IMPRS EPP Workshop

Weak Scale Baryogenesis in a Supersymmetric Scenario with R-parity violation.

Fabrizio Rompineve

École Polytechnique Fédérale de Lausanne

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Part I

A tale of two problems: Baryon Asymmetry and Naturalness

The observation

The Baryon Asymmetry in the Universe (BAU)

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10} \quad (1)$$

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$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{N_f}{32\pi^2}[g^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}] \neq 0 \tag{2}$$

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- Field configurations violating B (*sphalerons*) are efficient above the EW scale;

$\to$ Any preexisting B asymmetry would be washed out, unless it comes from a $(B - L)$ asymmetry, which would be conserved by sphalerons.

Baryogenesis

A more interesting possibility is to generate the BAU dinamically, at an energy scale Λ_B. However one would need to take care of the potentially dangerous sphalerons. Two well-known possibilities:

- *Leptogenesis*: generate first a lepton asymmetry, then convert it to a baryon asymmetry using the sphalerons;
- *Weak scale Baryogenesis*: $\Lambda_B \sim TeV$, when $\Gamma_{sph} \ll H$.

The general conditions for baryogenesis, whatever the scale, are:

Sakharov's conditions

- B violation;
- C and CP violation: B is odd under both symmetries, so if they are conserved there cannot be an asymmetry;
- Out-of-equilibrium: CPT invariance implies that the thermal average of B at equilibrium vanishes.

Beyond the SM, but where?

More on the out-of-equilibrium condition:

$$
\begin{aligned}
< B > = Tr[e^{-\beta\mathcal{H}}B] &= Tr[(CPT)(CPT)^{-1}e^{-\beta\mathcal{H}}B] \\
&= Tr[e^{-\beta\mathcal{H}}(CPT)^{-1}B(CPT)] = -Tr[e^{-\beta\mathcal{H}}B].
\end{aligned} \tag{3}
$$

Sakharov's conditions are satisfied in the SM.

→ $\not{B}$: sphalerons;

→ $\not{C}\not{P}$: Complex phase of the CKM matrix.

→ Out-of-equilibrium: impose $\Gamma < H(T) \simeq 1.66 g_*^{1/2} \frac{T^2}{M_{Pl}}$.

However, the complex phase of the CKM matrix does not provide enough CP asymmetry: it has been shown that, considering the decay of super heavy bosons, and using only the phase of CKM, η is too small by ≈ 8 orders of magnitude.

→ Supersymmetric extensions of the SM naturally accomodate B violating couplings, although these are usually neglected enforcing R-parity conservation.

The Minimal Supersymmetric Standard Model (MSSM)

$$W = \bar{u}\mathbf{y}_u Q H_u - \bar{d}\mathbf{y}_d Q H_d - \bar{e}\mathbf{y}_e L H_d + \mu H_u H_d, \tag{4}$$

Superfield	Spinor	Vector	$SU(3)_C, SU(2)_L, U(1)_Y$
G	$\tilde{G}$	G	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$
W	$\tilde{W}^{\pm} \quad \tilde{W}^0$	$W^{\pm} \quad W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
B	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Superfield	Scalar	Spinor	$SU(3)_C, SU(2)_L, U(1)_Y$
Q	$(\tilde{u}_L \quad \tilde{d}_L)$	$(u_L \quad d_L)$	$(\mathbf{3}, \mathbf{2}, 1/6)$
$\bar{u}$	$\tilde{\bar{u}}$	$\bar{u}$	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
$\bar{d}$	$\tilde{\bar{d}}$	$\bar{d}$	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
L	$(\tilde{\nu} \quad \tilde{e}_L)$	$(\nu \quad e_L)$	$(\mathbf{1}, \mathbf{2}, -1/2)$
$\bar{e}$	$\tilde{\bar{e}}$	$\bar{e}$	$(\mathbf{1}, \mathbf{1}, 1)$
H_u	$(H_u^+ \quad H_u^0)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, 1/2)$
H_d	$(H_d^0 \quad H_d^-$	$(\tilde{H}_d^0 \quad \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -1/2)$

R-parity

L and H_d have the same gauge quantum numbers! So W is not the most general renormalizable superpotential.

→ Lepton Number Violation:

$$W_{\not{L}} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda^{'ijk} L_i Q_j \bar{d}_k + \mu^{'i} L_i H_u \tag{5}$$

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→ The most general group of internal symmetries acting on Q is $U(1)$. *R-parity* is the remnant of a such a continuous symmetry, broken by the μ term and gaugino masses.

