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SUPERSYMMETRIC FLAVOUR AND *CP* PROBLEMS FROM A COSMOLOGICAL PERSPECTIVE*

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A solution to the supersymmetric flavour and CP problems in which the first two generations of sfermions are heavier than a few TeV and approximately degenerate in mass is re-considered from a cosmological perspective. It is shown that if the lightest supersymmetric particle is essentially bino-like then requiring that all flavour changing neutral current and CP-violating processes are adequately suppressed, imposes severe limits on the bino mass, typically $m_{\widetilde{B}} \gtrsim (200\text{–}300)$ GeV. This leads to difficulties for models implementing the scenario of heavy sfermion masses.

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1. Flavour and *CP* problems

Stringent experimental constraints on flavour-changing neutral current (FCNC) and CP-violating processes provide a very narrow gate for new physics beyond the Standard Model (SM). In the SM, the absence of large flavour and CP-violating processes may be regarded as an accidental property resulting from its particle content which is typically not shared by new physics models seeking to replace the SM. Such models by definition contain more states and interactions which invariably give new, and typically large, contributions to flavour and CP-violating processes. These new interactions are proportional to $1/\Lambda$ where Λ is the scale of new physics. Unless Λ can be pushed to very high values, a problem will occur and may sometimes even lead to fatal consequences (like in the case of technicolour models).

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These problems are also a serious challenge for supersymmetry (SUSY). There, the scale Λ is the SUSY breaking scale and is not expected to exceed the 1 TeV scale by too much. As a result, the requirement of consistency with experimental data imposed strong constraints on the structure of flavour and CP sectors in SUSY theories. This has far-reaching consequences for SUSY model building. Although the flavour changing elements in the sfermion mass matrices as well as the CP violating phases are free parameters in SUSY, ultimately their values have to be obtained from a theory of soft SUSY breaking and fermion mass generation. Therefore, experimental constraints provide us with useful suggestions towards such a theory.

There exist several classes of solutions to the SUSY flavour and CP problems. One is that for some reasons the pattern of the sfermion mass matrices at the weak scale is very special: they are either very close to the unity matrix in flavour space (flavour universality) [1] or they have a structure, but they are diagonal in the basis set by the quark mass matrix (alignment) [2]. Under these special conditions, the FCNC effects are tiny and the CP violating phases at the weak scale are either highly suppressed or efficiently screened. Furthermore, if high degeneracy of the first two sfermion generations occurs, their masses are bounded from below only by the present direct searches.

Another and perhaps the most straightforward possibility is to assume that the masses of the first and second generation of sfermions are larger than a few TeV [4, 5] and much larger than the masses of sfermions of the third generation. This does not necessarily lead to problems with naturalness [9]. The contribution to ε_K from the first two sfermion generations is generically still too large for CP violating phases $\sim \mathcal{O}(1)$. However, this scenario becomes tenable when further approximate degeneracy in the mass spectrum of the first two generations of squarks is present, such as in models with non-Abelian horizontal symmetries [5–7]. In this way, the suppression of FCNC effects in the MSSM is achieved and the SUSY contributions to CP violating observables are small even for CP violating phases of order unity. In other words, this "irrelevancy" approach alleviates both the flavour and CP problems.

On the other hand, the cosmological relic density of stable particles can often provide stringent bounds on the parameter space of a given model. In the MSSM with R-parity conservation, the lightest supersymmetric particle (LSP), is absolutely stable and its contribution to the relic abundance $\Omega_{\rm LSP}h^2$ in the Universe may be inconsistent with the bound $\Omega_{\rm LSP}h^2 \lesssim 1$. The relic abundance of the LSP is determined by its annihilation cross section, which depends sensitively upon the masses of the various particles mediating the annihilation processes. For instance, in the case when the LSP is a bino-like neutralino, which we denote by χ, large sfermion masses are typically inconsistent with the cosmological bound $\Omega_\chi h^2 \lesssim 1$, unless the annihilation rate of the LSP into scalar and gauge bosons is efficient enough and/or near resonances. It is therefore reasonable to expect that combining the experimental bounds on FCNC and CP violating phenomena with the bounds coming from cosmological considerations will help us in significantly constraining the parameter space of the MSSM.

