Signatures of heavy Majorana neutrinos and DESY HERA's isolated lepton events

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The graph of neutrinoless double beta decay is applied to DESY HERA data and generalized to final states with any two charged leptons. Considered is the case in which one of the two escapes typical identification criteria and the case when a produced tau decays hadronically. Both possibilities give one isolated lepton with high transverse momentum, hadronic activity, and an imbalance in transverse momentum. We examine the kinematical properties of these events and compare them with the high p_T isolated leptons reported by the H1 Collaboration. Their positive charged muon events can be explained by the ''double beta'' process and we discuss the possibilities for the precise determination which original final state produced the single isolated lepton. To confirm our hypothesis one should search in the data for high pseudorapidity and/or low p_T leptons or for additional separated jets.

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I. INTRODUCTION

Despite the impressive confirmation of predictions from the standard model (SM) it is generally believed that we are on the verge of fundamental new discoveries, be it production of new particles or significant deviations of observables in high-precision measurements. The effects of new physics might also be hidden in existing data sets and it is interesting to see what candidates are able to explain any unexpected events or measurements. A first step in this direction was done in terms of the observation of nonvanishing neutrino rest masses, most clearly seen in the up-down asymmetry of the atmospheric muon neutrino flux in SuperKamiokande [1]. The smallness of these masses can be related to very massive new particles via the seesaw mechanism [2]. In this respect it seems most natural to look for effects of heavy neutrinos; i.e., search for hints of these new particles in high- or low-energy experiments. The theoretical prejudice is that the neutrinos are Majorana particles — be it because they are delivered by the seesaw mechanism or pop out of almost every grand unified theory — and we shall follow this idea.

Especially for the case of heavy (few 100 GeV) Majorana neutrinos, the production at accelerators has been investigated by many authors. The different possibilities include e^+e^- [3], pp [4], $p\overline{p}$ [5], νN [6], ep [7,8], linear colliders and e^-e^- [9,10] or even $e\mu$ machines [11].

Heavy Majoranas neutrinos have also been studied within the context of low-energy experiments such as neutrinoless double beta decay ($0\nu\beta\beta$) [9,12] or kaon decays [13]. The respective Feynman diagrams as well as the concrete model differ in most publications and the interested reader might compare the papers with respect to that.

One of the anomalies in existing data is the existence of high p_T isolated leptons together with large missing transverse momentum ($\not{p}_T$) at the DESY ep collider HERA. Since the first event [14] was discovered by H1, five more were found [15] and at least three of them cannot be explained by W production or other SM processes. In contrast to that ZEUS ''sees'' no excess in these events [16], yet, at the present statistical level, there is no contradiction [17].

In [8] we examined the process (see Fig. 1)

$$e^+p\to\overline{\nu}_e\alpha^+\beta^+X \quad \text{with} \quad \alpha,\beta=e,\mu,\tau \tag{1}$$

and discussed the possible signals of these like-sign dileptons (LSD) and high $\not{p}_T$ final state. No such events are reported and previously unavailable direct limits on the elements of the Majorana mass matrix were derived [8,18].

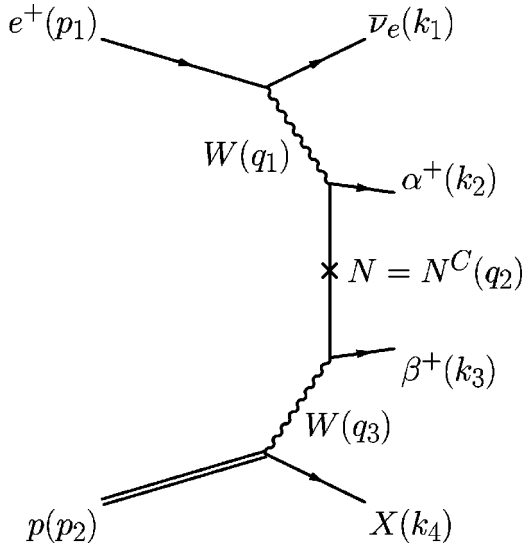

FIG. 1. Diagram for $e^+p\to\overline{\nu}_e\alpha^+\beta^+X$. Note that there is a crossed term and for $\alpha\neq\beta$ there are two possibilities for the leptons to be emitted from.

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However, it turns out that when the kinematical cuts used in H1's search for isolated leptons are applied to our process (1), they tend to ignore one of the two leptons. Especially the requirement of $p_T^{\text{lepton}} > 10\,\text{GeV}$ is often too much for both charged leptons to fulfill. The LSD signal of Eq. (1) is thus reduced to *one* isolated lepton with high $\not{p}_T$. This possibility can be checked by looking for an additional isolated low p_T and/or high pseudorapidity lepton. In addition, it is possible that a produced τ decays hadronically,[1] resulting also in single lepton final states. More than one isolated jet would be a signal for this kind of event. Since process (1) gives LSD with the same sign as the incoming lepton we concentrate on H1's positive charged muon events, because there are no positron events found. This fact might be explained if one incorporates also limits on the mixing of heavy neutrinos, as derived from $0\nu\beta\beta$. With this constraint the expected e signal is smaller than the μ signal.

