Probing CP and CPT-odd baryogenesis at low energies

Maxim Pospelov

University of Victoria/Perimeter Institute, Waterloo

Based on papers

hep-ph/0406089 *(J. Archambault, A. Czarnecki, MP)*

hep-ph/0610003 *(S. Huber, A. Ritz, MP)*

hep-ph/0610070 *(P. Bolokhov, MP)*

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction. Baryogenesis: CP or CPT?
2. Charged lepton EDMs vs minimal leptogenesis
3. Neutron EDM in the "effective" baryogenesis approach
4. Leptogenesis driven by dim=5 CPT-odd operators
5. Conclusions

Motivations

1. WMAP (+ other things) measure $\eta_b \simeq 6\times 10^{-10}$. Where does it come from? 50-some theories compete to explain one number…
2. Leptogenesis provides the most "relaxed" scenario, and has a nice connection to Majorana neutrino masses. Is there a chance of inducing [measurable] EDMs of charged leptons?
3. If EW baryogenesis is "minimal": no light states in 100-300 GeV range but only effective operators from the SM fields, is it possible to make one-to-one connection between η_b and EDMs? If yes, what is the remaining room for EWB if any?
4. However crazy, is it possible to use effective CPT violation to drive baryogenesis? What about CPT-odd leptogenesis? How much CPT violation do we really need?
5. Are the searches of CPT violation well motivated?

Baryogenesis: CP or CPT?

1. Baryon number violation
2. Departure from equilibrium
3. C and CP violation

(Sakharov)

1. Baryon number violation
2. CPT violation

(Zeldovich, Kuzmin, Dolgov …)

Another important issue: **CP (CPT) violation, is it a "transient" effect or something that "stays" and can be probed in experiment?**

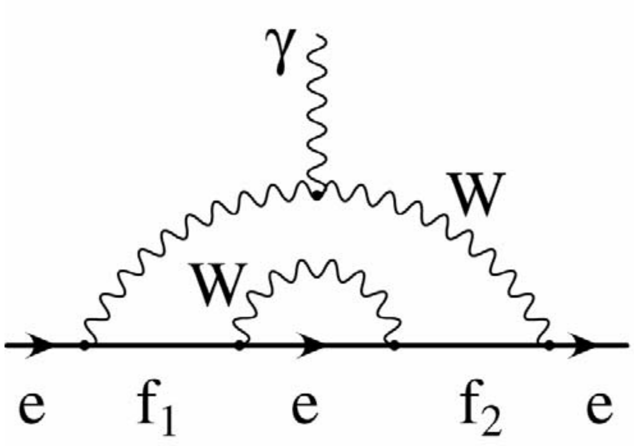
For example, $\phi\, \varepsilon_{\mu\nu\alpha\beta} W_{\mu\nu} W_{\alpha\beta}$ is CP-odd but will look CPT-odd should $d\phi/dt \neq 0$. Same issue for CP violation. (e.g. Davoudiasl, Langacker's talks)

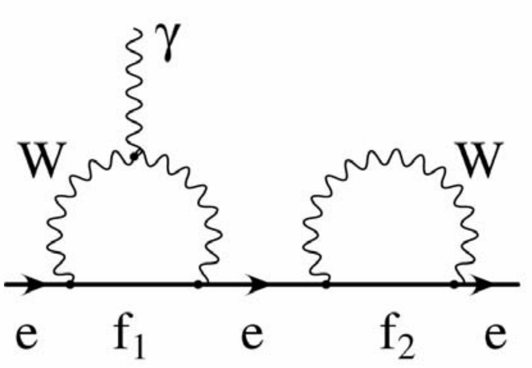
In this talk, I will assume "permanent" CP and/or CPT violation…

Majorana neutrinos and EDMs at two loops

hep-ph/0406089 *(J. Archambault, A. Czarnecki, MP)*

If neutrinos are Dirac particles, one needs 3 generations and three loops to generate a non-zero d_e



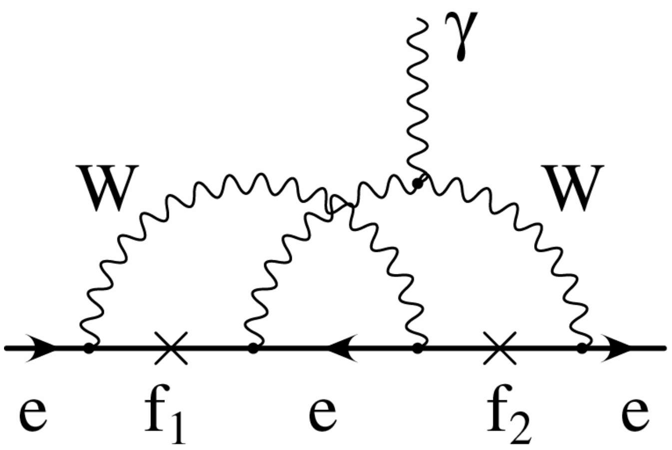


Vanishing of two-loop diagrams was shown by Shabalin (1982)

Majorana neutrinos and EDMs at two loops

For Majorana neutrinos new type of topology is possible,

and the result is not zero at two loops (Ng and Ng, 1995)



