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SEARCH FOR EXCITED LEPTONS IN THE NEXT
GENERATION OF EXPERIMENTS

by

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Abstract

We estimate production cross sections of excited leptons in e^+e^- annihilation experiments. Light excited states can be produced below the characteristic energy scale at which hypothetical constituents of leptons become bound: therefore the estimates are expected to be valid for $E_{cm} \lesssim 100$ GeV, and to a large degree, model independent. The results are expressed in terms of measurable low energy parameters. We conclude that high precision experiments are needed for an effective search for excited leptons.

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The discovery of excited leptons and/or quarks would be very important from a theoretical point of view, for it would lend direct support to the idea that matter is composed of constituents more elementary than either quarks or leptons¹⁾. Although the dynamics of such hypothetical subconstituents - "preons" - is ill-understood, there is no known counterexample to the statement that a composite system is either so weakly bound that it immediately disintegrates into its constituents (like the deuteron) or else it has excited levels.

If preons indeed exist, the characteristic energy scale of their dynamics must be at least a few hundred GeV, for the electrodynamics of "point-like" leptons is known to be accurate up to such an energy scale²⁾. Nevertheless, we showed that under favorable circumstances, excited states of either leptons or quarks may appear at masses which are almost two orders of magnitude smaller than the scale on which preons become bound³⁾. If this is indeed the case (as it is suggested by some presently popular, "conservative" preon models⁴⁾), a good way to look for a composite structure of leptons and quarks would be to look for their low-lying excited states. It is amusing to note that various production cross sections of light excited quarks or leptons ($M \ll \Lambda$, where M and Λ stand for the mass of the excited state and for the characteristic energy scale of preon dynamics, respectively) can be estimated without a detailed knowledge of preon dynamics, for, in this case, one is dealing with a low-energy phenomenology⁵⁾. (In essence, order-of-magnitude estimates can be obtained by extrapolating presently known results in conjunction with rather straight-forward scaling arguments.)

In view of recent interest in the search for excited leptons⁶⁾, it is of some importance to give theoretical estimates of their rates of production. Our estimates are based on some rather conservative assumptions:

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i) The validity of the standard model of weak and electromagnetic interactions at least up to energies of the order of Λ .

ii) Excited leptons are relatively light but their masses are compatible with known experimental lower limits on their masses⁷⁾. (Typically, we have $M \sim 20 \text{ GeV}$ in mind.)

iii) No dramatically new phenomena take place between the presently explored energy range and the scale of preon dynamics, Λ . (For instance, leptons do not develop appreciable coupling to the gluons of QCD, etc.)

On accepting these assumptions, it becomes clear that it is best to look for excited muons in an e^+e^- annihilation experiment. (This is being done at present⁶⁾, so even if it were not the best experiment, it would be the only one to be analyzed by theorists...)

Roughly, the argument in favor of $e^+e^- \rightarrow \mu^* \mu^+$ runs as follows, see II for a more detailed discussion.

a) Excited quarks are hard to observe, even though they should have masses comparable to those of excited leptons, see I. The reason is their confinement by QCD (whether it is an exact theory or just a useful phenomenology at low energies): "parton" distributions inside color singlets tend to smear out the effects of excited quarks.

b) Looking for an e^* is, basically, made hard by the fact that an e^* tends to decay into $e\gamma$ (of roughly equal energies in the rest-frame of the e^*). The resulting electromagnetic shower is likely to create a lot of debris from which it would be quite difficult to reconstruct the mass of the e^* . Moreover, if $e^* e^+$ were produced in an e^+e^- annihilation experiment, both "annihilation" and "exchange" diagrams would contribute according to the known rules of QED (viewed here as a time-honored phenomenological theory, trustworthy at $E_{\text{cm}} \lesssim \Lambda$).

The cleanest process for producing $\mu^* \mu$ appears to be

$$e^+e^- \rightarrow \mu^* \mu^+ \quad (1)$$

(No exchange diagrams, because, at least for $E_{\text{cm}} \ll \Lambda$, μ is certainly different from e . No hadronic debris either, because, under our assumptions, quarks are distinct from leptons in the same energy range.) The relevant intermediate states, to leading order, are γ and Z^0 in this process. It is also worth noting that once the cross section of (1) has been computed, it gives access to estimates of cross sections of $(\mu^* \mu)$ production in hadronic processes, such as

$$\begin{aligned} p\bar{p} &\rightarrow \mu^* \mu^+ X \\ p\bar{p} &\rightarrow \mu^* \mu^+ X \end{aligned} \quad (2)$$

by using the parton model of hadrons. In fact, all one has to do is to average the cross section of (1) - suitably scaled down for quarks - over the relevant parton distributions. Although, processes (2) may be "dirty" due to the presence of hadronic debris and naive parton model estimates neglect quark correlations, gluon Bremsstrahlung, etc., this question is worth investigating. (In particular, QCD, at least as a "low energy phenomenology", being asymptotically free, naive parton model estimates of the processes (2) should not be very far off the mark for a reasonable range of the mass of a μ^* : in fact, one should do better than in estimating $\mu^* \mu^+$ production via the standard Drell-Yan process.)