In this talk [9] I will aim to demonstrate how the cosmological bound $\Omega_{\rm LSP} h^2 \lesssim 1$ often significantly constrains the irrelevancy scenario. I will show that when parameters are chosen so that the LSP is predominantly a bino, the requirement $\Omega_\chi h^2 \lesssim 1$ often places a severe *lower* bound on the LSP mass. This result may have rich implications for the class of SUSY models which explain the suppression of the FCNC and CP violating effects by decoupling the first two generations of sfermions.

2. Limits from FCNC and CP on the 3rd generation sfermions

Let us first briefly discuss the limits one can infer from the FCNC and CP violating effects on the masses of the third sfermion generation in this scenario. We will generically assume that the third generation sfermions are lighter than a TeV. While bounds on the stops are fairly weak, larger effects arise for the sbottom and stau. The stringiest bound that one can obtain on the sbottom mass follows from the ε_K parameter of $K^0 - \bar{K}^0$ mixing. In the limit that $m_{\tilde{b}} \equiv m_{\tilde{b}_{\rm L}} \simeq m_{\tilde{b}_{\rm R}}$ the bound resulting from the ε_K parameter is [10, 11]

$$\left(\frac{1\ \text{TeV}}{m_{\tilde{b}}}\right)^2 \left|V^Q_{13} V^Q_{23} V^D_{13} V^D_{23}\right| \sin\varphi_1 \, f\left(\frac{m^2_{\tilde{g}}}{m^2_{\tilde{b}}}\right) \lesssim 3.24 \times 10^{-5} \,, \tag{1}$$

where $V^{Q,D}$ are flavour mixing matrices (that define the rotations which diagonalise the quark mass matrix in the basis where $m^2_{\tilde{Q},\tilde{D}}$ are diagonal), $\varphi_1 = \text{Arg}(V^Q_{13} V^{Q*}_{23} V^D_{13} V^{D*}_{23})$ is a CP-violating phase and $f(x)$ is given in Ref. [9]. Notice that the bound (1) depends on the particular details of the flavour mixing. Since we are considering models that do not have any special mechanisms for the flavour and CP-structure, we will generically assume the CP-phase to be maximal with $\sin\varphi_1 \sim 1$. In order to understand how the magnitude of the off-diagonal matrix elements affects the bound we will compare our results with a CKM-like parameterisation of the mixing matrices of the form

$$V^{Q,D} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \tag{2}$$

where $\lambda \sim 0.2$ is a Cabibbo-like angle. The bound (1) is very sensitive to the amount of mixing between the first two and third generations. For arbitrary parameterisations of the mixing matrix we will present our results by defining an average off-diagonal element $\overline{V}_1 \equiv \left| V^Q_{13} V^Q_{23} V^D_{13} V^D_{23} \right|^{1/4} / (0.2)^{5/2}$, where $\overline{V}_1 = 1$ corresponds to the CKM parameterisation (2). For the special limit $m_{\tilde{b}} \simeq m_{\tilde{g}}$ the sbottom mass bound arising from Eq. (1) is $m_{\tilde{b}} \gtrsim 800\, \overline{V}_1^2$ GeV. Clearly, the bound becomes weak when the amount of flavour mixing $\overline{V}_1 \to 0$. This is the case when there are special mechanisms operating such as universality or alignment. The general behaviour for arbitrary $m_{\tilde{b}}$ and $m_{\tilde{g}}$ can be seen in Fig. 1(a), where contours of the lower bound on the sbottom mass are shown for various values of $\overline{V}_1$. In the figure, $m_{\tilde{b}}$ is plotted as a function of the bino mass $m_{\tilde{B}}$ where at the electroweak scale $m_{\tilde{g}} \simeq 7 m_{\tilde{B}}$, which follows from our assumption of gaugino mass unification. One can see that, for values of $\overline{V}_1 \gtrsim 1$, the lower bounds on either

