_L(\Delta m, L)$. Note that Δm cannot be less than the experimental resolution, which practically decreases with m. Given an integrated luminosity L these data will have statistical errors

$$\Delta \frac{d\sigma^{SM}}{dm}(m) = \left(\frac{1}{L\Delta m} \frac{d\sigma^{SM}}{dm}(m) \right)^{1/2} . \qquad (18)$$

Some typical error bars are shown in Fig.2. We next calculate the χ^2 per degree-of-freedom of a "fit" to these data by a model, which besides the SM cross section, allows also for the contribution of the contact term (1), namely

$$\begin{aligned} \frac{\chi^2}{NDF} &= \frac{1}{N} \sum_{i=1}^{N(bins)} \left(\frac{d\sigma}{dm} - \frac{d\sigma^{SM}}{dm}\right)^2 \left(\Delta \frac{d\sigma^{SM}}{dm}\right)^{-2} \\ &\simeq \int_{m_0}^{m_L} \frac{dm}{m_L - m_0} \frac{d\sigma^{EX}}{dm}(m)^2 \left(\Delta \frac{d\sigma^{SM}}{dm}(m)\right)^{-2}, \end{aligned} \qquad (19)$$

to 95% CL, have been obtained by means of the total dilepton cross section

$$X_\Lambda(\hat{s}) = \eta_{JJ} \frac{4\pi\hat{s}}{\Lambda^2_{JJ}} \qquad (12)$$

where

$$\frac{d\sigma^{EX}}{dm} = \frac{d\sigma}{dm}(i, j = \gamma, Z^0, \Lambda) - \frac{d\sigma^{SM}}{dm}(i, j = \gamma, Z^0) \tag{20}$$

is the excess cross section relative to SM as a function of the dilepton invariant mass m. For a 50% confidence-level fit with $NDF \gg 1$ we require [9]

$$\frac{\chi^2}{NDF}(\Delta m, L, \Lambda) < 1, \tag{21}$$

which results in the statistical bounds on Λ presented in Fig.3. for the standard cases considered here. Notice the increase of these bounds with Δm: This is true as long as $NDF \gg 1$ (practically, e.g. $NDF > 3$) and the simplified criterion (21) holds true with small dependence on NDF; then the only appreciable dependence of (21) on Δm comes through the statistical errors (18), which reflects the fact that increasing Δm simply results in increasing the statistics within each bin, i.e. in smaller errors (18). Our results do not depend very much on the dilepton invariant mass cut in the range $m_0 \simeq 0.5 - 1.0$ TeV. Typically, for $m_0 \simeq 0.5$ TeV, $\Delta m \simeq 100$ GeV and $L \simeq 20\ fb^{-1}$ we obtain

$$\Lambda_{LL} \simeq \Lambda_{RR}, \Lambda_{AA}, \Lambda_{VV} \quad > \quad 28, 34, 44 \text{ TeV} \quad \text{with} \quad \eta_{JJ} = -1 \ , \tag{22}$$

$$\text{or} \quad > \quad 24, 26, 32 \text{ TeV} \quad \text{with} \quad \eta_{JJ} = +1 \ . \tag{23}$$

Notice the scaling relative to the Fermilab-Tevatron results (4,5). It is important to keep in mind that these bounds are purely statistical. An extra constant systematic error results in lower bounds and it becomes more difficult to improve them by increasing the statistics (integrated luminosity and/or binwidth). For example, a 50% systematic error on $d\sigma^{SM}/dm$, added quadratically to the statistical error in the expression (19) for the χ^2, suppresses the statistical bounds by about only 10% for $L\Delta m \sim 10^2$

GeV/fb (large statistical errors) but results to about half of their values at $L\Delta m \sim 10^4\ GeV/fb$ (see Fig.3a). Note that, although the statistical errors completely diminish for sufficiently large luminocities, the bounds obtained due to systematics still increase as a result of the extension of the measurable invariant-mass region. In practice the systematic experimental error due to the beam luminocity and the data normalization can be minimized by studying the normalized distribution $\sigma^{-1}d\sigma/dm$ and base the analysis solely on the change of its shape. This practice, in general, may lead to softer disturbances of the SM predictions and hence to smaller, though unlimited (by systematics) bounds. This means that for sufficiently high luminosities the latter method gives always the best bounds. Note that due to the relatively large invariant-mass cut required in this analysis we stay above $x > 10^{-3}$ and do not probe the region of appreciable theoretical uncertainty due to the structure functions. In all the calculations presented above we have used the structure-function set 2 of EHLQ [3].

