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SEARCHING FOR QUARK-LEPTON COMPOSITENESS AT LHC

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Abstract

The limits on the quark-lepton compositeness scale are investigated for one nominal year of running at the Large Hadron Collider to be built at CERN.

By comparing the $m_{e^+e^-}$ mass distribution above 1 TeV/c^2 for the Standard Model Drell-Yan process with that expected if quarks and leptons have common constituents and that from the main background at LHC, $t\bar{t} \to W^+ b\, W^- \bar{b} \to e^+ \nu b e^- \bar{\nu}\bar{b}$, it is found that we can reach the limits $\Lambda_{\bar{L}L}$ > 16 TeV or 26 TeV for an annual luminosity of 10^4 pb^{-1} or 10^5 pb^{-1} (normal), respectively, at the 5 s.d. level.

1. INTRODUCTION

It is generally believed that the standard model (SM) is rather part of a more complete theory characterized by an energy scale Λ. The consequences of the complete theory could be observerd at energies well below Λ and be expressed by a residual effective interaction called the contact term.

If quarks and leptons are made of more elementary constituents, the preons, then, contact terms could arise from preon interchange during the interaction of a quark with an antiquark producing a lepton-antilepton pair (Fig. 1a) or from the exchange between the preons of the carriers of the underlying metacolor force (Fig.1a,1b).

One could then expect deviations in the total or differential cross sections of the SM Drell-Yan process by the inclusion of the contact term (point) interaction described by the interaction of a quark and a lepton current, Fig.2.

Quark-lepton contact interactions are expressed by Eichten et al (1) in an effective Lagrangian of the chirally invariant form

$$L_{ef}^{eq} = \frac{g^2(\Lambda)}{2\Lambda^2} \sum_{\alpha} \sum_{\beta} \eta_{\alpha\beta}^{eq} (\bar{l}_\alpha \gamma^\mu l_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$$

$$\alpha, \beta = L \text{ or } R \qquad (1)$$

using the known lepton and quark fields in a variety of combinations depending on the choice of the real coefficients $\eta_{\alpha\beta}{}^{eq}$. We may determine the scale Λ unambigously by setting the coupling stength $g^2/4\pi=1$ and the maximum magnitude of $\eta_{\alpha\beta}{}^{eq}$ equal to unity. A contact term model may be defined by a particular choice of η's, as for example,

$$(\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1,0,0) \text{ symbolized by } \Lambda_{LL}^{\pm} \qquad (2)$$

which defines a contact weak-isoscalar interaction between the left-handed quark and lepton currents.

The differential cross section for the interaction $q\bar{q} \rightarrow l^+ l^-$ can be then expressed as, e.g.(3),

$$\frac{d\hat{\sigma}}{d\cos\theta^*} = \frac{1}{16\pi\hat{s}} \sum_{i,j} X^*{}_i(\hat{s}) X_j(\hat{s}).$$

$$\left[A_{ij}{}^q \left(\frac{1+\cos\theta^*}{\cos\theta^*}\right)^2 + A_{ij}{}^{-q} \left(\frac{1-\cos\theta^*}{\cos\theta^*}\right)^2\right] \qquad (3)$$

where i and j can be the γ, Z^o or contact term of Fig.2, θ^* is the lepton production angle in the interacting parton frame,

$$X_\gamma = e^2, \quad X_Z = \frac{e^2\hat{s}}{\hat{s}-M_Z{}^2+iM_Z\Gamma_Z}, \quad X_\Lambda = -\eta\frac{4\pi\hat{s}}{\Lambda^2} \qquad (4)$$

with η equal for example to η_{LL}.

The $A_{ij}{}^{q}$ and $A_{ij}{}^{\bar{q}}$ are bilinear combinations of various known couplings.

Finally the differential cross section for the LHC process $pp \to l^{+} l^{-}$ is given by

$$\frac{d\sigma}{d\cos\theta^{*}} = \sum_{\substack{u,c,t \\ d,s,b}} \int_{x_1} \int_{x_2} F_{q/p}(x_1)dx_1 \; F_{\bar{q}/p}(x_2)dx_2 \; \frac{d\hat{\sigma}}{d\cos\theta^{*}} + $$

$$+ \; q \longleftrightarrow \bar{q}, \quad \theta^{*} \to \pi-\theta^{*} \qquad (5)$$

where the $F_{q/p}(x)$ is the structure function of the parton q inside the proton carrying an x fraction of the latter's momentum.

