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Selectron Production in Quasi-Elastic Electron-Proton Scattering

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Abstract:

We calculate the cross section for the production of selectrons in quasi-elastic electron proton scattering at HERA energies. In the region of very small momentum transfer the cross section turns out to be large: e.g. σ = 36 pb for a selectron mass of 60 GeV, $t_{min} \leq |t| \leq t_{cut}$ = 0 (1 GeV²), and photino mass small compared to the selectron mass. Together with the clean experimental signature, this large cross section makes the reaction $e + P \to \tilde{e} + \tilde{\gamma} + P$ one of the most promising HERA-processes in connection with the search for supersymmetric particles.

The search for supersymmetric particles will be one of the major tasks of future accelerators. The production of these new particles is commonly discussed in the supersymmetric extension of the standard model [1]. For the HERA eP-machine two processes have been found to be realistic candidates for discovering supersymmetric particles: the direct production of selectron and squark [2] $e + q \to \tilde{e} + \tilde{q}$ and the production of a selectron and a photino at the lepton vertex [3),4)] $e + P \to \tilde{e}\tilde{\gamma} + X$. As to the latter case Altarelli et al. [4)] have recently pointed out that the cross sections for the (deep-) inelastic version of this process are too small to be of interest for HERA. From the experimental point of view on the other hand, it is the quasi-elastic process $eP \to \tilde{e}\tilde{\gamma}P \to e\tilde{\gamma}\tilde{\gamma}P$ with the outgoing proton being very close to the forward direction which is of particular interest: the outgoing proton is lost in the beam pipe, and if the photino is light and stable, one only sees an electron from the decay of the selectron. Its energy and angular distribution will differ from the nonsupersymmetric forward-process $eP \to eP$. At the same time the cross section for this process can be expected to be larger than for the inelastic reaction: for small momentum transfer the pole at t = 0 of the photon propagator will become important. In this letter we study this reaction in detail and calculate the cross section. The event rate is, in fact, larger than that of the inelastic reaction of Ref. 4; it is also larger than the estimate given in Ref. 3).

The kinematics of the reaction are shown in Fig. 1. As independent variables we choose $s = (p+q)^2$, $t = (q-q')^2$, $t' = (p-p')^2$, $\nu = p(q-q')$. In addition to these invariants we need one angle φ, which we choose to be the angle between the plane of the vectors p, p' and the plane of the vectors p, q' in the center of mass system of the selectron and the photino. The deep inelastic version of this reaction ($|t| > 1$ GeV² has been calculated and discussed in Refs. 3 and 4, and the cross sections have been found to be somewhat too small to be of interest for HERA. We therefore only give the formula for the quasielastic process. Since we expect the photon exchange diagram with the pole at t = 0 to be the dominant one, we neglect contributions from heavy Z exchange. With the standard ansatz for the coupling of the photon to the proton

$$\bar{u}(q')\gamma_\mu F_1 u(q) + \frac{i\mu}{2M_p}(q'-q)^\nu \bar{u}(q')\sigma_{\mu\nu} F_2 u(q) \quad (1)$$

$F_i(0) = 1$, μ = magnetic moment of the proton,

we find after squaring and averaging over initial spin for the hadronic tensor:

$$H_{\mu\nu} = (F_1 + \mu F_2)^2 H^{(1)}_{\mu\nu} + \left(F_1^2 - \frac{t}{4M_p^2}\mu^2 F_2^2\right) H^{(2)}_{\mu\nu} \quad (2)$$

with

$$H^{(1)}_{\mu\nu} = t\, g_{\mu\nu} - (q'-q)_\mu (q'-q)_\nu$$

$$H^{(2)}_{\mu\nu} = (q'+q)_\mu (q'+q)_\nu = (2q+q'-q)_\mu (2q+q'-q)_\nu \, . \tag{3}$$