One might argue that direct Majorana (N) production via a e^+NW vertex is more likely to occur since the cross section is larger. At present there is only an analysis in HERA's e^-p mode available [7] and it was found that detection is only possible if the N decays into e^+W^-, giving an isolated lepton with different charge than the incoming one. The reason for that is, of course, the large background from W production. However, a general analysis of all channels ($N \to \nu Z, N \to \mu W, \ldots$) remains still to be done and it might be interesting to compare the results with our signals in the future. Until that is done, we think that our process is worth considering, inasmuch as we have no restriction to the flavor of the final state lepton.

The paper is organized as follows: in Sec. II we discuss some general features of the process and the diagram and argue in Sec. III that the two lepton signal of Eq. (1) might very well be seen as a one lepton signal. Section IV sees a discussion of signals of the events and how one might distinguish the genuine final state from the measured one. Finally, Sec. V closes the paper with a conclusion and discussion.

II. THE PROCESS AND HEAVY MAJORANA NEUTRINOS

We work in a mild extension of the SM with no further specification of how heavy Majoranas might be created. The coupling to the usual leptons and gauge bosons is the familiar left-handed weak interaction. The three known light neutrinos ν_α are thus mixtures of light and heavy mass particles, this can be expressed by the replacement

$$\nu_\alpha \to \cos\theta_\alpha \nu_\alpha + \sin\theta_\alpha N_\alpha \tag{2}$$

in the (unmixed) Lagrangian for each family. For the sake of simplicity we take $N_\alpha = N$. The Lagrangian now reads

$$\begin{aligned} -\mathcal{L} = {} & \frac{g}{\sqrt{2}} W_\mu \{\cos\theta_\alpha \overline{\nu}_\alpha \gamma^\mu \gamma_- l + \sin\theta_\alpha \overline{N} \gamma^\mu \gamma_- l\} \\ & + \frac{g}{2\cos\theta_W} Z_\mu \Big\{ \cos^2\theta_\alpha \overline{\nu}_\alpha \gamma^\mu \gamma_- \nu_\alpha \\ & + \sin 2\theta_\alpha \overline{N} \gamma^\mu \gamma_- \nu_\alpha - \frac{1}{2}\sin^2\theta_\alpha \overline{N} \gamma_\mu \gamma_5 N \Big\} + \text{H. c.}, \end{aligned} \tag{3}$$

where $\gamma_- = \frac{1}{2}(1-\gamma_5)$ and there is no vector current between $\overline{N}$ and N due to their Majorana nature. We can keep it for the light neutrinos since for energies much larger than the (light) masses there is hardly a chance to find a difference between $2\overline{\nu}\gamma^\mu\gamma_-\nu$ and $\overline{\nu}\gamma^\mu\gamma_5\nu$ [19].

What can we expect for the values of the masses and the mixing parameter? Taking the typical seesaw formula we find

$$m_\nu \simeq \frac{m_D^2}{m_N} \Rightarrow m_N \simeq \frac{(10^5 - 10^{11})^2}{10^{-5} - 1}\,\text{eV} \simeq 100 - 10^{18}\,\text{GeV}, \tag{4}$$

where we took for the Dirac mass m_D every value from electron to top mass and for the light neutrino mass we allowed everything from the vacuum solution in a highly hierarchical scheme ($\sqrt{m^2} \simeq m_\nu \simeq 10^{-5}\,\text{eV}$) to a degenerate scheme [cosmological or also liquid scintillator neutrino detector (LSND's) mass scale] $\Sigma m_\nu \simeq$ few eV (see [18] for a detailed analysis of allowed schemes). For the mixing angle we have

$$\theta_\alpha \simeq \sin\theta_\alpha = \frac{m_D}{M_N} \simeq \frac{m_\nu}{m_D} \simeq 10^{-5} - 10^{-16}. \tag{5}$$

However, we shall use the current bounds on θ_α which are [20]:

$$\begin{aligned} \sin^2\theta_e &\leqslant 6.6 \times 10^{-3}, \\ \sin^2\theta_\mu \leqslant 6.0 \times 10^{-3} \quad &\text{and} \quad \sin^2\theta_\tau \leqslant 1.8 \times 10^{-2}. \end{aligned} \tag{6}$$

Note that the lowest value is for the muon neutrino. Equation (3) can now be applied to calculate the width of the Majorana, which is dominated by the two-body decays $N \to W\alpha$ and $N \to Z\nu_\alpha$, we find

$$\begin{aligned} \Gamma(N) = \sum_\alpha \frac{G_F \sin^2\theta_\alpha}{8\pi\sqrt{2}M_N^3} \{ & [(M_N^4 - M_W^4) + M_W^2(M_N^2 - M_W^2)] \\ & \times (M_N^2 - M_W^2) + \cos^2\theta_\alpha [(M_N^4 - M_Z^4) \\ & + M_Z^2(M_N^2 - M_Z^2)](M_N^2 - M_Z^2)\}. \end{aligned} \tag{7}$$