From (3) and (4), it is clear that we get a constructive interference between the SM and contact interaction terms when $\eta=-1$, a value argued by Suzuki (3) to be theoretically plausible. Thus compositeness could manifest itself by an excess of opposite-sign dilepton events over the SM expectations.

It should be noticed that because of flavor independence, we theoretically expect similar results for the dimuon final state.

The present limits on Λ_{LL} (9) for eeqq ($\mu\mu$qq) from the various accelerators are shown in Table 1:

TABLE 1. Current limits on $\Lambda_{LL}^{\pm}$ for eeqq ($\mu\mu$qq)

		Beams, CM energy
CDF (Dallas 92)	$\Lambda_{LL}^{-} > 2.2$ (1.6) TeV	pp, 1.8 TeV
	$\Lambda_{LL}^{+} > 1.7$ (1.4)	
TOPAZ	$\Lambda_{LL}^{-} > 1.6$	$e^{+}e^{-}$ 0.058 TeV
	$\Lambda_{LL}^{+} > 1.2$	
VENUS	$\Lambda_{LL}^{-} > 1.7$	"

The purpose of this note is to see through a Monte Carlo approach how compositeness would manifest itself at LHC energies and set limits on Λ_{LL}^{-}, with one nominal year of LHC running.

2. SIGNAL EXPECTATIONS AT LHC and SAMPLES

a. The analysis given in this note was based on samples of pp interactions generated with the Monte Carlo program Pythia 5.6(5) which has incorporated in it the Born-level matrix element of Eichten et al (1) for quark-lepton compositeness.

Specifically, samples of 1000 di-electron events were generated for the SM Drell-Yan process with and without the compositeness amplitude and using various choices for the proton structure functions $F_{q/p}(x)$.

Mainly the Eichten-Hinchliffe-Lane-Quigg (EHLQ) sets were used with QCD Λ=200 MeV (set 1) or Λ=290 MeV (set 2), which work fine when high accuracy is not a necessity(6). Indicatively, the Glück-Reya-Vogt (GRV) lower and higher order (LO,HI) sets were also used. The expected cross sections that were found for the various values of the scale parameter Λ are tabulated in Table 2, under the condition $m_{e^+e^-} > 500$ GeV/c^2. The statistical uncertainty of these numbers is not worse than 5%. It should be mentioned here that higher order corrections $\alpha_s{}^2$ on the σ's do not exceed 11% (4).

We see from this Table that in the region of about up to Λ=14 TeV we expect more than about 25% a cross section excess for η=-1. Thus, the analysis was concentrated in this sample for the integrated luminosity of 10^4 pb^{-1} expected for one nominal year, implying roughly an excess of 270 events over the 1140 SM ones.

TABLE 2. Expected cross sections for $m_{e^+e^-} > 500$ GeV/c^2

SM alone

EHLQ1	0.114 pb
EHLQ2	0.120
GRV LO	0.096
GRV HI	0.112

$$t\bar{t} \to W^+ b W^- \bar{b}, \quad W^- \to e^- \bar{\nu}, \quad W^+ \to e^+ \nu$$

$m_{t\bar{t}} > 400$ GeV/c^2, $p_T{}^t > 200$ GeV/c

$m_H = 800$ GeV/c^2

$\sigma = 0.089$ pb

SM + Compositeness

Λ	η	Str.funct.	σ
2 TeV	-1	EHLQ1	26.5 pb
4	-1	"	1.95
8	-1	"	0.266
12	-1	EHLQ1	0.157
12	+1	"	
12	+1	EHLQ2	0.116
12	+1	GRV LO	0.0925
14	-1	EHLQ1	0.141
14	-1	GRV LO	0.120
14	+1	EHLQ1	0.109
16	-1	EHLQ1	0.130
20	-1	EHLQ1	0.126
20	-1	GRV LO	0.104
20	-1	GRV LO	0.103

(all q composite)

b. **Backgrounds**

The main background to the above opposite dilepton process at LHC energies comes from the $t\bar{t}$ production through

$$pp \to t\bar{t}X \ , \quad t\bar{t} \to W^{+}bW^{-}\bar{b} \tag{6}$$

Here, $t \to Wb$ 100%, since the present lower mass limit (Fermilab) exceeds the Wb threshold, and $W \to e\bar{\nu}$ for 1/9 % of the times. In the on-mass shell process $t \to Wb$, the top quark first decays weakly and then hadronizes itself.