For the (gauge invariant) leptonic tensor we have from the two diagrams Fig. 2a and b

$$L^a_{\mu\nu} = \Big\{ (m^2_{\tilde\gamma} - m^2_{\tilde e})\, \mathrm{Tr}\Big[\frac{1+\sigma\gamma_5}{2} \not k' \gamma_\mu \not p \gamma_\nu\Big] + 2(m^2_{\tilde\gamma} + p'k')\, \mathrm{Tr}\Big[\frac{1+\sigma\gamma_5}{2} \not p' \gamma_\mu \not p \gamma_\nu\Big] \Big\} \frac{1}{(t+2\bar\nu)^2} \tag{4}$$

$$L^b_{\mu\nu} = 2(pk')(p+p'-k')_\mu (p+p'-k')_\nu \frac{1}{(t'+2\bar\nu - m^2_{\tilde\gamma})^2} \tag{5}$$

$$2\,\mathrm{Re}\, L^{ab}_{\mu\nu} = \frac{-4(p+p'-k')_\nu}{(t+2\bar\nu)(t'+2\bar\nu - m^2_{\tilde\gamma})} \Big\{ (m^2_{\tilde\gamma} + p'k') p_\mu + (pk') p'_\mu - (pp') k'_\mu \Big\} \tag{6}$$

Here $\sigma = +1$ (-1) stands for right-handed (left-handed) polarization of the incoming electron. When contracting hadronic and leptonic tensors, terms $\sim (q'-q)_\mu$ or $(q'-q)_\nu$ in $H^{(1)}_{\mu\nu}$ or $H^{(2)}_{\mu\nu}$ give zero contributions as a result of gauge invariance. The cross section then becomes:

$$\frac{d^4\sigma}{dt\, dt'\, d\bar\nu\, d\varphi} = \frac{1}{(2\pi)^4} \frac{1}{2^5 (2\bar\nu)^3} \Big(1 + \frac{s}{2\bar\nu + t}\Big) |M|^2 \cdot \frac{1}{t^2} \tag{7}$$

where

$$|M|^2 = e^6 \Big\{ (F_1 + \mu F_2)^2 t\, g^{\mu\nu} + \Big(F_1 - \frac{t}{4M_p^2}\mu^2 F_2^2\Big) 4 q^\mu q^\nu \Big\} \cdot \Big\{ L^a_{\mu\nu} + L^b_{\mu\nu} + 2\,\mathrm{Re}\, L^{ab}_{\mu\nu} \Big\} \, . \tag{8}$$

The evaluation of the tensor contraction leads after some algebra to the following result ($m_{\tilde e_L} = m_{\tilde e_R}$, unpolarized beams):

$$\frac{d^4\sigma}{dt\, dt'\, d\bar\nu\, d\varphi} = \frac{\alpha^3}{8\pi} \Big(1 + \frac{s}{2\bar\nu + t}\Big) \frac{1}{(2\bar\nu)^3}\, T \, , \tag{9}$$

$$T = \Big(F_1^2 - \frac{\mu^2}{4M_p^2} t F_2^2\Big) \Big\{ \frac{4M_p^2}{t^2} \Big[\frac{(s-2\bar\nu)(m^2_{\tilde\gamma} - t')}{(2\bar\nu)^2} + G_0 \Big] + \frac{G_1}{t^2} \Big\} + (F_1 + \mu F_2)^2 \frac{G_2}{t^2} \tag{10}$$

with

$$G_0 = \frac{2}{(2\bar\nu + t)^2} \Big\{ (m^2_{\tilde e} - m^2_{\tilde\gamma})(pk' + qk') + (m^2_{\tilde\gamma} + p'k')(t' - m^2_{\tilde e} - 2qp') \Big\} + \frac{4(qp')(m^2_{\tilde\gamma} + p'k')}{(2\bar\nu + t)(2\bar\nu + t' - m^2_{\tilde\gamma})} - \frac{(s-2\bar\nu)(m^2_{\tilde\gamma} - t')}{(2\bar\nu)^2} \, ; \tag{11}$$

$$G_1 = \frac{8s}{(2\bar\nu + t)^2} \Big\{ (qk')(m^2_{\tilde\gamma} - m^2_{\tilde e}) + 2(qp')(m^2_{\tilde\gamma} + p'k') \Big\} - \frac{4(4qp' - t)}{(2\bar\nu + t)(2\bar\nu + t' - m^2_{\tilde\gamma})} \Big\{ s(m^2_{\tilde\gamma} + p'k') + (t' - m^2_{\tilde e})(qk') + 2(pk')(qp') \Big\} + \frac{2(pk')}{(2\bar\nu + t' - m^2_{\tilde\gamma})^2} (4qp' - t)^2 \, ; \tag{12}$$