5 Conclusions

We have investigated the posibility of tracing an effective quark-lepton contact interaction by means of high-mass isolated dileptons at LHC. Such an interaction may be present if the quarks and the leptons are composite at a scale Λ and contain a common constituent or, else, it may simply be the low-energy tail of heavy exotic elementary particle exchange of the type of leptoquarks or heavy neutral vector bosons.

A novel feature of the present analysis is that it bases the bounds obtained as functions of the machine's luminosity on the distortion of the shape of the dilepton invariant-mass distribution (not simply on the total cross section) above a suitable cut $m_0 \simeq 0.5 - 1.0$ TeV for an appropriate binwidth $\Delta m \simeq 50 - 200$ GeV. By this cut the fake isolated dileptons due to $t\bar{t}$ (and $b\bar{b}$) production are practically removed and the only standard-model background which survives is due to $\gamma + Z^0$ Drell-Yan dilepton events. The same cut has the extra merit of reducing the systematic uncertainty of the theoretical calculation by excluding the small-x region.

Two vector currents provide a relatively larger effect and their contact interaction will be discovered at LHC if it occurs at scales $\Lambda \lesssim \mathcal{O}$ (100 TeV) for an integrated luminosity $L \lesssim 10^3 fb^{-1}$,depending also on the sign of its interference with the standard Drell-Yan terms. Other current structures lead to smaller cross sections and their possible contact interactions will be discovered provided they occur at scales $\Lambda \lesssim \mathcal{O}$ (50 TeV). Our results are not simply statistical bounds but incorporate an estimated $\sim 50\%$ constant systematic uncertainty, another novel feature of the present analysis. However, since our bounds arise due to the allowed shape distortion of the dilepton invariant-mass distribution this does not have a dramatic effect, reducing the purely statistical bounds by only about $\sim 50\%$.

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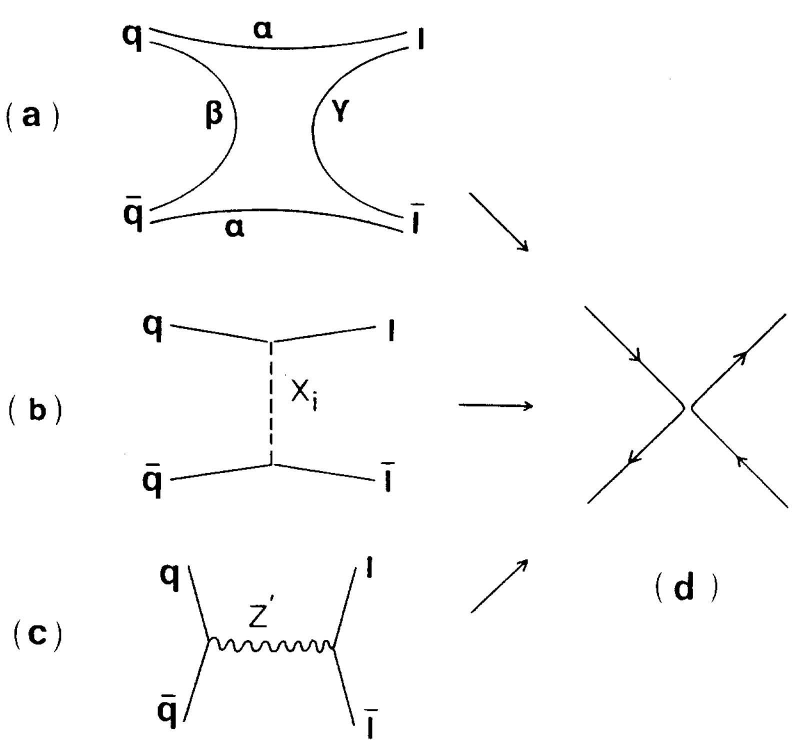
FIGURE CAPTIONS

Fig.1 Hypothetical constituent exchange,(a), giving rise to an effective quark-lepton contact interaction, (d), which can also be a low energy manifestation of heavy-leptoquark, (b), or of extra neutral vector-boson, (c), exchange.