Direct searches for heavy neutrinos give typical lower limits [21] on their mass of 70–100 GeV, depending on their character (Dirac in general gives a higher bound) and to which lepton family they couple to. Unfortunately, the maximal

[1] We use the term electron, muon or tau for both, particle and antiparticle.

value of the cross section of the process (1) in Fig. 1 is found to lie in that range as well [6,8]. The dependence on the mass goes as

$$d\sigma \propto \frac{M_N^2}{(q^2-M_N^2)^2} \rightarrow \begin{cases} M_N^2 & \text{for } M_N^2 \ll q^2, \\ M_N^{-2} & \text{for } M_N^2 \gg q^2, \end{cases} \tag{8}$$

where q is the momentum of the Majorana. The standard calculation gives, for the matrix element [6] (see Fig. 1 for the attachment of momenta),

$$\begin{aligned} &|\overline{\mathcal{M}}|^2(e^+q \rightarrow \overline{\nu}_e \alpha^+ \alpha^+ q') \\ &= \sin^4\theta_\alpha M_N^2 G_F^4 M_W^8 2^{12} \frac{1}{(q_1^2-M_W^2)^2(q_3^2-M_W^2)^2}(k_1\cdot p_2)\left[\frac{1}{(q_2^2-M_N^2)^2}(k_2\cdot p_1)(k_3\cdot k_4)+\frac{1}{(\tilde{q}_2^2-M_N^2)^2}(k_3\cdot p_1)(k_2\cdot k_4)\right. \\ &\left. -\frac{1}{(q_2^2-M_N^2)(\tilde{q}_2^2-M_N^2)}((k_2\cdot k_3)(p_1\cdot k_4)-(k_2\cdot p_1)(k_3\cdot k_4)-(k_3\cdot p_1)(k_2\cdot k_4))\right] \end{aligned} \tag{9}$$

and the scattering with an antiquark sees k_4 interchanged with p_2. Here $\tilde{q}_2$ denotes the momentum of the Majorana in the crossed diagram, which has a relative sign due to the interchange of two identical fermion lines. In addition one has to include a factor $\frac{1}{2}$ to avoid double counting in the phase-space integration. For the phase space we called the routine GENBOD [22] and for the parton distributions we applied the 1998 Glück-Reya-Vogt (GRV 98) set [23]. In the case where a τ is produced we additionally folded in its three-body decay. We inserted finite (W and N) width effects in our program and found them to be negligible.

An interesting statistical effect occurs when one considers the relative difference between, say, the $\mu\mu$ and the $\mu\tau$ final state (mass effects play no significant role): First, there is no factor $\frac{1}{2}$ for the latter case. Then, there is the possibility that a τ is produced at the (''upper'') $e^+\overline{\nu}_e W$ vertex or at the (''lower'') $qq'W$ vertex. Both diagrams are topologically distinct and thus have to be treated separately. This means, four diagrams lead to the $\mu\tau$ final state, whereas only two lead to the $\mu\mu$ final state. We see that there is a relative factor of 4 between the two cases. Note though that now the interference terms are *added* to the two squared amplitudes since there is no relative sign between the two. This reduces the relative factor to about 3. However, effects of kinematical cuts and the limits of Eq. (6) wash out this phenomenon.

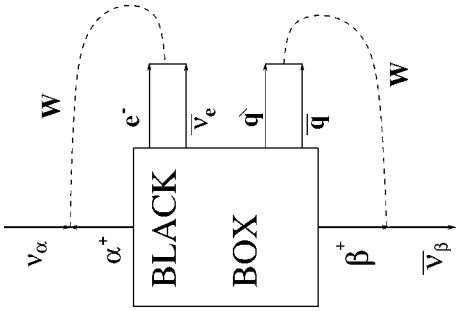

FIG. 2. Connection between Majorana mass term of ν_α and ν_β and the existence of process (1).

A similar situation occurs when one studies the $\tau\tau$ case and lets the τ's decay into different particles (e.g., $e\nu\nu$ and $\mu\nu\nu$). There is no way to tell into what the ''upper'' or ''lower'' tau decays, so one has to include both cases.

A question arises if one can conclude a Majorana mass term if we measure a process like Eq. (1). Here, a simple generalization of arguments first given by Schechter and Valle [24] for neutrinoless double beta decay applies: Assuming we found indubitable evidence for $e^+q \rightarrow \overline{\nu}_e\alpha^+\beta^+q'$, then crossing permits the process $0 \rightarrow e^-\overline{\nu}_e\alpha^+\beta^+q'\overline{q}$, realized by the ''black box'' in Fig. 2. Any reasonable gauge theory will have W's couple to quarks and leptons, so that a Majorana mass term for ν_α and ν_β is produced by coupling one W to the $\alpha^+e^-\overline{\nu}_e$ and one W to the $\beta^+q'\overline{q}$ vertex. Since we do not know which two quarks participate and which neutrino couples to the positron (the Schechter and Valle argument for $0\nu\beta\beta$ works with two pairs of u and d quarks), this theorem holds for a greater class of models, namely, e.g., those with direct $e^{-(-)}\nu_X$ coupling, with X being any flavor.