The cross section for $t\bar{t}X$ at the LHC CM energy of 15.6 TeV that Pythia finds is about 3000 pb for $m_t=140$ GeV and $m_H=800$ GeV (not very sensitive).

This cross section is much higher than the other background processes $\sigma(W^{+}W^{-})\sim 90$ pb, $\sigma(WZ)\sim 30$ pb and $\sigma(ZZ)\sim 10$ pb which could also give rise to opposite lepton pairs.

A sample of 500 $t\bar{t}$ events were generated demanding $m_{t\bar{t}}>400$ GeV/c^2, $p_T^t>200$ GeV/c and $m_{e^+e^-}>500$ GeV/c^2 (by modifying the subroutine PYEVNT so that the program satisfies the last condition in order to reduce generation time). This sample amounts to a cross section of 0.089 pb, comparable to the expected Drell-Yan, for the same interval of the dilepton mass.

3. FINDING A 5 S.D. EXCESS SIGNAL

The generated SM, SM including compositeness and $t\bar{t}$ event samples described in Section 2, were reduced into ntuple structures, which were further analyzed by PAW (7) at the CERN IBM or the Silicon Graphics work station of NTU Athens.

We have compared the transverse momentum weighted distribution of the expected events of both electrons for the three samples above and for the integrated luminosity 10^4 pb^{-1} . The harder p_T spectrum due to the presence of compositeness is clear for Λ=14 TeV. A cut of $|\eta_e|<2.5$ on the pseudorapidity of both electrons has been applied, to account for the lepton acceptance of the ATLAS detector of up to 2.8. The effect of this cut is shown in Table 3 for each sample.

Fig.3 shows the expected number of events for the sample with Λ=14 TeV as a function of the di-electron invariant mass and for the same integrated luminosity and rapidity cut as mentioned. Again, the excess of events due to compositeness is clear, whereas the $t\bar{t}$ background is diminished. The numbers shown should be multiplied by the electron (or muon) detection-reconstrunction efficiencies which are expected to be better than 90% for each electron in ATLAS.

Figure 4 compares the SM and $t\bar{t}$ expected event bistributions with those in case of compositeness, for scales Λ=14 and 16 TeV and luminosity 10^4 pb^{-1}, (Fig.4a and 4b, respectively) and for Λ=20 TeV and the high (normal running) luminositv of 10^5 pb^{-1} aimed at LHC per nominal year.

TABLE 3. Acceptance of $|\eta_e| < 2.5$ cut

SM + Compositeness	EHLQ1	76.1%
SM alone	EHLQ1	77.5%
$t\bar{t}$	EHLQ1	87.2%

Using the distributions of the last Figure (and multiplying with 0.81 to account for dilepton detection - reconstruction efficiency), we can form Table 4 for the expected results. The number of annually expected events is given for the indicated luminosity. From these, assuming a 25% systematic error coming from the structure functions and 5% statistical error from the event size added quadratically, we can find the number of standard deviations and its statistical error of actual signal events expected $N^{comp}_{SD} \pm \delta N$ that we should see exceeding the SM expectation at various scales Λ.

Finally, using the approximate (conservative) scaling that for a given dilepton mass the differential cross section is inversely proportional to Λ^4 and therefore

$$\frac{N_{exp}(\Lambda_1)}{N_{exp}(\Lambda_2)} = \frac{\Lambda_2{}^4}{\Lambda_1{}^4} \qquad (7)$$

we find the 5 standard deviation limits Λ shown in Table 4 for one nominal year. These are about 16 TeV for 10^4 pb^{-1} and 26 TeV for 10^5 pb^{-1}. It should be mentioned that the GEM Collaboration in their Technical Proposal(8) using a different method (comparison of the $dN/d\cos\theta^*$ distributions) expect 30-35 TeV for the muon-quark compositeness scale limit with the ultra-high (not normal conditions) luminosity of 10^{34} cm^{-2}. sec^{-1}.

