CHARGED CURRENT WEAK INTERACTION OF POLARIZED MUONS

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ABSTRACT
The polarization of the muon beam can be used to test the presence of right-handed couplings in charged current interaction of muons in process $\mu + N \rightarrow \nu + X$. The experimental feasibility and the limits which can be obtained on the mass of right-handed intermediate boson are discussed.

1. INTRODUCTION

At first glance it seems to be hopeless to detect charged current weak interaction of muons, because the typical electromagnetic cross-sections are about a million times larger even at an incoming muon energy of several hundred GeV. One should not forget, however, some remarkable merits of the muon beam.

a) **Energy**
Due to the kinematic properties of pion decay the average energy of muons is 3 times higher than the one of neutrinos. This may turn out to be rather important. On one hand, the weak cross-sections are linearly proportional to the beam energy and on the other hand the energy can be critical in presence of thresholds. In addition, the incoming muon energy can be preselected which provides more flexibility in the study of threshold phenomena.

b) **Helicity**
Due to their extremely small (if any) mass the helicity of neutrinos is uniquely pre-determined. In case of muons one can select helicity at will. This provides an unique possibility to look for such type of weak interactions which are impossible in case of neutrinos as it was noticed by K. Winter. Namely, if the pion momentum is denoted by $p_\pi$ then the decay muon with momentum

$$p_\mu^{\text{FORW}} \approx p_\pi$$

(forward decay in $\pi$-system) will have "unnatural" helicity (i.e. opposite to the helicity of the neutrino with the same lepton number). One can get "natural" helicity selecting muon momenta

$$p_\mu^{\text{BACK}} \approx (m_\mu/m_\pi)^2 p_\pi$$

(backward decay in $\pi$-system).

Thus if one is interested in normal left-handed interactions then the muon beam energy should be lowered relative to the parent pion energy. Even in this case it remains about a factor two higher than the average neutrino energy from the same pion decay.

c) **Beam handling**
Beam phase space can be measured easily. The well collimated muon beam spot can reduce by order(s) of magnitude the required lateral size of the target and the interaction vertex is well identified.

Severe difficulties compensate the flexibility of muon beam.

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One needs an extremely good (~10^{-6}) hardware rejection against events which have a muon in the final state in order to catch weak fishes from the QED ocean.

The final state is rather complicated. In absence of neutrino detection the relevant kinematic information should be extracted from the analysis of hadronic shower.

With modern experimental techniques these problems can be overcome in most of the kinematical range, thus at least in some areas muon experiments can challenge and/or complement neutrino experiments.

2. RIGHT-HANDED CURRENTS

The theoretical interest for weak effects with "unnatural" right-handed polarization can be summarized in the following way:

a) The dominantly V-A structure of weak interactions is well established at present energies but the search for deviations should still proceed.

b) The standard SU_L(2) x U(1) model is highly asymmetric and unaesthetic.

c) Right-handed neutrinos and intermediate bosons seem to be one of the simplest candidates which can "bloom" in the desert between 100 GeV and the grand unification mass^{2}).

In the following we discuss the experimental possibilities to search for right-handed neutrinos by muon beam in the framework of SU_L(2) x SU_R(2) x U(1) model. We start with a "manifestly right-left symmetric" Lagrangian where W_L and W_R are coupled to V-A and V+A currents, respectively:

\[ I_W = \frac{g}{2\sqrt{2}} \left[ (V - A)_L \cdot W_L + (V + A)_L \cdot W_R + H.C. \right] \]

where e.g. \((V - A)_L^{lep} = \bar{\nu}_\mu \gamma_\mu (\tau_+^\mu) \nu_\mu\) or \((V - A)_R^{had} = U_{\nu_L} (\tau_+^\mu) \nu_\mu\). The combinations \((V + hA)_L^{lep}\) and \((V + hA)_R^{had}\) represent leptonic and hadronic currents having non-vanishing matrix elements between only definite helicity states. For simplicity, here and in the next we neglect masses and Cabibbo or KM angles \((h = \pm 1)\). That is in a given vertex the transition is prohibited, for example between \(\mu_R^{\tau}(h = 1)\) and \(\nu_L^{\tau}(h = -1)\).