Let us be optimistic for the time being and assume that $\mu^* \mu$ production can be clearly identified either in (1) or in (2). The key question is:

- How frequently can we see a μ^* in process (1)?

In principle, the answer is obtained simply by substituting numbers into the appropriate formulae of I. This is not practical, however, because all the numbers so obtained would be highly sensitive to the choice of the characteristic energy, Λ . We can do better by bringing in the quantity which gives the most stringent constraint on lepton structure, namely, δa , the deviation of $(g-2)/2$ of the muon from its value calculated in QED. If one assumes that the entire deviation comes from structural effects, one obtains for the contribution of a μ^* of mass M :

$$|\delta a| \approx \frac{3\alpha}{4} \frac{\mu M}{\Lambda^2} \log \frac{\Lambda}{M} |v_M(0)|^2 \quad (3)$$

where μ is the mass of the muon and $v_M(q^2/\Lambda^2)$ is the magnetic transition form factor of the process $\mu^* \rightarrow \mu \gamma$. Electric transitions give negligible contributions, because their form factor vanishes at least as q^2/Λ^2 near $q^2 \rightarrow 0$, see II. In deriving eq.(3), one neglects the (unknown) dependence of v_M on q^2 and introduces a cutoff instead: this should give an estimate of δa of the correct order of magnitude. Eq. (3) is expected to give a good approximation provided the inequalities, $\mu \ll M \leq \Lambda$, are satisfied. (Numerically, $|\delta a| \approx 10^{-8}$, so with $\Lambda \approx 1\text{TeV}$, one gets $|v_M(0)| \approx 0.1$ which is a believable number.)

The key formula is eq. (3.4) in II: it gives the cross section for process (1), with a vector boson in the intermediate state. We quote this formula for the case when the CMS energy is small compared to Λ . In that case, electric transitions are negligible and we have:

$$d\sigma = \frac{\alpha^2 |\Delta(s)|^2}{\Lambda^4} \left\{ v a v_M a_M \frac{(t^2 - u^2)(t+u)}{2} - (v^2 + a^2)(v_M^2 + a_M^2) \left[(t+u)^3 + \frac{1}{2} t u (t+u) \right] \right\} \times \frac{M \Gamma}{(s+t+u-M^2)^2 + M^2 \Gamma^2} \frac{dt du}{s} \quad (4)$$

In this equation, s, t, u stand for the usual Mandelstam invariants of process (1), with $S \equiv E_{cm}^2 \gg \mu$. (Note, however, that μ^* is treated as a resonance of width Γ , as opposed to a stable particle. As a consequence, all three invariants are independent.) The meaning of the other symbols is the following. The scalar coefficient of the transverse part of the vector boson propagator is denoted by $\Delta(s)$; hence $\Delta_s^{-1} = S$, $\Delta_z^{-1} = M_0^2 - i M_0 \Gamma_0$, for an intermediate Z^0 and Z^0 , respectively, where M_0 and Γ_0 are the mass and total width of the Z^0 . The form factors v and a stand for elastic Dirac form factors of the vector and axial currents, respectively, sandwiched between the states $|e^+ e^- \rangle$ and the vacuum, whereas v_M and a_M are the corresponding (Sachs) magnetic transition form factors between $|\mu^* \mu \rangle$ and the vacuum. The standard model of weak and electromagnetic interactions determines v and a at $q^2 = 0$ in terms of the Weinberg angle. The result is summarized in Table I.

TABLE I

Vector Boson	Z	Z^0
$ v(0) $	1	$\left \frac{1-2\cos 2\theta_W}{2\sin 2\theta_W} \right $
$ a(0) $	0	$\left \frac{1}{2\sin 2\theta_W} \right $

In what follows, all form factors are approximated by their values at $S = 0$. (This means that we neglect corrections of $O(s/\Lambda^2)$, which should be small for all energies of interest.) In addition, we assume:

$$\frac{v}{v_M} \approx \frac{a}{a_M} \quad (5)$$

which, in essence, means that:

a) We neglect the (finite) renormalization of the axial current. (If presently known hadron dynamics can serve as a guide, we commit an error $\leq 20\%$ thereby.)

b) We regard v_M and a_M to arise from matrix elements of the form:

$$\langle 0 | \bar{\Psi} \gamma_\mu \Psi | \mu^{*+} \mu^- \rangle$$

and

$$\langle 0 | \bar{\Psi} \gamma_\mu \gamma_5 \Psi | \mu^{*+} \mu^- \rangle,$$

where Ψ stands for the field operator of a preon, coupled to the vector bosons of interest according to the standard model. (This is plausible in "conservative" preon models; however, it is to be realized that this is the least reliable of all the assumptions made in this paper; in particular, no quantitative error estimates can be given for the validity of eq. (5). However, we believe (5) to be essentially correct.)