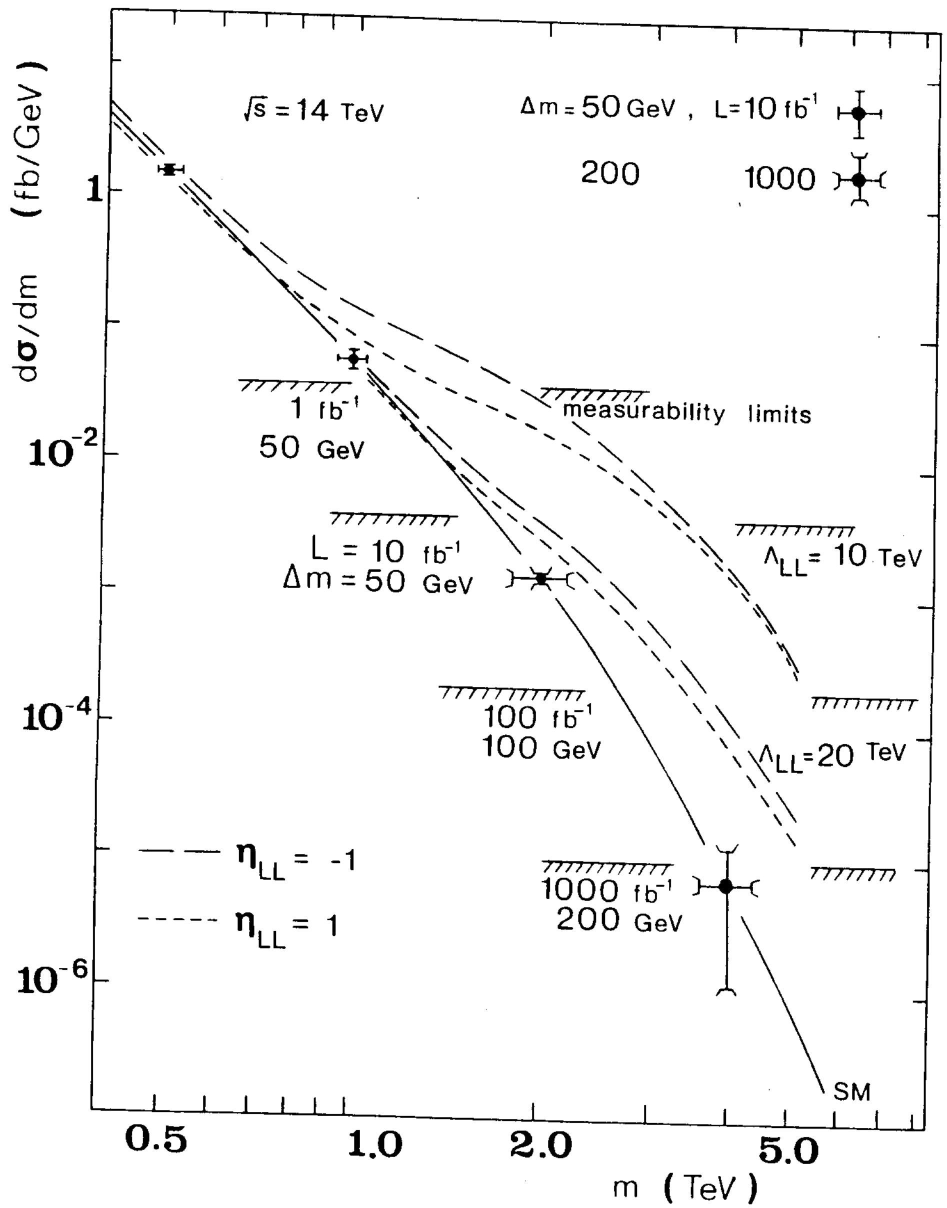
Fig.2 Isolated dilepton invariant-mass distribution from $pp \to l^+l^- + X$ due to $\gamma + Z^0$ Drell-Yan exchange (SM), in the dilepton c.m. frame for $160^0 > \theta^* > 20^0$. Its expected statistical errors are shown for typical luminocities and binwidths. Its shape deformation due to a contact interaction of two left-handed quark and lepton currents (indicative case) is also shown.