The left-right symmetry of \(I_W\) however is broken by an asymmetric vacuum. The Higgs potential and the vacuum expectation value of the Higgs-fields are arranged to yield to mass eigenstates which are linear combinations of unmixed chiral eigenstates,

\[ W_1 = W_L \cdot \cos \xi - W_R \cdot \sin \xi \]
\[ W_2 = W_L \cdot \sin \xi + W_R \cdot \cos \xi \]

for definiteness \(M_2 > M_1\).

The modified Lagrangian reads

\[ I_W = \frac{g}{2\sqrt{2}} \left\{ \left[ (V - A) \cos \xi - (V + A) \sin \xi \right] W_1 + \left[ (V - A) \sin \xi + (V + A) \cos \xi \right] W_2 + H.C. \right\} . \]

In case of left-handed \(\nu_L^\tau\) neutrinos (and also \(\mu_R^\tau\)) the \((V + A)_L^{lep}\) current does not give any contribution, in contrast with the hadronic current because \((u, d)\) quarks are occurring always in left-right symmetric combinations inside the nucleons. Thus one gets the "left-handed" effective four-fermion Lagrangian in the form:x)

\[ L_{LEFT} = \frac{g^2}{8} \left\{ \left( (V - A)_{lep} \cdot \cos \xi \right) \left[ (V - A)_{lep} \cdot \cos \xi - (V + A)_{lep} \cdot \sin \xi \right] + \left( V - A \right)_{lep} \cdot \sin \xi \left[ (V - A)_{lep} \cdot \sin \xi + (V + A)_{lep} \cdot \cos \xi \right] \right\} \]

x) At present energies \(Q^2\) dependence is negligible.
After some rearrangements one obtains

\[
L^{\text{LEFT}} = \frac{g^2}{8} \left\{ (V-A)^{++}_{\text{lep}} (V-A)_{\text{had}} \left[ \cos^2 \frac{\Delta M^2}{2M_1^2} + \sin^2 \frac{\Delta M^2}{2M_2^2} \right] - (V-A)^{++}_{\text{lep}} (V-A)_{\text{had}} \sin \phi \cos \left[ \frac{1}{M_1^2} - \frac{1}{M_2^2} \right] \right\}.
\]

This interaction can be studied by standard neutrino scattering because by default left-handed neutrino (and right-handed antineutrino) beams are available.

Assuming however the existence of right-handed \( \nu^+_R \) neutrinos the situation will be reversed and one should retain only \( (V+A)^{++}_{\text{lep}} \) leptonic currents which provide the effective four-fermion Lagrangian for right-handed neutrino (or \( \mu^+_R \)) scattering:

\[
L^{\text{RIGHT}} = \frac{g^2}{8} \left\{ (V+A)^{++}_{\text{lep}} (V+A)_{\text{had}} \left[ \sin^2 \frac{\Delta M^2}{2M_1^2} + \cos^2 \frac{\Delta M^2}{2M_2^2} \right] + (V+A)^{++}_{\text{lep}} (V+A)_{\text{had}} \sin \phi \cos \left[ \frac{1}{M_1^2} - \frac{1}{M_2^2} \right] \right\}.
\]

The cross-section calculations are reduced to the evaluation of matrix elements which have the general form:

\[
A \left( h_{\text{lep}}, h_{\text{had}} \right) = \left\langle \left| \frac{3}{8} \right| (V + h_{\text{lep}}^A + (V + h_{\text{had}}^A) \right| \rightrangle
\]

In this notation the differential cross-section can be written as

\[
\sigma_{\text{LEFT}}^{\nu} = \left| A (-1; -1) \right|^2 c_{\text{LL}}^2 + \left| A (-1; +1) \right|^2 c_{\text{LR}}^2 = \sigma_{-\nu}^L c_{\text{LL}}^2 + \sigma_{-\nu}^L c_{\text{LR}}^2
\]

\[
\sigma_{\text{RIGHT}}^{\nu'} = \left| A (+1; -1) \right|^2 c_{\text{RR}}^2 + \left| A (+1; +1) \right|^2 c_{\text{RL}}^2 = \sigma_{+\nu'}^R c_{\text{RR}}^2 + \sigma_{+\nu'}^R c_{\text{RL}}^2
\]

where the meaning of \( \sigma_{ij} \) is self-explanatory and

\[
c_{\text{LL}} = \frac{\cos^2 \theta}{M_1^2} + \frac{\sin^2 \theta}{M_2^2} ; \quad c_{\text{RR}} = \frac{\sin^2 \theta}{M_1^2} + \frac{\cos^2 \theta}{M_2^2} ; \quad -c_{\text{LR}} = \sin \phi \cos \left[ \frac{1}{M_1^2} - \frac{1}{M_2^2} \right] = c_{\text{RL}}.
\]

Some representative diagrams corresponding to different terms are shown in Figure 1.