Table 4. Expected events and limits

Sample of 1000 events	14 TeV	16 TeV	20 TeV	SM	$t\bar{t}$
σ pb $m_{ee}>500$	0.141	0.130	0.126	0.114	(+other cuts) 0.089
N_{expect}	111/ 10^4 pb^{-1}	84/ 10^4 pb^{-1}	755/ 10^5 pb^{-1}	43.4/ 10^4 pb^{-1}	4.4/ 10^4 pb^{-1}
$N_{SD}{}^{comp}\pm\delta N_{SD}$	9.2±2.6	5.6±1.6	13.9±4.0		
Λ_{LL}^-, eeqq $\mu\mu qq$	16.3 TeV	16.5 10^4 pb^{-1}	25.8 10^{-5} pb^{-1}	in one nominal year	
GEM SSC $\mu\mu qq$	30-35 TeV with 10^{34} cm^{-2} sec^{-1} (ultrahigh)				

4. CONCLUSIONS

The di-electron mass distributions of generated events have been compared above 1 TeV for the Standard Model alone, SM including compositeness and tt, at the LHC CM energy of 15.6 TeV. Imposing pseudorapidity cuts $|\eta|<2.5$ and transverse momentum $p_T>400$ GeV/c on both electrons, and assuming a 90% detection-reconstruction efficiency for each lepton, we find that with the low annual luminosity 10^4 pb^{-1}, we can set the limit on the quark lepton compositeness scale $\Lambda_{LL}^{-}=16$ TeV. With the high (normal) annual luminosity of 10^5 pb^{-1}, we can reach the limit of 26 TeV. Both results are at the 5 s.d.level.

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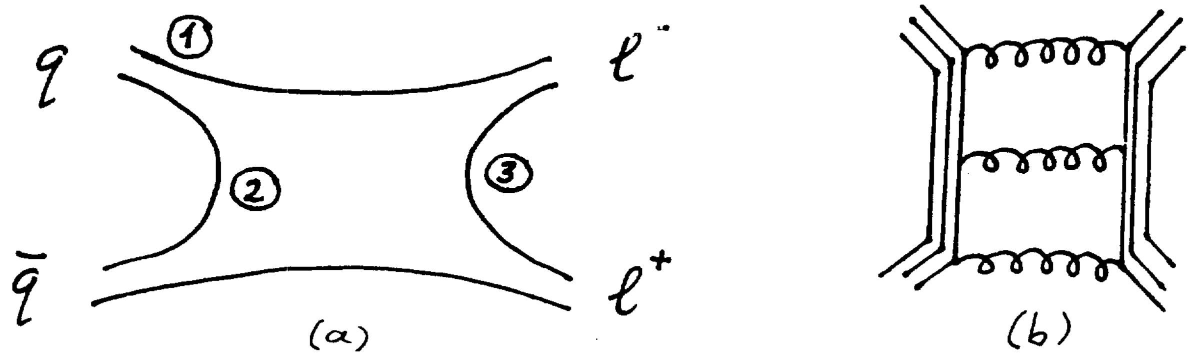

Fig. 1a. Constituent interchange between quark and leptons in $q\bar{q} \to l\bar{l}$ interactions.

Fig. 1b. Metacolor gluon exchange.

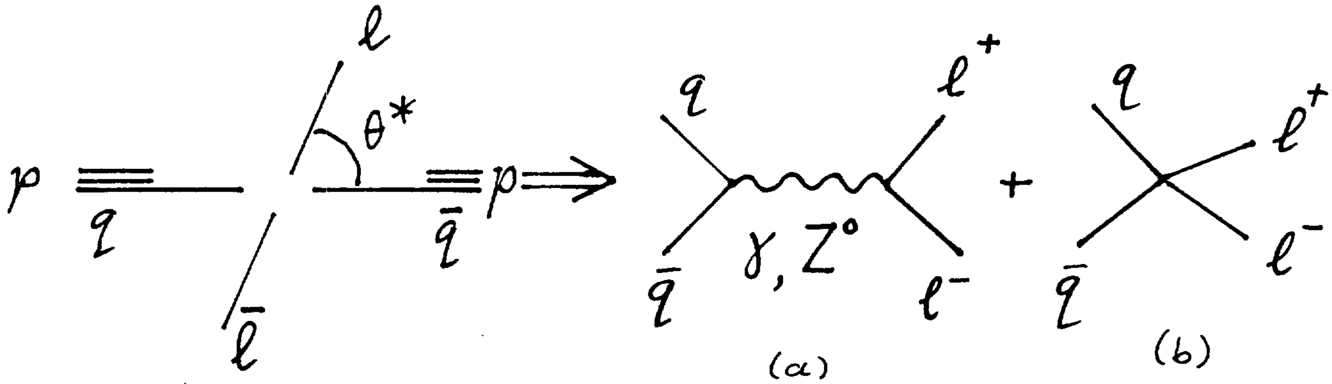

Fig. 2. $q\bar{q} \to l\bar{l}$ interaction could yield the Standard Model Drell-Yan process (a) and the contact term (b) due to compositeness (Fig. 1) or to the exchange of an exotic very heavy object.