Plus photon and fermion permutations

A model with two heavy and one light neutrinos

$$\mathrm{M} = \begin{pmatrix} 0 & m_{D1}e^{i\eta} & m_2 \\ m_{D1}e^{i\eta} & M_1 & 0 \\ m_2 & 0 & M_2 \end{pmatrix} \Rightarrow$$

$$\mathrm{M}^{diag} = \begin{pmatrix} -\frac{m_{D1}^2 e^{2i\eta}}{M_1} - \frac{m_{D2}^2}{M_2} & o_2 & o_2 \\ o_2 & M_1 + o_1 & o_1 \\ o_2 & o_1 & M_2 + o_1 \end{pmatrix}$$

After the diagonalization, the complex phase resides in the mixing matrix, and $o_n = m_D(m_D/M)^n$

The result of the two-loop calculation

$$d_e = e\left(\frac{G_F}{16\pi^2}\right)^2 m_e \frac{\Delta M m_{D1}^2 m_{D2}^2}{M^3}\left(\frac{32}{3}\ln\frac{M}{m_W} - \frac{260}{9} + \frac{112\pi^2}{27}\right)\sin 2\eta$$

and this is in the limit

$m_D^2 / M << m_l << m_W << M_{1,2}$; and $M_1 - M_2 << M$

As expected, the result scales as Yukawa^4 and M^{-2}

Is it totally hopeless?

For a regular see-saw hierarchy, $m_\nu \sim m_D^2/M$, the result is really small,

$$|d_e| = e\left(\frac{G_F}{16\pi^2}\right)^2 m_e m_\nu^2 \frac{|\Delta M|}{M^3}\left(10.7\ln\frac{M}{m_W}+12.1\right) < 10^{-43}\, e\mathrm{cm}$$

Only for large, EW-scale, Dirac masses there is a glimmer of hope,

For that we need $\delta = \eta - \pi/2$ to be small, while $m_{1,2}$ large

$m_\nu^2=[(m_1^2-m_2^2)^2+4m_1^2m_2^2\delta^2]/M^2$

Requiring Yukawa to stay perturbative, we still get $d_e < 10^{-34}$ ecm

(essentially in this limit $d_e \sim \delta \sim m_\nu$)

Conclusion I

Although the result is much enhanced relative to the Dirac mass model (two loops instead of three), the answer is very small.

Going over to the special case of large Dirac masses and cancellation of two terms in light neutrino masses (inverted see-saw?) the result is …still very small.

EDMs cannot probe minimal SM leptogenesis.

Electroweak Baryogenesis in "effective" framework

SM baryogenesis does not work because:

1. The transition between the two phases is very smooth
2. δ_{CKM} or θ_{QCD} are very weak sources of CP-violation in the Early Universe

Let us try to cure both problems by choosing the following framework:

$$\mathcal{L} = \mathcal{L}_{SM} + O^{CP\ even}/\Lambda^2 + O^{CP\ odd}/\Lambda_{CP}{}^2$$

"No new degrees of freedom" around 100-200 GeV

[*there is some degree of deception if I phrase it as effective theory*]

The choice of Effective Operators

(Grojeant, Servant, Wells; Bodeker et al., 2004)