After trace calculations one can get \( \sigma_{ij} \). In general case they consist of two parts which are \( i \leftrightarrow j \) symmetric in helicities:

\[
\sigma_{ij} = \left| A \left( h_i h_j \right) \right|^2 = h_i h_j K_1(p_k) + (1+h_i^2)(1+h_j^2) K_2(p_k)
\]

where \( K_1 \) and \( K_2 \) represent definite kinematic functions of particle momenta. Due to the fact that in our calculations the masses are neglected \( K_1 \) and \( K_2 \) are depending only on the CM-energy and CM-scattering angle which is equivalent to the scaling variable \( y \). Thus there remain only two possibilities

i) \( h_i h_j = +1 \) yields \( \frac{d\sigma}{dy} \propto 1 \)

ii) \( h_i h_j = -1 \) yields \( \frac{d\sigma}{dy} \propto (1-y)^2 \)

Of course, one has \( x \equiv 1 \) for "elastic scattering" on quarks. From these the usual procedure gives for charged current scattering on isoscalar nuclei

\[
\sigma_{-\nu} (x,y) = \sigma_{+\nu} (x,y) \propto q(x) + (1-y)^2 \overline{q}(x)
\]

\[
\sigma_{+\nu} (x,y) = \sigma_{-\nu} (x,y) \propto \overline{q}(x) + (1-y)^2 q(x)
\]

where \( q(x) \) and \( \overline{q}(x) \) represent the quark and anti-quark distribution inside target nuclei.

In the general case the muon beam consists of \( \mu^-_L \) and \( \mu^-_R \) components. Thus the charged
current cross-section for negative muon beam with polarization $\lambda$ can be written as a sum

$$\sigma' = \frac{1 - \lambda}{2} \sigma'_{\text{LEFT}} + \frac{1 + \lambda}{2} \sigma'_{\text{RIGHT}} = \frac{1 - \lambda}{2} \sigma_{-}^2 + \frac{1 + \lambda}{2} \sigma_{+}^2 + \sigma_{+}^2,$$

It is worth to remark that the left-right mixing term is independent of muon polarization, in accordance with the fact, that it is parity conserving. Of course, this left-right symmetry can be broken by mass terms and for too heavy $\nu_R$ the $\sigma_{\text{RIGHT}}$ part would be zero due to energy conservation.

For completeness, we write down the differential cross-sections in a more explicit way:

$$\frac{d^2\sigma}{dxdy} = \frac{1 - \lambda}{2} \sigma_{L}^2 + \frac{1 + \lambda}{2} \sigma_{R}^2 + \sigma_{RL} = \frac{1 - \lambda}{2} \left[q^{+}(1-y)^2 q^{2}\right]_{LL}^2 + \frac{1 + \lambda}{2} \left[q^{+}(1-y)^2 q^{2}\right]_{RR}^2 + \left[q^{+}(1-y)^2 q^{2}\right]_{RL}^2$$

$$\frac{d^2\sigma_{\mu^+}}{dxdy} = \frac{1 + \lambda}{2} \sigma_{L}^2 + \frac{1 - \lambda}{2} \sigma_{R}^2 + \sigma_{RL} = \frac{1 + \lambda}{2} \left[q^{+}(1-y)^2 q^{2}\right]_{LL}^2 + \frac{1 - \lambda}{2} \left[q^{+}(1-y)^2 q^{2}\right]_{RR}^2 + \left[q^{+}(1-y)^2 q^{2}\right]_{RL}^2$$

where the transition $\mu^- \leftrightarrow \mu^+$ is formally achieved by substituting $\lambda \leftrightarrow -\lambda$ and $q(x) \leftrightarrow q(x)$. One gets the corresponding neutrino cross-sections simply by setting $\lambda = \pm 1$:

$$\frac{d^2\sigma_{\nu^-}}{dxdy} = \sigma_{L}^2 + 0 + \sigma_{RL}^2 = \left[q^{+}(1-y)^2 q^{2}\right]_{LL}^2 + \left[q^{+}(1-y)^2 q^{2}\right]_{RL}^2$$

$$\frac{d^2\sigma_{\nu^+}}{dxdy} = \sigma_{L}^2 + 0 + \sigma_{RL}^2 = \left[q^{+}(1-y)^2 q^{2}\right]_{LL}^2 + \left[q^{+}(1-y)^2 q^{2}\right]_{RL}^2$$

In summary, the muon cross-sections consist generally of 3 parts: the parity violating piece includes pure left- and right-handed contributions, the parity conserving part contains their mixing which is within our approximation independent of $\lambda$. In the case of neutrino scattering the pure right-handed term is lost. The remaining terms contain $M_2$ in $\sin(\xi)M_2^2$ and $\sin^2(\xi)M_2^2$ combinations. Thus it is practically impossible to deduce any limit on the right-handed intermediate boson mass, $M_2$ from neutrino scattering.

3. PRESENT LIMITS ON RIGHT-HANDED PHENOMENA

A number of partial reviews have been published on this topic. One can derive limits for mixing angle $\xi$ and ratio $\delta = M_2^2/M_1^2$ from existing experimental data in the following interactions: $\mu$-decay ("direct, inverse"), $\beta$-decay, non-leptonic decay of strange particles and high energy $\nu$ scattering. These measurements can be classified (see Table 1) according to the following criteria:

a) sensitivity to massive right-handed neutrinos,

b) they give bounds on $\xi$, the mixing angle,

c) they give bounds on $\delta = M_2^2/M_1^2$,

d) special assumptions (if any) are required about hadron structure.

Theoretical and experimental efforts have been concentrated in the low energy leptonic and semi-leptonic area. By definition they were not sensitive to massive (greater than 1 GeV/c$^2$) neutrinos due to the lack of energy to produce them.
3.1. Pure leptonic processes

All the classical parameters are more or less sensitive to the (V-A) structure of muon decay. Latest compilation is shown in reference\textsuperscript{5}. The Michel parameter of energy spectrum gives a limit on mixing angle

$$|\xi| \leq 0.06.$$  

The angular asymmetry $\xi_{P_{\mu}}$ of electrons emitted from polarized muon decays defines an ellipse\textsuperscript{4} with axis $x$ and $y$

$$|x| = |\delta - \xi| \leq 0.23 \quad \text{and} \quad |y| = |\delta + \xi| \leq 0.115.$$  

Inverse muon decay (i.e. $\mu^+e^-$ scattering) measurements are preferring (V-A), but their accuracy is not good enough to deduce stringent limits on (V+A) parameters\textsuperscript{8}.

From Figure 2 which was taken from Sakurai's review based on talk of Strovink in Blacksberg conference one can deduce that pure leptonic processes can allow as low as 220 GeV mass for $M_2$ at mixing angle less than 0.06.

3.2 Semi-leptonic processes

Longitudinal polarization of electrons in pure Gamow-Teller nuclear beta decay is found to be equal\textsuperscript{9} to

$$(-c/v) \cdot p^{GT}_{N} = 1.001 \pm 0.008.$$  

This gives a bound on the parameter $y$:

$$|y| \leq 0.09.$$  

Angular asymmetry of electrons from decay of polarized $^{19}$Ne nucleus\textsuperscript{10} defines a hyperbola like area in ($\delta, \xi$) plane shown in Figure 2.

The semi-leptonic bounds are shrinking considerably the ($\delta, \xi$) domain allowed by pure leptonic processes but the minimal bound on $M_2$ is increased only up to about 250 GeV.

3.3 High energy neutrino interactions

$\bar{\nu}$-scattering on nucleons is very sensitive to right-handed currents in the high-$y$ region, and bounds are valid whatever the mass of right-handed neutrinos. The CDHS experiment\textsuperscript{11} yields a bound on mixing angle:

$$|\xi| \leq 0.095 \quad (90 \% \ C.L.)$$

It does not however give a significant constraint on $\delta = M_1^2/M_2^2$ mass ratio.