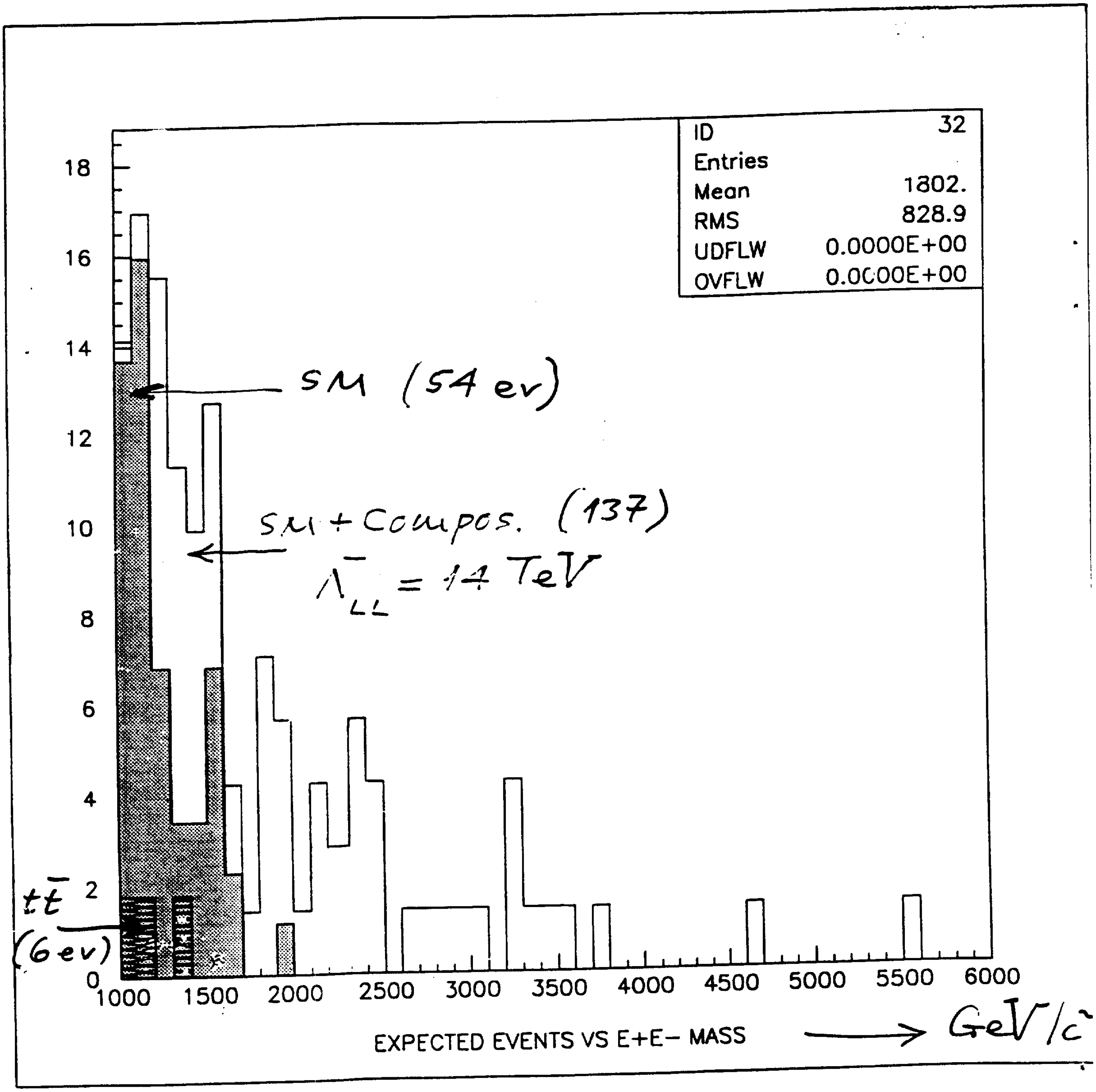

Fig. 3. Number of expected events vs. the e^+e^- invariant mass after the pseudo rapidity cut $|\eta_e|<2.5$ and the cut on the transverse momentum of each electron, $p_T{}^e>400$ GeV/c, for $m_{e^+e^-}>1$ TeV/c^2. (EHLQ1 set of structure functions): Standard model (dotted histogram), including compositeness with $\Lambda_{LL}{}^- = 14$ TeV (white) and $t\bar{t}$ (cross hatched) for integrated annual luminosity $10^4\,pb^{-1}$.