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- In the spirit of effective field theory, we may add non-renormalizable terms in W_{MSSM}, which respects R-parity, but violate B and L:

$$W \propto \frac{1}{\Lambda_{MSSM}} \bar{u}\bar{u}\bar{d}\bar{e}, \tag{7}$$

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- If $\not{R}$, no LSP: after all, the connection between Dark Matter and Naturalness is not a compulsory one. Something else may stabilize WIMPs.

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→ Justified in some frameworks: *Partial Compositness* or *Minimal Flavor Violation*.

→ Connection with Baryogenesis: the couplings λ''_{ijk} violate B, therefore they could play a rôle in the dynamical generation of the BAU.

A bit more on CP asymmetry

We will consider the out-of-equilibrium decay of a massive particle ($X \to f$) as the source of Baryogenesis. We still need to generate a CP asymmetry. Let us split the decay amplitude in tree level and one-loop terms:

$$\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_1 = c_0 \mathcal{A}_0 + c_1 \mathcal{A}_1, \tag{8}$$

Considering massless final states we obtain:

$$\epsilon_{CP} = \frac{\Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f})}{\Gamma(X \to \text{all}) + \Gamma(\bar{X} \to all)} = \frac{Im[c_0 c_1^*]}{\sum_{\text{all channels}} |c_0|^2} \frac{2 \int Im[\mathcal{A}_0 \mathcal{A}_1^*] d\Phi^{(n)}}{\int |\mathcal{A}_0|^2 d\Phi^{(n)}}, \tag{9}$$

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- $\to$ Loop diagrams develop an imaginary part when the virtual states go on shell!
- $\to$ All the decay channels must be considered in the denominator.

A tool of the Trade

A very useful result concerning CP asymmetry in the decay of massive particles has been obtained by Nanopoulos and Weinberg (1979):

Nanopoulos and Weinberg Theorem

Consider the decay of a particle X involving $\not{B}$ interactions. Assume that X is stable when the $\not{B}$ interactions are switched off. Then at first order in the baryon number violating interactions, the decay rate of X into all final states with a given value B of the baryon number equals the rate for the corresponding decay of the antiparticle $\bar{X}$ into all states with baryon number $-B$.

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- $\rightarrow$ We need to consider one loop diagrams at least of 2nd order in the $\not{B}$ couplings.
- $\rightarrow$ Caveat: if X is unstable because of B preserving interactions, then ϵ_{CP} can be generated even at $1st$ order in the $\not{B}$ coupling!
- $\rightarrow$ As a first task, we checked some proposed models of Baryogenesis through RPV in the literature: some of them seem not to take this theorem into account.

Part II

Baryogenesis from WIMPs in RPV SUSY.

Miracles and coincidences

- DM should be neutral under $U(1)$ and $SU(3)$. The abundance of cold relics is

$$\Omega_{\chi}^{\tau\to\infty} \simeq 0.1\left[\frac{g_{weak}}{g_{\chi/DM}}\right]^4\left[\frac{m_{med}^4}{m_{\chi}^2\cdot \mathrm{TeV}^2}\right] \simeq 0.1\frac{\alpha_{weak}^2/(TeV)^2}{<\sigma_A|v|>}, \tag{10}$$

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- Take it as an hint of a connection between DM and the BAU: could a metastable WIMP be responsible for Baryogenesis?

The Idea, recently put forth by Cui and Sundrum

- Consider a metastable WIMP χ, whose out-of-equilibrium decay generates a CP asymmetry.

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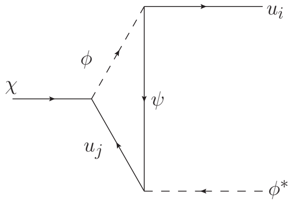
→ Goal: find a mechanism which provides $\epsilon_{CP} \sim O(1)$, and try to find its incarnation in Supersymmetric Models with R-parity violation.

1st Task: Check a Minimal Model

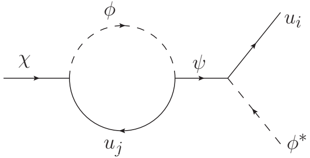
Add two Majorana fields χ and ψ and a scalar ϕ to the SM, and couple them to matter using three different couplings λ, ϵ_i, y_i.

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda_{ij}\phi d_i d_j + \epsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 + h.c. \qquad (12)$$

CP asymmetry is generated by the out-of-equilibrium decay $\chi \to \phi^* u_i$ and Baryon asymmetry is obtained through the decay $\phi \to d_i d_j$. In particular the relevant diagrams at one-loop level are:



(a)



(b)

Does it work?