3.4 Non-leptonic weak processes

Large enhancement factors for right-handed currents are found in hadronic weak processes but for their derivation additional assumption on hadron structure are necessary. Though this assumptions can be well founded, due to the complexity of hadrons one can not exclude the existence of other possible phenomena which can interfere with left-right symmetric weak effects distorting their appearance. Due to the absence of neutrinos either in the initial or in the final state these bounds are independent of right-handed neutrino mass. Only the right-handed intermediate boson mass does affect the matrix elements.

3.4.1 Hyperon decays: $\Lambda \to N \pi$, $\Sigma \to N \pi$, $\Xi \to \Lambda \pi$, $\Omega \to \Xi \pi$

I.I. Bigi and J.M. Frere\textsuperscript{12} argue, that "left-right couplings introduce a correction factor (1 - 120 $\sin^2 \xi$) into the factorizable contribution to the $\Delta I = 3/2$ amplitude for P-wave decays of hyperons". They use the observed departure from pure left-handed current
contribution as upper limit for the mixing angle

$$|\sin \zeta| \lesssim 1/120$$

(no limit for $\delta$).

According to M. Denis\(^7\) the applicability of factorization is questionable because it is neglecting the effect of soft gluons. In addition, right-handed effects are expected to give similar contribution to each process which is not the case.

3.4.2 $K \rightarrow 3\pi$ decay

J.F. Donoghue and B.R. Holstein\(^13\) say: "The most stringent bounds come from the deviation from PCAC predictions in $K$ decays both for $\Delta I = 1/2$ and $\Delta I = 3/2$. In the limit of no mixing

$$M_2 > 300 \text{ GeV}$$

($\approx \delta < 1/20$).

If the right-handed quark mixing angles are equal to their left-handed counterparts and $M_2$ is larger than $\sin \zeta < 0.004$\(^4\). These limits however are also very model dependent because they rely, e.g., on the bag-model.

3.4.3 $K^\pm - K^\mp$ mass difference

G. Beall et al.\(^14\) gets $\delta < 1/430$ corresponding to $M_2 > 1.6 \text{ TeV}$. M. Denis\(^7\) taking into account t-quark and "would be Goldstone" effects can remain however within the experimental limits if

$$\delta \approx 0.15 \quad (M_2 \approx 210 \text{ GeV}).$$

3.5 Overall conclusion from present data

Neglecting the controversial non-leptonic processes the best fit to low energy data obtained by Maalampi et al.\(^5\) provides $M_1/M_2 = 0.22$ or in terms of upper limits

$$M_1/M_2 < 0.29 \quad \text{ and } \quad |\zeta| < 4.2^\circ \quad [68.3 \% \text{ C. L.}]$$

which means $M_2 > 275 \text{ GeV}$ in case of $M_1 = 80 \text{ GeV}$. There are experiments in progress to improve limits arising from $\mu$ or $\rho$-decay. No experimental attempt is known, however, to get limits on $M_2$ mass in case of massive right-handed neutrinos. Therefore it would be important to perform experiments with right-handed $\mu$ beams which could give unique results on ($\delta, \zeta$) independently from $\nu^*_R$ mass and free from hadronic structure assumptions. Of course, $\nu^*_R$ mass should be within the kinematically allowed limits of $\mu^*_R$ scattering. Thus observation of the production threshold would provide exact value of $M_2$, unattainable for other experiments.

4. EXPECTED BOUNDS FROM $\mu$ EXPERIMENTS

4.1 No-mixing

In order to get a feeling for the experimental sensitivity, we discuss some special cases in detail. If the mixing angle $\zeta$ is so small that one gets

$$c_{RR} \gg c_{RL}$$

then the formula shows that there is no practical possibility to extract information on right-handed currents from $\nu$-scattering. Thus $\mu^*$ scattering provides unique possibility to measure $M_2$ directly i.e. one can discover the right-handed current even in total absence
of left-right interference. One can perform 2 measurements at different muon polarizations, for example, taking $\lambda_o = 0$ and $\lambda = \lambda = 0.9$ one gets:

$$N_o = \text{Monitor}_0 \cdot \frac{1}{2} \left[ \frac{1}{M_1^4} + \frac{1}{M_2^4} \right] \left[ q(x) + (1-y)^2 q(x) \right] = \text{Monitor}_0 \cdot \frac{1}{2} \left[ \sigma_L + \sigma_R \right]$$

$$N_1 = \text{Monitor}_1 \cdot \frac{1}{2} \left[ \frac{1-\lambda}{M_1^4} + \frac{1+\lambda}{M_2^4} \right] \left[ q(x) + (1-y)^2 q(x) \right] = \text{Monitor}_1 \cdot \frac{1}{2} \left[ (1-\lambda) \sigma_L^* + (1+\lambda) \sigma_R \right] .$$

Introducing notations: $\delta^2 = \frac{\sigma_R}{\sigma_L} = \frac{\sigma_1 -(1-\lambda) \sigma_0}{(1+\lambda) \sigma_0 - \sigma_1} \approx \frac{1}{2 \lambda} \left[ \frac{\sigma_1}{\sigma_0} - (1-\lambda) \right]$ because one expects $\sigma_R \ll \sigma_L$ which implies $\sigma_1 \approx (1-\lambda) \sigma_0$. Error propagation gives

$$\partial (\delta^2) = \frac{1}{2 \lambda} \partial \left( \frac{\sigma_1}{\sigma_0} \right) \approx \frac{1}{2 \lambda} \sqrt{\frac{\partial \sigma_1^2}{\sigma_1} + \frac{\partial \sigma_0^2}{\sigma_0}} \approx \frac{1-\lambda}{2 \lambda} \left[ \frac{1}{N_o} + \frac{1}{N_1} \right] = \frac{1-\lambda}{2 \lambda} \left[ \frac{1}{N_o} + \frac{1}{N_1} \right]$$

where $K = \text{Monitor}_1 / \text{Monitor}_0$ denotes the relative number of incoming muons with $\lambda_1$ and $\lambda_o$ polarization, respectively. For $K = 4$ and $\lambda = 0.9$ one gets numerically

$$\partial (\delta^2) = \partial \left( \frac{M_1^4}{M_2^4} \right) \approx 0.1 \frac{1}{N_o}$$

which means that $N_o = 100$ events can produce one standard deviation limit on right-handed mass $M_1/M_2 < \sqrt{\delta^2 / \partial \lambda} = 0.316$ corresponding to $M_2 > 250$ GeV. It seems to be an easy experiment. Don't forget, however, that in order to improve this limit by a factor of 2 one requires $(2^2) = 256$ times more muon (i.e. running time).

4.2 Right-handed boson is extremely heavy

If $M_2$ is so large that $c_{RR} \ll c_{RL}$ then the muon scattering is reduced formally to the neutrino one. Even in this case the muon beam has the advantage that the normal weak interaction will be suppressed by a factor of $(1-\lambda)/2$ relative to the mixing -term. Within our approximation measurements with $\mu^-$ and $\mu^+$ beams provide

$$\sigma^- = \frac{1-\lambda}{2} c_{LL}^2 \left[ q(x) + (1-y)^2 q(x) \right] + c_{RL}^2 \left[ \overline{q}(x) + (1-y)^2 \overline{q}(x) \right]$$

$$\sigma^+ = \frac{1+\lambda}{2} c_{LL}^2 \left[ \overline{q}(x) + (1-y)^2 \overline{q}(x) \right] + c_{RL}^2 \left[ q(x) + (1-y)^2 q(x) \right].$$

In case of magnetic field reversal (i.e. beam conjugation) one finds $\lambda^- = \lambda^+ = \lambda$. It is worth to define the combination

$$D(x) = \frac{\sigma^+ - (1-y)^2 \sigma^-}{\sigma^- - (1-y)^2 \sigma^+} \approx \frac{(1-\lambda)c_{LL}^2 \overline{q} + 2c_{RL}^2 q}{(1-\lambda)c_{LL}^2 q + 2c_{RL}^2 \overline{q}} \approx \frac{\overline{q}}{q} + \frac{2}{1-\lambda} c_{RL}^2$$

where one can neglect $c_{RL}^2 \overline{q}$ relative to the first term if $\delta^2 < (1-\lambda)/2$. In this case the mixing angle is given by the formula:

$$\delta^2 \approx c_{RL}^2 c_{LL}^2 \approx \left( D(x) - \overline{q}/q \right) \frac{2}{1-\lambda}$$