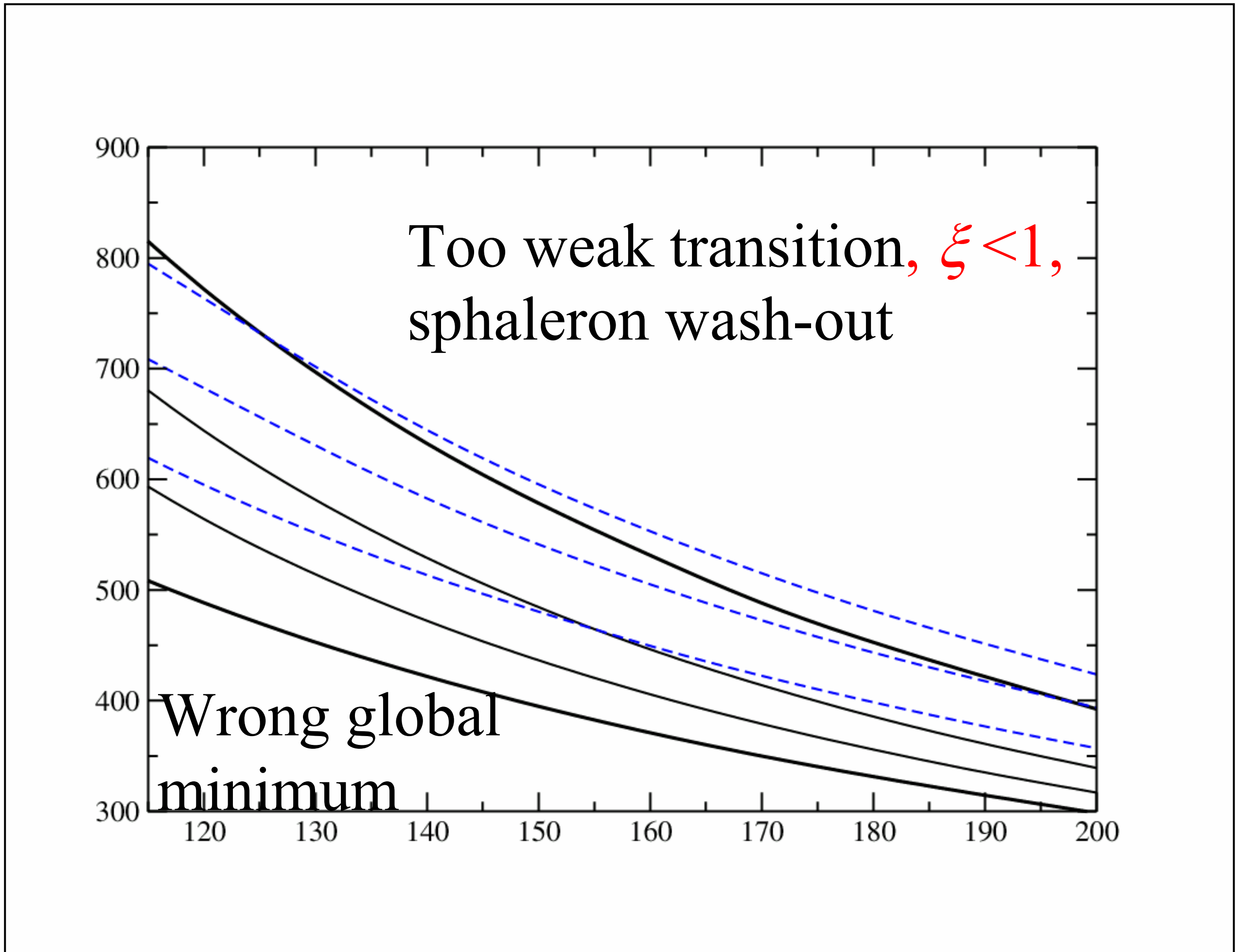
$$\mathcal{L} = \mathcal{L}_{SM} + (H^\dagger H)^3/M^2 + t^c H Q_3 (H^\dagger H) \times Z_t/M^2$$

- I will call $\mathrm{Im}(Z_t/M^2) \equiv 1/M_{CP}{}^2$
- You can trivially obtain this Lagrangian from two-Higgs doublet model by assuming mild hierarchy of mass scales and integrating out heavier Higgs field.
- Both terms are essentially tree-level terms unlike terms, whereas

  $\varepsilon_{\mu\nu\alpha\beta} W_{\mu\nu} W_{\alpha\beta} (H^\dagger H)^3$ is necessarily loop level no matter what kind of UV completion you have.

EW baryogenesis part: M vs m_h plot

The strength of the phase transition, $\xi = v_c/T_c > 1.1$, to avoid wash-out



EW baryogenesis part: *further comments*

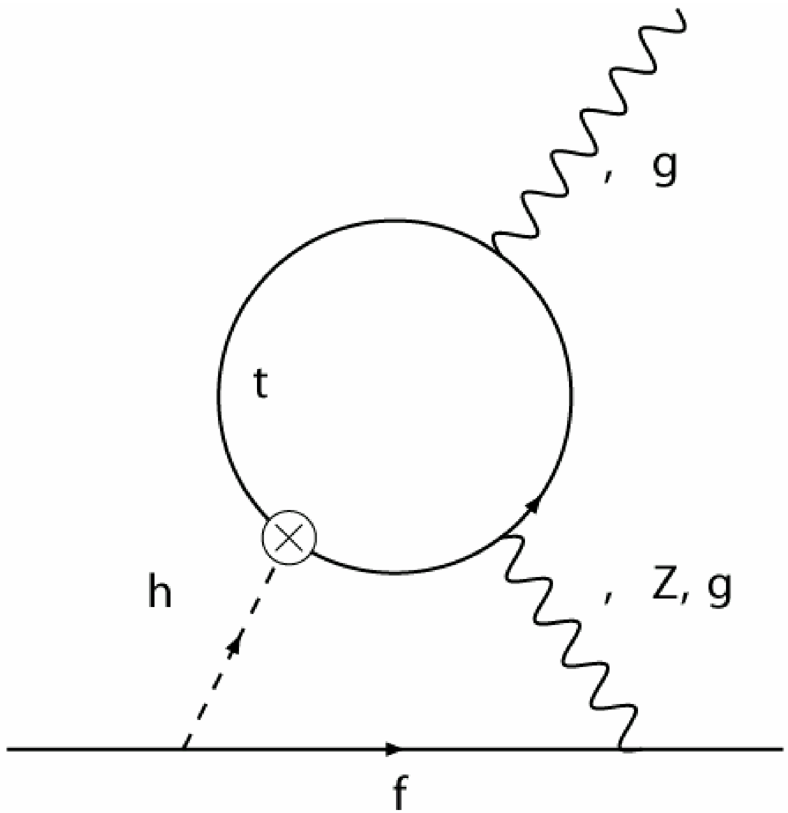
- Thick wall approximation, $L \sim O(10)\times T_C^{-1}$
- Real and imaginary part of the top mass vary differently inside the domain wall, $\mathrm{Re}\, m_t \sim v$; $\mathrm{Im}\, m_t \sim v^3$

  This is a CP-violating situation. Top and anti-top have different dispersion relations inside the wall.
- Very similar to the 2HDM where EWB was studied in a number of previous publications
- This is NOT a small modification of the SM as it might seem.