The imaginary part of those loop diagrams can be computed either directly, using Dimensional Regularization to regulate the integrals, or using the Cutkosky rules:

$\rightarrow$ Cut the loop through the propagators which can simultaneously be put on shell, and substitute the cut propagators according to the prescription:

$$\frac{1}{p_i^2 - m_i^2 + i\epsilon} \rightarrow -2\pi i \delta(p_i^2 - m_i^2), \tag{13}$$

- With both calculations we find:

$$\epsilon_{CP} = -\frac{1}{8\pi} \frac{Im[(\sum_i \epsilon_i y_i^*)^2]}{\sum_i |\epsilon_i|^2} g(x), \tag{14}$$

with $g(x) = \sqrt{x}\left[\frac{1}{2(1-x)} + 1 - (1+x)\log(\frac{1+x}{x})\right]$, and $x \equiv \frac{M_\psi}{M_\chi}^2$. The result is the same as in leptogenesis with RH neutrinos.

- Assuming a large hierarchy $M_\chi \ll M_\psi$ we reproduce the result of Cui and Sundrum:

$$\epsilon_{CP} \simeq \frac{1}{8\pi} \frac{Im[(\sum_i \epsilon_i y_i^*)^2]}{\sum_i |\epsilon_i|^2} \frac{M_\chi}{M_\psi}. \tag{15}$$

CP asymmetry

$$\epsilon_{CP} \simeq \frac{1}{8\pi} \frac{Im[(\sum_i \epsilon_i y_i^*)^2]}{\sum_i |\epsilon_i|^2} \frac{M_\chi}{M_\psi}. \qquad (16)$$

- If $y_i \sim O(1)$, the mechanism provides a large asymmetry.

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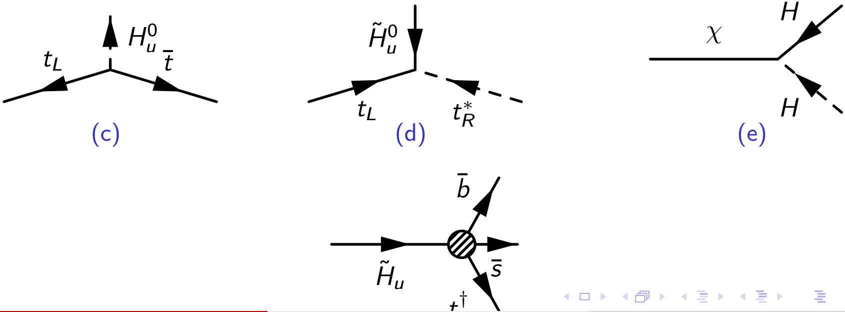
- One large coupling y, and another small one ϵ.

2nd Task: attempt at an incarnation in Split SUSY.

Let's try to incarnate the model of Cui and Sundrum in the framework of Split SUSY with R-parity violation:

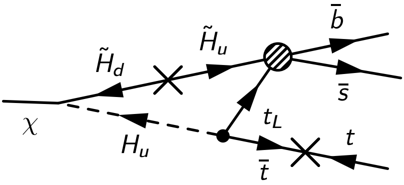
$$W = \lambda_{ij}\bar{t}\bar{d}_i\bar{d}_j + \epsilon\chi H_u H_d + y_t\bar{t}QH_u + \mu_\chi\chi^2 + \mu H_u H_d + \mu_S S^2 + \alpha\chi^2 S + \beta S H_u H_d. \quad (17)$$

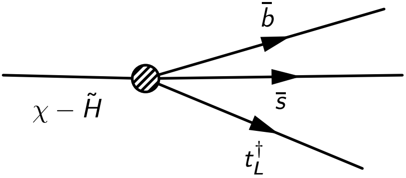
T, D_i, D_j contain the charge conjugated fermionic fields $\bar{d}_i = d^\dagger_{iR}$, while χ and S are chiral superfields. The superfield S contains a singlet scalar which is responsible for the annihilation of χ into SM states. In the effective theory obtained integrating out the squarks, the relevant vertices are:



The Majorana component of the WIMP χ can decay into quarks through the mixing with the Higgsino $\tilde{H}_u$. As usual, the CP asymmetry is generated by the interference between tree level and one loop amplitudes.

→ Neglect the contribution coming from the diagrams with $\tilde{b}$ and $\tilde{s}$, as they are proportional to $y_b, y_s \ll y_t$.