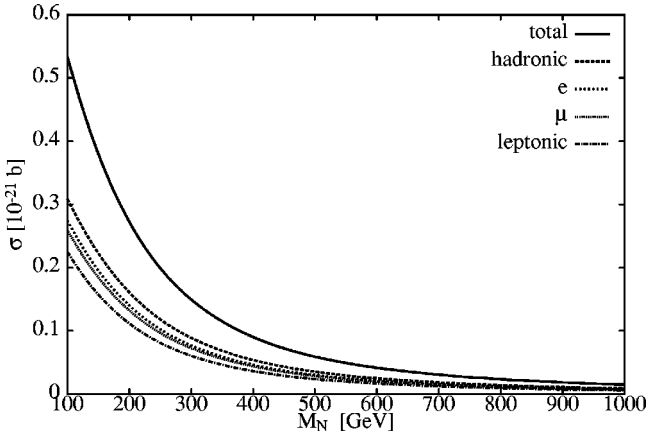

FIG. 3. Cross section of the expected isolated lepton signal from all possible final states as a function of the Majorana mass m_N.

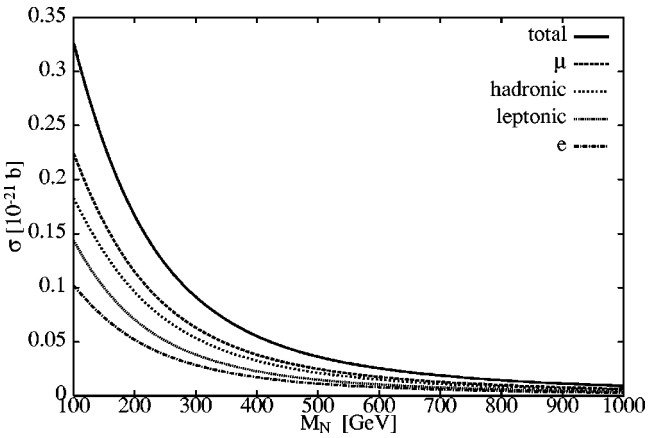

FIG. 4. Same as the previous figure if one also incorporates the $0\nu\beta\beta$ limit from Eq. (10).

The connection between a neutrinoless double beta decay signal and Majorana masses has been expanded in [25] to supersymmetric theories and it was found that it implies Majorana masses also for sneutrinos, the scalar superpartners of the neutrinos. However, in contrast to the signal in neutrinoless double beta decay experiments (two electrons with constant sum in energy) the identification of our process will be very difficult and deciding which $\alpha\beta$ final state was produced remains a hard task. In addition, the number of expected events turns out to be far less than one. Nevertheless, the demonstration of Majorana mass terms will be an exciting and important result, since different models predict different texture zeros in the mass matrix. In some models the ee entry in the mass matrix is zero and therefore the only direct information about the mass matrix might come from neutrino oscillations, cosmological considerations, global fits and direct searches, e. g., at the CERN e^+e^- collider LEP. This complicates the situation, since, e.g., in oscillation only mass-squared differences are measured and the additional phases induced by the Majorana nature are unobservable. To combine all information from the different approaches input from the models is required. Thus, the exact form of the matrix is highly nontrivial to find. Therefore, information

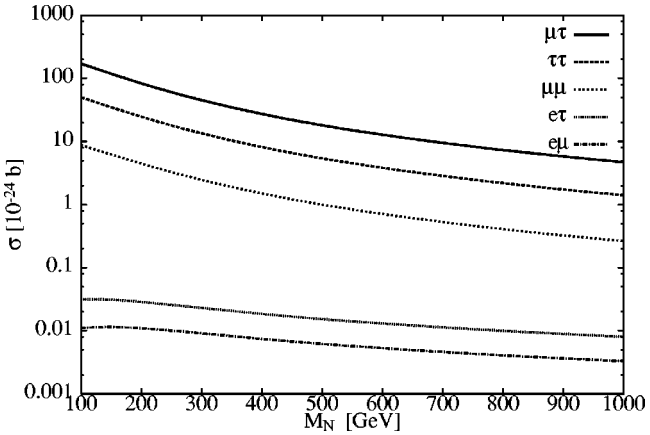

FIG. 5. Contribution of the different final states to the cross section of the muon signal as a function of the Majorana mass m_N.

TABLE I. Kinematical quantities of H1's candidates for positively charged muon events. Note that the charge for μ_5 is undetermined. All values in GeV, taken from [15]. The limits for μ_5 correspond to 95% C.L.

	μ_1	μ_2	μ_5
p_T^l	$23.4^{+7.5}_{-5.5}$	$28.0^{+8.7}_{-5.4}$	>44
$\not{p}_T$	$18.9^{+6.6}_{-8.3}$	$43.2^{+6.1}_{-7.7}$	>18
M_T	$3.0^{+1.5}_{-0.9}$	$22.8^{+6.7}_{-4.2}$	>54
δ	$18.9^{+3.9}_{-3.2}$	$17.1^{+2.5}_{-1.7}$	>22
p_T^X	42.2 ± 3.8	67.4 ± 5.4	30.0 ± 3.0

about nonvanishing entries in the mass matrix is very important and one has to take every opportunity to find out about all elements and the Majorana character in general. In addition, if such a lepton-number violating process is detected, it is surely helpful to know if the ''mildly extended'' SM can provide the signal or another theory, such as supersymmetry, has to be blamed.

