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CONTACT TERMS IN CHARGED CURRENT PROCESSES AT HERA

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ABSTRACT

We obtain bounds on the mass scales characterizing four-fermion contact interactions in charged current processes. The bounds arise from the Q^2 and x distributions in the processes $e^{\pm}p \to \overset{(-)}{\nu} X$ measured by the two HERA experiments, H1 and ZEUS.

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The two HERA experiments (H1 and ZEUS) have published determinations of the W mass from the measurement of the Q^2 distributions in charged current deep inelastic scattering processes $e^{\pm}p \to \overset{(-)}{\nu} X$. The results they have obtained:

$$M_W = 84^{+10}_{-7}\ GeV \quad \text{H1 [1]}$$
$$M_W = 79^{+8+4}_{-7-4}\ GeV \quad \text{ZEUS [2]}\ ,$$

are in good agreement with the value measured at TEVATRON: $M_W = 80.33 \pm 0.15\ GeV$ [3], where the W boson is produced on mass shell. The data used in these determinations are from the 1993 run with an electron beam energy of 26.7 GeV and the 1994 run with an electron and positron beam energy of 27.5 GeV. The collected integrated luminosities were: 0.33 pb^{-1} (H1) and 0.55 pb^{-1} (ZEUS) for e^-p scattering in 1993 and 0.36 (2.70) pb^{-1} (H1) and 0.27 (2.93) pb^{-1} (ZEUS) for e^-p (e^+p) scattering in 1994. The integrated luminosities used in these analysis are still very small and the precision of the W-mass measurements should improve when more data are analyzed. In any case, since the W only enters in a t-channel exchange in deep inelastic processes and the cross-section for on shell W production is very small [4], one cannot expect to achieve at HERA the precision obtained at TEVATRON [5], but a consistency check is still interesting.

The effects of new physics are often parametrized via effective, dimension 6 four-fermion interaction terms (contact terms) which are added to the Standard Model (SM) Lagrangian. These terms can be originated either via an exchange of a heavy particle or as a result of a possible composite nature of the fermions involved. In the first case, the mass scale appearing in the contact term is interpreted as the mass of the exchanged particle over the coupling constant, while in the second case it is related to the compositeness scale in the strong coupling regime [2].

The discussion on the effects of four-fermion contact interactions at HERA began with the first studies of the HERA physics potential, long before the collider was built [7]. The excess of events above SM predictions in $e^+p \to e^+$jet at high Q^2 recently observed by H1 [8] and ZEUS [9] has prompted a renewed interest on this subject [10, 11, 12, 13, 14, 15]. All these studies, including the old ones, concentrate on neutral current processes and only recently Altarelli and collaborators [16] have considered the effects of contact terms in charged current processes in relation with the neutral current excess of events. In this paper we will obtain bounds for the $e\nu q\bar{q}'$ contact terms contributing to charged current deep inelastic scattering from the published data for the Q^2 and x distributions in $e^{\pm}p \to \overset{(-)}{\nu} X$ [1, 2, 8].

Low energy effects of physics beyond the SM, characterized by a mass scale Λ much larger than the Fermi scale, can be studied by a non-renormalizable effective lagrangian, in

[2]See [6] for a recent discussion on the physical interpretation on the effective operators.

which all the operators are organized according to their dimensionality. Since the energies and momenta that can be reached in present experiments are much lower than Λ, it is expected that the lowest dimension operators provide the dominant corrections to the SM prediction. The relevant lagrangian for ep scattering, including dimension 6, four-fermion operators is:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_V + \mathcal{L}_S, \tag{1}$$

where $\mathcal{L}_{SM}$ is the SM lagrangian and the two dimension 6 operators have been splitted into one term containing vector currents and one containing scalar currents:

$$\begin{aligned}
\mathcal{L}_V &= \eta_{LL}^{(3),q}(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q) + \eta_{LL}^{(1),q}(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q) \\
&+ \eta_{LR}^{u}(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u) + \eta_{LR}^{d}(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d) \\
&+ \eta_{RL}^{q}(\bar{e}\gamma_\mu e)(\bar{q}\gamma^\mu q) \\
&+ \eta_{RR}^{u}(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u) + \eta_{RR}^{d}(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d) \\
\mathcal{L}_S &= \eta_d(\bar{l}e)(\bar{d}q) + \eta_u(\bar{l}e)(\bar{q}u) + \tilde{\eta}_u(\bar{l}u)(\bar{q}e) + c.c.
\end{aligned} \tag{2}$$