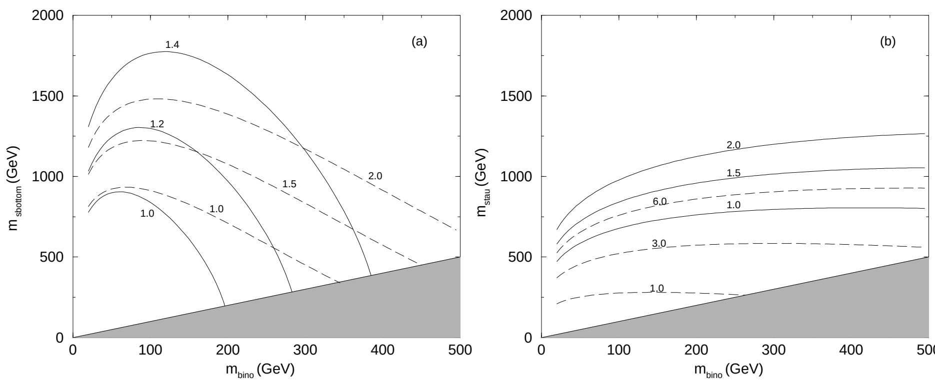

Fig. 1. (a) — Lower bounds on the sbottom mass for various contours of $\overline{V}_1$ from the ε_K parameter of $K^0 - \bar{K}^0$ mixing (solid line) and $\overline{V}_2$ from the down quark electric dipole moment (dashed line). (b) — Lower bounds on the stau mass for various contours of $\overline{V}_3$ from $\mu \to e\gamma$ (dashed line) and $\overline{V}_4$ from the electric dipole moment of the electron (solid line) where $A'_\tau = 1$ TeV and $\sin\varphi_4 \sim 1$.

the mass of the sbottom or the gluino is quite significant, in the range of hundreds of GeV or more. Notice, however, that the lower mass bound from $K^0 - \bar{K}^0$ mixing disappears as the mass of the gluino or sbottom exchanged in the loop becomes very large. However, for large gluino mass a stronger lower bound can be obtained by considering the contribution of the sbottom left–right mixing to the down quark electric dipole moment (EDM) [10, 11].

The expression for this contribution and relevant definitions can be found in Ref. [9] and is presented in Fig. 1(a), where $\overline{V}_2 \equiv \left|V_{13}^{\mathrm{Q}} V_{13}^{D}\right|^{1/2}/(0.2)^3$ is plotted for $A_b^{\prime} = 10$ TeV.

Similar bounds can also be obtained for the stau and these follow from the flavour-violating process $\mu \to e\gamma$ and the electron EDM [10, 11]. Again we will assume that $m_{\tilde{\tau}} \equiv m_{\tilde{\tau}_{\mathrm{L}}} \simeq m_{\tilde{\tau}_{\mathrm{R}}}$. They are discussed in detail in Ref. [9] and are presented in Fig. 1(b) for several values of $\overline{V}_3 \equiv (V_{13}^{L} V_{23}^{E})^{1/2}/(0.2)^{5/2}$ (dashed line) and $\overline{V}_4 = \left|V_{13}^{L} V_{13}^{E}\right|^{1/2}/(0.2)^3$ (solid line). Notice that the constraints on the stau mass obtained from the electron EDM are much stronger than those from $\mu \to e\gamma$.

3. Bounds from cosmology

Let us now turn to the cosmological implications on the bino mass from the stringent lower bounds on the mass of the third generation sfermions resulting from the FCNC and CP-violating processes. We will be particularly interested in the cosmological relic abundance of the LSP when it is a predominantly bino-like neutralino, with only a small admixture of the wino and the higgsino in its composition. In the MSSM one usually assumes that the neutralino is the LSP for astrophysical reasons: it is a weakly-interacting stable massive particle for which astrophysical bounds are very weak and it can serve as an excellent dark matter candidate when it is mostly a bino [12].

A predominantly bino-like LSP corresponds to the case $|\mu| \gtrsim M_1$ where μ is the Higgs/higgsino mass parameter and M_1 is the soft-mass of the bino. We note that a bino-like neutralino naturally arises as the only neutral LSP as a result of requiring radiative electroweak symmetry breaking (EWSB). While this has been shown to be true mainly in the case of universal soft masses at the unification scale [13], there are good reasons to believe that this will also remain valid in the case studied here [9].