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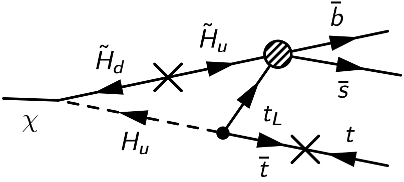

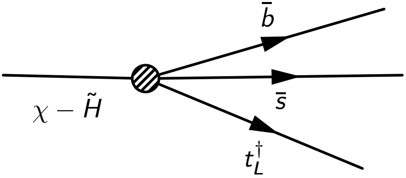

→ Only one power of the $\not{B}$ coupling λ''. However χ can decay through the B conserving channel $\chi \to \tilde{H}_d, H_u$, assuming the higgsinos to be lighter than the WIMP.

Calculation of the CP asymmetry

Remember:

$$\epsilon_{CP} = \frac{\Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f})}{\Gamma(X \to \text{all}) + \Gamma(\bar{X} \to all)} = \frac{Im[c_0 c_1^*]}{\sum_{\text{all channels}} |c_0|^2} \frac{2 \int Im[\mathcal{A}_0 \mathcal{A}_1^*] d\Phi^{(n)}}{\int |\mathcal{A}_0|^2 d\Phi^{(n)}}, \quad (18)$$

Tree Level Decay Rate:

$$\Gamma(\chi \to \bar{b}, \bar{s}, t_L^\dagger) = \frac{|\epsilon|^2 (|v|/M_\chi) \sin^2\beta |y_t|^2 |\lambda_{bs}|^2}{2^{10} \cdot 3\pi^3} \left(\frac{M_\chi}{M_{\tilde{t}}}\right)^4 |v|. \quad (19)$$

Interference with One Loop Diagram:

- The helicity structure of the diagram imposes the interference to be proportional to μ and m_t. We have to keep the mass of the virtual states in the calculation, and expand at the end.

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- The helicity structure of the diagram imposes the interference to be proportional to μ and m_t. We have to keep the mass of the virtual states in the calculation, and expand at the end.
- There are three possible cuts in the diagram, however only two, the ones passing through the higgsino propagator, give a contribution to the CP asymmetry. This is again an application of the result of Nanopoulos and Weinberg.

Result

$$\epsilon_{CP} \approx \frac{1}{8\pi} \frac{Im\{\epsilon^{*2} e^{-i\phi_\mu}\} y_t}{|\epsilon|^2 \sin\beta} \frac{|\mu| m_t}{v M_\chi} \frac{f(x_\mu, x_t, x_h)}{A}, \quad (20)$$

with $x_h = m_h/M_\chi, x_\mu = \mu/M_\chi, x_t = m_t/M_\chi$, and, at leading order in x_t, x_h, x_μ:

$$f(x_\mu, x_t, x_h) = \Big[-3\frac{x_h}{x_t} + \frac{1}{3}(2 - 8\ln\frac{1+\frac{1}{1-2x_h^2+2x_\mu^2}}{1-\frac{1}{1-2x_h+2x_\mu^2}} - 8\ln x_t + 12x_h^2 \ln x_t) \Big]. \quad (21)$$

A is a suppression factor:

$$A = 1 + \frac{2^6 \cdot 3 \cdot \pi^2 M_{\tilde{t}}^4}{|\lambda''_{bs}|^2 |y_t|^2 M_\chi^2 v^2 \sin^2\beta}. \quad (22)$$

$\rightarrow$ The suppression depends on the splitting between M_χ and $\tilde{M}$.

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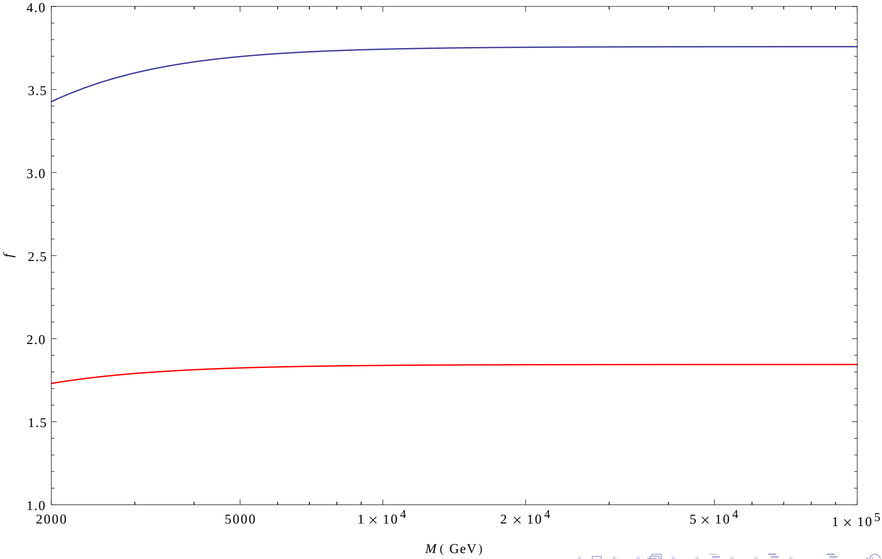
→ The suppression depends on the splitting between M_χ and $\tilde{M}$.