III. TWO BECOME ONE

We applied the same cuts as H1 in their search for isolated leptons: imbalance in transverse momentum $\not{p}_T \geqslant 25\,\mathrm{GeV}$; transverse momentum of lepton $p_T \geqslant 10\,\mathrm{GeV}$; pseudorapidity of lepton $|\eta| \leqslant 2.436$; distance between charged lepton and closest jet in $\eta-\phi$ space,[2] $\Delta R \geqslant 1.5$ where ϕ is the azimuthal angle; angle of a hadronic jet(s) $4^\circ \leqslant \theta^X \leqslant 178^\circ$.

This has to be compared with our cuts in [8], $\not{p}_T \geqslant 10\,\mathrm{GeV}$, $|\eta| \leqslant 2.0$ for all measured particles and $\Delta R \geqslant 0.5$ between the leptons and the hadronic remnants. It turns out that both sets of cuts deliver cross sections in the same ballpark. There are now two possibilities for the original LSD signal to appear as one single lepton.

(1) One lepton can have high pseudorapidity and/or low p_T. This lepton then also contributes to the missing transverse momentum.

(2) If one tau is produced it might decay hadronically, adding one neutrino to the imbalance in p_T and additional hadronic jets.

A detailed analysis of the LSD signal might be done if one finds such events. Collecting all possibilities for the $\alpha\beta$ final states and the τ decays results in Fig. 3. We denote with ''hadronic'' the signal coming from final states which also have additional hadronic activity from a τ decay. We call ''leptonic'' the signals coming from events in which two final-state leptons are produced from which one escapes the identification criteria. Those included therefore most channels, namely all of them except the ones with hadronic tau decay. One can see that muon events have a smaller cross section than the e signal, coming from the fact that their mixing with the heavy neutrino has the biggest constraint.

[2]Actually H1's value is 1.0 or 0.5, depending on the way they define jets for their respective analysis. We use a general value of 1.5 to account for hadronization effects.

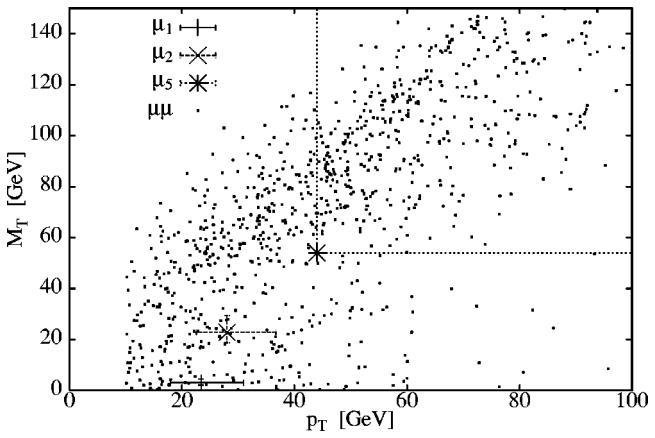

FIG. 6. Scatter plot of p_T of the measured lepton against M_T for the channel $e^+p\to\bar{\nu}_e\mu^+\mu^+X$ with one muon escaping the identification criteria.

Mass effects play no significant role. If the H1 anomaly is indeed explained by heavy Majorana neutrinos, one might ask why only muon events are detected. A possible reason for that might lie in the following fact: The experimental constraint from $0\nu\beta\beta$ on mixing with a heavy Majorana neutrino reads [9]

$$\sin^2\theta_e \leqslant 5\times 10^{-8}\frac{m_N}{\mathrm{GeV}}. \tag{10}$$

Incorporating this in Fig. 3 gives Fig. 4. Now the electron signal is far below the muon signal. In Fig. 5 we plot how the cross section for the production of a μ is composed. The biggest contribution comes from the $\mu\tau$ channel, which has its reason in the mentioned factor $\simeq 3$ relative to the $\alpha\alpha$ channels and the high hadronic tau branching ratio, BR($\tau\to\nu_\tau$ hadrons)$\simeq\frac{2}{3}$.

An additional reason why the $\tau\alpha$ channels add higher contributions is that when the tau decays it distributes its momentum to three particles, i.e., the p_T is in general lower and it can therefore escape the $p_T\geqslant 10\,\mathrm{GeV}$ cut more easily and thus has a higher cross section. Admittedly, the process

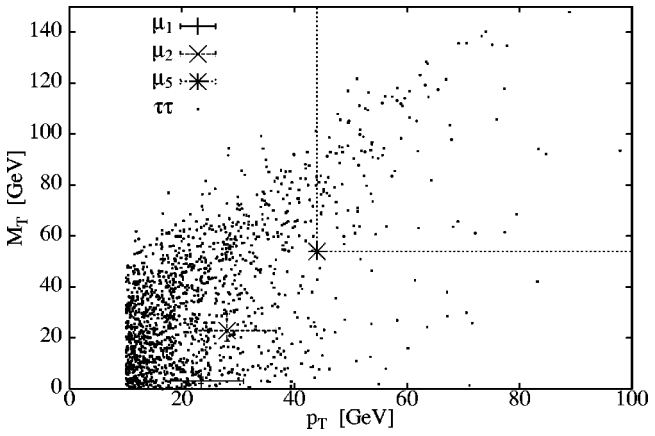

FIG. 7. Scatter plot of p_T of the measured lepton against M_T for the channel $e^+p\to\bar{\nu}_e\tau^+\tau^+X$ with one tau decaying hadronically.