  $\lambda\,(H^\dagger H)^2$ term is negative (!!!), which means that in the true EW vacuum both H^4 and H^6 terms are of the same order. This is NOT a small change. Condition used v_{min} =246 GeV, and $d^2 V/dH^2|_{min} = m_h^2$

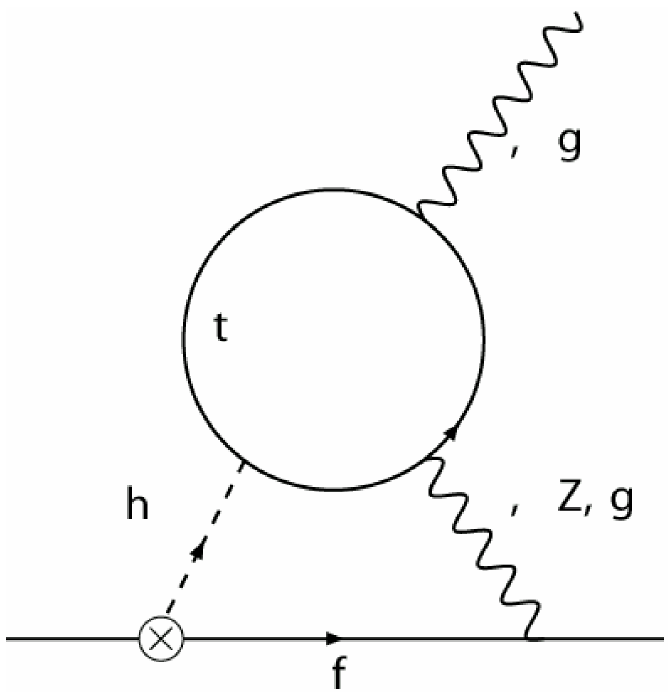
Old story: EDMs from CP-odd top-Higgs coupling

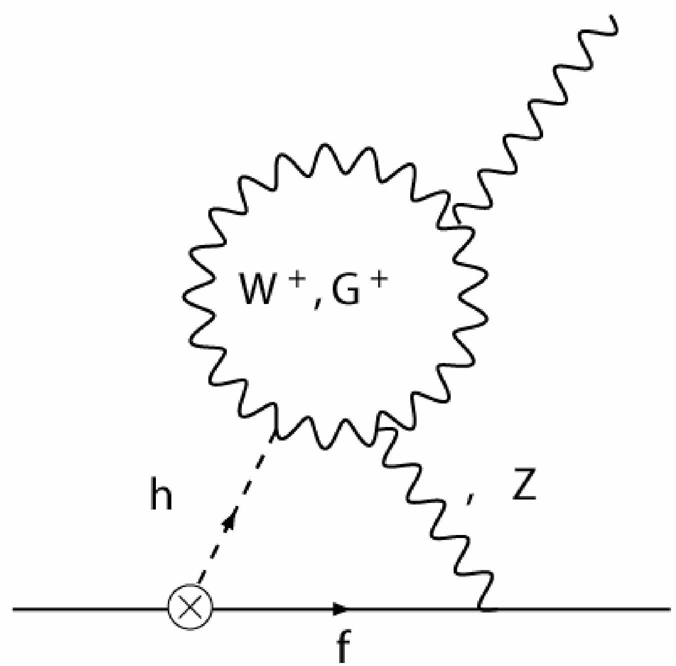
Does this look familiar? This is a Barr-Zee diagram with the SM Higgs, and a CP-odd top-Higgs vertex. It is well-known analytically



Additional diagrams from light quark operators

Additional diagrams from *UHQ($H^\dagger$ H)* operators needed to ensure the absence of FCNC