Where c.c. means conjugate terms, the $SU(2)$ doublets $l = (\nu, e)$ and $q = (u, d)$ denote left-handed fields ($Ll = l, Lq = q,$ with $L = \frac{1-\gamma_5}{2}$) and the SU(2) singlets e, u and d represent right-handed electron, up-quark and down-quark ($Re = e, Ru = u, Rd = d,$ with $R = \frac{1+\gamma_5}{2}$). It is customary to replace the coefficients η by a mass scale Λ:

$$\eta = \frac{\epsilon g^2}{\Lambda^2}, \tag{3}$$

with $\epsilon = \pm 1$ taking into account the two possible interference patterns. Λ is interpreted as the mass scale for new physics in the strong coupling regime, i.e. with

$$\frac{g^2}{4\pi} = 1. \tag{4}$$

The experimental bounds for Λ in $\mathcal{L}_V$ from direct searches in neutral current processes range between 1.4 TeV and 6.2 TeV at 95% $C.L.$, depending on the particles involved and the operator helicity structure [18, 19]. More stringent bounds can be obtained from parity violating interactions in Cesium [20], however they can be avoided if the new physics possess some global symmetries [15, 21]. None of these bounds apply to a $e\nu q\bar{q}'$ contact terms, which are the ones that we will study in these letter. In the case of $\mathcal{L}_S$ there are very strong bounds on Λ_S from the ratio $R = \dfrac{\Gamma(\pi \to \mu\nu)}{\Gamma(\pi \to e\nu)}$ due to the fact that the operators in $\mathcal{L}_S$ do not lead to a helicity suppression in these processes as the SM does [16, 22]. However, these bounds can be avoided if the new interaction is proportional to the fermion masses, as would be the case for the exchange of a heavy scalar, Higgs-like particle.

The relevant terms for charged current processes are the first term from $\mathcal{L}_V$ and the whole $\mathcal{L}_S$. It is interesting to point out here that there are two terms from $\mathcal{L}_V$ contributing to neutral current processes with an LL helicity structure, while only one of them contribute to charged current processes: the one proportional to $\eta_{LL}^{(3),q}$. Thus, both measurements are needed to completely study the effects of new physics.

The cross sections for $e^-p \to \nu X$ and $e^+p \to \bar{\nu} X$ can be obtained in a straightforward way :

$$\begin{aligned}\left(\frac{d^2\sigma_{e^-p\to\nu X}}{dQ^2dx}\right)_{CM} &= \frac{1}{\pi}\left(\frac{G_F}{\sqrt{2}}\frac{M_W^2}{Q^2+M_W^2} - \frac{\pi}{2}\frac{\epsilon}{\Lambda_{LL}^2}\right)^2 \sum_{i=1}^{2}\left[u_i(x,Q^2) + (1-y)^2\bar{d}_i(x,Q^2)\right] \\ &+ \frac{\pi}{16}\left(\frac{1}{\Lambda_d^4}+\frac{1}{\Lambda_u^4}\right) y^2 \sum_{i=1}^{2}\left[u_i(x,Q^2) + \bar{d}_i(x,Q^2)\right] \\ &+ \frac{\pi}{16\tilde{\Lambda}_u^4}\sum_{i=1}^{2}\left[(1-y)^2 u_i(x,Q^2) + \bar{d}_i(x,Q^2)\right], \end{aligned} \tag{5}$$