Fig.3 Discovery limits of an effective quark-lepton contact interaction expressed as 50% CL statistical bounds on the scale Λ for standard choices of current structures. a) Two left-handed or right-handed currents. The effect of a constant 50% systematic error on the SM cross section is also shown. b) Two vector or axial-vector currents.



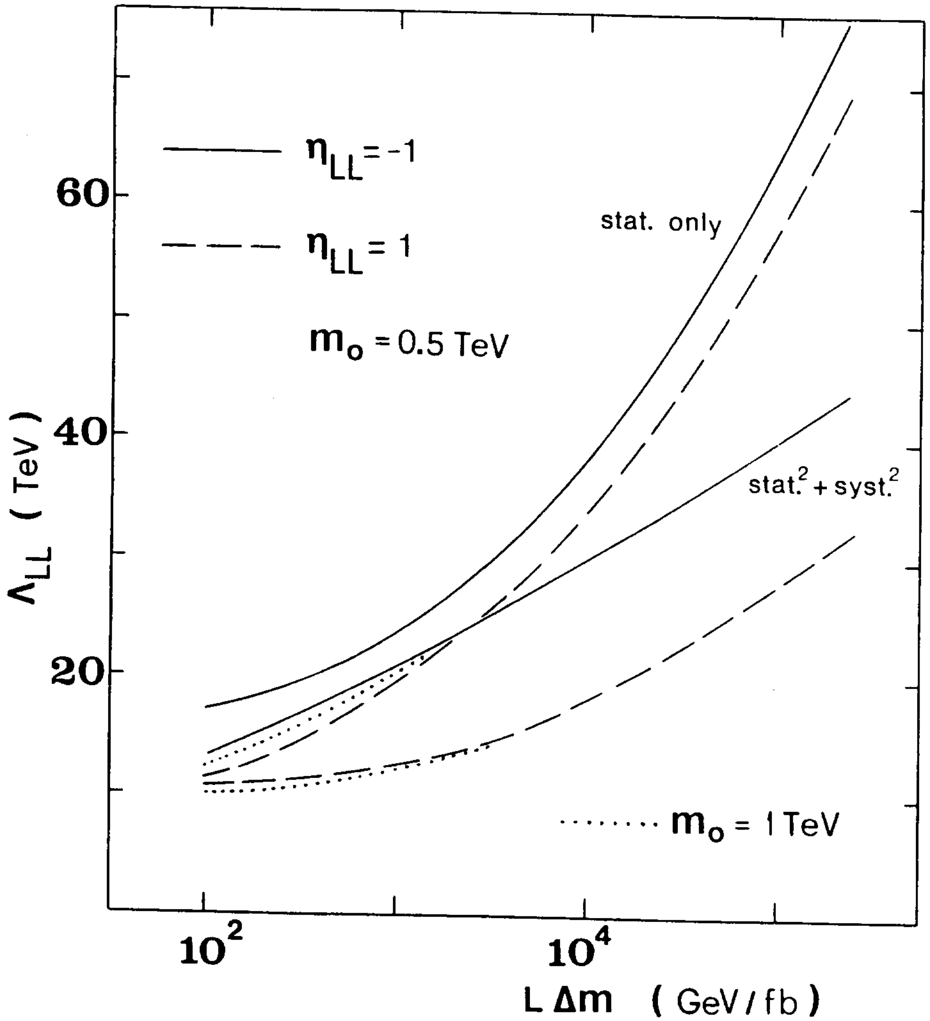
(a)
q
α
l
β
γ
q̄
α
l̄
(b)
q
l
X_i
q̄
l̄
(c)
q
l
Z′
q̄
l̄
(d)