$$\begin{aligned} G_2 = {} & \frac{4t}{(2\bar\nu + t)^2} \Big\{ (pk')(m^2_{\tilde e} - m^2_{\tilde\gamma}) - 2(pp')(m^2_{\tilde\gamma} + p'k') \Big\} \\ & - \frac{4t}{(2\bar\nu + t)(2\bar\nu + t' - m^2_{\tilde\gamma})^2} \Big\{ (m^2_{\tilde\gamma} + p'k')(pp' - pk') \\ & \qquad + (pk')(m^2_{\tilde e} + pp' - p'k') \\ & \qquad + (pp')(m^2_{\tilde\gamma} - pk' - p'k') \Big\} \\ & + \frac{8(pk')\,t}{(2\bar\nu + t' - m^2_{\tilde\gamma})^2} (m^2_{\tilde e} + p'q' - qp' + t/4) \end{aligned} \tag{13}$$

The scalar products in G_0, G_1, and G_2 can be expressed in terms of the invariant variables:

$$
\begin{aligned}
pq &= \frac{s - M_p^2}{2} \\
pq' &= \frac{s - M_p^2 - 2\bar{\nu}}{2} \\
qq' &= M_p^2 - \frac{t}{2} \\
pp' &= \frac{m_{\tilde{e}}^2 - t'}{2} \\
pk' &= \frac{2\bar{\nu} + t' - m_{\tilde{e}}^2}{2} \\
p'k' &= \frac{2\bar{\nu} + t - m_{\tilde{e}}^2 - m_{\tilde{\gamma}}^2}{2} \\
qp' &= p'q' + \frac{2\bar{\nu} + t' + t - m_{\tilde{\gamma}}^2}{2} \\
qk' &= -p'q' + \frac{s - M_p^2 - 2\bar{\nu} - t' + m_{\tilde{\gamma}}^2}{2} \\
p'q' &= p_0' q_0' - |\vec{p}\,'||\vec{q}\,'| \left(\cos\theta_{p'} \cos\theta_{q'} + \sin\theta_{p'} \sin\theta_{q'} \cos\varphi \right)
\end{aligned}
\tag{14}
$$

The angles are determined by

$$
\begin{aligned}
\cos\theta_{p'} &= \frac{t' - m_{\tilde{e}}^2 + 2 p_0 p_0'}{2 p_0 |\vec{p}\,'|} , \qquad \theta_{p'} = \sphericalangle(\vec{p}, \vec{p}\,') \\
\cos\theta_{q'} &= \frac{2 p_0 q_0' - s + 2\bar{\nu} + M_p^2}{2 p_0 |\vec{q}\,'|} , \qquad \theta_{q'} = \sphericalangle(\vec{p}, \vec{q}\,')
\end{aligned}
\tag{15}
$$

together with

$$
\begin{aligned}
p_0 &= \frac{2\bar{\nu}}{2\sqrt{2\bar{\nu} + t}} , \qquad p_0' = \frac{2\bar{\nu} + t + m_{\tilde{e}}^2 - m_{\tilde{\gamma}}^2}{2\sqrt{2\bar{\nu} + t}} . \\
q_0' &= \frac{s - M_p^2 - 2\bar{\nu} - t}{2\sqrt{2\bar{\nu} + t}} , \\
|\vec{q}\,'| &= \sqrt{q_0'^2 - M_p^2} , \qquad |\vec{p}\,'| = \sqrt{p_0'^2 - m_{\tilde{e}}^2} .
\end{aligned}
\tag{16}
$$

The form factors $F_{1,2}$ in (10) are related to the electric and magnetic form factors G_E, G_M by

$$
F_1 = \frac{G_E - \frac{t}{4M_p^2} G_M}{1 - \frac{t}{4M_p^2}} , \qquad \mu F_2 = \frac{G_M - G_E}{1 - \frac{t}{4M_p^2}} .
\tag{17}
$$