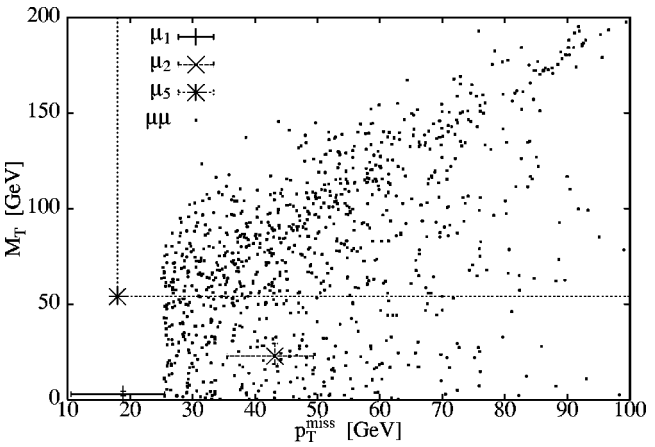

FIG. 8. Scatter plot of $\not{p}_T$ against M_T for the channel $e^+p\to\bar{\nu}_e\mu^+\mu^+X$ with one muon escaping the identification criteria.

gives only a tiny signal: Multiplying the cross section with the $36.5\,\mathrm{pb}^{-1}$ luminosity H1 analyzed, gives 10^{-8}–10^{-9}. However, as explained at the end of the previous section, one has to check every possible appearance of Majorana mass terms in order to get information about the mass matrix.

One sees that many LSD signals produce the same single lepton signature. In the next section we will discuss possibilities to distinguish different original final states from the measured ones.

IV. SIGNALS AND OBSERVABLES

Some kinematic quantities of H1's positive muon events are given in Table I. In their analysis [15] using $36.5\pm 1.1\,\mathrm{pb}^{-1}$ luminosity at $E_p=820\,\mathrm{GeV}$ and $E_e=27.5\,\mathrm{GeV}$, six events were found ($0e^+,1e^-,2\mu^+,2\mu^-$, and 1μ of undetermined charge), where about $2e$ and 1μ are expected from SM processes. From those, the most important ones are W production, neutral current (NC) events (for e^+ events) and photon-photon interactions ($\mu^\pm$). We also include the event with undetermined charge. The e^- and one μ^-, which also has a e^+, are very likely to stem from W production. In the following we will plot all distributions for $M_N=200\,\mathrm{GeV}$ since the quali-

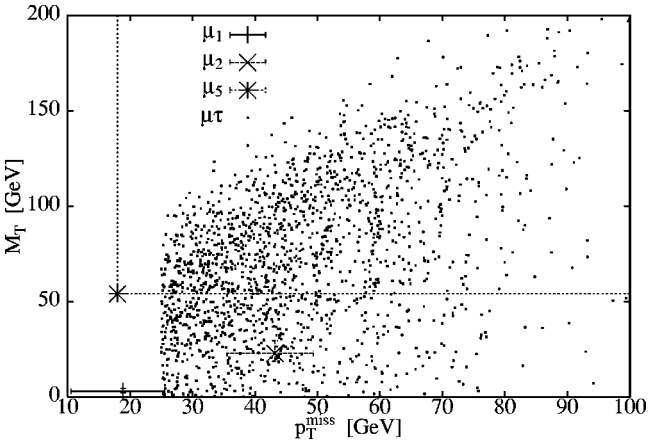

FIG. 9. Scatter plot of $\not{p}_T$ against M_T for the channel $e^+p\to\bar{\nu}_e\tau^+\mu^+X$ with the tau decaying hadronically.

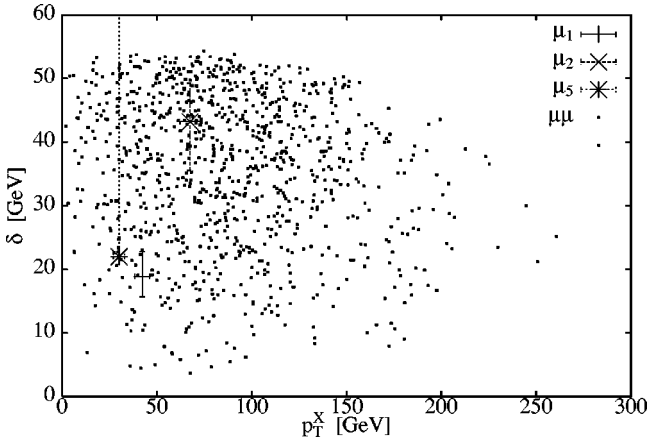

FIG. 10. Scatter plot of p_T^X against δ for the channel $e^+p \to \overline{\nu}_e \mu^+ \mu^+ X$ with one muon escaping the identification criteria.