fig. 1



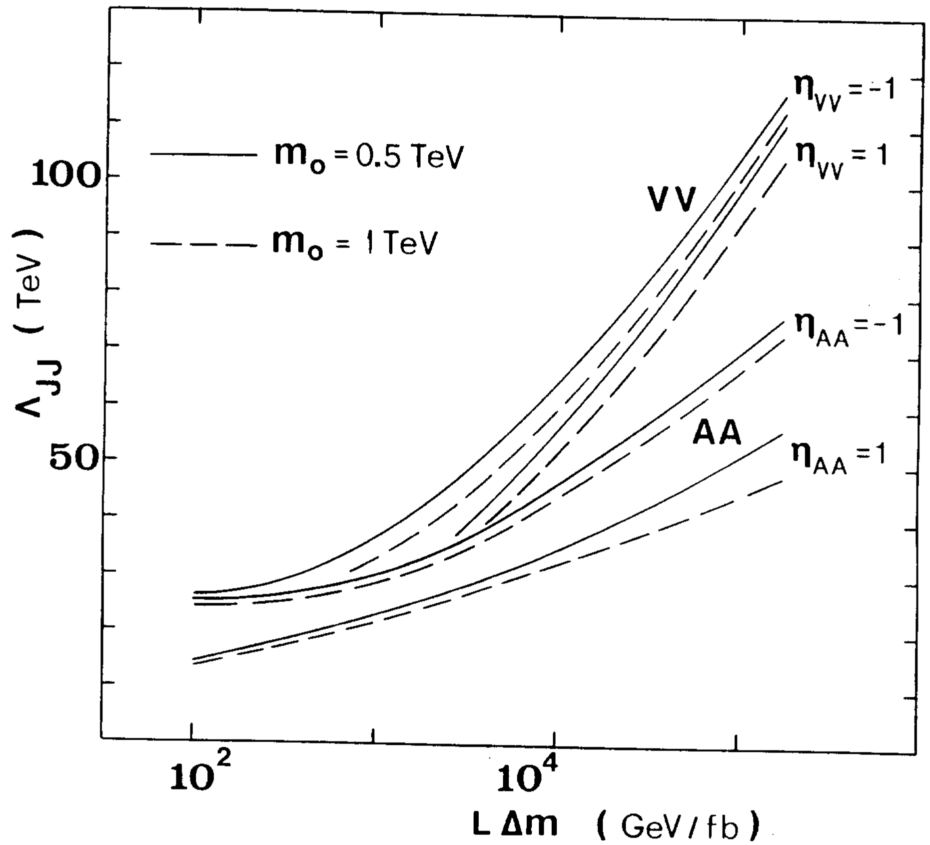
dσ/dm (fb/GeV)
√s = 14 TeV
Δm = 50 GeV , L=10 fb⁻¹
200
1000
1
10^{-2}
10^{-4}
10^{-6}
1 fb⁻¹
50 GeV
measurability limits
L = 10 fb⁻¹
Δm = 50 GeV
Λ_{LL}= 10 TeV
100 fb⁻¹
100 GeV
Λ_{LL}=20 TeV
η_{LL} = -1
η_{LL} = 1
1000 fb⁻¹
200 GeV
SM
0.5
1.0
2.0
5.0
m (TeV)

fig. 2



$\eta_{LL}=-1$
$\eta_{LL}=1$
$m_o = 0.5$ TeV
stat. only
$stat.^2 + syst.^2$
$m_o = 1$ TeV
60
40
20
Λ_{LL} (TeV)
10^2
10^4
L Δm (GeV / fb)

fig. 3a



$m_o = 0.5$ TeV
$m_o = 1$ TeV
$\eta_{VV}=-1$
$\eta_{VV}=1$
VV
$\eta_{AA}=-1$
AA
$\eta_{AA}=1$
100
50
Λ_{JJ} (TeV)
10^2
10^4
L Δm (GeV / fb)

fig. 3b