We make use of the dipole formula

$$
G_M \simeq (1 + \mu) G_E , \qquad G_E = \frac{1}{\left(1 - \frac{t}{0.71\,\mathrm{GeV}^2}\right)^2} .
\tag{18}
$$

Since the picture of a coherent interaction of the photon with the nucleon makes only sense for small t, we restrict our numerical discussion to a maximum value of the momentum transfer t_{cut},

$$
t_{min} \le |t| \le t_{cut} \quad \text{with} \quad t_{cut} \simeq M_p^2 .
\tag{19}
$$

Putting t_{cut} (somewhat arbitrary) to 1 GeV², the total production cross section for $(\tilde{e}\tilde{\gamma})$ can be written as the sum of our "elastic" result (corresponding to (19)) and the "inelastic" result from Ref. 4. Due to the rapid decrease of the differential cross section (9, 10) and the form factor with increasing $|t|$ the results are not sensitive to the actual choice of t_{cut}. In the following t_{cut} = 1 GeV² is used.

In this range of small t and in the limit

$$M_p^2 \ll (m_{\tilde e} + m_{\tilde\gamma})^2, \qquad M_p^2 \ll s - 2\bar\nu \tag{20}$$

the value for t_{min} is given by

$$t_{min} = M_p^2 \left(\frac{2\bar\nu}{s}\right)^2 \cdot \frac{s}{s-2\bar\nu} \quad . \tag{21}$$

The integrated quasi-elastic cross section then is derived from (9):

$$\sigma = \int_{\bar\nu_1}^{\bar\nu_2} d\bar\nu \int_{t_1'}^{t_2'} d|t'| \int_{t_{min}}^{t_{cut}} d|t| \int_0^{2\pi} d\varphi \; \frac{d^4\sigma}{dt\,dt'\,d\bar\nu\,d\varphi} \tag{22}$$

where

$$\begin{aligned} t'_{1,2} &= -m_{\tilde e}^2 + \frac{1}{2}\left[2\bar\nu + m_{\tilde e}^2 - m_{\tilde\gamma}^2 \mp \sqrt{(2\bar\nu + m_{\tilde e}^2 - m_{\tilde\gamma}^2)^2 - 4m_{\tilde e}^2 \cdot 2\bar\nu}\,\right], \\ \bar\nu_1 &= \frac{1}{2}(m_{\tilde e} + m_{\tilde\gamma})^2, \\ \bar\nu_2 &= s\,\frac{t_{cut}}{M_p^2}\left(\sqrt{1 + \frac{4M_p^2}{t_{cut}}} - 1\right) \quad . \end{aligned} \tag{23}$$

Our choice of t_{cut} ensures that the condition (20) for the allowed range of $\bar\nu$ is fullfilled:

$$t_{cut} = 1\ \text{GeV}^2: \qquad s - 2\bar\nu \geq s - 2\bar\nu_2 = s - 0.64s \gg M_p^2 .$$

Before we turn to a numerical evaluation of (22) we discuss an approximation to the somewhat lengthy expressions in (10) - (13).

If M_p were zero, the functions G_1 and G_2 in (11) and (12) would vanish for $t \to 0$ according to

$$G_{1,2} \simeq t \cdot G'_{1,2}(0) .$$

Qualitatively this becomes clear from the following argument: $t = 0$ implies $q_\mu \sim q'_\mu \sim (q-q')_\mu$. Then the contraction of the hadron tensor with the full lepton tensor $L_{\mu\nu}$ yields zero, since $q^\mu L_{\mu\nu} \sim (q-q')^\mu L_{\mu\nu} = 0$ because of gauge invariance.