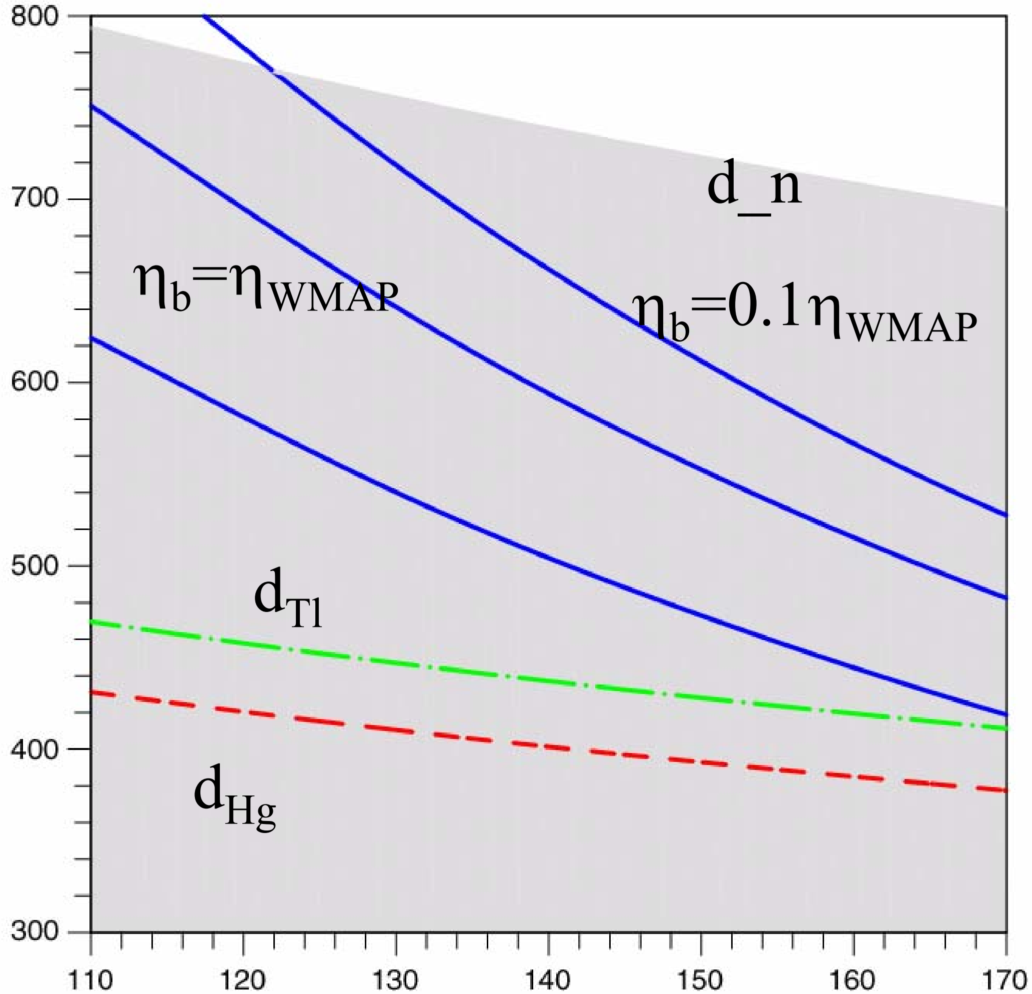




EDM results put pressure on "effective" EWB

1. When only the EWB driving phase is included, $M=M_{CP}$

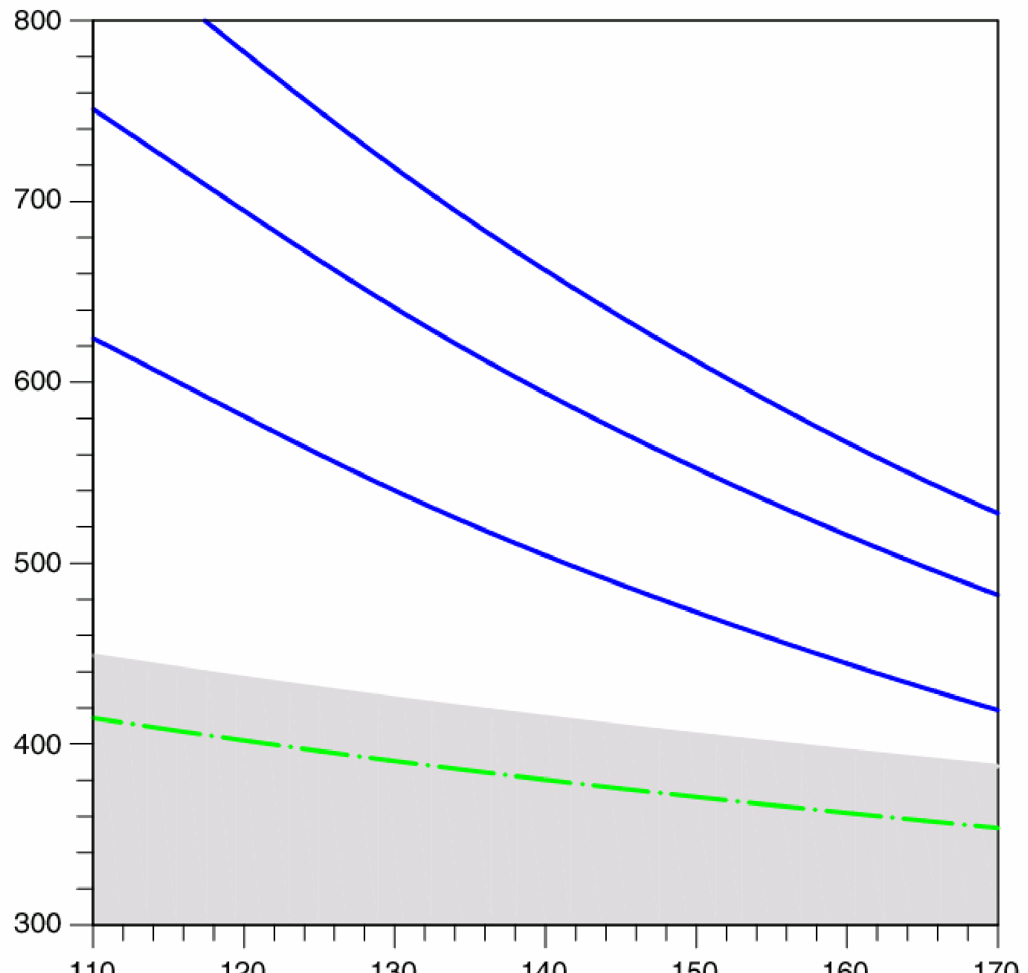
Effective scale M



m_h

Couplings to light fermions are included

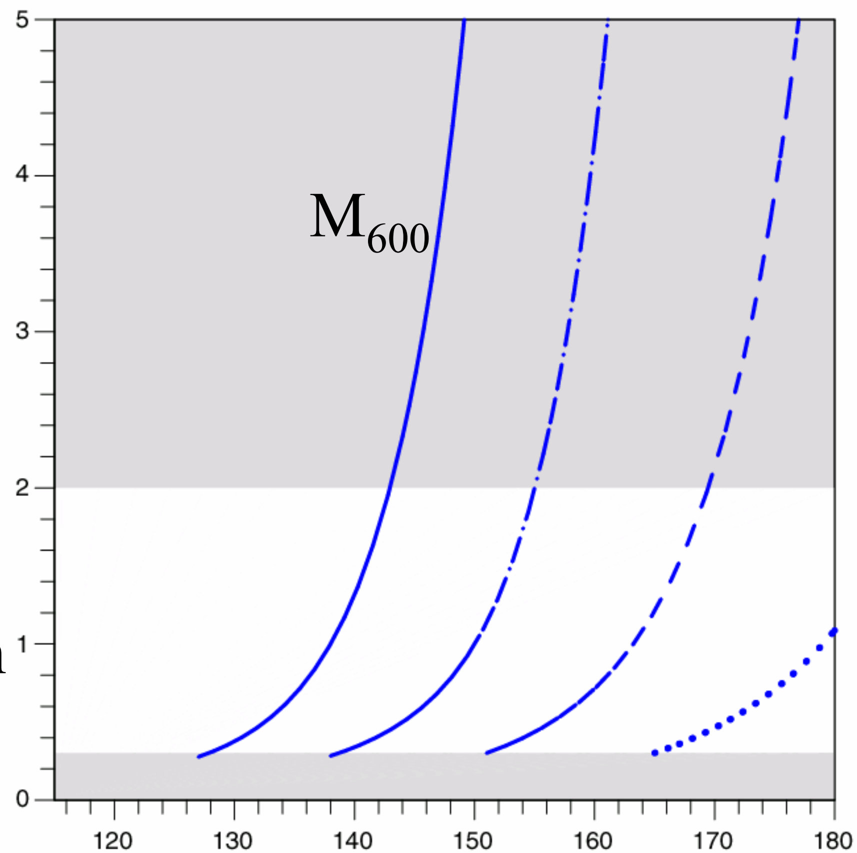
There is some mutual cancellation between diagrams, and the parameter space opens up (a little bit).



EDMs vs Higgs mass plot

Let us relax $M = M_{CP}$ assumption and impose $\eta = \eta_{\rm WMAP}$ constraint on (M, M_{CP}, m_h) parameter sp., and plot $d_n(M,m_h)$

$d_n = 3\ 10^{-26}\ e$cm



Upper part is excluded by EDM, lower part is excluded by stability of v=0 vacuum

Higgs mass

Conclusions II

- **The minimalistic choice of effective operators "fixes" the problem of EWB in the SM.**
- **The CP-odd Higgs-top coupling can drive EWB and source EDMs at two loops.**
- **Without any additional contributions, neutron EDM rules out our minimal model. Additional diagrams with CP-odd source on light quark mass make EDMs smaller and open up parameter space.**
- **Additional progress in neutron EDM by one order of magnitude would either rule out the model or find a non-zero result.**

CPT-odd baryo/leptogenesis: main idea

- See e.g. Dolgov's review of non-GUT baryogenesis (1992)