→ The price to pay to evade Nanopoulos and Weinberg: χ decays preserving B through a two-body channel, faster by at least a loop factor.

Plot of $f(x_\mu, x_t, x_h)$



Comments

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→ Even taking $\lambda''_{332} \sim O(1)$, the asymmetry is still suppressed by a loop factor and by the ratio $\frac{M_{\tilde{t}}^4}{M_\chi^2 v^2}$.

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- $\rightarrow$ Even taking $\lambda''_{332} \sim O(1)$, the asymmetry is still suppressed by a loop factor and by the ratio $\frac{M^4_{\tilde{t}}}{M^2_\chi v^2}$.
- $\rightarrow$ Hierarchy of masses and couplings of WIMPs is required to compensate the small ϵ_{CP}: if the splitting is minimal ($O(1)$), then:

$$\left[\frac{M_{DM}}{M_\chi}\right]^2 \left[\frac{g_{DM}}{g_\chi}\right]^4 \gtrsim 10^7, \quad (24)$$

which is satisfied for not too large hierarchies.

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- → Another, less important, constraint on the splitting comes from the out-of-equilibrium condition $\Gamma < H$:

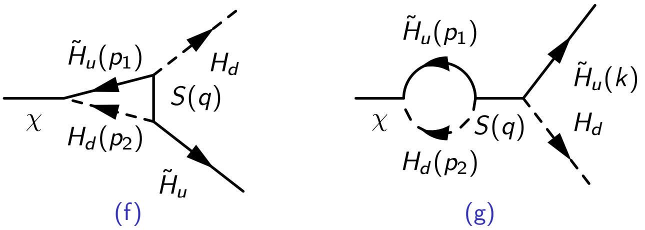
$$10^{-12} \left[\frac{M_\chi}{M_{\tilde{t}}}\right]^{-2} \lesssim \epsilon \lesssim 10^{-7} \left[\frac{M_\chi}{M_{\tilde{t}}}\right]^{-2} \qquad (25)$$

3rd Task: another incarnation.

$$W = \lambda_{ij}\bar{t}\bar{d}_i\bar{d}_j + \epsilon\chi H_u H_d + y_t \bar{t} Q H_u + \mu_\chi \chi^2 + \mu H_u H_d + \mu_S S^2 + \alpha\chi^2 S + \beta S H_u H_d. \quad (26)$$

Let us generate the BAU in two steps:

1 First generate CP asymmetry through the decay channel $\chi \to H, \tilde{H}$.



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1. First generate CP asymmetry through the decay channel $\chi \to H, \tilde{H}$.
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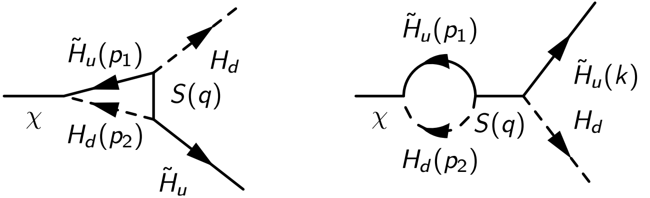

(h) (i)

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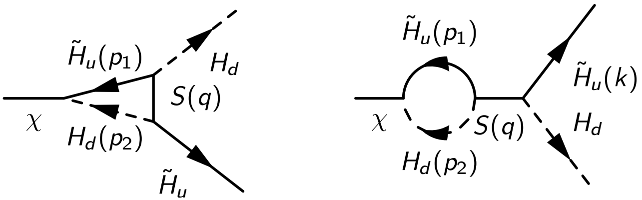
→ At one-loop, use the Majorana component of S. The computations are the same as those ones done in the first case.