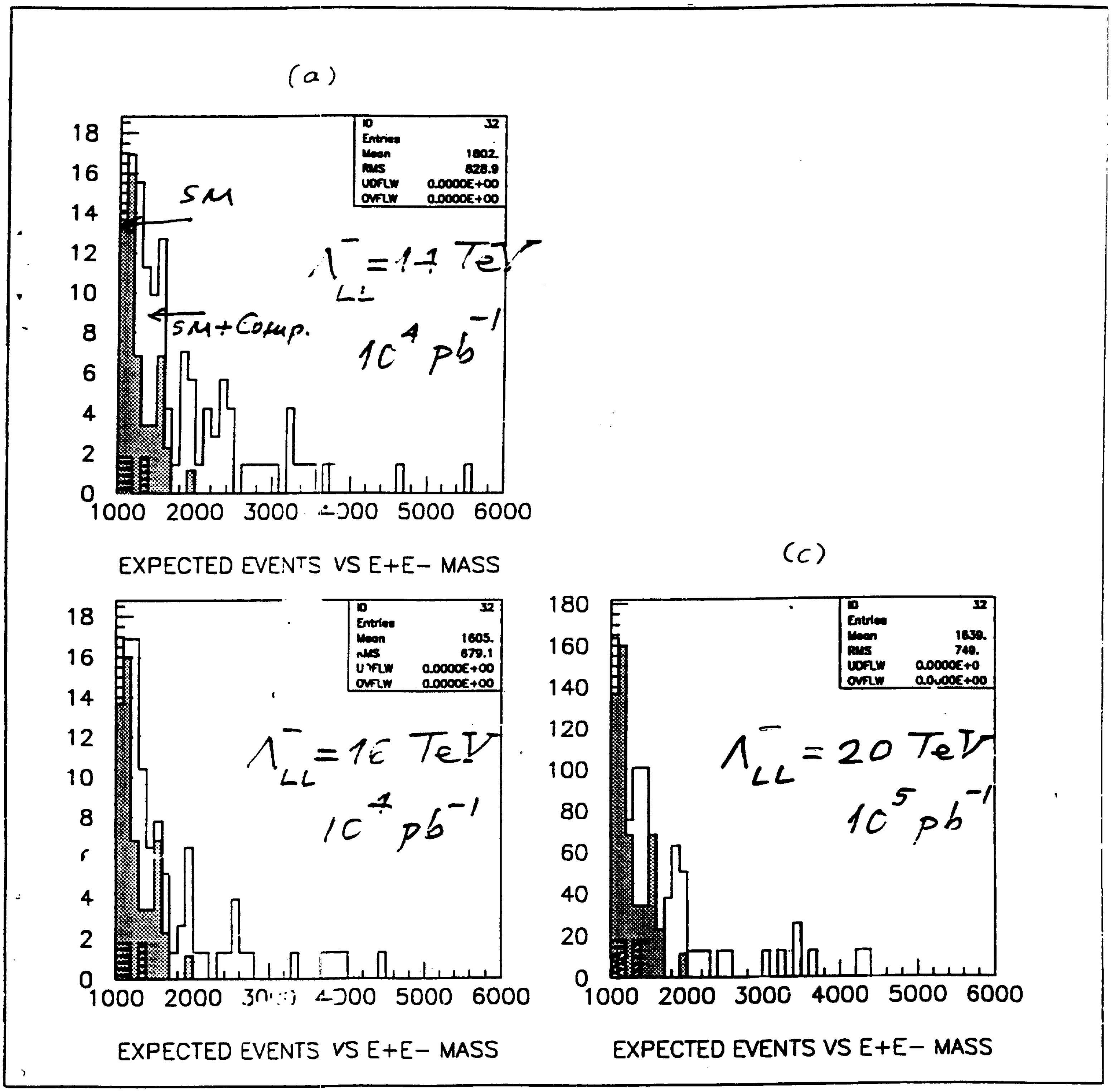

Fig. 4. a) As in Fig. 3 ($\Lambda_{LL}^- = 14$ TeV, integrated luminosity $10^4 pb^{-1}$).
b) Same luminosity as in (a), but for $\Lambda_{LL}^- = 16$ TeV and $10^4 pb^{-1}$,
c) Same as in (a) but for $\Lambda_{LL}^- = 20$ TeV and $10^5 pb^{-1}$.