In order for a bino-like neutralino to give $\Omega_\chi h^2 \sim 1$, at least some sfermion masses should normally not exceed a few hundred GeV [12]. In our numerical analysis we have included all relevant final states of the neutralino annihilation and all exchange channels for the general case of any neutralino composition. However, in the nearly pure bino limit the dominant annihilation channel is into final state (ordinary) charged fermions via the (lightest) sfermion exchange and the relic abundance is approximately given by $\Omega_\chi h^2 \propto m_{\tilde{f}}^4/m_\chi^2$ where $m_{\tilde{f}}$ is the sfermion mass. Thus it is clear that for sufficiently large sfermion masses imposing the bound $\Omega_\chi h^2 < 1$ will imply a *lower* bound on m_χ, unless other final-state channels can reduce the LSP relic abundance below one [9].

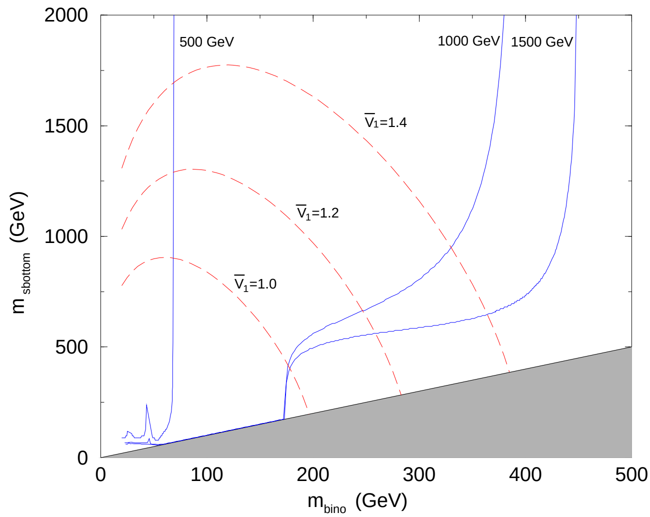

Fig. 2. Bounds on the sbottom mass as a function of the bino mass. The $\overline{V}_1$ contours arise from the ε_K parameter of $K^0-\bar{K}^0$ mixing (regions below them are excluded). The cosmological contours $\Omega_\chi h^2=1$ are labelled by various values of the μ parameter. (Regions to the left and above them are excluded.) In the figure we have assumed $m_{\tilde{t}}=m_{\tilde{b}}$, $\tan\beta=2$ and $m_A=m_{\tilde{\tau}}=1$ TeV.

Let us now combine the stringent limits on the masses of the third sfermion generation arising from the suppression of the FCNC and CP-violating processes with the cosmological constraint $\Omega_\chi h^2\lesssim 1$ for a predominantly bino-like LSP. We will consider three representative cases: $m_{\tilde{b}}=m_{\tilde{t}}$ with $m_{\tilde{\tau}}$ heavy in Fig. 2, $m_{\tilde{\tau}}=m_{\tilde{t}}$ with $m_{\tilde{b}}$ heavy in Fig. 3 and $m_{\tilde{b}}=m_{\tilde{\tau}}=m_{\tilde{t}}$ in Fig. 4. In each case we have used the best possible constraint arising from FCNC and CP-violating processes. For the sbottom mass this corresponds to the ε_K parameter, parameterised by contours of $\overline{V}_1$, while for the stau mass the electron EDM parameterised by $\overline{V}_4$ provides the most stringent constraint. The cosmological contour $\Omega_\chi h^2=1$ is shown for several choices of μ. Thus regions above and to the left of the cosmological contour are excluded.

In each figure we see that as $|\mu|$ decreases, the higgsino component of the neutralino increases, thus relaxing the cosmological bound. The combination of the exclusion curves from flavour and CP violating processes and from $\Omega_\chi h^2<1$ gives therefore strong *lower* limits on m_χ. The limits are particularly strong for large values of $|\mu|$ and m_A. For example, in Fig. 2 we see that for $|\mu|\gtrsim 1000$ GeV the bino has to be heavier than roughly m_t even for $\overline{V}_1=1$. This should be compared with the indicative upper bounds $m_\chi\lesssim 65$ GeV, obtained by requiring no significant fine-tuning in the