The differential cross section (9) therefore has a leading $\frac{1}{t}$ behaviour in the massless case, whereas for a massive proton the leading term is of the order $\frac{M_p^2}{t^2}$. Hence we expect that the dominant contribution to (9) for $t \to t_{min}$ comes from this most singular term in (10). We therefore evaluate (9) to leading order in $1/t^2$, putting $t = 0$ in the numerator. The result is then independent of φ ; performing the φ-integration one finds for the cross section (9):

$$\frac{d^3\sigma}{dt\,dt'\,d\bar\nu} \simeq \frac{\alpha^3}{4}\left(1 + \frac{s}{2\bar\nu}\right) \cdot \frac{4M_p^2}{t^2} \cdot \frac{(s-2\bar\nu)(m_{\tilde\gamma}^2 - t')}{(2\bar\nu)^5} \quad . \tag{24}$$

This approximation should be valid in the region

$$t_{min} \leq |t| \leq t_{cut} = O(1\ \text{GeV}^2)$$

$$(m_{\tilde e} + m_{\tilde\gamma})^2 \leq 2\bar\nu \leq 2\bar\nu_2 \quad .$$

For further simplifications we take $m_{\tilde\gamma} \ll m_{\tilde e}$. Then (22) can easily be integrated. For $t_{cut} = 1\ \text{GeV}^2$, $0 \leq |t'| \leq 2\bar\nu - m_e$ and $2\bar\nu \leq 2\bar\nu_2$ we obtain for $s = (300\ \text{GeV})^2$:

$\sigma = 0.17$ pb for $m_{\tilde e} = 100$ GeV

$\sigma = 36$ pb for $m_{\tilde e} = 60$ GeV.

A comparison with the inelastic parton model result of Ref. 4 immediately shows that the quasi-elastic production rate widely exceeds the inelastic expectation. It is also larger than the quasi-elastic result of Ref. 3. From what the authors of Ref. 3 say it seems to follow that they have done their calculation with $M_p = 0$.
The evaluation of (22) in the general case has been performed numerically. All terms of order M_p^2/s have been neglected. The results for the integrated cross section are displayed in Fig. 3 for various selectron and photino masses at a fixed $s = 10^5\ \text{GeV}^2$, and in Fig. 4 as a function of s. Again a comparison with Ref. 4 shows that the obtained cross sections are much larger than in the inelastic case.

If we assume that 0.1 pb is a realistic lower limit for detecting reactions experimentally the $\tilde{e}$ could be as heavy as 110 GeV for a very light $\tilde{\gamma}$. For a more detailed discussion the decay of the $\tilde{e}$ into e and $\tilde{\gamma}$ has to be taken into account. The e spectrum has to be compared with non supersymmetric standard processes leading to similar experimental signatures. We feel, however, that our results make the search for supersymmetric particles at HERA a very promising project.

We thank P. Mättig and R. Rückl for useful discussions.

References:

1) For an excellent review of the supersymmetric standard model see: H.E. Haber and G.L. Kane, Phys. Rep. 117, 75 (1985) and references therein.

2) S.K. Jones and C.H. Llewellyn Smith, Nucl. Phys. B217, 145 (1983).

3) P. Salati and J.C. Wallet, Phys. Letters 122B, 397 (1983).

4) G. Altarelli, G. Martinelli, B. Mele and R. Rückl, CERN-TH. 4094/85.

Figure Captions:

Fig. 1: Kinematic variables for the process $eP \to \tilde{e}\tilde{\gamma}P$.

Fig. 2: Diagrams contributing to $eP \to \tilde{e}\tilde{\gamma}P$ in the one photon exchange approximation.

Fig. 3: Integrated cross sections for various $\tilde{e}$ and $\tilde{\gamma}$ masses. $s = 10^5\ \mathrm{GeV}^2$. Cross sections below the horizontal line are too small for being of practical interest at HERA.

Fig. 4: Integrated cross section for $eP \to \tilde{e}\tilde{\gamma}P$ as function of s. $m_{\tilde{\gamma}} = 0$.