That is the sensitivity is increased by a factor of 20 in muon case relative to the neutrino one if the muon polarization is equal to $\lambda = 0.9$, which makes the experiment less sensitive to the error in $\overline{q}/q$ ratio determination.
5. EXPERIMENTAL DETECTION OF CHARGED CURRENT EVENTS

5.1 Rates
The cross-section for charged current process $\mu^- N \rightarrow \mu^- X$ is $\sigma = 0.62 E_\mu \times 10^{-38} \text{cm}^2/\text{muon/nucleon}$. The rate of interaction at 200 GeV on lead (uranium) target is then about $0.8 \times 10^{-9}$ events/muon/meter ($\sim 1.4 \times 10^{-9}$). A moderate flux of $10^7$ muons/burst yields $10^4$ events in 10 days on a lead (uranium) target of 10 m (6 m). The production rate by itself is therefore high enough to allow an investigation of the process. We should not however forget about the polarization factor of $(1-\lambda)/2$ as $\lambda$ will generally be about .9.

5.2 Signature
The final state is characterized by three features which can be used against potential backgrounds:

i) the absence of muons in the final state

ii) a large missing energy

iii) a hadronic shower at high $Q^2$.

As the $Q^2$ distribution of events with large missing energy clearly plays a key role in the measurements, the detector should have a good angular resolution.

5.3 Backgrounds
The main contributions to the background arise from events with fake muon interactions, such as muon decay in the initial state, or events where the scattered muon is undetected because it is soft or decays.

i) Muon decay in the initial state

There is only an electromagnetic shower at a rate of $8 \times 10^{-6}$ decays/muon/meter. These events will be strongly suppressed by requiring a hadronic shower with $Q^2 > 1 \text{ GeV}^2$.

ii) Undetected final muon

a) Decay of the final muon

According to Monte Carlo calculations, a cut on the transverse momentum of the hadronic shower in the final state reduces the ratio background/signal to a few percent.

b) Loss of soft final muons

Such events are eliminated by a request of a large missing energy in the final state.

5.4 Triggering
A trigger would require:

i) A large local energy deposition $y > .2$ which is readily obtained by the calorimeter threshold.

ii) No muon in the final state. One can check that there is no muon with energy less than $0.8 E_{\text{BEAM}}$ by inserting a beam analysis magnet and muon identifier after the calorimeter.

iii) A missing energy requirement $y < .8$ combined with muon veto will reduce the trigger rate to the level of $10^{-5}$ events/incoming muon.

The final event selection is performed by an off-line analysis imposing the high $Q^2$ requirement. Thanks to the length of the proposed calorimeter we can estimate the remaining background by selecting events when the hadronic shower is well separated from the eventual electron shower at the decay of the scattered muon.
5.5 Detector

The detector should consist of two parts: a dense, fine grained calorimeter and a veto-system to identify the surviving muons. The veto-system can be built from standard elements. The fine granularity can be achieved by a novel design based on scintillating fibres. The parameters of a possible uranium calorimeter are summarized below:

- uranium plate thickness: 1.5 millimeter
- scintillating fibre diameter: 0.5 millimeter
- number of plates: 6000
- average density: 14.4 g/cm$^3$
- total length: 12 m = 17280 g/cm$^2$
- lateral width: 40 cm
- lateral segmentation: 1 millimeter
- longitudinal segmentation $(x,y)$ interleaved: 8 millimeter
- number of read-out channels by $2 \times 2$ fibres: 1200000 channels

If one uses lead instead of uranium then all the above parameters should be rescaled by the density factor $\varphi_\mu / \varphi_{\mu L}$.