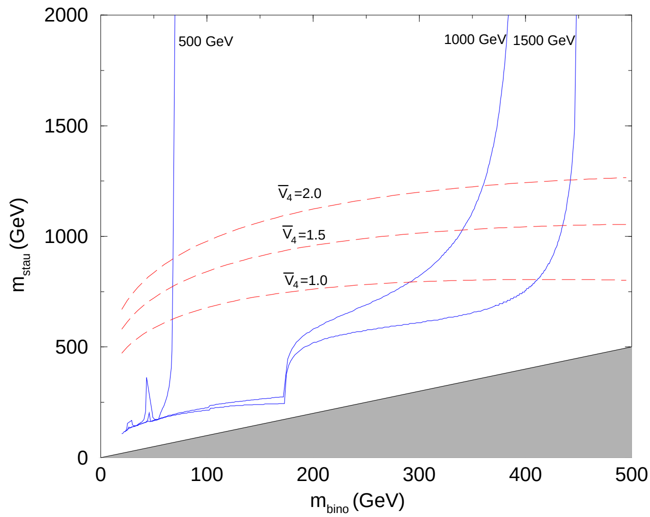

Fig. 3. Bounds on the stau mass as a function of the bino mass. The $\overline{V}_4$ contours arise from the electron EDM (regions below them are excluded). The cosmological contours $\Omega_\chi h^2 = 1$ are labelled by various values of the μ parameter. (Regions to the left and above them are excluded.) In the figure we have assumed $m_{\tilde{t}} = m_{\tilde{\tau}}, \tan\beta = 2$ and $m_A = m_{\tilde{b}} = A'_\tau = 1$ TeV.

parameters of the MSSM [8]. Actually, since the motivation for this scenario is to allow for basically unconstrained entries in the mixing matrices, one would expect $\overline{V}_1$ significantly larger than one, in which case the lower limit on m_χ would be further significantly increased.

A similar picture emerges when one considers the bounds on the stau mass arising from the electron EDM. Since the bounds on $m_{\tilde{\tau}}$ from $\overline{V}_4$ are more stringent than $\overline{V}_1$ we obtain a stronger lower limit on the bino mass. For the case plotted in Fig. 3 we find $m_\chi \gtrsim 300$ GeV for $\overline{V}_4 = 1$ and $|\mu| \gtrsim 1000$ GeV. Finally in Fig. 4 the sbottom and stau are now both assumed to be light and we need to simultaneously satisfy the constraints on the sbottom and stau from the suppression of FCNC and CP-violating processes. In this case since $\overline{V}_4$ sets the best limit we again find that $m_\chi \gtrsim 300$ GeV for $|\mu| \gtrsim 1000$ GeV and $m_A = 1000$ GeV as shown in Fig. 4.

The bounds on m_χ can be relaxed in several ways: by decreasing $|\mu|$ (thus increasing the higgsino component of the LSP), by lowering m_A, increasing $\tan\beta$, or by making the stop much lighter than the other sfermions [9]. In the last case this gives $m_\chi > m_t$ which is already a very strong lower bound. On the other hand, we have found that for $\mu < 0$ the bounds are even more stringent.

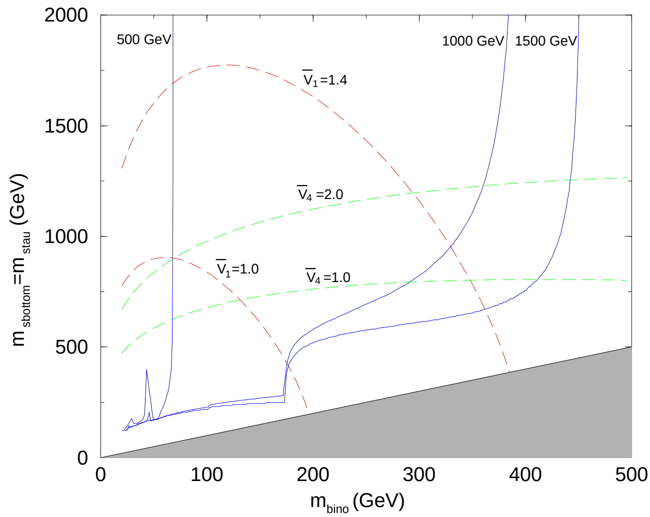

Fig. 4. Bounds on the stau and sbottom mass as a function of the bino mass. The contours $\overline{V}_1$ are for the sbottom mass, while $\overline{V}_4$ constrains the stau mass. The cosmological contours $\Omega_\chi h^2 = 1$ are labelled by various values of the μ parameter. In the figure we have assumed $m_{\tilde{t}} = m_{\tilde{\tau}} = m_{\tilde{b}}, \tan\beta = 2$ and $m_A = A'_\tau = 1$ TeV.