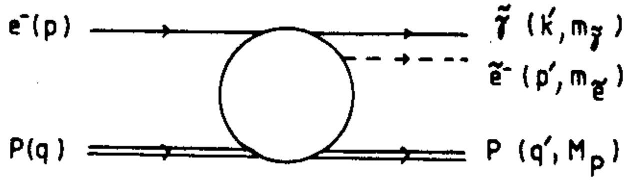

Fig. 1

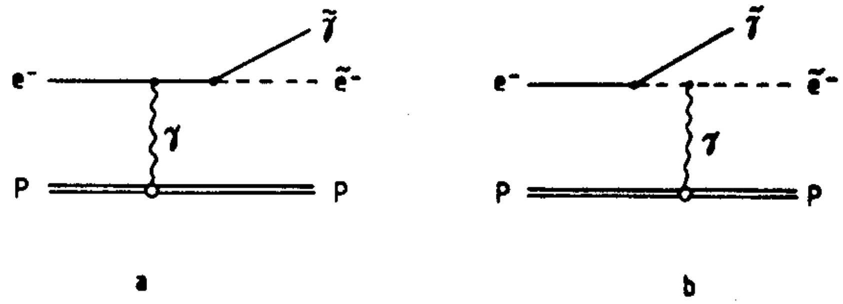

Fig. 2

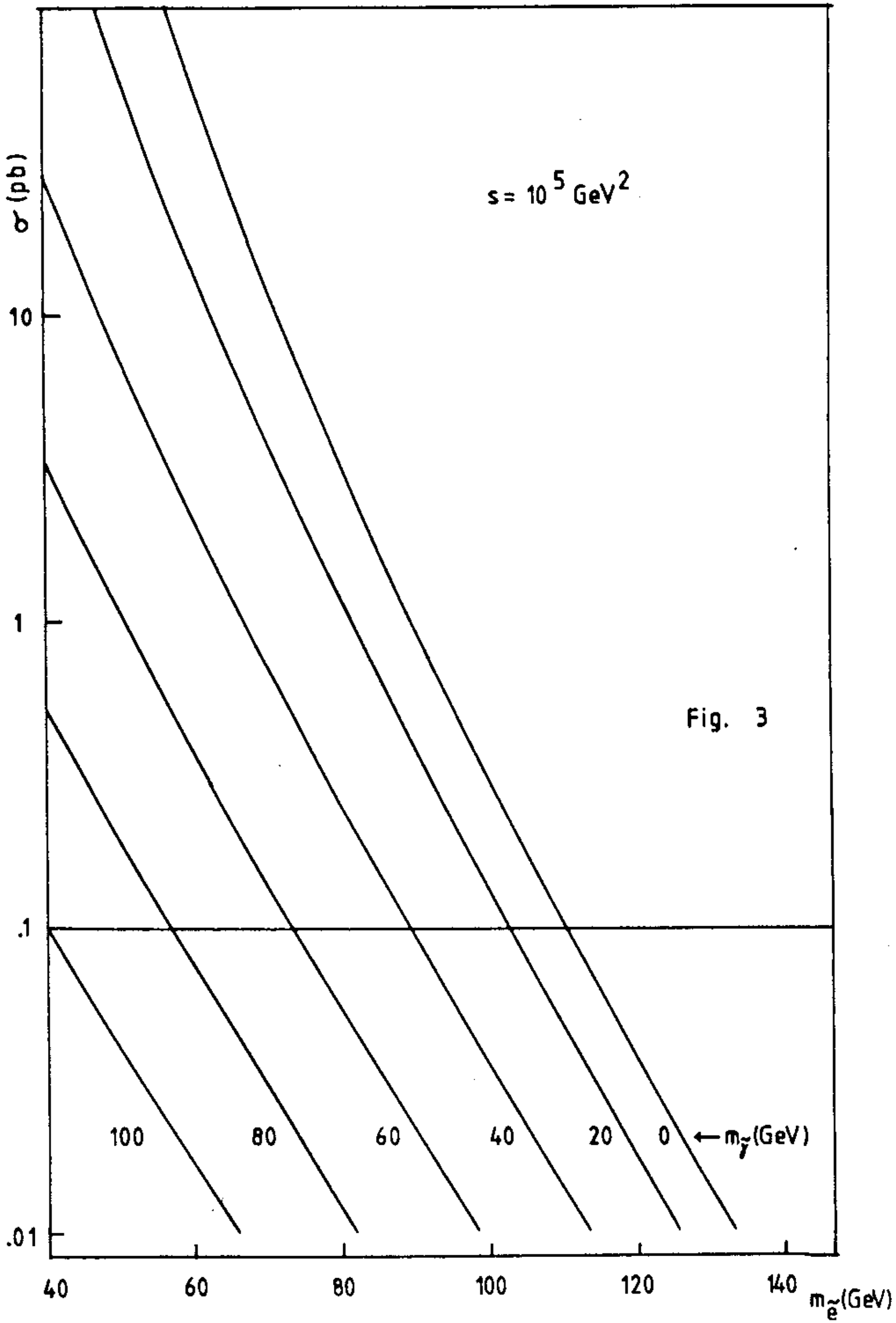
σ (pb)
s = 10^5 GeV^2
10
1
.1
.01
100
80
60
40
20
0
← m_γ̃ (GeV)
40
60
80
100
120
140
m_ẽ (GeV)