(j) (k)

Comments

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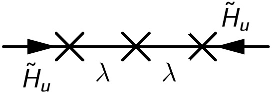

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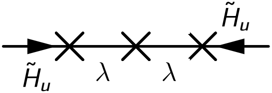

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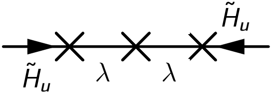

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→ Work in progress...

Thanks for your attention!

A step back: why BSM?

The SM in a Nutshell

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$\mathcal{L}_{SM}$ is renormalizable and describes *almost* everything that we see. Nevertheless there are some reasons not to be too presumptuous:

→ Gravity should become important at $\Lambda_{Planck} \approx 10^{18}$GeV, and it is not described by $\mathcal{L}_{SM}$;

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The ways of Nature are infinite, or not?

Let us focus on the Higgs Mass term. It is true that one could fine tune the coefficient of the Higgs mass term in such a way as to reproduce the observed value. Apart from this rather unsatisfactory device, how can one avoid the coupling of the Fermi scale to any other higher scale in the theory?

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Add fermionic generators to the Poincarè algebra and build representations of the *Super-Poincarè* group:

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→ Extra-dimensions.

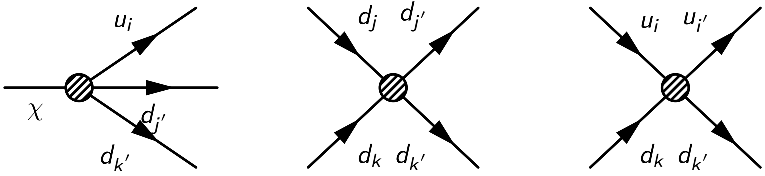
2nd Task: Can we do it with only the $\not{R}$ couplings?

$$\mathcal{L}_{int} = \lambda_{ijk}\phi_{u_i}d_jd_k + \lambda_{ijk}u_i\phi_{d_j}d_k + \epsilon_i\chi\bar{u}_i\phi_{u_i} + \frac{1}{+}\mathcal{L}_{mass} + c.c.. \qquad (34)$$

Assume that the scalars of the theory are much heavier than the fermions, and integrate them out. We obtain the following effective vertices:

$$c_a = \frac{\epsilon\lambda^*_{ij'k'}}{M^2_{\phi_{u_i}}} \quad c_b = \frac{\lambda_{ijk}\lambda^*_{ij'k'}}{M^2_{\phi_{u_i}}} \quad c_c = \frac{\lambda_{ijk}\lambda^*_{i'jk'}}{M^2_{\phi_{d_j}}}. \qquad (35)$$

→ Only c_a violates B!



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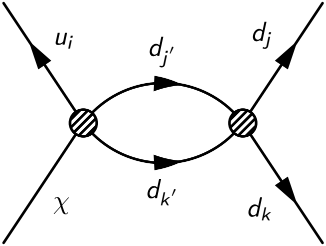

By Nanopoulos and Weinberg, one loop diagrams in the effective theory give a vanishing contribution to ϵ_{CP}! Indeed:

$$\epsilon_{CP,i} \propto Im\{c_o c_1^*\} = Im\{\frac{|\epsilon_i|^2 |\lambda_{ij'k'}|^2 |\lambda^*_{ijk}|^2}{M^6_{\phi_{\boldsymbol{u_i}}}}\} = 0, \qquad (36)$$

for each value of the indices. We need to go at two loops, and by dimensional analysis:

$$\epsilon_{CP} \sim \frac{\lambda^2 M_\chi^4}{M_\phi^4} \times (\text{loop factor}). \qquad (37)$$

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- Moral of the Story: models with only one coupling controlling the CP asymmetry and the out-of-equilibrium condition are highly constrained!

An aside: Large Expectations

In the spirit of effective field theory, let's write down the most general Lagrangian in 4d expanding in $1/Mass$:

$$\mathcal{L} = (\Lambda_{NP})^4\sqrt{g}A + L_{SM+\theta_{QCD}} + \frac{1}{\Lambda_{NP}}[(l^a C l^b)H_a H_b + \ldots] \quad (39)$$

$$+ (\frac{1}{\Lambda_{NP}})^2[(u_\alpha C\gamma_\mu u_\beta)(eC\gamma^\mu d_\delta)\epsilon^{\alpha\beta\gamma} + \ldots] + \ldots \quad (40)$$

Absence or smallness of phenomena coming from higher order terms hints at a very high fundamental scale, $\Lambda_{NP} \gtrsim 10^{14}$ GeV. However two important terms with $d < 4$ *naturally* blow up if Λ is big:

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