4. Summary and implications for model building

We have shown that by combining the constraints arising from the suppression of FCNC and CP-violating processes with bounds on the cosmological relic abundance, the bino mass can be severely restricted. This places severe limitations on models in which the LSP is mostly a bino (which is both a natural and cosmologically desired choice) and in which the first two sfermion generations are heavy and almost degenerate in mass and the SUSY contributions to the FCNC's and CP violating observables mainly come from the third squark generation.

Such a mass spectrum has been argued to be the best from the phenomenological point of view [14] and may be obtained if the three families belong to a $\mathbf{2+1}$ representation of a horizontal symmetry group G_H. It has also been recently pointed out that D-term contributions from the anomalous U(1) gauge group in string theory may naturally lead to such a mass spectrum for the sfermions. On the other hand, a generic problem of this class of models is the generation of sizeable gaugino masses. In this paper we have pointed out that having the first two generations of sfermions heavy and approximately degenerate requires driving the mass of the bino-like LSP to quite large values when considerations about the present cosmological abundance of the LSP are taken into account. This leads to serious difficulties for models implementing the scenario of heavy sfermion masses although one can think about several ways of relaxing our bounds.

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REFERENCES

[1] S. Dimopoulos, H. Georgi, *Nucl. Phys.* **B193**, 150 (1981).

[2] Y. Nir, N. Seiberg, *Phys. Lett.* **B309**, 337 (1993).

[3] Y. Kawamura *et al., Phys. Rev.* **D51**, 1337 (1995); A. Pomarol, S. Dimopoulos, *Nucl. Phys.* **B453**, 83 (1995); R. Rattazzi, *Phys. Lett.* **B375**, 181 (1996).

[4] M. Dine, A. Kagan, R.G. Leigh, *Phys. Rev.* **D48**, 4269 (1993).

[5] A. Pomarol, D. Tommasini, *Nucl. Phys.* **B466**, 3 (1996).

[6] A.G. Cohen, D.B. Kaplan, A.E. Nelson, *Phys. Lett.* **B388**, 588 (1996); P. Binetruy, E. Dudas, *Phys. Lett.* **B389**, 503 (1996); G. Dvali, A. Pomarol, *Phys. Rev. Lett.* **77**, 3728 (1996); R.N. Mohapatra, A. Riotto, *Phys. Rev.* **D55**, 1138 (1997); *Phys. Rev.* **D55**, 4262 (1997); A.E. Nelson, D. Wright, *Phys. Rev.* **D56**, 1598 (1997); N. Arkani-Hamed, M. Dine, S.P. Martin, *Phys. Lett.* **B431**, 329 (1998).

[7] E. Dudas, C. Savoy, *Phys. Lett.* **B369**, 255 (1996); E. Dudas, C. Grojean, S. Pokorski, C. Savoy, *Nucl. Phys.* **B481**, 85 (1996).

[8] S. Dimopoulos, G.F. Giudice, *Phys. Lett.* **B357**, 573 (1995).

[9] A. Gherghetta, A. Riotto, L. Roszkowski, *Phys. Lett.* **B440**, 287 (1998).

[10] J. Hagelin, S. Kelley, T. Tanaka, *Nucl. Phys.* **B415**, 293 (1994).

[11] F. Gabbiani, E. Gabrielli, A. Masiero, L. Silvestrini, *Nucl. Phys.* **B477**, 321 (1996).

[12] L. Roszkowski, *Phys. Lett.* **B262**, 59 (1991).

[13] R. Roberts, L. Roszkowski, *Phys. Lett.* **B309**, 329 (1993); G. Kane, C. Kolda, L. Roszkowski, J. Wells, *Phys. Rev.* **D49**, 6173 (1994).

[14] See A.G. Cohen, D.B. Kaplan, A.E. Nelson in Ref. [6].