Fig. 3

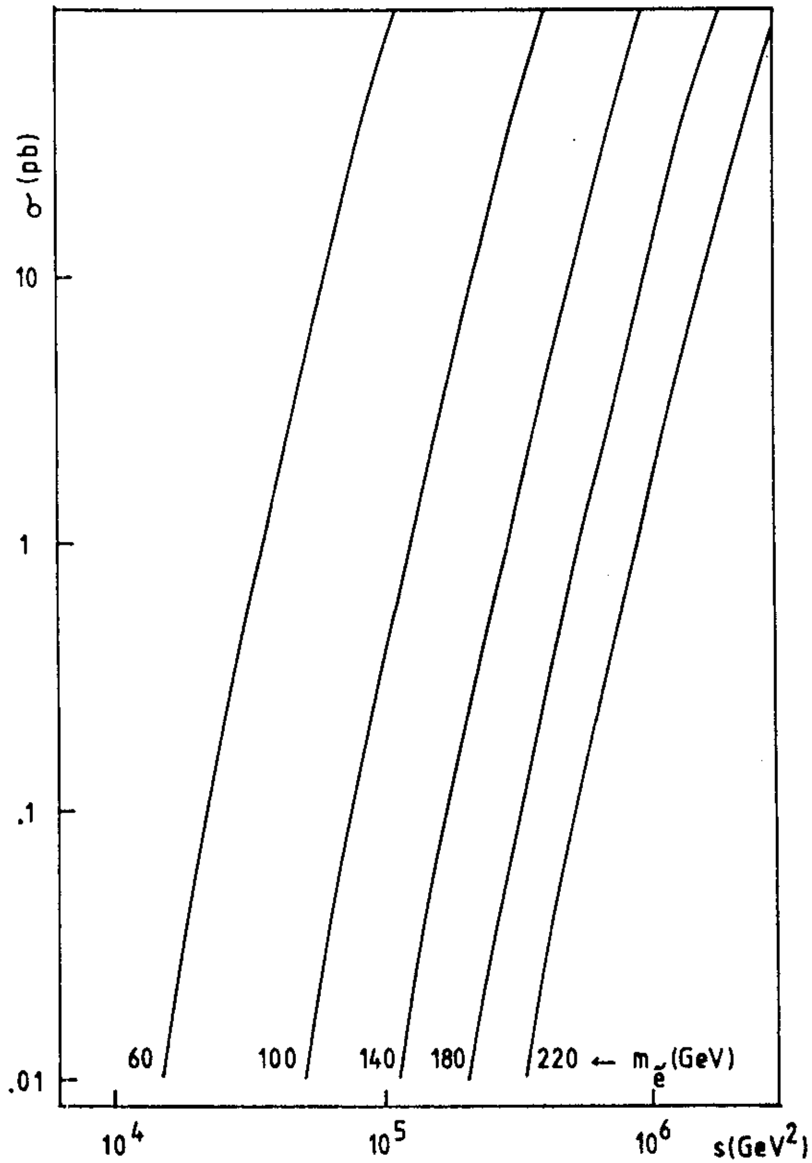
σ (pb)
10
1
.1
.01
60
100
140
180
220 ← m_ẽ (GeV)
10^4
10^5
10^6
s(GeV^2)

Fig. 4