$$\begin{aligned}\left(\frac{d^2\sigma_{e^+p\to\bar{\nu} X}}{dQ^2dx}\right)_{CM} &= \frac{1}{\pi}\left(\frac{G_F}{\sqrt{2}}\frac{M_W^2}{Q^2+M_W^2} - \frac{\pi}{2}\frac{\epsilon}{\Lambda_{LL}^2}\right)^2 \sum_{i=1}^{2}\left[\bar{u}_i(x,Q^2) + (1-y)^2 d_i(x,Q^2)\right] \\ &+ \frac{\pi}{16}\left(\frac{1}{\Lambda_d^4}+\frac{1}{\Lambda_u^4}\right) y^2 \sum_{i=1}^{2}\left[\bar{u}_i(x,Q^2) + d_i(x,Q^2)\right] \\ &+ \frac{\pi}{16\tilde{\Lambda}_u^4}\sum_{i=1}^{2}\left[(1-y)^2 \bar{u}_i(x,Q^2) + d_i(x,Q^2)\right], \end{aligned} \tag{6}$$

where we have neglected the interference between $O(p^6)$ terms. Since the terms in $\mathcal{L}_S$ are helicity changing there is no interference between these terms and the SM. Thus, the bounds we will obtain for Λ_u, Λ_d and $\tilde{\Lambda}_u$ will be much smaller than the ones for Λ_{LL}. The vector contact terms increase (decrease) the cross-section when η_{LL} is negative (positive), while the scalar contact terms always increase the value of the cross-section with respect to the SM prediction. It is obvious from Eqs. (5) and (6) that the effects will be larger for larger values of Q^2. We illustrate these in Fig. 1 were we show the differential cross-section $\frac{d\sigma}{dQ^2}$ for $e^-p \to \nu X$ in the Standard Model and with the addition of vector contact term with $\Lambda_{LL} = 1\, TeV$ and the two values of ϵ. The differential cross-section $\frac{d\sigma}{dx}$ is also modified and the effects are larger for larger x (see Fig. 2). Actually, the partonic cross-section violates unitarity with the introduction of the new terms and a form-factor has to be introduced to decrease the value of the cross-section at very high energy. However, since the quark distribution functions decrease very quickly for large x, we can neglect the effects of such form-factors.

We have performed a χ^2 fit to the Q^2 distributions published by the two experiments at HERA: Table 1 in [1], Tables 2 and 3 in [2] and Table 3 in [8]. In the fits of the data from the first two references we have included statistical and systematic errors, while for the third one only statistical errors are included. The data from the third reference has been converted into a distribution in bins of Q^2 in such a way that it can be combined with the data from the other references. We have always used the MRSA parton density parametrization [23], as the experimental groups have done in their fits to the W mass. In our fit we have included the SM radiative corrections, but we have neglected the interference between these radiative corrections and the contact terms. Certainly, all the fits are compatible with the SM and only lower bounds on the mass scales Λ are obtained. These bounds do not change when we change the W mass within its experimental error. We have taken $M_W = 80.33 \pm 0.15\ GeV$. The bounds we have obtained at 95% CL are shown in Table 1, where we have assumed a family independent contact term. If only a contact term between members of the first family is allowed, the bounds are relaxed a 10% for the vector and a 2% for the scalar contact terms to those shown in Table 2. The bounds on Λ_{LL} are a factor 2.5 lower than bounds obtained by the OPAL Collaboration [19]. However, we should remind the reader at this point that the operators relevant in neutral current processes are different than those in charged current processes. Indeed, the latter involve only the term proportional to $\eta_{LL}^{(3)}$, i.e. the operator in which the currents transform as an $SU(2)_L$ triplet, while neutral current processes, even for the LL helicity combination, also receive a contribution from the operator involving $SU(2)_L$ singlet currents. More definitely, in neutral current one is actually measuring the sum $\eta_{LL}^{(3)} + \eta_{LL}^{(1)}$. Thus, measurements on both processes are needed to completely fix the constants in the lagrangian (2).

The distribution $\frac{d\sigma}{dx}$ can also be used to obtain bounds for Λ. In this case we have used the data from Table 4 in [2]. The results of the fit, see Table 3, are similar to those obtain from the Q^2 distributions. In particular, due to the presence of the interference between the vector contact term and the SM, the bounds on Λ_{LL}^- improve with respect to the ones obtained from the Q^2-distribution, while the bounds for Λ_{LL}^+ are somewhat weaker. Since the effect of the scalar contact term is also an increase in the cross-section, as it is the case for the vector contact term with $\epsilon = -1$, the x-distribution is also more sensitive to the presence of these terms.