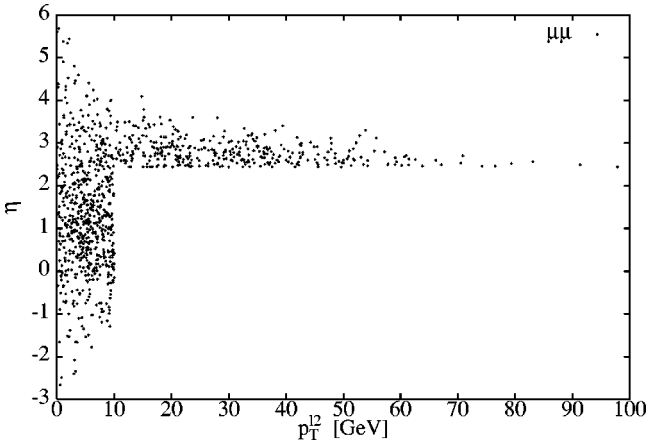

FIG. 12. Scatter plot of p_T of the escaping charged lepton against its pseudorapidity for the channel $e^+p \to \overline{\nu}_e \mu^+ \mu^+ X$. The sharp edge is due to the applied cuts from H1.

tative conclusions we draw remain valid for all masses considered. In our analysis it turned out that — with the kinematics from Table I — scatter plots of $p_T, \not{p}_T$ and the transverse mass $M_T = \sqrt{(\not{p}_T + p_T)^2 - (\vec{\not{p}}_T + \vec{p}_T)^2}$ are most useful. We stress again that for different final states the composition of the missing transverse momentum can be made of two particles (1 neutrino and 1 charged lepton for ee, $e\mu$, or $\mu\mu$ final states) to 6 (1 lepton and 5 neutrinos, $\tau\tau$ channel with two leptonic decays) thus changing the area in which events populate, say, the $M_T - p_T$ space. The transverse momentum is also very sensitive on the original final state since τ decays share the initial momentum to three particles thereby reducing the average p_T. This is displayed in Figs. 6 ($\mu\mu$ final state) and 7 ($\tau\tau$, one hadronic decay). If both taus decay leptonically the distribution looks similar. Obviously, the $\tau\tau$ case has in general low p_T and M_T, whereas the $\mu\mu$ case displays a uniform distribution with a slight band in the center region indicated.

Turning now to $\not{p}_T$ we see in Figs. 8 ($\mu\mu$) and 9 ($\mu\tau$, hadronic decay) that the situation is not as clear in the ''mixed'' channels, i.e., channels with two different final-state charged leptons. Though the population in $\not{p}_T - M_T$ space is different (lower values in the latter case), it is not as obvious as for the $\mu\mu/\tau\tau$ case. Because of its low M_T, event μ_1 seems to be less probable in all figures, though no definite statement can be made.

Now we consider the quantities connected with the hadronic remnants. We found that the muon signal is composed of roughly 1/3 purely leptonic final states and 2/3 events with additional jets. An interesting quantity is $\delta = \Sigma E_i (1 - \cos\theta_i)$ where the sum goes over all measured final-state particles. In Figs. 10 and 11 one sees that the presence of three jets keeps δ more or less in the same area, whereas the transverse momentum of the hadronic system p_T^X is shifted towards lower values. Here also μ_1 lies in a less crowded area.

What are now the signals of the escaping charged lepton (if there is one)? In Figs. 12 and 13 we plot the pseudorapidity η of the undetected lepton against its transverse momentum. Again, the $\mu\mu$ and the $\tau\tau$ case can be distinguished since the latter has far lower p_T. The τ boosts its decay

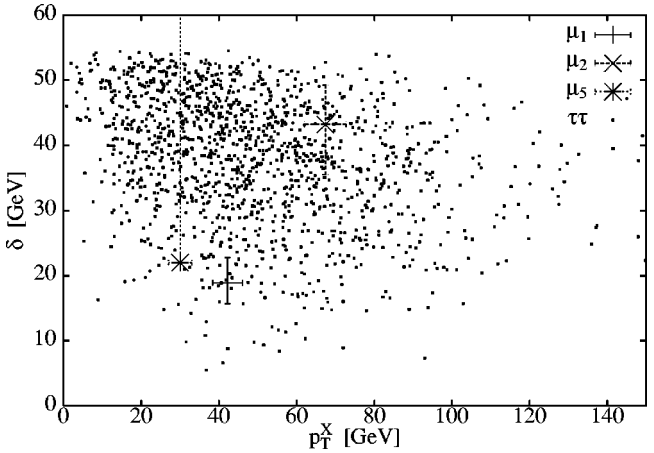

FIG. 11. Scatter plot of p_T^X against δ for the channel $e^+p \to \overline{\nu}_e \mu^+ \tau^+ X$ with the tau decaying hadronically. Note that the p_T^X range is half as wide as in the previous figure.