Suppose, there is a "CPT-odd mass part of the top-quark",

$\Delta\, m_{CPT}$: $E^2 = p^2 + m^2 \pm m\Delta m_{CPT}$

If there are processes that flip top into anti-top and back (e.g. sphalerons), then $\Delta\, m_{CPT}$ will serve as a chemical potential for particles. There will be a net asymmetry proportional to the CPT-odd mass deformation. 10^{-6} as Δm_{CPT} in the quark sector will do the job, as spalerons freeze-out around $T \sim 100$ GeV.

There are two slight problems with that:

1. There is no such thing as $\Delta\, m_{CPT}$, at least not without Lorentz breaking
2. In effective theory parametrization of Lorentz violating effects, $\Delta\, m_{CPT}$ is typically constrained better than 10^{-22} eV

Recent literature on CPT-odd baryogenesis

- One got to use higher-dimensional operators. (Bertolami, Kostelecky, Potting, 1997). It pushes baryogenesis to higher temperature scales. The decays of heavy particles in the GUT type of B-violation with CPT-odd sources were considered.
- In a recent paper, S. Carroll and J. Shu (2005) considered several dynamical (or semi-dynamical) models of CPT violation (see next talk).
- P. Bolokhov and MP (2006) used higher-dimensional CPT-odd sources plus lepton violation to store non-zero (B-L) number, e.g. in essence CPT-odd leptogenesis.