The bounds obtained for the scalar operators from the HERA data are three orders of magnitude lower than those obtained from pion decays [16, 22]. In order to avoid these bounds we have also considered that the couplings of the dimension 6 operators are proportional to the masses of the down-type particles involved in the process. In particular, as an example, we have considered $\eta_S^s = 20\eta_S^d$ and repeated the same fits. The results from the Q^2 and x distributions are shown in Table 4.

In summary, we have obtained bounds on the mass scales appearing in the dimension 6, $e\nu q\bar{q}'$ four-fermion contact interactions relevant for charged current processes. This contact term has not been studied very much in the past getting to the point that there is no entry for it in the Particle Data Group compilation on the search for compositeness [18]. Our bounds have been obtained from fits to the Q^2 and x distributions measured at HERA by H1 and ZEUS. The Q^2-distribution provides the strongest bound on a vector contact term with $\epsilon = 1$, while for $\epsilon = -1$ and for an scalar contact term it is the x-distribution the one that provides the strongest bounds. This is just an accident from the set of data we have used. Both distributions are sensitive to the presence of a contact term in a characteristic way which may be useful to pin down the origin of a possible departure of the data from the SM predictions. The lower bounds we obtain are lower than $3\,TeV$, which is the value needed to explain the excess of events observed in neutral currents. We agree, thus, with the authors of Ref. [16] on their conclusion that no effects on charged current processes must have been observed if the anomaly in the neutral current cross-section is due to a four-fermion contact term.

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	ZEUS	H1(93-94)	ZEUS + H1(93-94)	H1(94-96)
Λ_{LL}^{+}	2.58	2.39	3.00	2.16
Λ_{LL}^{-}	3.38	2.39	3.38	5.01
$\Lambda_{d}^{\pm}, \Lambda_{u}^{\pm}$	0.63	0.67	0.70	0.81
$\tilde{\Lambda}_{u}^{\pm}$	0.77	0.72	0.79	1.07

Table 1: Lower bounds (in TeV) on contact term mass scales obtained from various Q^2-distribution experimental data. Universal contact terms are used.

	ZEUS	H1(93-94)	ZEUS + H1(93-94)	H1(94-96)
Λ_{LL}^{+}	2.34	2.20	2.72	1.95
Λ_{LL}^{-}	3.00	2.24	3.11	4.58
$\Lambda_{d}^{\pm}, \Lambda_{u}^{\pm}$	0.59	0.66	0.68	0.79
$\tilde{\Lambda}_{u}^{\pm}$	0.74	0.69	0.77	1.02

Table 2: Lower bounds (in TeV) on contact term mass scales obtained from various Q^2-distribution experimental data. Only first family contact terms are used.

	universal	first family
Λ_{LL}^{+}	2.24	2.05
Λ_{LL}^{-}	4.58	3.96
$\Lambda_{d}^{\pm}, \Lambda_{u}^{\pm}$	0.72	0.68
$\tilde{\Lambda}_{u}^{\pm}$	0.86	0.81

Table 3: Lower bounds (in TeV) on contact term mass scales obtained from the x-distribution data measured by ZEUS [2].

	ZEUS	H1(93-94)	ZEUS + H1(93-94)	H1(94-96)	ZEUS (x distribution)
$\Lambda_{d}^{\pm}, \Lambda_{u}^{\pm}$	1.92	1.59	1.92	1.98	2.24
$\tilde{\Lambda}_{u}^{\pm}$	2.34	1.87	2.34	2.64	2.64

Table 4: Lower bounds (in TeV) on scalar contact term mass scales obtained from the experimental data on Q^2-distribution (first four columns) and x-distribution (last column). We have assumed $\eta_S^s = 20\eta_S^d$.

Figure Captions

Fig. 1: Q^2-distribution for $e^- p \to \nu X$ in the Standard Model (solid line) and with a vector four-fermion contact term with $\Lambda_{LL} = 1\ TeV$ and $\epsilon = 1$ (dashed line) and $\epsilon = -1$ (dotted line). In all the cases a cut $x > 0.006$ has been applied.

Fig. 2: x distribution for $e^- p \to \nu X$ with the same conventions as in the previous figure. Now a cut $Q^2 > 200\ GeV^2$ has been applied.