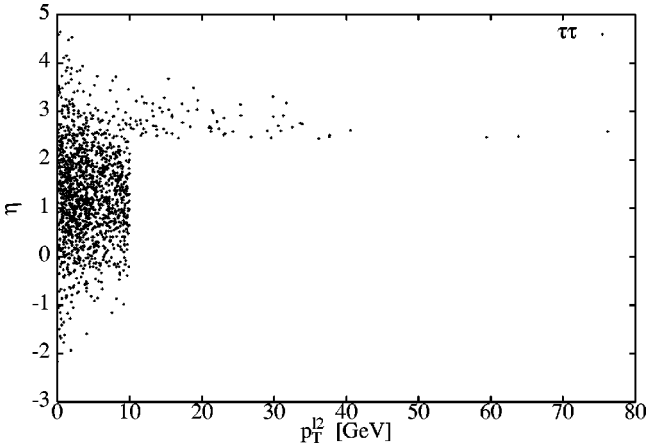

FIG. 13. Scatter plot of p_T of the escaping charged lepton against its pseudorapidity for the channel $e^+p \to \overline{\nu}_e \tau^+ \tau^+ X$. The sharp edge is due to the applied cuts from H1.

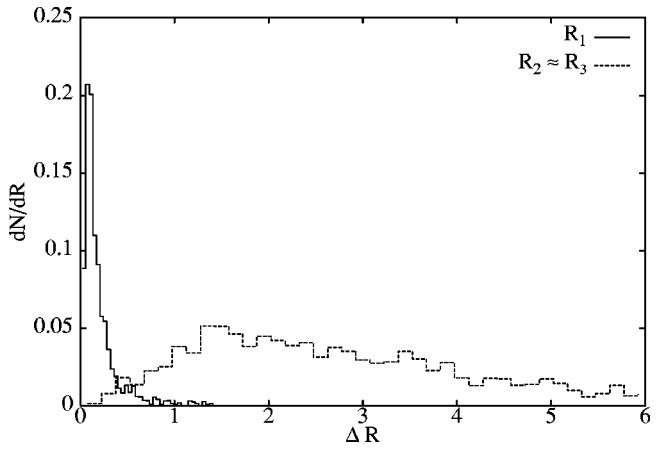

FIG. 14. Distance of the three jets in $\eta-\phi$ space with R_i ordered with ascending value for the process $e^+p\to\overline{\nu}_e\tau^+\tau^+X$ with one τ decaying hadronically.

products more or less in its forward direction so that η does not alter much. The problem one might encounter is that the escaping lepton is hiding in the hadronic jet. Demanding a distance of $\Delta R\geqslant 1.5$ reduces the cross section by 10–15 % but does not change the distributions in Figs. 12 and 13.

We mimicked the hadronic τ decay via two quark jets and ignored the effects of modes like $\tau\to\pi' s\nu_\tau$. Thus, due to the boost of the τ, two of the three jets of events with a hadronically decaying tau will be very close together. Figure 14 displays the normalized distribution of the distance in $\eta-\phi$ space. We denote with R_i the distance ordered with ascending value. One distance is centered significantly below one, therefore, probably two jets instead of three will be measured. However, the τ identification is hard to do and Fig. 14 serves only as an indication of how things might work. Information on the jet multiplicity is not given in Ref. [15], though μ_1 and μ_5 seem to have additional separated tracks in their event displays as can be seen in Fig. 2 of Ref. [15].

V. CONCLUSIONS

In light of recent data we did a full analysis of the analog of the neutrinoless double beta decay graph with all possible two charged leptons in the final state. One lepton can escape the identification criteria by either having low transverse momentum and/or high pseudorapidity or (if it is a τ) via hadronic decay. Signatures of these events are discussed and compared to H1's isolated leptons with large missing transverse momentum. All their positive muon events lie in the regions typically populated by the ''double beta'' process, though μ_1 is always in a less crowded area. Due to its high errors μ_5 is mostly in the favored region (but for the same reason always in the region populated by SM processes [15]). Though the process represents an attractive explanation, the smallness of the expected signal might spoil our interpretation. Nevertheless, any information about mass matrix entries and Majorana particles in general is very important and worth looking for, regardless of the small expected signal. Other extensions of the SM might give larger signals to the discussed final states and it is then helpful to know how the ''SM + heavy Majorana'' extension contributes.

To confirm our hypothesis direct production of heavy Majorana neutrinos will be the only possibility since cross sections or decay widths of other $0\nu\beta\beta$-like processes are probably too small to be detected [18]. Here, either HERA itself or the CERN Large Hadron Collider (LHC) will be the candidates for this observation. We did not consider the mass reconstruction of the Majorana since the large number of unmeasured particles does not permit that.

Other proposed explanations [14] for the events were flavor charging neutral current (FCNC) interactions (topologically identical to leptoquark production) or high p_T jets from which one fakes a muon signal. Production of supersymmetric particles is suggested in [26] to explain the results. A definite answer regarding all detector or identification issues can only be given by the collaboration itself. From the ''new physics'' side we believe that massive neutrinos provide one of the most natural possibilities.

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