CPT-odd leptogenesis: main advantage

Suppose that there are dim=5 CPT-odd (and Lorentz violating) terms in the Lagrangian. For example, those that give energy-dependent modification of dispersion relations:

$E^2 = p^2 + m^2 \pm \eta\, E^3/M_{Pl}$

Let us "project" them into B-L and B+L.

The baryon asymmetry due to B+L part will scale as

$\Delta B/s \sim 10^{-2}\eta\, T_{sph.\ freeze\text{-}out}/M_{Pl} \sim 10^{-2}\eta\, m_W/M_{Pl} < 10^{-18}$

Very small!! On the other hand

$\Delta B/s \sim \eta\, T_{L\ violation\ freeze\text{-}out}/M_{Pl} \sim \eta\, 10^{11}\ \mathrm{GeV}/M_{Pl} \sim 10^{-9}$

One got to combine lepton violation with CPT violation for more efficient use of UV-enhanced CPT-odd sources

CPT and LV sources

- Lepton violation is sourced by

$$y^2 M^{-1}(LH)(LH) \quad \text{terms}$$

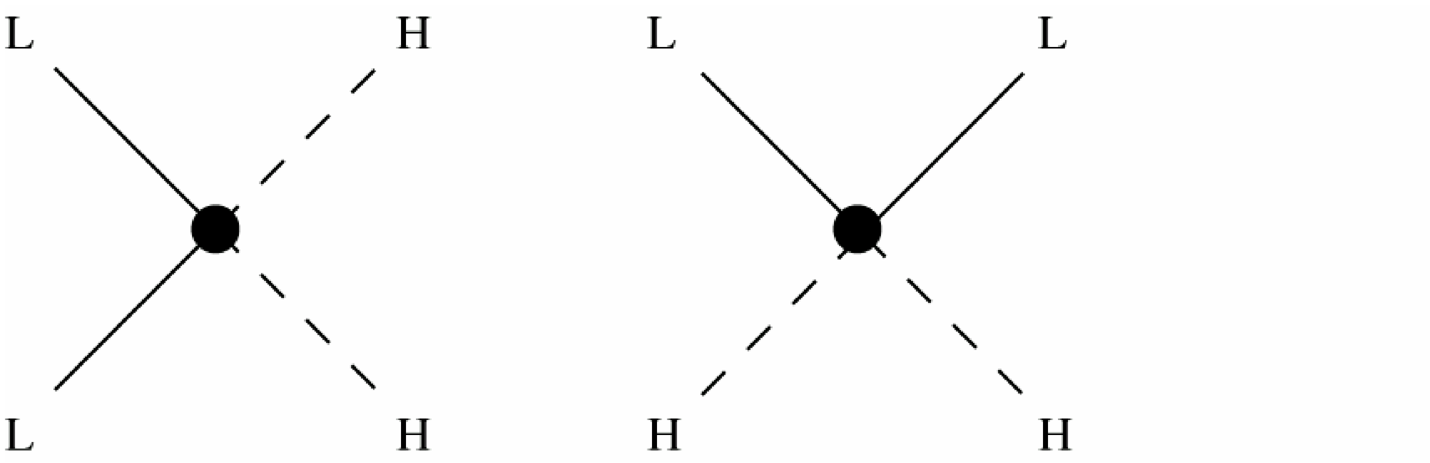
(Although we do not insist on see-saw, we assume that these operators stay local until very high energies)

- CPT violation is sourced by

$$\sum_{quark,leptons} \eta_{\mu\nu\rho} \overline{\psi}\gamma_\mu \partial_\nu \partial_\rho \psi$$

Tensors $\eta_{\mu\nu\rho}$ are traceless to prevent the "leaking" into dim 3 operators at loop level. This is a subset of [numerous] dimension 5 LV operators analyzed in Myers, MP (2003), Bolokhov, MP (2007). Tensor η specifies the preferred frame.

Δ L =2 processes and chemical potential



The rate of $\Gamma_{\Delta L=2} \sim T^3 y^4/M^2 \;\; \rightarrow m_\nu^2 T^3/vev^4$

For realistic m_ν it becomes smaller than Hubble at $T_R \sim 10^{12}$-10^{13} GeV. The larger – the better.