Strong assumptions are expected to yield substantial rewards. This is indeed the case with eq. (5), for once it is assumed to be valid, all the relevant production cross sections can be expressed in terms of the quantities: α , Λ , M , M_0 , Γ_0 , ν and $|\delta a|$; this is important, because a proper choice of Λ is uncertain at this time.)

Inspection of the diagrams contributing to (1) shows that interference terms between γ and Z^0 intermediate states are small; hence, in a first approximation, an intermediate γ and Z^0 may be regarded as incoherent contributions. Bearing this in mind, contributions to eq. (4) may be divided into two classes.

i) Contributions outside the Z^0 resonance region. In the standard model, $M_0 = 90$ GeV, $\Gamma_0 = 2.7$ GeV, so that if s is in the complement of the interval $(87.3 \text{ GeV} \leq s \leq 92.7 \text{ GeV})$, the cross section of (1) is dominated by the one-photon intermediate state.

ii) Within the interval $M_0 - \Gamma_0 \leq \sqrt{s} \leq M_0 + \Gamma_0$ (the "resonance region") one-photon contributions are negligible.

Consequently, a reasonable way to present the cross section of process (1) consists of

- 1) Integrating over the kinematic variables in eq (4).
- 2) Separating contributions of γ and Z^0 .
- 3) Combining eqs. (3), (4), (5) and entries of Table I, using $|\delta a| = 3 \times 10^{-8}$.

As a result, we obtain for the one-photon contribution:

$$\sigma_\gamma(s) = \frac{7\pi^2 \alpha}{36} |\delta a| \left(1 - \frac{M^2}{s}\right)^4 \frac{s}{\Lambda^2} \frac{1}{\mu M \log \frac{\Lambda}{M}} \quad (6)$$

The resonance contribution in the Z^0 -region is best given in the form of the cross section averaged over the Breit-Wigner peak:

$$\langle \sigma_Z \rangle = \frac{1}{2M_0 \Gamma_0} \int ds \sigma_Z(s)$$

(This expression is unambiguously defined only if a narrow resonance approximation is used, i.e. the Breit-Wigner denominator is replaced by a δ -function. This is justified, because $\Gamma_0/M_0 \leq 1/30$). We find:

$$\begin{aligned} \langle \sigma_Z \rangle &= \frac{7\pi^2 \alpha}{72} |\delta a| \frac{(1 - 2\cos 2\Theta_W + 2\cos^2 2\Theta_W)^2}{\sin^2 2\Theta_W} \frac{M_0^2}{\Gamma_0^2} \\ &= \left(1 - \frac{M^2}{M_0^2}\right)^4 \frac{M_0^2}{\Lambda^2} \frac{1}{\mu M \log \frac{\Lambda}{M}} \end{aligned} \quad (7)$$

It is important that the known value, $|\delta a| = 3 \times 10^{-8}$, suppresses both cross sections considerably. By substituting in numbers with $\sin^2 \Theta_W = 0.22$,

we obtain the estimates:

$$\sigma_{\gamma}(s) \approx 1.68 \left(1 - \frac{M^2}{s}\right)^4 \frac{s}{\Lambda^2} \frac{1}{M \log \frac{\Lambda}{M}} [\text{picobarns}]$$

$$\langle \sigma_2 \rangle \approx 380 \left(1 - \frac{M^2}{M_0^2}\right)^4 \frac{M_0^2}{\Lambda^2} \frac{1}{M \log \frac{\Lambda}{M}} [\text{picobarns}] \quad (8)$$

all masses and energies being measured in GeV units. (Throughout this paper $\hbar = c = 1$.) In Fig. 1, we plotted the photon contribution to the cross section of process (1) for some representative values of M and Λ . Likewise, in Fig. 2, the resonance contribution is plotted as a function of the mass of μ^* .

Conclusion.

We believe that our formulae, though approximate, are reasonably model independent: they represent low-energy approximations ($E_{\text{cm}} \ll \Lambda$) to the cross section of μ^* production. Due to the fact that both cross sections, eqs. (6) and (7), are proportional to $|\delta a|$, we are not surprised to learn that the observation of a μ^* requires high precision experiments. (The question of background at PEP energies has been discussed in a recent paper by Tsai.⁸⁾ For instance, we find at PEP energies, the ratio $\sigma_{\gamma}/c(e\bar{e} \rightarrow \mu\bar{\mu}) \approx 10^{-7}$. With some luck, a relatively light μ^* may be observable, for instance, at SLC or some similar machine, provided the characteristic energy scale is not higher than a TeV or so: the resonant contribution is almost a picobarn there.

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Footnotes and References.

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Figure Captions

Fig. 1 Cross section of $e^+e^- \rightarrow \mu^{*+}\mu^{*-}$ via an intermediate photon.

Fig. 2 Cross section of $e^+e^- \rightarrow \mu^{*+}\mu^{*-}$ on the Z^0 resonance as a function of the mass of μ^* . The cross section is averaged over the width of Z^0 .

Fig. 1.