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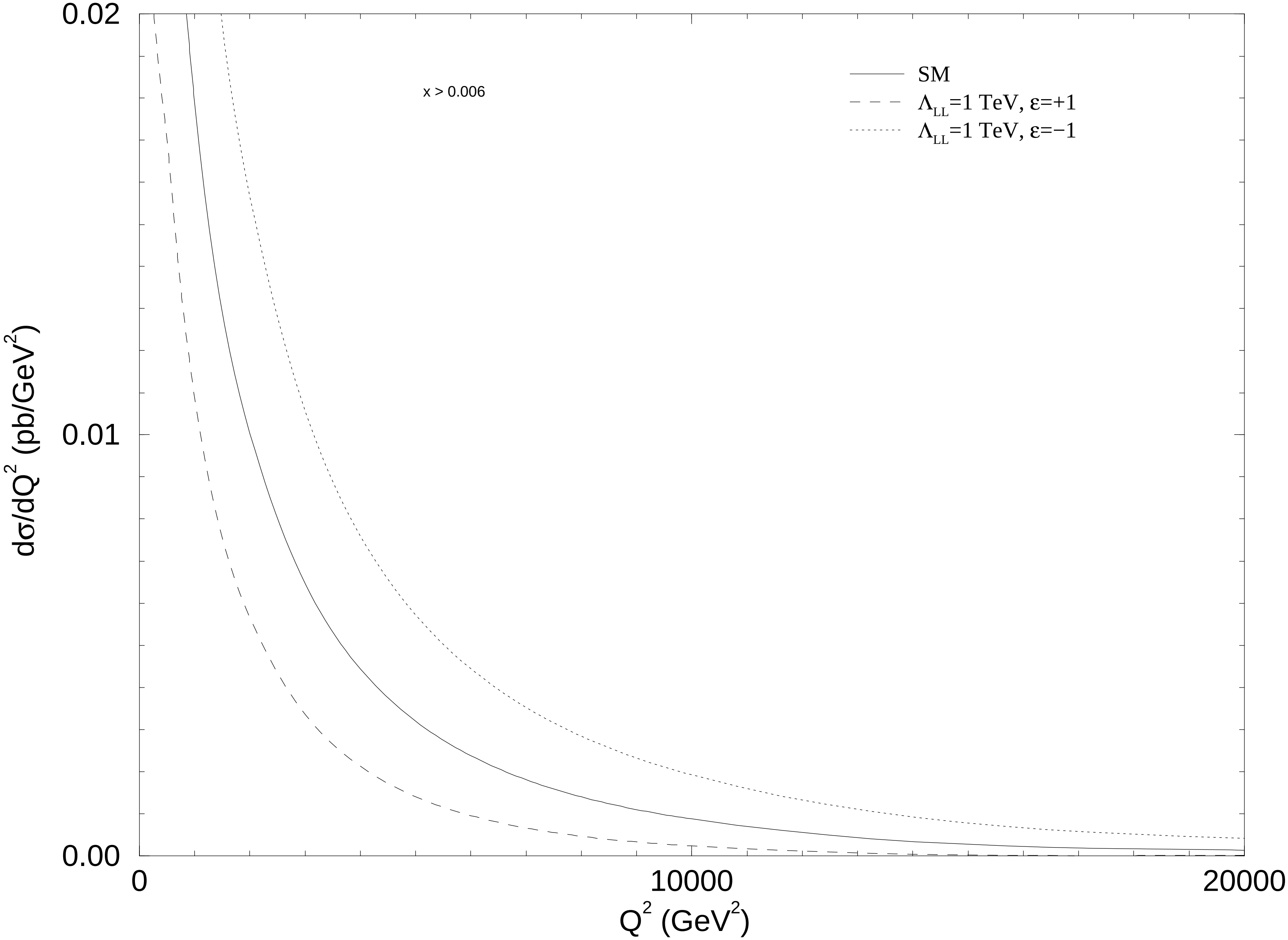
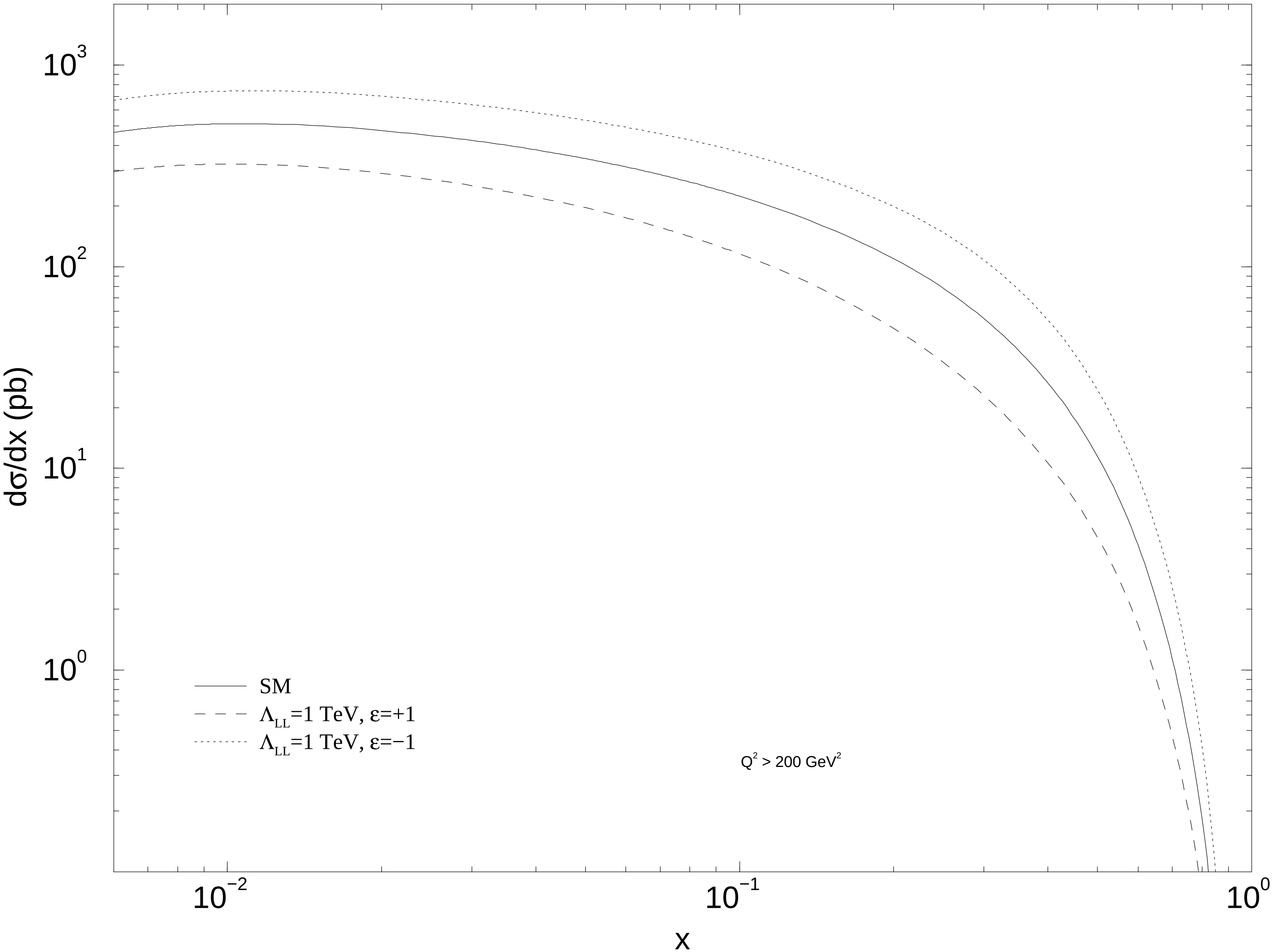
Fig. 1



0.02
0.01
0.00
0
10000
20000
$d\sigma/dQ^2$ (pb/GeV^2)
Q^2 (GeV^2)
x > 0.006
SM
Λ_{LL}=1 TeV, ε=+1
Λ_{LL}=1 TeV, ε=−1

Fig. 2


dσ/dx (pb)
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
x
SM
Λ_{LL}=1 TeV, ε=+1
Λ_{LL}=1 TeV, ε=−1
Q^2 > 200 GeV^2