Effective over-abundance of L over anti-L in equilibrium $\sim \eta_L\, T$

In principle, one heavy neutrino will suffice (unlike the CP-odd case)

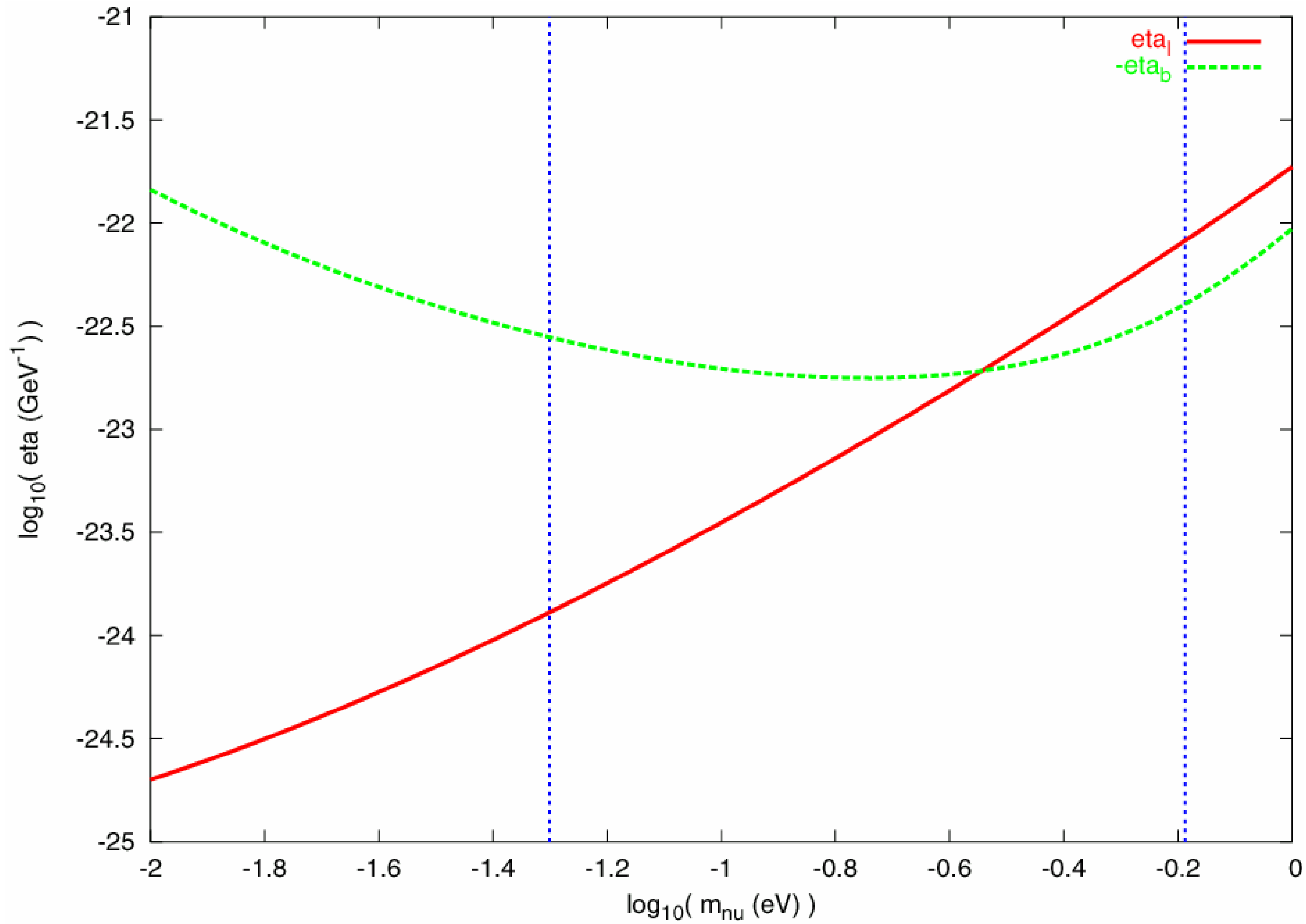
How much CPT violation do we really need?

Analytic estimate of the freeze-out abundance [neglecting the impact of sphalerons in Boltzmann equation] gives

$\text{Asymmetry} \sim 10\,(\eta_L M_R^2 g_*^{1/2})/(M_{Pl}\,y^4)$, while $T_R \sim 10^{12}$ GeV

A more accurate solution of Boltzmann equations give

Leptonic(Red) and Baryonic(Green) sources of CPT required to reproduce observed BAU
More than $1/M_{Pl}$ suppressed operators will work!



Constraints on transplanckian CPT violation

Constraints on dim=5 Lorentz violation is pretty stringent:

1. UV-enhanced operators are constrained by Cherenkov radiation in vacuum (Coleman, Glashow) and by the very existence of high-energy cosmic rays (Moore, Gagnon)

   Constraints on η's are better than $10^{-15}/M_{Pl}$!

   But there are "islands" where Lorentz violation can survive,

   e.g. (in up-quark sector, when proton decays to Δ^{++})
2. By low-energy spin precession data (Myers, MP) which for light quarks η_{CPT} are ruled out at 10^{-8}-$10^{-7}/M_{Pl}$ level. This is at least four-five orders of magnitude more stringent than than the level needed for the CPT-odd leptogenesis.

Conclusions III

Storing a non-zero B-L improves the survival of CPT-odd baryogenesis

By adding both L and CPT violation via dimension 5 operators we calculated the baryon asymmetry to find that $10^{-22} - 10^{-24}$ GeV^{-1} strength of CPT-odd sources is needed.

This is already in trouble in view of the stringent laboratory constraints on spin precession, and from the propagation of high-energy cosmic rays