By this detector 1 day running with $\lambda_0 = 0$ and 4 days with $\lambda_4 = 0.9$ can provide a bound

$$M_2 \geq 250 \text{ GeV} \quad (68.3\% \text{ C.L.})$$

In case of $\lambda_4 = 0.95$ after 150 days ($1.5 \times 10^{13}$ incoming $\mu^-_R$) it is possible to reach

$$M_2 \geq 450 \text{ GeV} \quad (68.3\% \text{ C.L.})$$

In order to realize this theoretical possibilities significant developments are required in the fibre read-out technology which would make feasible the digitization of the information from about one million optical channels. Some preliminary studies would be very useful by the help of the uranium calorimeter proposed by the EMC collaboration$^{15}$ for $b\bar{b}$ studies.

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REFERENCES

Table 1

Present bounds on left-right symmetry

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>( \xi )</th>
<th>( \delta )</th>
<th>Valid for massive ( \nu_R )?</th>
<th>Without additional theoretical assumptions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon-decay: Michel parameter</td>
<td>(&lt; 0.06)</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Muon-decay: ( e^- ) asymmetry</td>
<td>(</td>
<td>\delta - \xi</td>
<td>\leq 0.115)</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>\delta - \xi</td>
<td>\leq 0.23)</td>
<td></td>
</tr>
<tr>
<td>Beta-decay: ( e^- ) helicity/(v/c)</td>
<td>(</td>
<td>\delta + \xi</td>
<td>\leq 0.09)</td>
<td>NO</td>
</tr>
<tr>
<td>Beta-decay: e-asymmetry</td>
<td>Hyperbolic area</td>
<td>NO</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>( \Sigma N ) - scattering (CDHS)</td>
<td>(&lt; 0.095)</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Hyperon decays ( \Lambda, \Sigma, \Xi, \Omega )</td>
<td>(&lt; 1/120)</td>
<td>NO</td>
<td>YES</td>
<td>Factorization hypothesis</td>
</tr>
<tr>
<td>( K \rightarrow 3 \pi )</td>
<td>(&lt; 1/250)</td>
<td>(&lt; 1/20)</td>
<td>YES</td>
<td>PCAC Bag model</td>
</tr>
<tr>
<td>( \Delta M_{KL,LS} )</td>
<td>NO</td>
<td>(&lt; 1/430)</td>
<td>YES</td>
<td>Neglect t-quark t-quark+&quot;Goldstone&quot;</td>
</tr>
<tr>
<td>( \pm N ) - scattering</td>
<td>Possible</td>
<td>Possible</td>
<td>YES</td>
<td>( \text{upto-20 GeV} )</td>
</tr>
<tr>
<td>$\lambda = -1$</td>
<td>$\mu_R^{-} + q \rightarrow \nu^\mu_L + q$</td>
<td>$\lambda = -1$</td>
<td>$\mu_R^{-} + \bar{q} \rightarrow \nu^\mu_L + \bar{q}$</td>
<td></td>
</tr>
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<td>----------------</td>
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<td></td>
</tr>
<tr>
<td>$P$-violated</td>
<td>$\mu_L^{-} \cos \frac{\pi}{3} \nu^\mu_L + \sin \frac{\pi}{3} \nu^\mu_L + \nu^\mu_L$</td>
<td>$P$-violated</td>
<td>$\mu_L^{-} \cos \frac{\pi}{3} \nu^\mu_L + \sin \frac{\pi}{3} \nu^\mu_L + \nu^\mu_L$</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dy \sim 1$</td>
<td>$w_1 \sin \frac{\pi}{3} d_L u_L \sin \frac{\pi}{3} d_L$</td>
<td>$d\sigma/dy \sim (1-y)^2$</td>
<td>$w_1 \sin \frac{\pi}{3} d_R u_L \sin \frac{\pi}{3} d_R$</td>
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</tr>
<tr>
<td>$P$-conserved</td>
<td>$\mu_L^{-} \cos \frac{\pi}{3} \nu^\mu_L + \sin \frac{\pi}{3} \nu^\mu_L + \nu^\mu_L$</td>
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<td>$\mu_L^{-} \cos \frac{\pi}{3} \nu^\mu_L + \sin \frac{\pi}{3} \nu^\mu_L + \nu^\mu_L$</td>
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<th>$\lambda = +1$</th>
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Figure 1: Representative $SU_L(2) \times SU_R(2) \times U(1)$ diagrams

![Graph showing M(W_R) vs. \delta = M^2(W_L)/M^2(W_R)](image)

Figure 2: Low-ended bounds on right-handed current parameters